DESIGN OF A PROPULSION SYSTEM WITH DOUBLE-LAYER POWER CAPACITORS AND SOFT-SWITCHED CONVERTERS FOR A HYBRID AUTOMOBILE

By

Luis Eduardo Zubieta

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Graduate Department of Electrical and Computer Engineering
University of Toronto

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0-612-58962-5
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ABSTRACT

The increasing pollution levels, especially in cities, have made the development of more environmental friendly vehicles an urgent need. Although millions of dollars have been spent on electric vehicle research, no electric vehicle capable of competing with normal vehicles based only on internal combustion engines has been developed. The problem is associated with the difficulty to store the amount of energy needed and supply it at high power levels. Hybrid electric vehicles represent a very attractive option to reduce pollution while maintaining good performance.

The double-layer power capacitors are an attractive option in hybrid vehicles due to their high power density and long lifetime. However, these devices are new, and the assembling of large energy storage units has to be studied before using them in vehicle systems. Voltage sharing is especially critical since many devices have to be connected in series to reach the technically required voltages.

To improve the global efficiency for the vehicle, the electric propulsion system has to be designed to minimise weight and size. The use of higher switching frequencies brings important
reductions in weight mainly for the magnetic components. However, due to the switching losses, the switching frequency cannot be increased unless soft-switching technologies are used. When using an energy storage device with low energy density in a hybrid vehicle, the energy management strategy is of great importance to reduce the energy storage capability required to achieve the desired performance. The energy manager takes the actions needed to operate the energy storage unit and the engine according to the specifications and maximises the energy utilisation under different driving conditions.

This thesis deals with the design of a propulsion system for a series hybrid vehicle. It includes the study of an energy storage unit using double-layer capacitors and a lightweight soft-switched converter system, two innovative components in series hybrid vehicles. Furthermore, the thesis formulates an easy-to-follow design strategy for vehicles using similar configurations and directed to minimise the fuel consumption. The thesis also includes the formulation of an energy management strategy optimised for the vehicle characteristics and the implementation of an experimental prototype for the proposed system.
ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Professor Richard Bonert for his guidance and devotion to this project. His recommendations, corrections, and support made it possible the successful completion of this thesis.

My parents, Carlos and Cecilia, and my brother, Juan, all of whom I admire, have been a source of support and inspiration throughout my studies. I especially thank my wife for her sincere love, understanding, and support in these four years.

I also thank the Professors in the Department of Electrical and Computer Engineering and especially Professor Francis Dawson for their recommendations and useful comments. I thank Mr. Jack Goldstein from the Power Laboratory for his friendship and assistance during the many hours spent in the lab. I also thank Stefan Reichert, Christian Spagno, Philip Hürlimann, Dionysios Kouroussis, and Andrew Brzezinski who were valued collaborators in the practical implementation and testing of the prototype.

Finally, I would like to thank my friends from the Power Group for their comments and recommendations, and my friends from Charles St. Family Housing for their humour and companionship, giving me distraction and fun throughout my studies.
DEDICATORY

This thesis is dedicated to my first child, soon to be born. All my effort is aimed to your welfare and happiness.
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INTRODUCTION

Cars have become a fundamental part in the everyday lives of millions of people. Every year, tens of millions of cars are sold all around the world. Internal combustion engines propel almost all of these vehicles. The drawback of cars is the high pollution from internal combustion engines. The toxic emissions from vehicles, going into the atmosphere, are making the air in big cities difficult to breathe, and represent a serious threat to the ecological equilibrium of the entire planet. Although important reductions in the level of emissions from cars have been achieved over the last decades, these improvements are not enough to compensate for the steady increase in the number of vehicles around the world. The problem appears to be getting worse as more people all over the world are now able to acquire vehicles, and too often these vehicles are operated without the proper maintenance, polluting even more.

In standard cars, the engine size is determined by the desired acceleration performance. In practice, the power required for acceleration may be six times the average power used for city driving and more than twice the power required to drive at highway speeds [1]. In consequence, the engine is severely under utilised except in periods of acceleration; this is more notable in city driving. As the engine efficiency depends heavily on the loading with lower efficiency at lower loads, the engine operates most of the time far from its maximum efficiency. Furthermore, the internal combustion engine has to follow the fast transients of the drive cycle to provide the required performance, and the sudden changes in delivered power increase the pollution from the engine.

One of the main questions to be answered by engineers is how to reduce pollution caused by cars particularly in cities. A more environmentally friendly transportation vehicle is required to answer this question. However, the performance of standard vehicles, apart from pollution, is so good that it is difficult to find another technology capable of reaching a similar performance and popular acceptance.

Electric cars are often seen as an alternative to cars with internal combustion engines since they do not produce pollution while operating. But electric vehicles with batteries have a large weight, poor performance in acceleration and driving range, and short lifetime. The disadvantages result mainly from the fact that there is no economical method available to store electrical energy in large quantities and with fast recharging possibilities.
Another option is to find a way to operate the internal combustion engine under more efficient and less polluting conditions. Combining an electric drive system with an internal combustion engine, a hybrid drive can be built. Hybrid vehicles take advantage of the high energy density from fuel and the conversion efficiency and cleanliness of electric drives. The advantage of a hybrid drive is a very good driving performance regarding acceleration and driving range with considerably less fuel consumption and pollution. This is achieved since the engine operates only in high efficiency regions and provides the average energy required for driving, whereas the electric drive system, including an electric energy storage device, provides the required acceleration and electric braking. This principle, known as load levelling, has been used in the past to make loads with a wide range of power demands more efficient. In a hybrid drive, the engine operation is partially or completely decoupled from the driving transients, allowing the use of a smaller engine rated only for steady state conditions and controlling its operation to get the maximum possible efficiency and the minimum pollution. Furthermore, the engine can be operated in a quasi-steady state mode, i.e. under slow transients, which reduces the pollution levels even more. In addition, the use of electric machines makes it possible to recuperate, during braking, the kinetic energy stored in the vehicle mass thus improving the energy utilisation. The concept of load levelling is applicable not only in hybrid vehicles, but also with minor modifications it would bring improvements in efficiency and size to designs using fuel cells or advanced batteries that have high energy density but usually lower power capability.

To build a hybrid vehicle system that uses the principle of load levelling, it is necessary to get sufficient performance from the different components required for the design: electric machines, energy storage technology, converter technology, and microelectronics technology. As the hybrid vehicle is propelled at least in part by electric machines, they have to be capable of providing the required power and torque for steady state and acceleration, with good efficiency, and smooth and fast response.

A hybrid vehicle requires an energy storage technology capable of storing the amount of energy required, delivering it at the power levels needed, and having several years lifetime. This thesis studies the double-layer power capacitors (DLCs), a new technology to store electric energy, as a possible energy storage component in hybrid vehicles. These devices offer the advantage of very good power density and long lifetime compared with batteries, which makes them attractive in the automotive field. Batteries could also be considered as energy storage devices; however, they have limitations detrimental to the hybrid vehicle performance. Batteries in general have better specific energy than DLCs, but they have poor power performance if the
energy has to be released fast as is required for acceleration. Furthermore, most batteries lifetimes are too short to last the 10 years expected lifetime of a vehicle.

The hybrid electric drive system needs an electronic control system or converter made of power electronic devices to efficiently regulate the power flow. The converter technology has been used and known for industrial applications. However, in contrast with vehicles, weight is usually not an issue for immobile equipment and the existing components may be quite heavy for high power applications. It is proposed in this thesis to use a soft-switching topology for the vehicle converters in order to increase the switching frequency and reduce the weight especially for the magnetic components.

The design of a hybrid vehicle with an engine, electric machines, energy storage devices, and power converters requires advanced technology in microelectronics. Embedded control computers are needed to control the converters, manage the energy flow, and provide the desired vehicle performance at the best achievable fuel efficiency and lowest pollution.

1.1 Thesis Objectives

This thesis first explores the electric energy storage unit and the converter system, two essential components of a hybrid vehicle. It is proposed to use the recently developed double-layer power capacitors as energy storage devices and a lightweight soft-switched converter system. The first objective for the thesis is the analysis, design, implementation, and testing of these components.

A second objective is to design, based on the proposed components, a complete hybrid electric drive. The emphasis is on the development of design criteria adapted to the characteristics of the proposed components. The systematisation of the design procedure enables the easy design of different vehicle sizes using a similar configuration by following the given guidelines.

A third objective is the development of an energy management strategy adapted to the proposed configuration. It will be demonstrated that an energy management system is especially important for hybrid electric vehicles since it has a big influence on the rating of the components.

Based on the propulsion system designed, a fourth objective is to develop a complete model of the hybrid vehicle that can be used in simulations to do further studies on system design, driving performance, and fuel consumption.

The final objective is the implementation and testing of a reduced experimental prototype to verify the strategies and models introduced in the thesis.
1.2 Thesis Outline

This thesis consists of eight chapters. The introduction sets the focus on the problem and establishes the thesis objectives. Chapter two presents a review of electric and hybrid vehicles and proposes a hybrid electric vehicle concept based on double-layer power capacitors and an advanced converter configuration. The desired qualities in the search for a perfect vehicle are introduced, and the limitations of electric and gasoline vehicles to achieve this perfect vehicle are mentioned. Later, the hybrid vehicle as a closer alternative to the ideal vehicle goal is discussed and the possible configurations are presented. Finally, the series hybrid configuration is selected for this design and the structure for the proposed electric propulsion system is introduced.

Chapter three deals with the implementation of the energy storage unit using double layer power capacitors. The equivalent circuit model and terminal behaviour of the DLC are reviewed to get an insight about the considerations to be taken in account when implementing a large energy storage system using double-layer capacitors. Special attention is given to the voltage sharing amongst DLC cells connected in series. Later, an equivalent empirical thermal model is introduced, and used to estimate the cooling requirements and current rating for the energy storage unit. The final part of chapter three pays special attention to the design and testing of an energy storage unit using double-layer power capacitors.

Chapter four explores the use of an advanced soft-switching converter configuration for the proposed electric propulsion system, based on the importance of lightweight components for automotive applications. It also presents the difficulties in finding a suitable soft-switching configuration that is economically viable. A configuration capable of soft-switching several converters with only one resonant tank is selected for this design. The proposed topology has several drawbacks, but it will be shown that they can be overcome by an intelligent control strategy. This converter system provides the desired lightweight elements. The final part of the chapter is dedicated to the design, implementation, and testing of the soft-switched converter system.

Chapter five discusses the modelling of the complete hybrid electric propulsion system based on the components proposed in chapters three and four. The vehicle electric propulsion system is divided into three sections, and each one of them is mathematically modelled. The purpose of the models is to simulate the vehicle performance and the energy efficiency resulting in the estimation of the fuel consumption under different driving conditions. In addition, reliable further studies are possible after an adequate model for the system has been developed.
Chapter six presents the design of the electric hybrid vehicle and of a reduced scale experimental system. First, the chapter presents and justifies the main constraints and parameters associated with the vehicle operation that affect the design process. That section includes the design of the energy management strategy. The energy manager is responsible for keeping the capacitor voltage within adequate limits. It also makes use of the driving conditions to maximise the use of the energy stored in the capacitors. A more efficient energy manager results in a lower energy requirement for the electric energy storage unit and in a greater improvement in fuel efficiency. With the requirements and mathematical models clearly established, the second part of the chapter deals with the design of the different elements of the propulsion system. The last part of chapter six presents the design of the experimental system implemented to verify the principles introduced in the thesis.

Chapter seven is dedicated to present results for the proposed propulsion system. First, the chapter will present results from simple tests to confirm the operation of the experimental prototype implemented in the laboratory. Later, chapter seven will present comparisons between experimental and simulated results for the experimental prototype under several driving cycles. These comparisons will be used to verify and calibrate the developed models. The final part of the chapter is dedicated to provide additional results for the full size vehicle based on the developed models. Several simulations directed to give quantitative results for the fuel efficiency will indicate the effectiveness of the design in reducing toxic emissions.

Chapter eight summarises the conclusions and contributions made during this research. It will be shown that the concepts developed in the thesis are applicable in other designs using technologies under development and possible future work will be proposed.
CHAPTER 2

HYBRID ELECTRIC VEHICLES

2.1 In Search for a Perfect Vehicle

The automobile has provided people with fantastic mobility. We are able to go from one town to another in no more than a few hours. We are even able to travel around a continent in a couple of days. However, vehicles also burden the earth and particularly the cities with very high pollution detrimental to the population’s health. As society will not give up the mobility, the search is on for the well performing, least polluting, “perfect” automobile. This automobile should have the following characteristics:

a) **Long driving range between recharging/refuelling**: Normal fuel-based vehicles can be driven for several hundred of kilometres between refuelling and refuelled in only a few minutes. A vehicle user would ask for a comparable range between recharging/refuelling in future vehicles and a similar recharge time. Some proposals in electric vehicles have been directed to design “urban” vehicles to be used in relatively short driving trips to and from work, and recharged overnight. This kind of vehicle may be accepted by part of the population in wealthy countries, where some people use different cars for city driving and for long trips between cities. However, they will not substitute the present cars in large quantities, and the acceptance level in third world countries would be slim.

b) **Sufficient acceleration capability and fast response**: This is not only a requirement for the user comfort but, even more important, it is a safety feature in vehicles. When a driver is accessing a highway, the acceleration should be quick enough to reach the normal traffic speed on the acceleration ramp. In addition, the car should have good acceleration capability at high speeds to pass other vehicles on highways and other fast roads.

c) **Reasonable lifetime**: A vehicle represents an important investment for most of the people. Therefore, they ask from the vehicle a good performance for some considerable time. In general, the life expectancy for a gasoline vehicle is longer than 10 years and a similar lifetime is expected from any future vehicle technology.

d) **Minimum energy consumption**: The generation of energy is costly and in many cases the resources are limited. Furthermore, it affects negatively in one way or another the
environment. If less energy were required to transport people from one place to another, the conservation of energy and natural resources would be improved.

e) **Minimum pollution:** This is the main motivating factor behind electric driven vehicles. A reduction in the pollution level especially in cities is needed to keep the health of the population and to maintain the ecological equilibrium.

### 2.2 Vehicles Historical Development

#### A. Electric Vehicles with Batteries

The electric vehicle’s history began over a century ago when the first battery operated vehicle was built in Paris in 1881. Until 1920, electric vehicles were competing for the market with steam vehicles and gasoline vehicles. Yet, within a decade, the development of the electric starter for gasoline engines and the public demand for speed and power gave a clear advantage to the gasoline car [2]. While the interest for electric vehicles disappeared for about forty years, notable improvements in performance and efficiency were achieved in vehicles with internal combustion engines.

In the 1960’s the increasing awareness of air quality and the instability in several of the main oil producing countries revived the interest in electric vehicles. From those years, the advances in electronics, electric machines, and electric drives have opened a wide range of possibilities in designing electric vehicles. Many vehicles have been designed and tested by automobile manufacturers and researchers all around the world. However, all of them present limitations that leave them far from being the perfect vehicle.

The problem to fulfil the requirements for a perfect vehicle is easily understood when we look at the specific energy values for mature battery technologies. As an example, let us take lead-acid batteries that have been used for over 100 years, and represent the batteries most extensively used in electric vehicles. The specific energy for the conventional lead-acid battery is about 30 Wh/kg. This value is a few hundred times lower than the close to 12-kWh/kg specific energy from gasoline [3]. This huge difference is not compensated by the low efficiency of gasoline engines. Looking at the power density, the situation is not much better since the batteries are based on electrochemical principles that do not allow a fast delivery of the stored energy. In addition, batteries still have insufficient lifetime for vehicle applications and the high power demand reduces the lifetime even further. All the factors mentioned above result in a poor
vehicle performance with regard to acceleration, driving range, and lifetime. All these problems are associated with the batteries.

Several attempts to develop new batteries and to improve established technologies already established have achieved modest improvements in specific energy [3]. However, these improvements have been accompanied by reductions in the power capability and/or lifetime for the final product. It appears clear at this point that these three characteristics of batteries are strongly linked. It is not possible to increase one of them without reducing one or both of the others. At this point, despite their operation with no pollution, the electric vehicles with batteries are not commercially acceptable.

B. Vehicles Directly Driven by an Internal Combustion Engine

The development of fuel-based vehicles has come a long way during the last century. The improvements have result in an exceptional performance in acceleration, driving range, and lifetime up to a point that better performance in these aspects is hardly needed. However, the improvements in efficiency and pollution, although existent, have not been enough to reduce the burden on the environment. Internal combustion engines as operated in cars are inherently inefficient. This fact is more apparent in city driving, where most of the driving occurs. Furthermore, the pollution resulting from vehicles is still too much, and, as more and more vehicles are being driven around cities, this aspect becomes less and less acceptable. The environmental concerns have made it clear than despite the excellent performance from actual cars, they are not the perfect transportation vehicles.

2.3 Hybrid Electric Vehicles

Another option to be considered in the search for a perfect vehicle is the hybrid vehicle. The idea behind the hybrid electric vehicle is to combine the best from an internal combustion engine with the best from an electric drive. This would result in a vehicle with good performance and lower energy consumption and pollution.

Using an internal combustion engine would result in a vehicle with long driving range since it takes advantage of the high energy density from fuel. At the same time, the electric drive is able to give excellent driving performance, very fast response, and good acceleration if sufficient power is available. The electric energy storage has to be able to provide the required power to get the desired performance from the electric drive. Since the electric drive "helps" the engine in certain driving conditions, the engine does not have to be over-sized for acceleration,
and it can be operated under more efficient and less polluting conditions. Furthermore, the energy storage unit does not have to provide at the same time high power and high energy, as the engine would help to reduce one or both of these requirements. A hybrid vehicle with electric energy storage is the technology required even if fuel cells replace the internal combustion engine as the primary source of energy. In that case, the electric energy storage unit would avoid designs with large and costly fuel cells. In hybrid vehicles, the energy management and the strategy to increase efficiency and reduce pollution change considerably from one design to another, and they depend considerably on the energy and power capability of the electric energy source.

Several hybrid vehicles have been developed demonstrating the potential benefits from the concept. In 1995, Toyota presented the Prius [4], an innovative hybrid-electric vehicle developed with the goal to double the fuel efficiency in city driving. The model has been technologically successful, and it has been sold to the public in Japan since 1998. The commercial model uses nickel-metal hydride batteries especially optimised for hybrid vehicle applications. Several other hybrid models have been presented during the late 1990's and some of them are being sold already in the North American market [5]. High cost and unknown lifetime are the two main concerns for these first commercial vehicles.

Hybrid vehicles are classified in three groups: Series hybrid vehicles, parallel hybrid vehicles, and series-parallel hybrid. The characteristics for each one of the configurations are

![Figure 2-1 Series Hybrid Electric Vehicle Configuration](image-url)
explained next:

a) **Series hybrid vehicle:** Figure 2-1 shows the concept of the series hybrid configuration. An internal combustion engine drives a generator that converts the mechanical energy into electrical energy, and the resulting energy is used to propel the vehicle or added to the energy stored. Electric power is transferred to an electric motor that is used to propel the vehicle. The electric machine may be used as a generator when the vehicle is braking. The main advantage of the series configuration is that the engine operation is completely independent from the road and driving conditions. This allows the operation of the engine in the maximum efficiency / lower emissions region. The main function of the engine in this configuration is to increase the driving range for the vehicle so that a low energy capability in the energy storage device is acceptable. The main disadvantage of the series configuration is the double energy conversion required for the energy coming from the engine; however, the higher efficiency achieved from the internal combustion engine helps to compensate for this disadvantage.

b) **Parallel hybrid vehicle:** Figure 2-2 shows the diagram for this configuration. In this configuration the power coming from the electric energy source through an electric motor is mechanically added to the power coming from the engine and is used to propel the vehicle. The electric energy source is limited to relatively low power such that the car can be operated in a fully electric mode only in low power driving conditions, such as

![Figure 2-2 Parallel Hybrid Electric Vehicle Configuration](image-url)
city driving. When the power demand increases, the engine starts to provide the extra power required. At the same time, the engine may recharge the electric energy storage unit if required. The level of decoupling between the engine and the driving conditions is lower in the parallel configuration than in the series one resulting in harder engine transients and higher emissions. The main strategy to reduce pollution and increase efficiency rests in the fact that most of the driving in big cities is a low power demand driving; consequently, the vehicle operates most of the time in an all electric mode. Furthermore, the engine rated power is usually lower and this permits to achieve better average engine efficiency.

c) **Series-Parallel Hybrid Vehicle**: Figure 2-3 shows this configuration, not very common before, but made popular by the introduction of the Toyota Prius. The energy from the engine may be used directly to propel the vehicle or converted into electric energy and used to recharge the electric storage unit. The vehicle operates as a series vehicle under some driving conditions and as a parallel hybrid under others. The main advantage is that for city driving conditions the vehicle is used as a series hybrid in which the engine operates in quasi-steady state and independent of the driving conditions, but under highway driving conditions the more efficient parallel configuration is used. In this configuration, a trade off between the series and the parallel configurations is achieved.

*Figure 2-3 Series-Parallel Hybrid Electric Vehicle Configuration*
such that both the energy and the power requirement for the energy storage unit are smaller than for all electric vehicles, but larger than for the only series or only parallel configuration respectively. This configuration is complex compared with the previous ones and require good energy and power capability from the energy storage unit to get a good reduction in pollution levels.

2.4 Proposed Hybrid Vehicle Propulsion System

Figure 2-4 shows the configuration for the proposed hybrid vehicle propulsion system. The series configuration is chosen because it provides the best decoupling for the engine operation with respect to the driving transients. This condition is expected to give lower fuel consumption and pollution levels compared with the other configurations. Furthermore, this configuration is easily adaptable to systems using new primary energy sources such as fuel cells, which gives excellent perspectives to use similar systems in the long-term future.

It is proposed to use double-layer power capacitors as the only electric energy storage device. These new devices have enough energy density and excellent power density to make them an interesting option especially in the series hybrid configuration. The DLCs also have high efficiency and lifetime compared with electrochemical batteries. An energy storage unit with many capacitors in series and rated according to the vehicle energy requirements is used to provide the high power required for acceleration and braking.

A permanent magnet synchronous machine (PMSM) is used to propel the vehicle. This type of machine was chosen because it can be easily controlled, has high power density, and has

![Diagram of Proposed Hybrid Electric Vehicle Configuration](image)
high efficiency. The use of an electric machine allows using regenerative braking. In other words, when the vehicle is braking, the PMSM operates as a generator sending power back to the electric energy storage unit. This technique gives considerable improvements in driving range and fuel economy [6].

An internal combustion engine is the primary energy source supplying the average energy required by the vehicle. As the engine is not required to provide power peaks for acceleration, its size is smaller than for traditional vehicles and it is operated under more efficient and less polluting conditions. The engine is coupled to an electric generator that converts the mechanical energy into electrical energy. The generator is controlled to keep the engine operating at the desired optimal conditions.

Two DC/AC converters are required in the system. One controls the propulsion motor according to the demand from the driver. The other one controls the generator to produce the desired engine operation. A DC/DC converter is used to control the power going into or coming from the electric energy storage unit. In order to develop a more efficient system, the weight of the propulsion system has to be minimised. The high power density of the double-layer capacitors and the reduced size of the internal combustion engine contribute to achieve this objective. However, additional reductions in weight are possible by using lightweight converters to transfer the energy between the engine/generator unit, the energy storage unit, and the propulsion motor. The lightweight converter system uses soft-switching technologies to perform the power conversion process, giving the possibility to increase the switching frequency and, in consequence, reducing the size and weight of the magnetic components.

The three converters are connected to a DC-link formed by a standard electrolytic capacitor whose voltage is used as common input supply for all three converters. The complete system is operated such that the DC-link voltage is kept constant.

The hybrid vehicle system, as proposed, requires an energy management system to regulate the operation of the engine and maintain the energy content for the energy storage unit between designed limits, but providing the performance commanded by the driver.

To implement the proposed hybrid vehicle concept, it is first necessary to explore the two major components: the double-layer capacitor as electric energy storage device and the lightweight soft-switched converter system. Chapters three and four will look separately at each one of these components.
CHAPTER 3

DOUBLE-LAYER POWER CAPACITORS

Double-Layer capacitors are electric energy storage devices that base their operation on the principle of the double-layer charge distribution. Although the double-layer charge distribution phenomenon has been known for over 100 years, it was only until the 1970’s that it began to be used in capacitors. Double-layer capacitors with rated values of under 1 F have been produced and used for over two decades. They are low power devices used mainly as short time energy backup in electronic circuits and microprocessors. In 1991, the development of a double-layer capacitor capable of operating at high power levels was reported [7]. This capacitor uses activated carbon particles with high specific area to increase the specific capacitance. The double-layer is established between the carbon particles and an electrolytic solution in which the carbon assembly is immersed. Since 1991, the capacitance values as well as the current capability have increased considerably, reaching values attractive for power electronics applications. In this chapter the double-layer power capacitors are studied to evaluate their applicability as energy storage devices to be used in hybrid electric vehicles.

3.1 Double-Layer Power Capacitors Characteristics

The double-layer power capacitors are based on a physical principle that states that when substances in two different phases are in contact, charge separation occurs at the boundary [8]. The charge separation is a result of the migration of ions from one material to the other. The difference in inner potential between the materials in two different phases gives the energy that allows the ions migration. If an external voltage is applied between the two materials, the potential difference across the double-layer changes, and the number of charges needed to establish the equilibrium also changes. Therefore, a capacitor is formed across the double-layer charge distribution. The relation between the charge stored and the voltage applied will define the specific capacitance for the double-layer structure. The specific capacitance of the double-layer charge distribution is very high because of two reasons: first, the distance between the positive and the negative charges is at the atomic level; second, if a porous material is used, the specific area of contact between the two substances is high.
The double-layer power capacitors (DLCs) are relatively new devices; therefore, the characteristics and properties for the devices are changing constantly as the manufacturing process improves. Some of the characteristics for the DLCs, specified by the manufacturer, and corresponding to the devices used in the experimental energy storage unit to be presented later, are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Voltage</td>
<td>2.3 V</td>
</tr>
<tr>
<td>Rated Capacitance</td>
<td>1500 F</td>
</tr>
<tr>
<td>Internal Resistance</td>
<td>&lt;1.5 mΩ</td>
</tr>
<tr>
<td>Maximum Charging Current</td>
<td>&gt;150 A</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>1.6 Wh/kg</td>
</tr>
<tr>
<td>Energy Density</td>
<td>2.2 Wh/l</td>
</tr>
<tr>
<td>Specific Power</td>
<td>430 W/kg at rated voltage</td>
</tr>
<tr>
<td>Lifetime</td>
<td>&gt;200,000 cycles</td>
</tr>
</tbody>
</table>

Table 1. Double-Layer Power Capacitor Specifications

Based on the values from Table 1, the double-layer power capacitors have properties very attractive for hybrid vehicle applications: First, if operated within the voltage specifications, the double-layer capacitors are electric devices so that there is no irreversible chemical reaction occurring inside the device. This fact gives them much longer lifetime than batteries. Second, the internal resistance is small and additional reductions have been achieved over the last few years, which makes it possible to operate these capacitors at high current and power levels. Currents up to 400 A for a short time are specified for some recent DLC models [9]. Third, the specific energy, although considerably smaller than for batteries, is much higher than for electrolytic capacitors. The specific energy and energy density values for devices already available allow for the possibility of setting units with acceptable total weight and volume and holding the energy needed to accelerate a compact vehicle. Using double-layer capacitors may help to overcome the low lifetime and power capability of electrochemical batteries in hybrid vehicle designs. Table 2 shows a comparison between the energy and power capabilities for the double-layer power capacitors and some of the battery technologies most often used in electric vehicles [3]. The values in the table confirm the advantage in power capability and lifetime for DLCs over batteries as well as the much lower specific energy as expected. The values in Table 2 for the double-layer power capacitors correspond to the latest models available [9].
Chapter 3. Double-Layer Power Capacitors

Table 2. Electric Energy Storage Technologies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pb-acid</th>
<th>NiMH</th>
<th>Li-polymer</th>
<th>DLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy, Wh/kg</td>
<td>40</td>
<td>60</td>
<td>100</td>
<td>2.9</td>
</tr>
<tr>
<td>Energy Density, Wh/L</td>
<td>70</td>
<td>175</td>
<td>200</td>
<td>3.2</td>
</tr>
<tr>
<td>Specific Power, W/kg</td>
<td>150</td>
<td>200</td>
<td>200</td>
<td>1250</td>
</tr>
<tr>
<td>Lifetime, full-discharge cycles</td>
<td>300</td>
<td>600</td>
<td>200</td>
<td>&gt;500,000</td>
</tr>
</tbody>
</table>

On the other hand, the devices have some limitations and unknown facts that have limited their use: first, because of the physical principles behind the charge storage process, the devices have a capacitance value that is a function of the voltage across the device [10]. Second, complex internal processes of charge distribution and ion rearrangement, with time constants in the order of up to several days, occur in the devices. This process is called in [11] “internal charge redistribution process”. The two previous phenomena produce unexpected results if the energy content is estimated based only on the terminal voltage. Third, the voltage of a single cell is limited to less than three volts to avoid irreversible chemical reactions and especially the dissociation of the electrolyte. The low voltage for a single cell, like in batteries, obliges one to connect many cells in series to achieve the voltages required in power electronics applications. Due to the complex electric behaviour of the device, the voltage sharing amongst many devices connected in series has to be explored.

It is important to mention that the double-layer power capacitors have attracted the attention of the hybrid electric vehicle designers since they were initially developed. In fact, the Toyota Prius, arguably the most successful electric vehicle so far, used double-layer capacitors in its original design [4]. The DLCs were later changed in Prius commercial models to nickel-metal hydride batteries mainly for economic reasons since the double-layer power capacitor technology was still in its early stages and the costs of production were still high.

3.2 Double-Layer Power Capacitor Equivalent Model

The double-layer capacitor is a complex device as can be seen by assessing the equivalent model for the device presented in [10]. Figure 3-1 shows the proposed equivalent model including typical values measured for a device rated 1500 F. The equivalent circuit model consists of three RC branches in parallel, each one with a distinct time constant, and a leakage resistor in parallel. The idea behind the model structure is that each branch dominates the...
Chapter 3. Double-Layer Power Capacitors

Figure 3-1 Double-Layer Power Capacitor Equivalent Circuit Model

dynamic terminal response of the device to external charging actions during some specific interval. The first or immediate branch, with a resistor (Ri) and two parallel capacitors (Ci0 and Civ), has a small time constant and responds quickly to external charging actions. The charge, initially stored in the immediate branch, then begins to flow into the second or delayed branch (Rd, Cd) that has a longer time constant and dominates the terminal behaviour up to ten minutes after the charging process has stopped. For times longer than ten minutes, the third branch (Rl, Cl), called long-term branch, predominates. The first branch includes a voltage dependant capacitor (Civ) as justified by the physics of the double-layer. A large leakage resistor (Rlea) is in parallel with the three RC branches. Several consequences result from the equivalent model for the DLC:

a) The non-linearity results in a variable capacitance depending on the voltage. Therefore the capacitance rating should include a voltage dependent term. Because of the non-linear effect, the stored energy cannot be calculated using the classical equation for capacitor energy. Instead, it includes a cubic term given by the voltage dependent capacitance. The total energy stored in the immediate branch can be calculated from the parameters in figure 3.1 and it is given by:

$$E = Ci0 \frac{Vci^2}{2} + K \frac{Vci^3}{3}$$  \hspace{1cm} (3-1)

b) As the differential capacitance increases with an increase in terminal voltage, the amount of energy stored at higher voltages is greater than for linear capacitors. This is important because the total energy available for some specific voltage range is larger for the DLC than for a linear device holding the same total energy. The non-linearity affects the rating
Chapter 3. Double-Layer Power Capacitors

Figure 3-2 Energy Stored in a DLC Compared with a Linear 1500 F Capacitor

of the energy system by up to 30% with respect to the rated capacitance value. Figure 3-2 shows a graphic comparing the energy stored in a linear 1500 F capacitor with the energy calculated for the immediate branch of the equivalent circuit model. Note the extra energy storage capability for higher voltages, especially over 1.7 volts.

c) After a fast charging action, the charge will redistribute inside the device. This will produce a change in terminal voltage that must not be mistaken as losses in the device, but only as a process in which charge goes to regions not immediately accessible in the device. As a result of this internal charge redistribution process, there is no clear relation between the terminal voltage and the total charge stored in the device.

d) Not all the energy stored in the capacitor is available for high power applications. Only the energy stored in the immediate branch and associated with short time constants can be quickly delivered to the load.

e) Many factors and internal physical phenomena may have an effect on the voltage sharing amongst DLC cells connected in series, and it is needed to explore the voltage sharing properties amongst devices.

3.3 Voltage Sharing amongst Double-Layer Capacitors

Before setting a large energy storage unit using double-layer power capacitors, it is necessary to study the voltage sharing amongst DLCs connected in series. Reference [12] presents an analysis, based on the equivalent model, of the mechanisms that influence the voltage
sharing amongst capacitors under steady state and transient conditions. Transient is defined as the time during external charge or discharge actions and the time interval necessary for the internal distribution of charge among the capacitors of the equivalent circuit model. Then, knowing which equivalent circuit model parameters have a greater effect on the voltage sharing characteristics, a statistical analysis for the devices to be connected in series will allow a quantitative estimation of the voltage sharing properties.

A. **Steady State Voltage Sharing**

In steady state, the voltages across all the circuit model equivalent capacitors are the same, and they are connected in parallel. Under these conditions, the capacitor voltage depends only on the total charge stored in the device \( Q_i \) and the total device capacitance \( C_i \). Using the equivalent circuit model, the device voltage is given by the following equation:

\[
V_i = \frac{Q_i}{C_i} = \frac{Q_i}{C_i(V_c) + C_d + C_l}
\]

where \( C_i(V_c) \) is the voltage dependant immediate capacitance \( (C_i0 + C_i) \).

If many double-layer power capacitors are connected in series, they receive the same charge; and therefore, the differences in terminal voltage depend only on the differences in total device capacitance \( C_i = C_i(V_c) + C_d + C_l \). Differences in the capacitance and resistance values of individual equivalent branches do not have any effect on the steady state voltages, as they only determine how fast the charge is internally redistributed inside the double-layer capacitor. Furthermore, the differences in total capacitance do not produce an accumulative effect in the voltage distribution of repeated charge/discharge processes. In other words, independently of how many times the capacitors have been cycled, if the total charge inside the capacitors is the same, the same voltage difference in steady state is measured.

The deviation in leakage resistance among devices is another condition that can influence the voltage sharing in steady state. A smaller leakage resistance results in a larger leakage current and therefore in a faster self discharge. Note that the effect of the leakage resistance is accumulative; the longer the capacitor has been kept charged the more energy has been dissipated in the leakage resistance. This is the only factor that may result in an increasing difference in the terminal voltage for capacitors connected in series. To solve the problem of unequal leakage, low tolerance resistors can be placed across each device. The value for this resistor should be much smaller than the leakage resistance and it would equalise the capacitor losses and reduce the voltage differences due to unequal leakage.
Another factor that may influence the voltage sharing is the difference in operating temperature amongst capacitors. The data sheet given by the manufacturer suggests that the capacitance may change up to 30% depending on the device temperature. In addition, the internal resistance is expected to increase up to several times the rated value if the temperature is reduced below -30 degrees Celsius. Nevertheless, in the range of 0 to 60 degrees Celsius, the variations in temperature dependant parameters are much less. To take this factor into account, the thermal behaviour for the double-layer capacitors was investigated, and conditions for keeping all the capacitors at a similar temperature will be proposed later.

B. **Dynamic Voltage Sharing**

All the elements in the equivalent circuit model affect, in one way or another, the voltage sharing during transients. The equivalent immediate resistance, \( R_i \) in figure 3-1, is important when high currents are used to charge or discharge the capacitors because differences in the order of tens of millivolts may result from unequal immediate resistance values. The equivalent immediate capacitance (\( C_i(V_{ci}) \)) is also important for voltage sharing as it holds most of the energy inside the capacitor. A small immediate capacitance value produces high terminal voltage during a fast charging action even if the total capacitance of the device does not deviate from the other capacitors. This parameter is especially important in high power applications because it defines the voltage sharing during the charging and discharging actions.

During the internal charge redistribution process, the time constants for the delayed and long-term branches are of importance. A lower time constant suggests that the charge would be transferred faster to that branch and, therefore, a transitory lower voltage would be measured at the capacitor terminals. Again, this effect would be transitory and it is important only if the temporary deviation in terminal voltage during continuous or frequent charging and discharging actions represents an overvoltage that may result in deterioration of one or more devices.

It should be mentioned that the non-linear capacitance as presented in the equivalent model does not represent any detriment in the voltage sharing among capacitors. Instead, the non-linearity helps to reduce the voltage differences which can be demonstrated by the following example: Assume two capacitors A and B, at the same initial voltage \( V_o \), and the capacitance of A been smaller than the capacitance of B. If the same amount of charge were fed into both capacitors, the voltage of capacitor A would grow to a higher value than the voltage of capacitor B. The higher voltage results in a higher factor \( K \cdot V_{ci} \) and therefore the capacitance for device A would increase more than the capacitance of device B. This would then reduce the difference
between the initial capacitance values and reduce the voltage difference between both capacitors as they accumulate more charge.

C. **Equivalent Model Parameters Analysis**

To quantify the influence of the equivalent circuit model parameters on the voltage sharing amongst capacitors, an analysis on the variance for the different equivalent model parameters was done. The parameters for the equivalent circuit model shown in figure 3-1 were measured for 100 single-cell double-layer power capacitors using the procedure presented in [10].

As mentioned in the previous section, the total DLC capacitance is the main factor that determines the steady state voltage sharing amongst devices. Figure 3-3 shows a graph grouping the capacitors according to the deviation from the average for the total DLC capacitance at rated voltage. All the values are between ±10% of the average value, which suggests that the voltage sharing in steady state, neglecting the leakage effect should be good. Based on these results, if the complete energy system is charged to rated voltage, then all the devices should be at a voltage lower than 2.5 V. Therefore, no dangerous voltages that may damage the devices would occur.

For transitory voltage sharing, the immediate resistance is important during charging with high currents, the immediate capacitance is important for the voltage sharing during fast charges, and the differences in other parameters will have an influence during the internal charge redistribution process. The measurements for each of these parameters will be analysed next.

Differences of up to 500 μΩ were measured in the immediate resistance. This amount of resistance would result in a difference of 50 mV at the terminal voltage during 100 A charging.

![Figure 3-3 Total Device Capacitance Distribution for the 100 Devices Tested](image-url)
Figure 3-4 Immediate Branch Capacitance Measured for the 100 DLCs Tested

However, this voltage difference is not important since it appears only during the charging or discharging transient, is only around 2% of the device rated voltage, and has no effect on the voltage sharing under steady state. The parameter deviations for the immediate branch capacitance are especially important in power applications since energy is quickly fed or removed from the capacitors. Figure 3-4 shows the measured immediate capacitance at rated voltage for each of the 100 devices. In the plot, the average capacitance and the limits for 10% deviation are also included. Again the results are well between ±10% of the average value, and the voltage sharing during fast charge and discharge is expected to be good.

Although the deviation in parameters for the delayed and long term branch is wider (about ±20% for resistance values and ±15% for capacitance values), their effect on the terminal voltage during transients is limited. This is because the sum of the delayed capacitance and the long-term capacitance is only about one third of the immediate branch capacitance. Also, the differences in time constants are smaller than 20% as large values of resistance are associated with low capacitance values. It is important to note that although the deviation on a single parameter may have higher tolerance, the analysis of the measurements indicates that the differences in one parameter are compensated by the differences in other parameters. So that the two important quantities in power applications (total capacitance and immediate capacitance) have a narrower tolerance. In addition, the most recent double-layer capacitor present much smaller delayed and long-term capacitance values with respect to the immediate branch capacitance, which reduces the importance of the differences in those parameters.
A deviation in the order of ±20% in the leakage resistance is expected. This parameter was not measured for all the devices because the identification is inaccurate and time consuming. But even deviations of less than 10% would result in an important unbalance in voltage sharing after long periods of time. As the value of the leakage resistor is in the order of 6 kΩ, placing a 100 Ω low tolerance resistor in parallel with each capacitor would reduce the effect of unequal leakage resistance by over 98%. Furthermore, each 100 Ω resistor would represent only about 50 mW of losses at rated voltage. Appendix A has plots showing the values measured for all one hundred devices, the average values, and the ±10% deviation limits corresponding to all the equivalent circuit model parameters.

### 3.4 Thermal Considerations

As mentioned in section 3.3 temperature is another factor that would influence the voltage sharing among devices, if it is not taken into account. Capacitance values differing by up to 30% and internal resistance values up to four times the rated value may be measured depending on the temperature for the operating temperature range. High temperature differences amongst cells produce high capacitance differences and therefore, increase the difference in terminal voltage amongst capacitors. However, if the capacitor temperature is kept between 0 and 60 degrees Celsius, the resistance and capacitance values are fairly constant for small changes in temperature. According to this, all the devices should operate at similar temperatures to reduce the thermal effect on voltage sharing.

To assess the thermal behaviour in steady state conditions, the equivalent thermal model presented in figure 3-5 could describe the double-layer capacitor. This is an intuitive model

![Figure 3-5 DLC Equivalent Thermal Circuit Model](image-url)
Chapter 3. Double-Layer Power Capacitors

based on the physical structure of the capacitor. In figure 3-5, the letter A denotes the ambient, letter F denotes the spiral foil inside the capacitor, T1 is the positive terminal, T2 is the negative terminal, and C is the case. \( T_n \) is the temperature at the corresponding point n and \( R_{mn} \) is the thermal resistance between m and n. The model consists of three sources of heat, two in the terminals and one in the electrolyte, and three dissipation paths, one through the case and two through the terminals. The variable resistors in figure 3-5 represent the thermal resistors that can be modified by the cooling conditions.

Clearly, identifying all these elements through external measurements is not possible. The equivalent model should then be simplified to get an identifiable model. The model is simplified based on the following assumptions:

a) If the external terminal connectors are similar in material and dimensions, both terminals are at the same temperature and the dissipation paths through the terminals may be assumed in parallel. This also makes it possible to use one equivalent source of losses for both terminals.

b) It is impossible to estimate from external measurements the thermal resistance between the internal components of the capacitor and the terminal leads. The capacitor terminals are the best indication of the temperature inside the device and they will be used as reference for the current rating. The high thermal conductivity for carbon (main component of these double layer capacitors) and aluminium suggests that the thermal resistance between inner material and terminal is small compared with the other thermal resistance values. Therefore, this resistance will be neglected in the simplified equivalent thermal model. Nevertheless, to avoid exceeding the temperature rating by estimating it using this simplification, five degrees Celsius below the maximum temperature specified by the manufacturer will be given when finding the capacitor current rating. This difference represents a margin for the temperature difference between the electrolyte and the terminals.

According to the previous considerations, the equivalent model is reduced to the one shown in figure 3-6. For the identification of the thermal model parameters, continuous current operation is used. Continuous current operation is defined as the continuous cycling of the capacitor between a minimum voltage and rated voltage using a controlled current source of the same amplitude for both charging and discharging. The power dissipated is calculated from the equivalent circuit model in figure 3-1 assuming a constant current source. Even using the simplified thermal model, it is necessary to find an additional relation since three parameters have
Chapter 3. Double-Layer Power Capacitors

Figure 3-6 Reduced Equivalent Thermal Model for the DLC

to be identified from measurements at two points. This additional relation will be established from the transient thermal behaviour of the DLC.

The first group of experiments was focussed on finding a pattern for the heat dissipation. Figures 3-7 a and 3-7 b show the terminal and case temperature respectively for three different tests using a 80 A continuous charging current: without cooling, with forced air cooling only over the terminals, and with forced air cooling only over the case. In figure 3-7 a, for the no cooling test, the temperature grows with a time constant of about 50 minutes reaching about 45 degrees Celsius over the ambient temperature. With air cooling to the terminals, the time constant is only about 25 minutes and the steady state temperature is only about 13 degrees higher than the ambient temperature. Finally, using air cooling for the case, the time constant and final values are very close to the ones for the no cooling test. Similar tendencies are observed in figure 3-7 b but with lower absolute temperatures. The conclusion for the tests is that, if sufficient copper area for the connector is used, the main dissipation path is through the terminals (\(R_{TA} < 10 (R_{TC} + R_{CA})\)); consequently, the thermal time constant is proportional to \(R_{TA}\).

Based on this justified simplification, the thermal model parameters are identified measuring the temperature change for two conditions (with and without forced cooling), and using the time constants of the results to get a relation between the thermal resistance \(R_{TA}\) for both conditions. The thermal equation for the steady state temperature in the experiment without cooling is the following:

\[
R_{eq} = \frac{(R_{TC} + R_{CA})R_{TA1}}{R_{TC} + R_{CA} + R_{TA1}} = \frac{\Delta T_1}{P_d} \quad (3-3)
\]
Figure 3.7 a) Terminal and b) Case Temperature Measured for a DLC Tested Under Different Cooling Conditions
Another equation results from the steady state condition for the test with forced air-cooling in which the thermal resistance from terminal to ambient is modified by the cooling effect:

\[ R_{m2} = \frac{(R_{TC} + R_{CA})R_{TA2}}{R_{TC} + R_{CA} + R_{TA2}} = \frac{\Delta T_2}{P_d} \quad (3-4) \]

The ratio between \( R_{TC} \) and \( R_{CA} \) can be found from one set of measurements using the case temperature according to the following equation:

\[ \frac{R_{CA}}{R_{TC}} = \frac{T_T - T_C}{T_C - T_A} \quad (3-5) \]

A fourth equation is obtained from the ratio between the thermal time constants for both experiments:

\[ \frac{R_{TA1}}{R_{TA2}} = \frac{\tau_1}{\tau_2} \quad (3-6) \]

Using (3-3) to (3-6) the thermal parameters can be identified. The parameters were identified using a 80 A continuous current resulting in \( R_{TC} = 20.15 \, ^\circ C/W \), \( R_{CA} = 32.83 \, ^\circ C/W \), \( R_{TA(NO \, FAN)} = 5.218 \, ^\circ C/W \), \( R_{TA(FAN)} = 1.899 \, ^\circ C/W \). These results were then verified for 60 A and 100 A continuous current.

Several conclusions, useful for the design of an energy storage system, result from the equivalent thermal model and the experiments used in its identification. First, the heat dissipation occurs mainly through the terminals; therefore, if forced cooling is going to be provided, it is important to supply air to the terminals. Second, the physical dimensions of the connectors have a notable influence on the thermal behaviour of the device. Connectors differing by 50% in dissipation area produce differences in temperature of up to 15 degrees Celsius. Consequently, the design of the connectors is not only given by their current capability, but also by the area of heat dissipation. Furthermore, all the capacitors used in an energy storage system should have similar connectors to guarantee a similar temperature in all the cells. Third, for continuous currents over 60 A, forced air-cooling is required. Using moderate forced air-cooling, a continuous current rating of 120 A is achieved for this type of capacitor. These continuous current ratings, based on thermal behaviour, are valid using copper connectors like those used in the experimental energy storage unit.
3.5 Design and Building of a 400 kWsec Energy Storage System

An experimental energy storage system consisting of one hundred double-layer capacitors connected in series was reported in [12]. Each capacitor is rated 1500 F and 2.3 V, producing an energy storage system rated 15 F and 230 V. The decision about mounting of the capacitor cells was influenced by the thermal behaviour of the DLC as discussed in section 3.4. Using the results from the thermal study, forced air-cooling may or may not be needed in the hybrid vehicle application depending on the maximum average power requirement for the vehicle. However, forced ventilation was included to allow the extensive testing of the energy storage unit with current in excess of 100 A. Figure 3-8 shows the experimental energy storage unit. The capacitors are standing on a grid placed in a wooden box. Forced air is supplied from below at a rate of 112 CFM. The capacitors are arranged in a 10x10 matrix; the square distribution gives sufficient natural air channels between the capacitors to allow for free airflow. This configuration also allows the cooling air to easily reach the terminal connectors as required to improve the cooling efficiency.

Copper bars with similar geometry and a dissipation area of 38.5 cm² each are used to connect the capacitors. Similar connectors were used in the thermal study, which provides a similar thermal response. Using connectors with the same area in all the devices gives uniform heat dissipation at the terminals and allows keeping all of the cells at a similar temperature. The connector copper bars can be observed in the two front capacitor rows in figure 3-8.

![Figure 3-8 Experimental Energy Storage Unit during Assembling](image-url)
A 100 Ω resistor was placed in parallel with each capacitor to equalise the leakage losses and maintain a good voltage sharing. All the capacitors were previously normalised or fully discharged according to the procedure introduced in [11] to assure the same initial conditions in all the cells.

The system was designed to operate between half the rated voltage (115 V) and the rated voltage (230 V). Calculating the usable energy based on a constant linear capacitor of 15 F (rated value) results in an energy availability of 297.5 kWsec. Using the values measured for the equivalent circuit model shown in figure 3-1, and extending the result to 100 capacitors in series, gives an energy capability of 391.5 kWsec. This result proves the huge impact of the non-linearity in the energy rating of an energy system based on double-layer power capacitors. Experimentally an energy capability of 376.2 kWsec was measured for the same voltage range.

As the main concern respecting the energy storage unit is the voltage sharing amongst capacitor units, it was decided to equip the energy storage system with a system to monitor the voltage across each unit. The monitoring unit measures and processes the voltage at each capacitor to study steady state and dynamic voltage sharing. The low voltage and high current rating of each device, the high absolute voltage of some of the devices in the series chain with respect to ground, and the high electromagnetic interference resulting from the complete hybrid vehicle represented strong challenges in the design of the measurement system. The electronics used to measure the individual cell voltage can be seen on top of the capacitors in the back rows in figure 3-8. Details of the measurement system design can be found in [13].

### 3.6 Energy Storage Unit Experimental Results

The objective of the first group of experiments using the energy storage system was to verify the thermal design of the energy system. A continuous current of up to 120 A was applied to the capacitors until the terminal temperature reached the steady state value. The temperature at the copper connector was measured at several points of the array. Figure 3-9 shows the temperature of several capacitors as function of time for a 100 A continuous current. The sign in the legend indicates if the temperature was measured on the positive or negative terminal. The differences in temperature are less than 5 degrees Celsius for all the capacitors except the first and last on the chain. For these two capacitors, the temperature at one terminal is about eight degrees lower than the average for the rest of the capacitors due to the larger terminal dissipation area as the copper bar extends to the external system connector (see in figure 3-8). This temperature difference occurs only at the terminal with the longer connector, which confirms the dramatic
influence of the connector size on the heat dissipation. With these small temperature differences, very little thermal effect on the equivalent model parameters is expected. Using forced ventilation, a continuous current of 120 A can be applied to the capacitors without exceeding the maximum temperature specification.

To study the experimental voltage sharing under different charge conditions, extended experimental testing of the energy storage unit, using a current up to 120 A for several hours, was performed. Additional tests included different cycles of charging and discharging similar to the ones used to test electric vehicles, and with variable duty cycles and waiting times between cycles. The experiments have produced the following conclusions:

a) In all the experiments, the deviation of the terminal voltage with respect to the average voltage is between ±10% of the rated voltage. In steady state, the deviation is only about ±6%. These results are consistent with the results of the deviation using the equivalent model parameters presented before.

b) There are no observations of runaway in voltage sharing as longer and more complex charge cycles are applied to the capacitors.

c) Consistent behaviour has been observed in temperature and voltage in the individual capacitor units when applying the same test several times to the system.

d) The results are notably consistent with the equivalent model parameters measured for each device. For example, for high charge/discharge currents the capacitor with higher/lower internal resistance produces the higher measured voltage. Capacitors with higher total capacitance have a lower voltage under steady state conditions.

![Figure 3-9 Temperature Balance in the Energy Storage Unit](image_url)
Another experiment directed to study the leakage effect on voltage sharing was done. The experiment consisted of charging the capacitor up to 240 V using a low current. Then, the terminal connection was opened and the terminal voltage sharing was monitored during the next three days. It was noted that the distribution around the average value did not increase after the capacitors were kept charged longer. In fact, from an initial distribution in which all the capacitors were between ±5% of the rated value, the deviation changed to a distribution with ±3.8% difference with respect to the average value. If a similar experiment is run without the 100Ω resistors used to equalise the losses, the voltage distribution increases from 5% of the rated value to over 10% of the rated value in three days. This set of experiments confirms the increasing differences in terminal voltage when the capacitors are kept charged for long periods if no parallel resistor is included, as well as the notable improvement resulting from placing a resistor in parallel with each capacitor.

In conclusion, it is possible to use a large number of double-layer power capacitors in series to implement a 230 V, 400 kWsec energy storage unit with a continuous current rating of 120 A, and weighting only 85 kg. Based on more recent capacitor models, current levels in excess of 400 A and energy capability in the order of 800 kWsec are achievable in an energy storage unit with similar volume and weight.
CHAPTER 4

SOFT-SWITCHED CONVERTER SELECTION AND DESIGN

The use of soft-switched converters in electric and hybrid vehicles is a topic that has sparked many articles, discussions, and seminars [14]. The use of soft-switching technologies brings the advantages of reduced weight in magnetic devices, reduced losses, and to a certain degree lower electromagnetic interference [15]. However, the benefits from the soft-switching topology have to be weighted against the extra effort and cost involved in the design and implementation of the soft switching technology. In most stationary industrial equipment, the use of a soft-switched technology does not bring any advantage. But, in automobiles where weight has a special premium, a reduction in converter weight due to lighter electromagnetic components may provide considerable benefits.

The selection amongst the different soft-switching topologies has to be done with good knowledge of strengths and weaknesses of each topology. High peak currents or voltages with respect to the hard-switching case, variable switching frequency, too many additional components, and complex control are usual drawbacks in the soft-switching topologies. All these aspects have to be taken into account keeping in mind the main objective of reducing the weight of the converters.

4.1 Use of a Soft-Switching Topology in the Proposed Design

Figure 4-1 shows an electric representation for the proposed hybrid vehicle drive. Three voltage sources: the generator, the motor, and the double-layer capacitors have to be connected to exchange electrical energy. As it is not possible to connect voltage sources directly at the terminals, switched power converters and inductors make the connection.

The use of a DC-link to connect the converters is a good practice since it separates the operation of each converter and has no synchronisation problems as an AC-link would have. The minimum acceptable DC-link voltage is determined by the fact that the DC/AC converter requires a DC input voltage larger than the peak AC voltage. Using DLCs, which are low voltage devices, results in the need for a DC/DC converter to boost the voltage from the energy storage unit to the

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Figure 4-1 Electrical Representation of the Hybrid Drive

voltage required at the DC-link. In this form, the voltage of the DLC unit can be freely varying to achieve an optimal use of the energy stored.

The electric machines already have an inner inductance and, if the switching frequency is high enough, no further magnetic components have to be added. The DLC energy storage unit has a very low inner inductance and, therefore, an external inductance \( L_{DC} \) has to be provided. This inductor may have a considerably weight depending on the switching frequency. To keep the inductor weight low and have low ripple in the machine currents, the switching frequency of the converters should be as high as possible.

A preliminary design of the component parts in a hybrid vehicle using double-layer capacitors was presented in [16]. According to the results from that research, the weight of the DC/DC converter inductor, assuming a switching frequency of 4 kHz, was estimated to be about 100 kg. This may be about 10% of the typical sub-compact vehicle weight, and it is heavier than the double-layer capacitor unit presented in chapter three. Using the same simplified method to estimate the inductor weight, and assuming that the switching frequency is increased by a factor of ten and the current level is kept constant, gives an inductor weight of approximately 10 kg. This gives a considerable reduction in total weight and therefore, an important increase in driving range and general efficiency.

However, as the switching losses are proportional to the switching frequency, the switching frequency cannot be increased much in hard-switched converters; this is even a greater restriction at the power levels required by the vehicle. The only option is then to use soft-switching techniques to be able to increase the frequency keeping the switching losses low. The goal now is to find a soft-switching topology simple enough not to overcome the advantages of a
lighter inductor. Although soft-switching the DC/AC converter does not bring reductions in system weight, the possibility to soft-switch the converter used to control the motor with no additional components will be taken in account in the decision about the soft-switching topology. However, in this thesis the soft switching of the converter connected to the engine / generator set is not considered, leaving open the possibility to modify the primary energy source.

4.2 **Zero-Voltage Switching versus Zero-Current Switching**

Switching losses occur when the electronic switches turn on or off high inductive load currents at high link voltages. When the switch is turned on, the switch current increases slightly before the voltage across the switch drops, which results in high power dissipation in the switch. When the switch is turned off, the voltage increases and subsequently the current decays producing again high losses. Two different strategies may be used to reduce the switching losses: zero-voltage switching and zero-current switching. In the zero-voltage switching option, an auxiliary circuit brings the voltage across the switches down to zero before the switching occurs. In the zero-current option, the current flowing through the switch is made zero before the switching process is initiated. Ideally both options would make the switching losses equal to zero, but the parasitic elements in the circuit and the physical principles occurring in the switches during turn-on and turn-off actions still produce some losses.

In [17], the losses in IGBTs under hard switching, zero-current switching, and zero-voltage switching are compared. According to this reference, the turn-on losses are reduced by about 70% using zero-current switching and by about 95% using zero-voltage switching with respect to the hard switching case. The turn-off losses are reduced by 95% using zero-current switching and by 70% using zero-voltage switching. For IGBTs, about 65% of the total switching losses occur at turn off. Therefore, the previous results indicate that zero-current switching is the preferable option to reduce the switching losses in IGBTs. The total reduction in switching losses would be 86.25% for zero current switching, and 78.75% for zero voltage switching. However, the difference between the reduction in losses for the two soft-switching technologies is not so much, and other factors may have a greater impact when selecting a topology.

If zero-current switching is used, a resonant tank has to be placed between the switches and each element that can be modelled, for high frequencies, as a current source. This resonant tank would divert the current source from the IGBTs allowing the soft switching process. For the DC/DC converter needed in this design, the presence of the inductor determines that a resonant
tank has to be included between the inductor and the converter. If zero-voltage switching is used, a resonant tank has to be placed between the switches and the elements that can be modelled, for high frequencies, as a voltage source. This resonant tank would make the voltage across the switch zero before the commutation. For the DC/DC converter, the resonant converter should be placed between the DC link and the converter. The locations of the resonant tanks for the zero-current option and for the zero-voltage option are shown in figure 4-2. In the figure, the tanks needed to soft-switch the inverter are included; however, as explained in section 4.1, from the weight point of view, it is not necessary to soft-switch the inverter. Therefore, the selection of the soft-switching technology will depend mainly on the possibility to increase the switching frequency of the DC/DC converter.

From the large number of configurations proposed to soft-switch DC/DC converters, only a few of them are capable of bi-directional operation, which is a clear requirement for the proposed design in order to recharge the energy storage unit. The simplest zero current switching options include a single LC structure, which would result in peak currents more than twice as large as the load current. Some more complex topologies need a peak switch current of at least 1.5 times the load current, and include several additional elements and complex control. The high peak current results in higher conduction losses and more expensive switches. Furthermore, additional elements increase the complexity and cost of the system. Due to these problems, zero voltage switching topologies were also considered as they may bring more advantages for the present case.

Most zero voltage topologies have the penalty of high peak voltage across the switches. For simple resonant circuits, the peak voltage across the switches is at least two times the DC link voltage, which increases the ratings and cost of the devices. A configuration proposed initially in 1986 [18], and improved two years later to limit the peak voltage [19], allows getting zero voltage switching with very low penalty in the peak current and limiting the peak voltage to only about

![Figure 4-2 Resonant Tanks Location when Using ZVS and ZCS](image)
1.4 times the DC link voltage. In addition, as it will be shown later, this topology allows soft-switching of both the DC/DC converter and the DC/AC converter using only one resonant tank; getting, with no extra effort, the advantages of soft-switching the inverter. The topology, called Actively Clamped Quasi-Resonant DC Link, was selected for this design and is discussed in detail in the next section.

### 4.3 Actively Clamped Quasi Resonant DC Link Converter

The idea behind the actively clamped quasi-resonant DC link converter (ACQRDL) is to produce, from a constant DC-link voltage, a waveform whose amplitude periodically drops to zero volts, and use this waveform to feed the converter. Then, the converter is switched only at discreet points at which the pulsating voltage is zero. The circuit for the ACQRDL converter is shown in figure 4-3. The main resonance is established between the inductor $L$ and the capacitor $C_{res}$. $I_{load}$ is the equivalent load current for the resonant tank, and it corresponds to the current going into the converter. Due to the inductive properties of the converter load, $I_{load}$ is assumed constant for the short interval between zero voltage instants.

To explain the function of the other elements in the circuit, let us analyse the operation of the simple resonant tank as shown in Figure 4-4. The differential equation that describe the circuit is given by:

$$V_{DC} = LC_{res} \frac{d^2 V_{res}}{dt^2} + V_{res} \quad (4-1)$$

Solving equation 4-1, the voltage $V_{res}$ is a sinusoidal waveform between 0 and $2V_{DC}$. Ideally, this waveform is enough to give zero volts at periodic instances, and it would be a perfect

![Figure 4-3 ACQRDL Circuit](image)
sine wave with a peak voltage that doubles the DC-link voltage. However, in practice the elements involved in the circuit have losses, and it is not possible to keep the resonance going if these losses are not compensated. The switch S1, in figure 4-3, is used to put enough energy in the inductor during every zero voltage phase to compensate for the circuit losses. The switch S2, its anti-parallel diode D2, and the capacitor $C_{n}$ whose value is larger than $C_{res}$, are used to limit the maximum output voltage, clamping it to a designed value.

To explain the operation of the complete circuit, the resonant cycle is divided into four phases as shown in figure 4-5. The operation of the circuit in each phase is explained in a simplified way in the next paragraphs:

a) **Rising phase**: At the beginning of this phase, the voltage across the resonant capacitor is zero, and the current flowing through the inductor is slightly larger than the load current. (In the lossless case, the current through the inductor is exactly equal to the load current). A resonance begins between the resonant capacitor and the inductor, and it results in an increase in capacitor voltage according to the following equation:

$$V_{C_{res}} = (1 + Sin(\omega_{r1}t - \pi / 2))V_{DC} \quad (4-2)$$

where $\omega_{r1}$ is the resonant frequency given by:

$$\omega_{r1} = \frac{1}{\sqrt{LC_{res}}} \quad (4-3)$$

The clamping capacitor has to be pre-charged to a designed value ($V_{C_{c}}$) such that the resonant voltage is clamped at $V_{DC} + V_{C_{c}}$. When the resonant voltage equals the clamping voltage, the diode D2 turns on and the clamping circuit begins to operate. At this point, the rising phase finishes, and the clamping phase begins.
Figure 4.5 ACQRDL Operation
b) **Clamping phase:** In this phase, the clamping capacitor \( (C_c) \) is connected to the resonant capacitor \( (C_{res}) \), and a resonance occurs between the inductor and the sum of both capacitors. The resonance frequency for this phase is given by the following equation:

\[
\omega_{r2} = \frac{1}{\sqrt{L(C_c + C_{res})}}
\]  

(4-4)

If the clamping capacitor is large enough, \( C_{res} \) can be neglected and the change in voltage across the capacitors due to the energy stored in the inductor would be very small; consequently, the resonant voltage is basically clamped during the whole phase. Then, the voltage across the inductor is equal to the voltage across the clamping capacitor and the current flowing through the inductor first decays and then reverses. When the current through the clamping switch reverses, the switch S2 begins to conduct and the clamping capacitor begins to discharge. After some time, the energy in the clamping capacitor has reached again the same level from the beginning of the clamping phase and switch S2 is turned off ending the clamping phase.

c) **Falling phase:** This phase is the complementary waveform of the rising phase. When S2 is turned off, the current flowing through L has to flow only through the resonant capacitor \( (C_{res}) \). A resonance between the resonant capacitor and the inductor begins with these initial conditions. The amplitude of this current is, neglecting the losses, equal to the current at the end of the rising phase, and it discharges the resonant capacitor until it reaches zero volts.

d) **Short-circuit phase:** During this phase the resonant capacitor has reached zero volts and the switch S1 is turned on with minimum losses. The full DC-link voltage is then applied to the inductor and the current starts to increase according to the following equation:

\[
V_{DC} = L \frac{di_L}{dt}
\]  

(4-5)

When the current is high enough to compensate for the losses during the next period, switch S1 is turned off and the cycle is completed. If the pulsating voltage is feeding a full leg converter such as the configuration in figure 4.6, an additional electronic switch to perform the function of S1 is not required. This is because two switches from the same converter leg can be activated simultaneously such that they are equivalent to the short circuit switch S1.
In the previous description of the resonant circuit operation, it was assumed that the load current is constant. If this is the case, the time interval between zero voltage occurrences is constant and the resonant current is oscillating around the value for $I_{\text{load}}$. However, if the pulsating voltage is feeding a converter, the current going into the converter ($I_{\text{load}}$ in figure 4-6) suffers a sudden change every time the converter is switched. Due to the zero-voltage operation principle for the ACQRDL, the switching and correspondingly the change in $I_{\text{load}}$ occurs only during the short circuit phase explained above. Step changes in $I_{\text{load}}$ have an important effect on the resonant tank operation as the converter has to react in order to adjust the resonant current to the new conditions. Figure 4-7 shows a plot for the resonant voltage and resonant current from a simulation of the resonant converter. The graphic shows the effect of a positive and a negative load step in the circuit waveforms.

When the current $I_{\text{load}}$ steps to a higher value, the duration of the short circuit phase has to be longer allowing the resonant current to reach the new load current. This is necessary to store enough energy in the inductor to complete the next resonant pulse. At the end of the short circuit phase, the normal conditions for the resonant tank are recovered and the circuit continues operating as explained before. The total time between zero voltage instants would be long compared with the normal case and the effective switching frequency is reduced.
When the current $I_{\text{load}}$ steps to a lower value, the resonant current and, therefore, the energy stored in the resonant inductor is larger than required. Therefore, switch S1 does not have to be turned on and the short circuit phase lasts only until the converter switching process is completed. The extra energy stored in the resonant inductor has to be transferred to the resonant and clamping capacitors, which results in a longer clamping phase. As the energy in the clamping capacitor has to be balanced at the end of the clamping, the resonant current has to decrease in a magnitude approximately equal to the load current step, below the new load current. Because of this large negative resonant current peak, the short circuit phase for the next cycle also has to be extended. The ratio between the switching period for the worst transient case and for the steady state case depends on the values for the resonant inductor and the resonant capacitor as well as the magnitude of the load step.

### 4.4 Soft-switching of Several Converters Using a Single Resonant Tank

As explained in the previous section, the idea behind the ACQRDL converter is to generate a resonance around the DC link voltage and use it to produce a pulsating voltage that goes frequently to zero. This pulsating voltage is then used as the input to the converter, and the
IGBTs are switched when the input voltage is zero. In the proposed configuration shown in figure 2-4, the DC link is used to feed one DC/DC converter and two DC/AC converters. Therefore, the same pulsating voltage can be used as input for all of the converters and to soft-switch all of them with only one resonant tank. The idea was introduced in [20] for the case of switching two DC/AC converters with one resonant tank, and it is extended here to soft-switch one DC/DC and one DC/AC converter. The second AC/DC converter is not included in the soft-switching system in this thesis because it leaves open the possibility of using alternative main energy sources and different configurations. However, the concept may be extended to soft-switch three or even more converters.

Going back to the operation for the ACQRDL converter, the analysis assumes that a constant load current is applied to the resonant tank during a resonant period. For the resonant tank operation, it does not matter if the load current is providing energy to one converter or to many of them. The only condition is that each one of these converters acts as a current source for the resonant tank during the resonant period. With many converters connected to a single resonant tank, the transient problem arises since all converters may switch at the same time and produce an accumulative load step. Consequently, a larger worst case transient would result when connecting more converters to the same resonant tank. However, it will be shown that this problem may be reduced by an intelligent control of the resonant tank.

4.5 Practical Problems and Limitations for the ACQRDL

The use of the ACQRDL resonant circuit in high power applications has been limited due to several operational problems that limit its performance. The main disadvantages for the topology are the following:

a) The switching of the converter(s) can occur only at discrete instants in which the pulsating voltage is zero. Therefore, standard pulse width modulation techniques (PWM) cannot be used with this converter. As PWM is the most common control technique for converters, many authors have been reluctant to use the mentioned resonant topology. An option to use PWM with the DC link resonant topology was proposed in [21], but its control is complex, additional components are needed, and the losses are increased. Two control techniques are the most commonly used with the ACQRDL converter: In the first one, called pulse density modulation, a large number of resonating pulses (usually more than 25) are grouped in one converter switching period. Then, the usual pulse width modulation technique is used but the switching time is approximated to the closest zero
voltage instant available. In the second one, called discreet pulse modulation, the reference signal and the feedback signal are compared at the end of each resonant pulse, and according to the comparison the state of the switches for the next period is decided. As the objective of this converter design is to increase the switching frequency for the DC/DC converter as much as possible, the discreet pulse modulation technique is used. The converter switching frequency, although variable, is much higher using this technique in comparison to the one achieved using pulse density modulation.

b) The effective load for the resonant tank, represented by a current source in figure 4-3, changes every time the converter is switched as a result of the change in the state of the switches. As explained in the previous section, this load change has a strong impact on the behaviour of the resonant tank, and the consequence is a lower switching frequency under high load conditions. For high current levels, the average switching frequency is considerably reduced with respect to the designed value and this reduction in switching frequency may be unacceptable in some designs. If the value of the resonant inductor is reduced, the effect of the load step is also reduced, but the resonant ripple current increases and; consequently, the losses. In general, the ACQRDL topology has been limited to low current (up to 30 A) applications mainly because of this problem.

c) If the same resonant voltage is used to soft switch more than one converter, the current step in the effective load current for the resonant tank \((I_{load})\) is equal to the sum of all the individual current steps from each converter. This accumulative effect makes the problem mentioned in b) worse and limits the number of converters that can be switched with a single resonant tank. A preliminary design of the resonant converter system operating at the typical power rating required by a subcompact vehicle, indicated that, under maximum load, the time between zero voltage instants for the worst load step change may be up to three times the designed value. This estimation suggests an important disadvantage in this design namely a 200 kHz resonant frequency requirement to get a worst case converter switching frequency of 40 kHz.

4.6 Proposed Strategies to Overcome the Limitations of the ACQRDL

A combination of three techniques associated with the control of the resonant converter is proposed to improve the transient behaviour of the converter and improve its operation in this specific configuration. These three techniques are explained next:
Use of the zero voltage vector in the DC/AC converter: When a voltage source inverter is used to control the current going into a three phase electric machine, eight valid switch combinations are possible for the six converter switches. Two of these combinations are equivalent: when the three upper switches are on, or when the three lower switches are on. This state is known as the zero state because the voltage applied to the load in this pattern is equal to zero volts. The simplest discrete pulse modulator, called delta modulator, does not use the zero state since the states for the switches are only the result of high gain comparisons. Extensive research in discrete modulators has indicated that the optimum control is achieved using the zero state and an additional feedback state (motor counter EMF) [22]. However, this type of controller is difficult to implement and it depends on the machine parameters. Reference [23] introduced a discrete pulse

Figure 4-8 Possible Switching Vectors in a Voltage Source Inverter
modulator that uses the zero state without an additional feedback state. If the three phase voltages for each valid state are transformed to two-phase co-ordinates, they can be plotted on the same two-dimensional graph. In this graph, the six non-zero vectors are placed forming a circle around the origin, and the zero state is placed in the origin as it is shown in figure 4-8. In this new regulator, the only state transitions that are allowed are those between adjacent states. If the result of the comparisons mandates a transition between states not adjacent, a zero state is introduced in between such a transition. For example if the present state is state one, resulting in the voltage vector \( V_1 \), and the next required state would give vector \( V_5 \), the converter would be switched to the zero state first and after one resonant period to state five. Although the objective in [23] is to find a simple current modulator close to the optimum one, it brings benefits to the soft-switched converter transient operation. The resulting modulator never produces +1 to -1 transitions in the DC current going into the converter so that the maximum current step in the load for the resonant tank is reduced by half with respect to a non zero vector modulation strategy.

b) **Synchronisation between converters:** In using a soft-switching topology for the proposed system, the objective is to maximise the switching frequency of the DC/DC converter in order to reduce the size of the inductor. A high switching frequency for the DC/AC converter is less critical since the inner inductance in the machine is sufficiently large. Taking this into account, a second technique to improve the transient behaviour of the resonant converter is proposed. The controller finds the required state for the DC/DC converter switches during the next cycle and estimates the current step to be produced by the converter switching. Then, the controller examines the desired state for the inverter during the next cycle. If the switching for the inverter is going to produce a current step in the same direction as the one produced by the DC/DC converter, then the inverter switching is delayed one cycle. This technique clearly reduces the average switching frequency of the inverter, but it also limits the current step magnitude to the larger current step of the two converters.

c) **Clamping time reduction:** The worst transient case for the resonant tank is when a high negative step in the load current occurs. In this case, the next voltage pulse is much longer than the one occurring under steady state conditions. This is because the extra energy stored in the inductor has to be transferred to the clamping capacitor and then transferred back to the inductor. Looking again at figure 4-7, a big part of the problem is associated with the fact that the energy in the clamping capacitor has to be balanced at the
end of each resonant pulse. An analysis of the resonant circuit indicates that the only requirement to keep the resonance running is to have enough current flowing through the inductor, when the clamping switch is turned off, so as to discharge the resonant capacitor. To reach zero volts across the resonant capacitor the energy balance has to fulfil the following relation:

\[
\frac{C_{\text{res}}(V_{\text{cc}} - V_{\text{dc}})^2}{2} + \frac{L_i^2}{2} \geq \frac{C_{\text{res}}V_{\text{dc}}^2}{2} \tag{4-6}
\]

From equation (4-6) the minimum inductor current required to achieve zero volts is found to be:

\[
I_L(\text{min}) = \sqrt{\frac{C_{\text{res}}}{L}(2V_{\text{cc}}V_{\text{dc}} - V_{\text{cc}}^2)} \tag{4-7}
\]

When a large step down in $I_{\text{load}}$ occurs, the minimum inductor current is reached some time before the energy stored in the clamping capacitor is balanced. If the clamping capacitor energy is balanced every cycle as usual in this converter topology, a large negative resonant current peak and a long transient occurs. A possibility is to transfer the extra energy stored in the clamping capacitor to the inductor over several
cycles. To maintain the resonance circuit oscillating, the clamping has to be released when the minimum current given by (4-7) is reached. In the following cycle, the clamping voltage is initially higher than for the steady state case but the next cycle or cycles are used to balance again the energy in the clamping capacitor. The result is that the long period produced by the step in load is distributed over two or several periods instead of having a single very long resonant pulse. Figure 4-9 shows the simulated resonant voltage and resonant current for the same load change from figure 4-7 but including the results using the clamping time reduction strategy.

4.7 Design of the ACQRDL Circuit

The design of the resonant converter system involves two different aspects: first, the design of the resonant tank to get some desired time interval between zero voltage instants; and second, the rating of the converter switches. The rating of the converter switches will be decided in chapter six when designing the propulsion system. In this section, the focus is on designing the resonant tank to produce oscillations at the required frequency.

Running a preliminary simulation for the circuit using the techniques presented in section 4.6, it was estimated that a resonant tank frequency of 100 kHz would result in an average converter switching frequency close to 40 kHz, and that would reduce the weight of the inductor considerably.

The design of the resonant tank will be done neglecting the resonant tank losses; afterwards, the short circuit current required to compensate the losses will be estimated. A more precise methodology would only complicate the design process and equations, and it will not bring more accuracy, as the losses have to be estimated anyway. The conditions and specifications for the resonant tank design are shown in the following table:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady State Resonant Frequency</td>
<td>100 kHz</td>
</tr>
<tr>
<td>DC-link Voltage</td>
<td>300 V</td>
</tr>
<tr>
<td>Clamping Voltage</td>
<td>1.3*VDC =390 V</td>
</tr>
<tr>
<td>Maximum Resonant Voltage</td>
<td>&lt; 600 V</td>
</tr>
<tr>
<td>Maximum Load Step</td>
<td>150 A</td>
</tr>
</tbody>
</table>

Table 3. Specifications for the Resonant Tank
The short circuit phase includes two sections: In the first section, the resonant current freewheels through the diodes in anti-parallel with the short circuit switch. This part results from the excess of energy stored initially in the resonant inductor. In the second part, the shorting switch conducts and the current through the resonant inductor increases. This phase is used to store energy to compensate for the power losses during the next cycle. If the losses are neglected, the short circuit time is zero. That is because the resonant waveform would barely reach zero volts and immediately the next cycle would start. In a practical case, the short circuit phase must be at least equal to the switching time for the devices in order to minimise the switching losses.

The rising phase is a simple resonance between the resonant inductor (L) and the resonant capacitor (C_res). The initial conditions for the rising phase assuming no losses are I_L(t=0) = 0 and V_{Cres}(t=0) = 0. Therefore, the resonant capacitor voltage is described by the following equation:

\[ V_{Cres}(t) = V_{DC} (1 - \cos(\omega_r t)) \] (4-8)

The current flowing through the resonant inductor can be calculated from the resonant tank circuit and equation (4-8), resulting in the following equation:

\[ I_L(t) = I_{load} + \frac{C_{res}}{L} V_{DC} \sin(\omega_r t) \] (4-9)

This equation is valid until the clamping phase begins. If the resonant voltage is clamped at V_{C}=1.3 V_{DC}, the rising phase time is calculated by substituting V_{Cres} with 1.3*V_{DC} in (4-8). This gives:

\[ t_{ris} = 1.8755 \sqrt{L \cdot C_{res}} \] (4-10)

The clamping phase is associated with a resonance between the resonant inductor and an equivalent capacitance given by the clamping capacitor in parallel with the resonant capacitor. The initial conditions for the clamping phase are the final conditions for the rising phase that may be calculated by (4-8) and (4-9) with \( t \) equal to \( t_{ris} \). The voltage waveform may be seen as the upper section of a sinusoidal wave that swings around \( V_{DC} \) and has its peak \( (V_{DC}+V_{max}) \) at the middle of the clamping phase. Such a waveform is mathematically represented by the following equation:

\[ V(t) = V_{DC} + V_{max} \sin(\omega_r t) \] (4-11)
Equation (4-11) is valid between $\pi/2 - \omega_2 t_0$ and $\pi/2 + \omega_2 t_0$, where $\omega_2 t_0$ is calculated from (4-11) as the angle in which the waveform crosses the clamping voltage. Solving equation (4-11) for this condition results in the following clamping time:

$$t_{\text{clamp}} = 2 \sqrt{L \left( C_C + C_{\text{res}} \right) \left( \pi / 2 - \arcsin \left( \frac{V_{\text{ce}} - V_{\text{DC}}}{V_{\text{max}}} \right) \right)}$$ (4-12)

The peak voltage ($V_{\text{max}}$) may be found using the energy conservation equation between the beginning of the clamping phase and the time of the peak voltage:

$$\frac{L \cdot I_{L(\text{ris})}^2}{2} + \frac{C_{\text{res}} + C_C}{2} \left( V_{\text{cl}} - V_{\text{DC}} \right)^2 = \frac{(C_{\text{res}} + C_C) \cdot V_{\text{max}}^2}{2}$$ (4-13)

resulting in the following relation:

$$V_{\text{max}} = \sqrt{\frac{L}{C_{\text{res}} + C_C} \cdot I_{L(\text{ris})}^2 + (V_{\text{cl}} - V_{\text{DC}})^2}$$ (4-14)

The falling phase is the complement of the rising phase and under steady state conditions has the same time duration. Then, the total resonant cycle time is given by:

$$t_{\text{res}} = 2 \cdot t_{\text{ris}} + t_{\text{clamp}}$$ (4-15)

To find the values for the component parts, it is necessary to establish a relation between their values. The clamping capacitor has to have a much higher capacitance than the resonant capacitor to effectively hold the voltage at the required point. The specification establishes a maximum step current of 150 A and a maximum resonant voltage lower than 600 V. Inserting these values in (4-14) results in a quotient between the resonant inductor and the clamping capacitor of no more than 3.6 to satisfy the conditions. A clamping capacitor value equal to the resonant inductance value satisfies the condition and is taken in this design.

The relation between the resonant inductor and the resonant capacitor values determines the peak resonant current under steady state conditions. Under no load conditions, the energy transferred from the capacitor to the inductor produces a peak current given by the energy balance equation:

$$\frac{L \cdot I_{\text{peak}}^2}{2} = \frac{C_{\text{res}} \cdot V_{\text{peak}}^2}{2}$$ (4-16)
where $V_{\text{peak}}$ is equal to the DC-link voltage. If the peak resonant current is set at 40 A, the quotient $L/C_{\text{res}}$ is equal to 100. Using equation (4-9) under no load conditions, the value for the current at the end of the rising phases is found to be 38.2 A. The maximum voltage is then calculated substituting $I_{\text{L(min)}}$ in (4-14). This gives 125.9 V. Then, substituting the values in (4-12) results in:

$$t_{\text{clamp}} = 0.697\sqrt{L \cdot (C_C + C_{\text{res}})} \quad (4-17)$$

With $C_C=100C_{\text{res}}$ the total resonance time from (4-15) is:

$$t_{\text{res}} = 10.756\sqrt{L \cdot C_{\text{res}}} \quad (4-18)$$

The component values are estimated by choosing a resonant period of 10µs (100 kHz resonant frequency) in (4-18) and using the ratio between resonant inductor and the resonant capacitor, resulting in the following values:

- $C_{\text{res}} = 93nF$
- $L = 9.3\mu H$
- $C_C = 9.3\mu F$

The current needed in the resonant inductor at the end of the short circuit phase depends on the losses of the resonant tank. The losses can be measured or estimated, and using this value, the average energy lost in a cycle is easily calculated as:

$$E_{\text{loss}} = P_{\text{loss}} \cdot t_{\text{res}} \quad (4-19)$$

The same amount of energy has to be stored in the inductor during each short circuit phase. Therefore, the current needed when releasing the short circuit is given by:

$$I_{\text{short}} = \sqrt{\frac{2 \cdot E_{\text{loss}}}{L}} \quad (4-20)$$

A simulation of the soft-switched converter system was developed to verify the design and estimate the worst case operation. It was found that under the conditions specified in the design, the minimum switching frequency is 38.9 kHz. The simulation programs are shown in appendix C.
4.8 Soft-Switched Converter Experimental Results

An experimental soft-switched converter system was implemented to test the concept of soft-switching two converters with one resonant tank. The implemented circuit is equivalent to the one in figure 4-6 but a three-phase DC/AC converter is also fed from the resonant capacitor voltage ($C_{\text{res}}$). In the practical implementation, the resonant frequency was limited to 60 kHz instead of the designed 100 kHz due to the fact that intelligent IGBT modules were used and they have an internal delay in the order of 1 microsecond resulting from the control electronics in the module. The internal delay sets a restriction mainly in the minimum short circuit time and therefore, requires the use of a larger inductor thus limiting the maximum operating frequency.

Results for the experimental implementation are given in detail in [24]. In this section, only general results for the converter operation are presented. The values for the components in the resonant tank used in the experimental implementation and resulting in a resonant frequency of 60 kHz are the following:

- $C_{\text{res}} = 160 nF$
- $L = 16.7 \mu H$
- $C_c = 10 \mu F$

Figure 4-10 shows an oscilloscope plot for the resonant converter voltage and current under no load conditions. The figure shows that the voltage is clamped at about 400 V as it was designed, and the current ripple is slightly under 40 A. The resonant frequency is 59.8 kHz.

Figure 4-11 shows the converter response to a switching process at high constant load.

![Figure 4-10 ACQRDL Experimental Waveforms](image)
current. The switching process results in a step of about 100 A in the current equivalent to the resonant tank load. Figure 4-11.a shows the results without the techniques to improve the transient behaviour and figure 4-11.b shows the results using the improved resonant tank control. The benefits in switching frequency and current ripple are clear in the results.

The losses for the resonant tank and for the converters under load were measured to get an indication of system efficiency. These measurements were taken based on the power balance for the system rather than using high precision equipment. The results are shown in the following table:

<table>
<thead>
<tr>
<th>Test</th>
<th>Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only Resonant Tank (No Load)</td>
<td>180 W</td>
</tr>
<tr>
<td>DC/DC Converter Loaded at 10 kW (50A), DC/AC off</td>
<td>740 W</td>
</tr>
<tr>
<td>DC/AC Converter Loaded at 9.2 kW (20 A), DC/DC off</td>
<td>360 W</td>
</tr>
</tbody>
</table>

Table 4. Soft-Switched Converter System Losses

In the first test, both converters were off and only the resonant tank was operating to produce the pulsating voltage. In other words, no power was being transferred to the converters or the load and the only losses were a result of the resonant process. In the second test, the DC/AC converter was off such that no voltage was applied to the motor and therefore no losses in the full bridge and motor occurred. Also, constant power was being supplied to the capacitors and the losses were measured when the capacitor current was 50 A. In the third test, the DC/DC
converter was not operating and no losses were associated with the half bridge and the DUC bank. In this test, constant current and constant power were being delivered to a constant AC load.

Although the losses in the DC/DC converter may appear high, these losses include the resistive losses in the capacitor bank and in the inductor that are estimated to be more than 50% of the measured losses. Furthermore, the resistive losses in the DC/AC converter are estimated to be about 100 W. These observations indicate that the switching losses in the converters are very small.
CHAPTER 5

MODELLING OF THE ENERGY SYSTEM

After the detailed study and design of the two main components for the propulsion system presented in chapters three and four, this chapter deals with the development of an equivalent model for the system to be used in simulations to perform additional studies. The model also allows analysing easily the effect of changing one or several of the design parameters in the vehicle performance and efficiency. The simulation focuses on producing information about vehicle performance, power requirements, efficiency, and energy management. At this level, a detailed description of the soft-switched converter system is not required since it is only a configuration used to perform the general task of transferring energy amongst the different subsystems. However, the losses in the converters have to be modelled because they have an impact on the system efficiency. Due to the large number of elements involved in the system, the simulation was divided in three main subsystems: energy storage section, traction section, and engine section. Figure 5-1 shows the complete proposed traction hybrid system divided into the three sections mentioned. The modelling for each one of the sections is presented next.

5.1 Energy Storage Section

This section includes the double-layer capacitor bank, the DC/DC converter, the resonant tank, the converter control, and the converter losses.

A. Double-Layer Capacitor Bank

The double layer capacitor bank consists of 100 DLCs connected in series. The bank was modelled based on the equivalent circuit model presented in chapter 3 for the 1500 F device, and extended to the series chain of capacitors. The actual equivalent parameter values for each device depend on the energy requirements for the complete vehicle, and they will be decided later in the design stage. The model consists of three RC branches connected in parallel and a parallel resistor. Each element in the complete model has a value given by the series connection of 100 correspondent single DLC elements. In other words, the immediate resistance is equal to 100 times the immediate resistance for a single cell, the immediate capacitance is equal to the single cell immediate capacitance divided by 100, etc. The equivalent parallel resistance is equal to 10
kΩ because, according to the observation on chapter 3, a 100 Ω resistor is connected in parallel with each DLC to guarantee a good voltage sharing. In this form, the capacitor bank appears as a single capacitor with the same equivalent model structure used for a single DLC cell. The DLC bank model is presented in figure 5-2 with the values for the experimental energy storage unit introduced in chapter 3. To simulate the capacitor electric behaviour, three differential equations, one for each equivalent circuit capacitor, are required. The three differential equations are the following:

\[
\frac{dV_{ci}}{dt} = \frac{(V_{cap} - V_{ci})}{(Ri(Ci0 + KV_{ci}))}
\]  

(5-1)
Chapter 5. Modelling of the Energy System

Figure 5-2 DLC Bank Equivalent Model

\[
\frac{dV_{Cd}}{dt} = \frac{(V_{\text{capa}} - V_{Cd})}{(RdCd)} \quad (5-2)
\]

\[
\frac{dV_{Cl}}{dt} = \frac{(V_{\text{capa}} - V_{Cl})}{(RlCl)} \quad (5-3)
\]

where \( V_{\text{capa}} \) is the capacitor terminal voltage calculated from the equivalent model capacitance voltages and the device current \( I_{DLC} \) through the following equation:

\[
V_{\text{capa}} = \frac{-I_{DLC} + V_{Cl} / R_1 + V_{Cd} / R_d + V_{Cl} / R_l}{1/R_1 + 1/R_d + 1/R_l} \quad (5-4)
\]

B. RESONANT TANK

Since the goal of this simulation is to study the energy consumption and energy management for the hybrid system, a precise simulation of the resonant circuit is not necessary. Detailed simulation of the high frequency converter would increase considerably the simulation time, and it would not provide any useful information for the energy management. A more complete simulation of the ACQDL was done to verify the converter operation and the control techniques as explained in chapter 4. The resonant circuit gives two important parameters associated with the converter operation. First, the resonant tank fixes the interval between switching instants for the converters. Second, the resonant circuit determines the average input voltage supplied to the converters. Although, due to the effect of the converter switching, the period between switching instants for the ACQDL is not constant, in the simulation it is assumed a constant switching period of 15 microseconds. According to the results in chapter 4, this value is close to the worst case switching period for a 100 kHz steady state design. Since the resonant
system was designed to produce an average input voltage approximately equal to the DC-link voltage, the simulation assumes a constant converter input voltage equal to the DC-link voltage.

C. DC/DC CONVERTER

The objective of the DC/DC converter is to transfer power between the DLC bank and the DC-link keeping the DC-link voltage constant. The power transfer is achieved by setting a controlled current ($I_{\text{DLC}}$) at the inductor $L_{\text{DC}}$ shown in figure 5-1. Based on the observations for the modelling of the resonant tank, the converter is modelled as an ideal hard-switched converter with constant input voltage and operating in current control mode. The conduction and switching losses for the switches are calculated independently of the converter operation and added later in the simulation. The state of the switches may change only at discrete time instants every 15 microseconds. Every 15 microseconds, a comparison between the current reference and the feedback current defines if the inductor current has to increase or decrease, and accordingly, the state of the switches for the next period. The state of the switches fixes the voltage applied to the inductance $L_{\text{DC}}$, and this gives the change in current at the inductor according to the following equation:

$$\frac{di_{\text{DLC}}}{dt} = \frac{V_{L_{\text{DC}}}}{L_{\text{DC}}} \quad (5-5)$$

The reference for the inductor current is set by the converter controller to keep the DC-link voltage constant, as explained below.

D. DC/DC CONVERTER CONTROL

The converter controller sets the current going into the energy storage unit to keep the DC-link voltage constant. Figure 5-3 presents a diagram for the DC/DC converter control strategy. The current reference ($I_{\text{DLC}^*}$) results from a controller designed to keep the DC-link voltage at some reference value ($V_{\text{DClink}^*}$) and it is followed using an internal current control loop synchronised to the resonant tank operation. The voltage controller is slow to improve the stability in case of disturbances on the measured DC-link voltage. The voltage controller is sufficient to keep the average DC-link voltage constant; however, due to the highly variable power demand, transients in the voltage occur while the controller responds to sudden power changes. The DC-link voltage transients may produce a malfunction in the resonant tank. Therefore, a feed-forward component proportional to the difference between the power coming
Figure 5-3 Control Strategy for the DC/DC Converter

from the engine and the power going to the motor is added to the reference current. This feed-forward component improves the transient performance when a sudden change in load occurs.

E. CONVERTER LOSSES

Conduction losses occur when current flows through diodes or IGBTs. The instantaneous current flowing through each diode and IGBT depends on the state of the switches and the magnitude and direction of the load current. In the simulation, when conducting, diodes and IGBTs are modelled as a resistance in series with a voltage source. The values for the resistance and intrinsic voltage were taken from data sheets for IGBTs in the power range required for the application. The data sheets for the devices used in the experimental implementation are included in appendix B. During every period, the simulation calculates the total average current flowing through diodes (I_{dio}) and the total average current flowing through IGBTs (I_{sw}), and applies the following equation to estimate the conduction losses during the interval:

$$P_{\text{cond}} = I_{\text{sw}} \cdot V_{\text{sw}} + I_{\text{sw}}^2 \cdot R_{\text{sw}} + I_{\text{dio}} \cdot V_{\text{dio}} + I_{\text{dio}}^2 \cdot R_{\text{dio}} \quad (5-6)$$

Reference [25] discusses the modelling of switching losses for zero voltage switching converters. According to this reference, for zero voltage switching, the turn on losses are expected to be very low due to the fact that current is freewheeling through the anti-parallel diodes when the IGBTs are turned on. These losses are assumed zero in the simulation. For the turn off losses, it is assumed that the load currents are constant during the device turnoff time. This is a valid approximation because the switching time is very short and the loads are inductive. Under these conditions, the equivalent circuit for the turn off process is shown in figure 5-4. Then, the device current during the switching process (0 ≤ t ≤ t) can be approximated as:
where $I_{\text{dc}}$ is the current being switched off, and $t_f$ is the turn off time for the IGBT. The difference between the load current and the switch current is then flowing through the resonant capacitor, and is given by:

$$i_c = I_{\text{dc}} \frac{t}{t_f} \quad (5-8)$$

As a result of the zero voltage switching strategy, the resonant capacitor is initially discharged. Therefore, its voltage during turn off is proportional to the integral of (5-8) and the result is:

$$v_c = \frac{I_{\text{dc}}}{2C} \frac{t^2}{t_f} \quad (5-9)$$

The average power dissipated in the IGBT is the integral of $i_d \cdot v_c$ between $t=0$ and $t=t_f$ and it results in:

$$P_{\text{sw}} = \frac{I_{\text{dc}}^2 \cdot t_f^2}{24C} \int_{t_f}^{t_f} f_{\text{sw}} \quad (5-10)$$

The simulation finds at every switching point those IGBTs that are being turned off and the current being switched off in each one of them. Then, the previous equation is used to calculate the switching losses.

### 5.2 Traction Section

This section includes the permanent magnet synchronous machine, the DC/AC converter, the converter controller, the converter losses, the road load, and the gearbox.
A. **Resonant Tank**

As mentioned in the previous section, a detailed simulation of the resonant circuit is not necessary for a simulation focused on energy usage. The resonant tank fixes the interval between switching points and the input voltage to the inverter. The simulation takes a constant switching period of 15 microseconds for the inverter and a constant voltage input equal to the DC-link voltage. After every period, the current control is applied and the losses are calculated.

B. **Converter Losses**

The DC/AC converter losses are calculated in the same way that it was done for the DC/DC converter. In this case, the simulation has to calculate the total current flowing through the six IGBTs and the six diodes in the inverter, as well as the total current being turned off by all the switches. With those results, equation (5-6) and (5-10) are used to estimate the losses.

The losses in the resonant tank auxiliary circuit are included in the motor section. The resonant circuit includes only one additional IGBT and its anti-parallel diode that are used in the clamping phase. For the conduction losses, the average current flowing through the clamping switch and the clamping diode have to be estimated. The approximate waveform for the current flowing through the clamping branch is shown in figure 5-5. The peak current \( I_{\text{ripple}} \) in the figure and the time instants depend on the values for the resonant inductance and capacitance. They are easily calculated using the simulation for the resonant converter. With those values, the average current through the diode and IGBT are easily estimated and used to calculate the conduction losses.

![Figure 5-5 Clamping Current Approximated Waveform](image-url)
losses.

For the switching losses, it is necessary to study the operation of the clamping switch. The clamping switch is turned on when current is flowing through its anti-parallel diode. Therefore, the turn-on losses are very small and neglected in the simulation. Under constant load conditions, the current being turned off by the switch is equal to \( I_{\text{ripple}} \) in figure 5-5. However, when the load current has a step down at the beginning of a cycle, the current turned off by the switch is approximately equal to the magnitude of the current step. The simulation calculates the current being turned off by the switch depending on the load step, and then equation (5-10) is used to calculate the turn off losses for the clamping switch.

C. **Permanent Magnet Synchronous Machine**

The PMSM is modelled in a rotor reference frame based on [26]. The differential equations for the flux components in rotor frame are as follows:

\[
\frac{d\lambda_d}{dt} = V_d - I_d R_s + \omega_r \lambda_q \\
\frac{d\lambda_q}{dt} = V_q - I_q R_s + \omega_r \lambda_d
\]

where \( \lambda_d \) and \( \lambda_q \) are the fluxes, and \( V_d \) and \( V_q \) are the voltages in the respective frame (d,q) and \( \omega_r \) is the rotor speed. The following equations relate the rotor frame currents to the rotor frame fluxes:

\[
\lambda_d = \lambda_{\text{mag}} + I_d L_d \\
\lambda_q = I_q L_q
\]

where \( \lambda_{\text{mag}} \) is the magnetic field produced by the permanent magnets. Therefore, the machine torque is given by:

\[
T_{q_m} = I_q \lambda_{\text{mag}} + I_d L_d I_q - I_q L_q I_d
\]

For the specific case of a non-salient rotor, the machine inductance components in the rotor frame are the same (\( L_d = L_q \)), and the differential equation for the machine speed is given by:

\[
\frac{d\omega_r}{dt} = \frac{I_q \lambda_{\text{mag}} - T_{\text{load}}}{T_m}
\]
where $T_m$ is the mechanical constant of the machine and $T_{\text{load}}$ is the load torque applied to the shaft. An optimal machine torque control would then set the $I_q$ as required to accelerate or brake the vehicle. $I_d$ may be equal to zero since the excitation is provided by the permanent magnets.

In the simulation, the three phase voltages during each switching interval are the result of a three phase current control. Then, $V_d$ and $V_q$ are calculated using the usual transformations from a three-phase system to a two-phase system and from frame to frame. With those results, equations (5-11) to (5-14) are used to find the motor speed and the rotor frame currents. Finally, the currents are transformed again to three phase currents and used as feedback currents in the converter current control.

D. **Motor Control**

The DC/AC converter is operated in a current control mode in which the motor reference currents in the rotor frame are followed. Figure 5-6 shows a diagram for the motor controller. The reference for the torque-producing component ($I_{q\text{com}}$) may be introduced using the keyboard (acceleration or deceleration demand) or it may be the result of a speed controller. The reference currents in the rotor frame are then transformed to three phase reference currents. Every period, these references are compared with the line currents from the feedback (see PMSM modelling), and the state of the inverter switches is determined according to the control principles mentioned in the resonant converter description. The state of the converter switches determines the three phase voltages applied to the machine. It has to be mentioned that the modifications in the inverter switching control, i.e. zero-vector use and synchronisation between converters, are included in the simulation. These modifications resulted from the techniques to improve the transient response for the resonant converter introduced in chapter 4.

The maximum motor torque is limited to three times the continuous rated torque according to the vehicle design to be presented in chapter 6. Since an open loop torque control is used, the torque is limited to a lower value if the machine speed is high such that the maximum power delivered to the machine is no more than 2.5 times the continuous rated power.

E. **Vehicle and Roadway**

The vehicle and road modelling is based on [27] and adapted to the vehicle size and specifications. The load exerted by the road on the vehicle consists of three components: the rolling resistance caused by the tires deformation on the road, the aerodynamic drag caused by the
Figure 5-6 Control Strategy for the PM Motor and DC/AC Converter
air resistance to the movement of the vehicle, and the climbing resistance resulting from the slope of the road. Each one of these components is modelled independently:

a) **The rolling resistance (Fric):** This is a force exerted by the road surface over the vehicle, it depends on the vehicle mass, the type of tires, the type of pavement, and the tire's air pressure. The last three factors are usually grouped in a coefficient called rolling coefficient (rolres). This force is mathematically given by:

\[ Fric = rolres \cdot V_{mass} \cdot g \quad (5-15) \]

where \( V_{mass} \) is the vehicle mass and \( g \) is the gravitational constant.

b) **The aerodynamic drag (airres):** This is the force of the air acting upon the vehicle. It is a function of the air density, the vehicle area, and the drag coefficient. In this simulation these three factors are grouped in one constant (K). This force is given by:

\[ airres = K(V_{exp} + V_{wind})^2 \quad (5-16) \]

where \( V_{exp} \) is the vehicle speed and \( V_{wind} \) is the wind velocity in direction frontal to the vehicle.

c) **The climbing resistance (grade):** This is the gravitational force acting on the vehicle when it is climbing a ramp. This resistive force is given by:

\[ grade = V_{mass} \cdot g \cdot \sin(\alpha) \quad (5-17) \]

where \( \alpha \) is the grade angle of the hill.

The total force (\( F_{load} \)) over the vehicle is then given by:

\[ F_{load} = fric + airres + grade \quad (5-18) \]

This load force is calculated every period, and transformed to a load torque (\( T_{load} \)) acting on the motor shaft using the tire diameter (tire) and the total gear ratio (gra) between the motor and the wheels according to the following equation:

\[ T_{load} = F_{load} \cdot \frac{tire}{gra} \quad (5-19) \]
Then the load torque as seen by the motor is used in equation (5-14) to calculate the motor speed, and this speed is transformed to get the vehicle speed ($V_{\text{esp}}$) using the following relation:

$$V_{\text{esp}} = \omega \cdot \frac{tire}{\text{gra}} \quad (5-20)$$

**F. GEARBOX**

The gear ratio between the motor and the wheels introduced in the previous section includes a fixed gear and a variable one used to improve the acceleration performance for the vehicle. In the next chapter, the number of gears and the gear ratios will be designed according to the performance specifications. There, it will be shown that, for the chosen motor size, a three-stage gearbox is required to achieve the performance requirements.

The change of gear stages affects the mechanical constant for the motor and the ratio between vehicle speed and motor speed. As the inertia of the electric machine is much lower than the inertia of the vehicle, the change in motor speed during the change of gear is fast compared with the vehicle speed transients. Consequently, the time needed to change the motor speed during the gear change is neglected in the simulation. In the simulation, when the vehicle speed reaches the set point to change gears, the new time constant is calculated and the motor speed is set to the new required value to match the vehicle speed. A 2-km/h hysteresis between the gear up speed and the gear down speed was chosen to avoid oscillations in the simulation when the speed is around the gear change set point.

**5.3 Engine/Generator Section**

This section includes the engine, the permanent magnet generator, its controller, and the DC link capacitor. The modelling of each of these parts is described below.

**A. ENGINE**

The engine is modelled in a simplified way as an element capable of providing mechanical power. Although the simulation does not deal with the engine controller, it is assumed that the engine control results in an engine mechanical power that follows a reference signal ($P_{\text{in}}^*$). This reference signal is limited in the rate of change by the engine manager to keep the engine operating under quasi-steady state conditions and to reduce emissions as it will be discussed in chapter 6. A non-rate limited power reference ($P^*$) is derived from the vehicle
operation and the energy left in the capacitors according to the energy management and used as input to the engine manager.

An electric generator is coupled to the engine and it represents the load for the engine. A constant gear ratio may be present between the engine and the generator. However, since the important quantity for the simulation is the total power transferred to the generator, the engine speed and torque values are referred to the electric generator. The electric generator is controlled using a speed loop to get the desired torque versus speed operating point of the engine. The choice of the engine operating point at every instant depends on the strategy to operate it in an optimum efficiency region and to minimise the emissions. This strategy is part of the energy management and it will be discussed in chapter six. With the engine speed set by the generator, the engine torque supplied to the permanent magnet generator is calculated as the ratio between the engine power and the generator speed. As the rate of change for the engine power and speed reference are limited, the engine torque rate of change is also limited.

B. **PERMANENT MAGNET GENERATOR**

The generator is modelled in the same way as the motor used in section 5.2. Based on the state of the converter switches, the phase voltages are transformed to rotor frame co-ordinates and used to get the rotor frame fluxes using the relations in equation (5-11). Then, the currents in rotor frame are calculated using the relations in equation (5-12). The rotor frame currents are transformed again to a three-phase system and used in the current control. The only difference with the motor model is that in this case the torque from the engine (Tq_eng) drives the generator and the internal machine torque acts as a load. Furthermore, a torque loss (Tq_loss) proportional to the speed is included in the speed equation. The differential equation for the generator speed is the following:

\[
\frac{d\omega_r}{dt} = \frac{Tq_{eng} - Tq_{loss} - I_q \lambda_{mag}}{T_g} \tag{5-21}
\]

where Tg is the mechanical constant for the system including the engine and generator inertia.

C. **GENERATOR CONTROLLER**

The permanent magnet generator is modelled and controlled in a rotor frame. A voltage source inverter is used to supply the required currents. The current reference (Iq*) is the result of
a PID speed controller. The energy management gives the speed reference for the PID controller according to the desired engine operation. The rotor frame current reference is converted to three phase currents and they are used as reference for the current control. Although the DC/AC controller is operated hard switched and it is possible to use pulse-width modulation in the current control, the simulation assumes that discrete pulse modulation similar to the one used in the motor controller is used. This leaves open the possibility to use the same resonant tank to soft-switch this converter. High gain comparisons between the phase currents and the reference currents decide the state of the electronic switches and, according to the resonant tank timing, the converter is switched. Figure 5-7 shows the diagram for the generator and engine control.

**D. DC-LINK CAPACITOR**

The DC link capacitor is the element that joins the three individual sections in the simulation. Each one of the sections has a converter that is fed from the DC-link capacitor and that transfers power to/from the DLC bank, the engine/generator, or the motor. The result of each converter simulation is a pulsating current going into or coming from the DC-link and calculated every period according to the load currents and the state of the switches. The current from the engine section converter (Iloadg), the current to the motor section (Iloadm), and the current from the capacitors (Iloadch) are added every simulation step to get the total current drained from the DC-link capacitor. In addition, the power losses are added as being drained from the DC-link since they represent energy being dissipated around the system. With the total equivalent current coming from the DC-link capacitor, the change in capacitor voltage is given by a differential equation. The resulting differential equation for the DC-link voltage is the following:

\[
\frac{dV_{dc}}{dt} = \frac{I_{loadg} - I_{loadm} + I_{loadch} - \text{Plosses}}{C_{dc}} V_{dc} \quad (5-22)
\]

where the direction assumed respectively for each current is shown in figure 5-1.
Chapter 5. Modelling of the Energy System
CHAPTER 6

HYBRID ELECTRIC VEHICLE DESIGN

After the description of the components presented in chapters three and four and the modelling for the complete system presented in chapter five, this chapter is dedicated to the development of a methodology for the design of a propulsion drive with the characteristics of the system proposed in this thesis. The vehicle design begins by formulating and justifying several specifications and operating constraints set to design a well performing and efficient vehicle. These specifications have a large effect on the rating of the propulsion system. The decisions about the specifications and requirements are not simple due to the large number of factors involved and the wide range of performance results covered by normal vehicles. After formulating all the operational constraints, the design process is straightforward since it consists of the translation of those constraints into quantitative ratings.

6.1 Propulsion System Operating Constraints

A. VEHICLE PARAMETERS AND SPECIFICATIONS

The design process begins by establishing specifications for the vehicle performance and choosing the parameters associated with the vehicle operation. Due to the large number of vehicle models available, the vehicle performance numbers are highly variable; consequently, the process to set the specifications is arbitrary. However, as the goal of the thesis is to examine the feasibility of using two new major components, the double-layer power capacitors and the soft-switched converter system, in a sub-compact vehicle, a set of values, which are believed to be typical for this kind of vehicle, were chosen.

A vehicle with curb weight of 1100 kg was chosen as a base for the present design, and 100 kg was assigned to the driver in all of the simulations. This is a typical weight for sub-compact vehicles available in the market. The car must be able to sustain at least 120-km/h constant speed on levelled ground, and it should also be able to sustain at least 80 km/h on hills with a 5% slope. Short hills can be climbed faster as the energy stored helps to maintain the speed. The acceleration capability for gasoline vehicles is widely variable depending on the model; however, a specification of acceleration from zero to 100 km/h in less than 14 seconds is
chosen since it would result in a vehicle with good response. To provide good passing capability, the vehicle has to accelerate from 60 to 80 km/h in about three seconds.

The vehicle performance depends on a number of vehicle physical parameters since they determine the road load for the vehicle. These parameters were selected based on the literature available for studies on typical vehicles and are specified next:

a) A rolling resistance coefficient (rolres) of 0.013 is used. With the latest radial tires, coefficients between 0.010 and 0.014 are achieved. Therefore, this assumption is realistic and slightly conservative.

b) The aerodynamic drag coefficient used is equal to 0.3. This value is highly variable depending on the external vehicle design, with typical values between 0.2 and 0.35. Values lower than 0.3 are common in most of the sub-compact vehicles; in fact, the electric or hybrid vehicles that have reached the North American market, e.g. General Motors’ Impact, Honda’s Insight, and Toyota’s Prius have drag coefficients below 0.3. With this coefficient and assuming a frontal area of 1.9 m$^2$ and an air density of 1.23 kg/m$^3$, the resulting constant $K$ in equation (5-16) is equal to 0.35 kg/m.

c) The climbing resistance depends only on the vehicle mass, already specified, and no additional coefficients are required.

d) The radius for the vehicle tires is assumed as 0.25 m, which is typical for small vehicles.

Figure 6-1 shows the road resistive force over the vehicle as function of the vehicle speed for driving on levelled ground. The graphic indicates that for speeds below 60 km/h the rolling resistance dominates, but for speeds over 80 km/h the aerodynamic drag takes priority. The parameters and specifications for the vehicle to be designed are summarised in Table 5.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Weight</td>
<td>1200 kg</td>
</tr>
<tr>
<td>Maximum Continuous Speed</td>
<td>120 km/h</td>
</tr>
<tr>
<td>Acceleration (0-100 km/h)</td>
<td>&lt;14 sec</td>
</tr>
<tr>
<td>Acceleration (60-80 km/h)</td>
<td>≈ 3 sec</td>
</tr>
<tr>
<td>Rolling Resistance Coefficient</td>
<td>0.013</td>
</tr>
<tr>
<td>Air Drag Coefficient</td>
<td>0.3 kg/m</td>
</tr>
<tr>
<td>Tires Radius</td>
<td>0.25 m</td>
</tr>
</tbody>
</table>

Table 5. Vehicle Characteristics and Performance Requirements
Keeping in mind the motivation behind the research on hybrid vehicles which is to reduce the fuel consumption and the toxic emissions, a set of specifications associated with the engine operation have to be formulated to maximise the benefits from the design. These specifications, described below, are the result of research and consultation with specialists in internal combustion engines:

a) **Operation in high fuel efficiency regions:** The specific fuel consumption for an internal combustion engine in steady state can be described by the engine pressure versus speed (PV) diagram such as the one shown in figure 6-2. The maximum efficiency is achieved only for a small range of pressure and speed; and therefore, for a limited output power range. However, in conventional cars, due to the variable power required from the engine depending on the power consumed by the vehicle, the engine cannot be operated continuously in this maximum efficiency region. In hybrid vehicles, since an energy storage device is used, the engine does not have to follow exactly the power demand from the vehicle and it can be operated at or close to the maximum fuel efficiency region. A good specification to maximise the global engine efficiency is to operate the engine at all
times in a region with an efficiency of at least 80% of the maximum achievable fuel efficiency. In figure 6-2, the minimum achievable specific fuel consumption is about 250 g/kWh. To fulfill the specification of at least 80% of the maximum efficiency, the engine has to work always in a point with fuel consumption better than 315 g/kWh. Following this restriction, the engine characterised in figure 6-2 may operate between point a and point b, which gives a ratio between maximum and minimum acceptable power of about 4. This ratio is good enough to follow the average power demand of the vehicle.

b) On/Off engine operation: Commonly, in city driving or under conditions of traffic congestion, the average power required by the car is lower than the minimum acceptable engine power specification to keep the fuel efficiency in the specified range. Therefore, under those conditions the engine has to be turned off during some periods and the vehicle runs only from the electric energy stored. The fuel efficiency and emissions from

Figure 6-2 Engine PV Diagram
engines operated in on/off mode have been the subject of some research [28] [29], and the results indicate that if the engine cycling period is not too short, the engine performance is not degraded by this pulsating operation. Nevertheless, in some cases it may be necessary to take precautions to preheat the engine before the start since much higher emissions result from cold engine operation. If the average power consumed by the vehicle is high enough to keep the engine operating in the high efficiency region, then the engine is kept operating continuously providing such average power. The power value used the as limit between on/off and continuous operation depends on the specific engine efficiency diagram and the energy management strategy and it will be decided later.

c) Engine operation preferable at maximum power: Most of the hybrid vehicle designs and results have been reached using engines designed for gasoline-only vehicles; and consequently, optimised for different operating conditions. Extensive research is being done to develop engines more suitable for hybrid vehicles and this is expected to bring improvements in the engine’s performance. The engines in series hybrid vehicles have a lower power rating and are operated at higher relative load than the engines used in gasoline-only vehicles since they are not required to supply peaks of power or operate at very low power demands. For this reason, the engines designed and used in hybrid vehicles tend to be more efficient operating close to the rated power [28]. Consequently, it was decided that, when the engine is operating in on/off mode, in every start, the engine power will be increased until the maximum power is reached. The engine will be kept operating at this point until the energy management sends the command to turn it off.

d) Quasi-steady state operation: It is well known that sudden transients in the engine torque or speed considerably increase the pollution with respect of the steady state operation [30]. One of the main advantages for the series hybrid configuration rests in the fact that the engine operation is independent of the driving pattern; therefore, it is not necessary to operate the engine with fast or sudden transients. A specification directed to reduce the emissions from the engine limits the rate of change in engine speed and engine torque such that the engine operates in a quasi-steady state. Based on the recommendation resulting from discussions with Prof. Wallace from the Department of Mechanical and Industrial Engineering, the change in speed is limited to 1250 rpm in one second. From the same discussion, it was learned that the torque change can be much faster than the speed change. In only about ten cycles it is possible to increase the engine torque from
minimum to maximum keeping the engine in a very low emissions region. Accordingly, it is specified that the torque can be increased from minimum to maximum in about 0.75 seconds.

e) **Specific trajectory followed in the PV diagram:** When the engine is operating, a specific trajectory can be selected to move between the minimum and the maximum power points. The trajectory has to be selected trying to minimise the fuel consumption and the engine emissions and also looking for a faster response for the engine to power demand changes. Certainly, the new developments in engines for hybrid vehicle applications will have an effect on this selection. However, the important feature of this design is that any trajectory across the high efficiency region can be selected and precisely followed thanks to the high decoupling between engine operation and driving conditions.

For this design, the trajectory to be followed by the engine is indicated in figure 6-2. It was decided that from the minimum power point (a), the power is increased rising the engine/generator speed and keeping the torque constant until the maximum engine speed is reached. After that point, if more power is needed, the engine/generator speed is kept constant and the torque is increased until reaching the maximum power point (b). When the power is decreasing, the same trajectory is followed in the opposite direction. This trajectory was selected mainly for three reasons: First, the engine operates continuously when the average power consumed by the vehicle is relatively high (see b); in this case, the engine power follows the average power consumed by the vehicle and changes continuously. As the maximum allowed rate of change in torque is faster than the maximum allowed rate of change in speed (see d), this strategy would give a faster response. Second, the amount of toxic emissions is increased into a greater degree by transients in speed than by transients in torque [30]. This strategy minimises the speed transients as this region is only used during engine starting and stopping. Third, the losses in both the engine and the generator are proportional to the torque; therefore, lower losses are expected using this trajectory.

C. **Gear Selection Considerations**

The number of gears to be included in the vehicle determines the maximum torque and power required from the electric motor to achieve the desired acceleration performance. The highest gear ratio has to be set such that the vehicle reaches at least the maximum required speed at the maximum motor speed. At the same time, the mechanical time constant for the motor depends on the gear ratio according to the following equation:
\[ T_m = \frac{(j_w + V_{\text{mass}} \cdot \text{tire}^2 / \text{gear}) + j_m}{n_{\text{pp}}^2} \] 

(6-1)

where \( j_w \) refers to the wheels and transmission inertia, \( \text{tire} \) is the radius of the vehicle tires, \( j_m \) is the motor inertia, and \( n_{\text{pp}} \) is the number of pairs of poles for the motor.

If the gear ratio is small, the effective inertia over the motor is high; therefore, higher torque has to be applied to the vehicle to achieve the same acceleration. Using a single fixed gear results in a simpler and less costly gearbox. In this case, the single gear ratio has to be small to achieve high maximum speed and, consequently, the mechanical time constant is long. This means that a very large ratio of more than 10 to 1 in the peak torque and peak power with respect to the continuous ratings are necessary to achieve a good acceleration performance. Such a high peak to average ratio would increase the losses and require big and heavy electric machines.

With a multi-stage gearbox, the lowest gear ratio is selected to achieve the maximum speed as in the single gear case. The other gear ratios are selected to get a motor speed close to the rated value of the vehicle speed at which the gear change occurs. The gear change points are distributed through the vehicle speed range to optimise the acceleration. All the additional gears have a higher ratio and lower equivalent inertia over the motor, which allows accelerating the car at the same rate with a lower torque applied (Equation 6.1); and consequently, using a smaller electric motor. In this form, different acceleration slopes are achieved over different speed ranges depending on the gear ratio. The selection of the number of gears present in the gearbox is then a trade-off between the required motor torque and the gearbox complexity.

D. ENERGY STORAGE UNIT SIZING CONSIDERATIONS

The energy storage unit to be used in the vehicle design is based on double-layer power capacitors as presented in chapter 3. This unit has a terminal voltage that varies widely depending on the state of charge. The voltage range of operation for the unit has to be limited based on operative conditions for the unit. A high voltage for the unit results in high voltage for individual cells and, as explained in chapter 3, a reduction in the lifetime of the device. The minimum voltage for the energy storage unit has also to be limited since the lower the voltage, the higher the current required to provide the required power, which results in larger converter ratings. In addition, it is not meaningful to use the unit at too low voltages since most of the energy in capacitors is stored at higher voltages. The minimum acceptable voltage will depend on the power and the energy requirements for the unit.
The selection of the energy storage capacity for the unit depends on the requirements to operate the engine and, in general, the vehicle as specified. In order to decouple completely the engine operation from the driving conditions, the energy storage capacity has to be at least equal to the energy required to provide acceleration capability from stand still to highway speeds. In this thesis it is assumed that the vehicle has to guarantee the specified acceleration up to 100 km/h. In this form, the engine can be operated in quasi-steady state even under the most severe driving conditions. If the energy storage capability is equal or too close to this minimum value, very frequent and unnecessary engine starts would occur since the energy manager has to keep that much energy reserved in case of an acceleration demand. This means that the engine operating point is most of the time moving along the selected trajectory and not operating at the maximum power as desired, furthermore, extra fuel is consumed due to too frequent engine starts and these facts negatively affect the fuel efficiency. Therefore, extra energy capability has to be given to the energy storage unit to reduce the engine on/off cycling. Deciding on how much extra energy is given to the energy storage unit is a matter of compromise between the engine on/off period and the size, weight, and cost for the energy storage unit.

E. ENERGY MANAGEMENT CONSIDERATIONS

The energy manager is responsible for keeping the energy stored in the double-layer capacitors within acceptable limits, maximising its use, and guaranteeing the vehicle maximum performance when needed. The energy management strategy also has to consider the engine operating constraints, take measurements to fulfil those constraints, and anticipate their effect on the system operation.

It is necessary to give a set of requirements associated with the energy management strategy and directed to guarantee the desired operation of the propulsion system. First, the energy level in the capacitor, or more adequately the terminal voltage for the energy storage unit, has to be kept within the limits mentioned in the previous section. Second, the energy manager has to take the required precautions to allow a quasi-steady state engine start and stop without exceeding the energy storage unit limits. Third, the energy storage capability has to be used as efficiently as possible to reduce the number of engine starts so that they have no impact on the emission levels. Fourth, the vehicle has to be able to achieve the designed acceleration performance under every condition, independently of the state of charge of the energy storage unit. Finally, the vehicle must be able to keep the maximum speed on levelled ground and on hills as specified in section 6.1 A.
Many energy management strategies can be used to achieve the requirements mentioned above. A simple energy manager would result in a high rating of the energy storage unit, a more elaborated one would provide the same performance using a smaller energy storage unit. Some possible strategies will be discussed in the next paragraphs.

a) Energy Management Based Only on Energy Content: A simple energy management strategy estimates the energy reserve left in the energy storage unit and decides when to start and when to stop the engine. As the goal is to make a good use of the energy stored, the energy manager starts the engine when the energy drops to a value that would result, under the worst conditions, in the minimum acceptable energy storage voltage ($E_{min}$). Similarly, the energy manager turns off the engine when the energy rises to a value that would result in the maximum DLC safe voltage ($E_{max}$). Due to the slow engine transients, the energy manager has to start (stop) the engine when the energy stored is higher (lower) than $E_{min}$ ($E_{max}$) in a value equal to the worst case energy consumed (generated) during the slow engine transient ($E_{tr}$). To guarantee the acceleration performance, the energy manager has to start the engine leaving an additional energy amount ($E_{acc}$) which is enough to provide the required vehicle acceleration. The engine

![Graph](image)

**Figure 6-3 Worst Case Vehicle Acceleration Without $E_{acc}$**
also has to stop when the energy reaches the maximum acceptable value minus a margin for regenerative braking (Edcc). The margins for acceleration and braking are especially important if an energy storage unit with low rating is used.

Figure 6-3 shows the result of a simulation for the case in which the driver requires a hard acceleration when the energy content is very close to minimum and no energy reserve was left for acceleration. Although the engine starts at the required instant, the power demand from the motor to get the maximum acceleration is higher than the power delivered by the engine. This would result in deeper discharge for the energy storage unit, which is unacceptable. Consequently, the system limits the maximum power delivered to maintain the energy storage unit voltage, and the vehicle is not accelerated at the designed rate. These energy margins are required to provide consistent driving performance. The following relation represents the energy management strategy:

\[
\text{Eng.On \ldots } E \leq E_{\text{min}} + E_{\text{acc}} + E_{\text{tr}} \rightarrow P_{\text{eng}} > P_{\text{min}} \\
\text{Eng.Off \ldots } E \geq E_{\text{max}} - E_{\text{dec}} - E_{\text{tr}} \rightarrow P_{\text{eng}} = 0 \quad (6-2)
\]

The energy usable to drive the vehicle with the engine off is then given by:

\[
\Delta E = E_{\text{max}} - E_{\text{dec}} - E_{\text{min}} - E_{\text{acc}} - 2*E_{\text{tr}} \quad (6-3)
\]

The energy storage unit has to be designed to provide a \( \Delta E \) large enough to get the desired engine operation. \( \Delta E \) determines the period for the engine on/off cycling and has to be chosen according to the engine specifications.

b) **Energy Management Based on Energy Content and Power Feed-Forward Component:** As explained in the previous energy management strategy, a worst case energy reserve (Etr) has to be left in the upper and lower range of the energy stored. These margins foresee a possible high power demand from the vehicle while the engine power is changing slowly. To improve the energy management and compensate for this effect a feed-forward component proportional to the power delivered to the motor is added to the energy start and stop set points. The goal of the feed-forward component is to produce an early engine start when the power demand from the vehicle is high but a better energy utilisation if low power is being consumed. The coefficient for the power term (Kff) is calculated to result in an additional energy equal to the energy consumed by the vehicle while the engine power is building up. The energy management strategy is then represented by:
The feed-forward component has to be filtered to avoid unnecessary engine starts resulting from high but short power demands. The energy usable for vehicle driving is now given by:

\[
\Delta E = E_{\text{max}} - E_{\text{dec}} - E_{\text{min}} - E_{\text{acc}}
\]  

(6-5)

Comparing this result with equation (6.3) shows that a lower energy capacity would be needed for the same vehicle and engine performance.

c) Energy Management Including a Term Proportional to the Vehicle Speed: For the energy management strategies presented in a) and b), the energy reserved for acceleration and braking is not needed under most conditions. They are reserved for situations in which a strong acceleration coincides with a low energy condition or an extended regenerative braking coincides with a high-energy condition. These proposals guarantee the vehicle performance; however, they are not optimal as can be concluded analysing the performance for a vehicle running at around 80-km/h constant speed for several kilometres.

Figure 6-4 Energy Manager Operation at High Speed

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Figure 6.4 shows a simulation for the vehicle using the energy management strategy presented in b). Observing figure 6.4 one question comes to mind: Why should the energy management keep an energy reserve enough to accelerate the vehicle from zero to maximum speed, if in the worst case the vehicle would be accelerated only from 80 to let us say 100 km/h? An energy management that improves the energy utilisation includes the idea of leaving as reserve only the energy needed to accelerate from the actual speed to 100 km/h instead of a worst case constant energy margin for acceleration. Similarly, only some energy margin, function of the vehicle speed (Vesp), is required for braking. The general description for the energy management is given by the following equation:

\[
\begin{align*}
\text{Eng.On} \ldots E &\leq E_{\text{min}} + E_{\text{acc}} + K_{\text{ff}} \cdot P_{\text{mot}} - f_1(\text{Vesp}) \rightarrow P_{\text{eng}} \geq P_{\text{min}} \\
\text{Eng.Off} \ldots E &\geq E_{\text{max}} - E_{\text{dec}} + K_{\text{ff}} \cdot P_{\text{mot}} + f_2(\text{Vesp}) \rightarrow P_{\text{eng}} = 0
\end{align*}
\]

(6-6)

Since \(E_{\text{acc}}\) and \(E_{\text{dec}}\) represent the worst case condition, \(f_1(\text{Vesp})\) and \(f_2(\text{Vesp})\) are always positive and the energy range \(\Delta E\) for the same total energy capacity is improved.

The key factor to judge the energy management to be used is the ratio between the energy usable (\(\Delta E\)) and the total energy storage capability (\(E_{\text{min}} - E_{\text{max}}\)). If the energy storage capability is large, the ratio is close to one and the energy management can be highly simplified by using the strategy in a). However, using low energy density devices such as the DLCs, the energy capability has to be minimised for a fixed usable \(\Delta E\). A strategy similar to the description in b) was introduced and simulated in [27] for a hybrid vehicle with low energy storage capability. It shows that the performance has to be compromised, otherwise the energy will be under-utilised to get a good control of the energy storage unit voltage. The energy management strategy discussed in c) is selected because it brings important reductions in the energy capacity required.

### 6.2 Design of the Power Drive System

With the vehicle parameters and specifications explained above and with the help of a simulation for the propulsion section, the design procedure is systematic and easy to understand. The design includes engine size and operation, number of gears and gear ratios, electric component ratings, energy management strategy, and energy storage unit capability. Each one of those topics is presented next:
A. **Engine Design**

The engine power capability has to be enough to maintain the maximum continuous specifications for vehicle performance. The vehicle specifications require 120-km/h sustained speed on levelled ground and 80-km/h sustained speed on a 5% slope long hill. The stronger of these two requirements will define the power rating of the internal combustion engine. A simulation was run for the vehicle propulsion section using the vehicle parameters introduced in section 6.1. The simulation indicated that to drive the vehicle continuously at 120 km/h, a power of 17.5 kW is required. Similarly, to drive the vehicle at 80 km/h on a 5% uphill, 20 kW is required. Therefore, the engine has to provide at least 20 kW continuously to the generator. A smaller power capability for the engine would result in discharging of the electric energy storage unit; and therefore, the inability of maintaining the required speed. An extra 10% is given to the engine maximum power to account for power losses.

Assuming an engine with an efficiency map similar to the one shown in figure 6.2 but capable of providing 22 kW maximum along the selected trajectory, the speed range may be selected between 1800 rpm and 4500 rpm, and the pressure range between 4.5 bar and 7.7 bar. If the maximum power point corresponds to 22 kW then, the minimum power within the high efficiency region is 5.1 kW. As explained in section 6.1, the trajectory to be followed by the engine when increasing the power consists of a speed increase at constant torque first, and a torque increase at constant speed after that. For the speed range selected and using the specification for maximum rate of speed change in the engine, 2.16 seconds are needed to increase the power from 5.1 kW to 12.9 kW. Using the specification for maximum rate of torque change, 0.3 seconds are needed to increase the power from 12.9 kW to 22 kW. Then, the total time required to build up the maximum power in the engine using quasi-steady state operation is 2.46 seconds.

Another design decision associated with the engine operation is the boundary between on/off and continuous operation. Reference [28] gives results for the fuel consumption under continuous and on/off operation for different cycles. It concludes that, for an engine similar to the one assumed in this design, on/off operation is preferable if the average power demand is lower than 70% of the maximum engine power. Based on this result, the engine will operate continuously, following the vehicle power demand, only if the average power consumed is higher than 15 kW. That is at highway speeds. Since for power levels higher than 15 kW the engine trajectory produces a constant speed operation, the engine response is well under half a second for this continuous mode.
B. Electric Components and Gearbox Design

These two designs are done simultaneously since the maximum ratings for the electric components are linked to the number of gears used in the design. The power rating for the electric machine is given by the specified maximum continuous power required by the vehicle. In the previous section, it was shown that 20 kW is the maximum continuous power required by the vehicle. Consequently, the electric motor has to be rated for 20 kW. From this point, a permanent magnet synchronous machine with 3600-rpm maximum speed is assumed. Any variation in the maximum speed will only affect the gear ratios.

The design for the maximum power and maximum torque conditions depends on the acceleration requirements and the gear selection. As explained in section 6.1, a single constant gear ratio cannot be used since a high peak torque and peak power of more than ten times the continuous value would be required from the motor to achieve the desired acceleration. Using a two-stage gearbox, the lower gear ratio has to be selected to get the maximum speed. A total gear ratio of 2.83 gives 120-km/h vehicle speed at 3600 rpm motor speed. The higher gear ratio is selected to get a gear change at 50 km/h with the motor running at maximum speed. This gives a higher total gear ratio of 6.79. Under this condition, acceleration of 13.6 seconds from 0 to 100 km/h is achievable limiting the peak power to 60 kW (3 times the continuous rated power) and limiting the maximum torque to about 4 times the rated torque. Although this design is able to fulfill the requirement for acceleration from 0 to 100 km/h, it has limitations. First, the time needed to accelerate from 60 to 80 km/h is about 4 sec, which is longer than the specified value. Second, at second gear, the maximum motor speed barely results in a 120-km/h vehicle speed, which gives very little over speed capability. Third, the ratio peak torque over rated torque is still quite high.

A design with a three-stage gearbox and gear changes at 40 km/h and 80 km/h results in gear ratios of 2.4, 3.6, and 6.8. Such a gearbox design gives acceleration from 0 to 100 km/h in 13.1 seconds, acceleration from 60 to 80 km/h in 3 seconds, and a maximum speed of 140 km/h without exceeding the motor rated speed. The peak torque required for such a performance is three times the rated one and the maximum power is limited to 50 kW or 2.5 times the continuous rating. This design is proposed for the vehicle since it brings improvements in motor size and vehicle maximum speed at the expense of only one extra gear stage.

Based on the previous paragraph, the DC/AC converter and the permanent magnet machine have to be rated for 50 kW peak power. For the energy storage unit and the DC/DC converter, the average power rating depends on the average power demand from the vehicle. If the vehicle is stopped, no power is required from the energy storage unit. Similarly, if the engine
is operating in continuous mode, the energy storage unit delivers zero average power. The worst case average power occurs for an engine duty cycle of 50%, which is the case when the vehicle demand is 10 kW. In this case the energy storage unit drives the vehicle with 10 kW for half of the time and it is recharged at 10 kW for half of the time. 10 kW continuous power rating and 115 V minimum voltage results in a maximum continuous current of about 87 A so that the energy storage unit has to be thermally rated for this continuous current operation. The peak power from the energy storage unit and DC/DC converter is equal to the peak power demand from the vehicle or 50 kW.

C. ENERGY MANAGEMENT DESIGN

The minimum acceptable DLC bank voltage is chosen to be 115 volts or half the rated voltage. This condition results in an energy utilisation of about 82% of the total energy stored in the capacitors and keeps the energy storage unit current under 500 A for the worst case. That is, maximum power required with minimum voltage available. Figure 6.5 shows the energy needed to accelerate the car to 100 km/h as a function of the initial speed. It also shows the minimum DLC energy storage voltage needed to achieve such acceleration using only the electric source and without driving the voltage lower than 115 V. Figure 6.6 shows the energy storage capability needed to achieve regenerative braking to stand still as a function of the initial speed and the initial voltage required to avoid a terminal voltage higher than 250 V. The strategy is to start the engine following the curve for voltage versus speed in figure 6.5, and stop the engine following the voltage versus speed curve in figure 6.6. If equation 6.6 is referred to the measurable energy storage voltage instead of the energy content, the mathematical representations of the curves in figure 6.6 correspond to \( f_1 \) and \( f_2 \). For the engine turn on point the mathematical equation used in the energy management is the following:

\[
f_1(vesp) = 68 \times (vesp/100)^3 \quad (6-7)
\]

For the engine shut down point, the engine shut down point is limited to a maximum of 230 V since that is the rated capacitor voltage. Some extra energy storage capability is needed only for speeds over 88 km/h. For that range, a straight line approximates the curve and it is given by the following equation:

\[
f_2(vesp) = 48.25 \times (vesp/100) \quad (6-8)
\]

After the engine is turned on, it increases the delivered power up to the maximum power point (22 kW) in order to recharge the energy storage unit as fast as possible. As mentioned
Figure 6-5 Energy Needed to Accelerate to 100 km/h

Figure 6-6 Energy Reserve Needed for Regenerative Braking
before, if the average power demand is higher than 15 kW the engine is kept operating continuously. To do this, when the capacitor voltage reaches the turn off point, the energy manager calculates the average power being consumed by the motor in time windows of 10 seconds, if the power being consumed by the motor is more than 15 kW the engine is not turned off. Instead, a controller sets the engine power to keep the energy storage unit voltage constant by balancing the engine power with the motor demand. The engine is turned off if the average power drops below 15 kW or the brake is pressed. This strategy avoids unnecessary shorter engine off periods when the car is being driven at fairly constant high-speed conditions.

D. Energy Storage Capability Design

The decision about the energy storage capability is mainly given by the minimum off time specification for the engine. The engine off time should not be too short since the losses produced in the engine restart and the extra fuel consumed in the engine restart would effect the fuel efficiency and emission levels. A one-minute minimum off time for the engine is a specification conservative for most engines [28]. In the previous section, it was explained that for an average output power over 15 kW, the engine operates continuously. Therefore, the maximum power consumed for on/off operation resulting in the shortest engine off time is 15 kW. With 15 kW and one minute off time, the usable energy $\Delta E$ must be equal to 900 kWsec. This energy has to be stored in the DLC bank and available according to the energy management strategy. Using figure 6.5, it is estimated that the energy required to accelerate the vehicle from 0 to 100 km/h is 600 kWsec. Similarly, from figure 6.6, the recoverable energy during regenerative braking from 100 to 0 km/h is about 400 kWsec. Furthermore, the slow engine turn on process takes 2.46 sec and may represent up to 25 kWsec in vehicle energy consumption ($E_{tr}$). If a simple energy manager such as the one defined in (6-2) is used for the vehicle, the energy capability has to be 1950 kWsec to provide the required $\Delta E$. However, if the improved energy management strategy from (6-6) is simulated and the same conditions of hard acceleration and 15 kW average power demand are considered, a energy capacity of about 1200 kWsec is enough to give 60 seconds engine off time. The previous numbers indicate the important reduction in energy storage size achieved when using a more sophisticated energy management strategy.
6.3 Experimental System Design

An experimental model for the proposed propulsion system was designed and set up to verify the concepts introduced in the thesis. Based on the components available to build the system in the laboratory, the experimental prototype is a 1:3 reduced model with respect to the ratings for the designed vehicle. Although the reduced model has differences in inertia and relative losses with respect to the full size one, it is believed that such a model size is representative of the designed system performance. Furthermore, simulation models adapted to the size and characteristics for the experimental system were developed as a base of comparison.

Figure 6-7 shows the diagram for the experimental implementation. A permanent magnet synchronous machine rated 7.5 kW is used to provide propulsion to the vehicle. It is a six-pole machine with 2000-rpm maximum speed, capable of providing three times the rated torque and three times the rated power for a short time, making it acceptable for acceleration testing. Appendix B includes the specifications for the machine used.

The energy storage unit based on double-layer capacitors and presented in chapter three

![Diagram for the Experimental Prototype](image-url)
is used in the experimental system. It has 100 DLCs connected in series resulting in a 400-kWsec energy storage capability between 115 and 230 volts. A soft-switched converter system based on the ACQRDL, as described in chapter four, and rated at 40 kW is used to transfer energy amongst the energy storage unit, the motor, and a 300-volt DC-link. The values for the different components in figure 6-7 are specified in the following table:

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_{DC}</td>
<td>100 μH</td>
</tr>
<tr>
<td>C_{res}</td>
<td>80 nF</td>
</tr>
<tr>
<td>L</td>
<td>16.7 μH</td>
</tr>
<tr>
<td>C_{C}</td>
<td>10 μF</td>
</tr>
<tr>
<td>L_{e}</td>
<td>2.5 mH</td>
</tr>
<tr>
<td>C_{DC1}</td>
<td>4800 μF</td>
</tr>
<tr>
<td>C_{DC2}</td>
<td>9600 μF</td>
</tr>
<tr>
<td>C_{fil}</td>
<td>4800 μF</td>
</tr>
<tr>
<td>L_{fil}</td>
<td>5 mH</td>
</tr>
<tr>
<td>R_{l}</td>
<td>4.6 Ω</td>
</tr>
</tbody>
</table>

Table 6. Experimental Prototype Component Values

Since a multistage gearbox was not available to couple the electric motor with the load, the prototype only covers the vehicle operation in first gear. In order to be able to run the federal urban driving cycle, which reaches 50 km/h maximum speed, the design for this experimental first gear ratio and the resulting inertia were modified to reach up to 55 km/h at the maximum motor speed. The motor is coupled directly to two large and heavy induction machines that provide high inertia to the rotational system comparable to the inertia resulting from the vehicle mass. Although the measured experimental inertia (1.66 Wsec^2) is not exactly equal to the required value for a 1:3 model, the simulation parameters were adjusted to represent the practical implementation. One of the induction machines is controlled to model the force over the vehicle according to the road modelling. To do this, the mechanical losses for the mechanical assembly were measured as a function of the speed. The difference between the required load torque, found using the simulation model, and the mechanical losses dictate how much load has to be applied to the induction machines as a function of the machine speed. Figure 6-8 shows the measured mechanical losses in the system, the required road torque, and the difference between them to be applied externally.
Chapter 6. Hybrid Electric Vehicle Design

Figure 6-8 Road Load Experimental Modelling

An internal combustion engine / generator set was not available and is not included in the prototype; instead, a unidirectional current controlled DC-source is used to provide the same power that should be provided by the engine. The current source is controlled to give slow power transients similar to those specified for the engine.

A microprocessor-based control board is used to control the current source equivalent to the engine and to execute all the energy management strategies. Due to the high frequency of the soft-switched converter system, a fast control board based on FPGAs is used for this purpose. All the controls, filters and interfacing circuits are built compactly resulting in a single control box. Figure 6-9 shows photographs of the experimental set up.
Figure 6.9 a) Propulsion System Experimental Implementation

Figure 6.9 b) Soft-Switched Converter System Implementation
Figure 6-9 c) Vehicle and Road Experimental Model
CHAPTER 7

HYBRID VEHICLE PERFORMANCE STUDIES

This chapter presents results for the vehicle performance under different driving conditions using the proposed model for the system presented in chapter five and the design considerations from chapter six. Furthermore, the studies explore and quantify the benefits from the propulsion system designed. The first part of the chapter presents results for the experimental implementation of the propulsion system. This includes simple tests to verify the correct operation of the complete system and several more complex tests to verify and calibrate the developed models.

With the confidence built in the accuracy of the model, the second part of the chapter includes further studies for the real size vehicle performance using the simulation model. Results for the energy management operation under several driving cycles will be used to produce quantitative results about the fuel consumption.

7.1 Test Results for the Prototype Implementation

A. BASIC SYSTEM TESTING

Experimental test results for the individual components developed, the energy storage unit and the soft-switched converter system, were presented in chapters 3 and 4 respectively. This section gives results that confirm the correct operation of the complete propulsion system. The first task was to connect the different components and check that it was possible to operate the electric motor and charge the energy storage unit from the engine model implementation.

After verifying the correct general operation of the system, the next step was to verify in detail that the experimental system as shown in figure 6-7 performs the required functions. Figure 7-1 shows an oscilloscope shot for the DC-link voltage and the energy storage current. The machine torque steps from 0 to 80 N.m and three seconds later to -80 N.m. These steps are more than twice the system rated torque of 37.5 N.m. The plot shows that the voltage is very well controlled even during a very hard system transient like this.

The following test was used to test the motor speed controller. Figure 7-2 shows an oscilloscope shot of the machine speed and the quadrature component of the motor current for a
step in the speed reference between 0 and 40 km/h. The motor is accelerated in about seven seconds and with a smooth speed response. The maximum acceleration torque is 95 N.m and the measured speed overshoot is only 1.5 km/h.

Another basic test consisted in measuring the engine start up and shut down process. This test verifies the slow build-up process in the engine power according to the requirements to minimise pollution. Figure 7-3 shows the turn on process for the engine. The engine needs about 3 seconds to move from minimum to maximum power or vice-versa. It is important to mention that in the experimental prototype, the engine speed build-up process and the engine torque build-up process have the same rate of change which is not the case for the designed vehicle. This is considered to have a negligible effect on the energy efficiency since the total power build-up time is similar.

An experimental test was run to verify the modelling for the road and vehicle. The test consisted in accelerating the vehicle to 40 km/h and then to turn-off the motor (no torque applied)
such that the vehicle decelerates only due to the road load resistance. The measured time to decelerate to zero was 51 seconds, very close to the simulated time of 46 seconds.

B. Cycle Testing and Model Verification

The experimental prototype was used to verify and calibrate the system and to evaluate the performance of the complete experimental propulsion system under driving conditions similar to the real ones. Several driving cycles were run using the experimental prototype to verify the energy management operation and to verify the accuracy for the models.
Figure 7-4 shows the capacitor voltage and engine power for a test driving the vehicle at a constant speed of 40 km/h. There is an excellent agreement in both the capacitor voltage and the engine operation cycles. Note that the engine operation time is about 10% longer for the simulated results; this is justified by the fact that engine/generator losses are included in the model but are not present in the experimental prototype. This test is good to confirm the consistency between simulation and experiment for the energy capability of the double-layer capacitor bank.

Figure 7-5 shows a plot including the capacitor voltage, the vehicle speed, and the engine power for the Federal Urban Driving Cycle Test. This cycle has been used extensively in North America to evaluate the performance of vehicles under city driving conditions. The engine operation cycles reflect some differences between experiments and models that are expected for a complex cycle like this one. The variations are the result of the decisions taken by the energy manager, and influenced by fast changes in motor power and vehicle speed. For example, in the simulation the engine starts its second cycle just at the end of an acceleration phase while in the experiment the voltage is barely over the engine start point when the acceleration ends; this results in a delayed engine start for the prototype. Nevertheless, the agreement in total engine operation time and capacitor voltage is very good.

Figure 7-6 shows the results for a hard acceleration and braking driving cycle. The speed reference is a square wave between zero and 45 km/h with a 40 seconds period. This cycle was
selected as it includes the worst transient case for the converter operation when the power changes suddenly from high driving power to high braking power with the engine in operation. Experimentally, the maximum total power step into the energy storage unit was measured at 17.3 kW with the converter system responding well to overcome the transient. Notice that the regenerative braking action increases the capacitor voltage. Once more, the agreement between model and experiments is very good.

This group of experiments validates the modelling process especially the energy capability for the energy storage unit and the losses for the system. After developing confidence in the model using the experimental prototype, extended studies can be pursued using the full-scale vehicle model.

### 7.2 Full Scale Vehicle Results

After having verified the model using the experimental prototype, extensive studies for the full-size vehicle were run using the simulation. Some tests were run to verify that the vehicle fulfills the general performance requirements. Figure 7-7 shows the vehicle speed during hard acceleration from stand still. The figure indicates that the total acceleration time from 0 to 100 km/h is 12.8 seconds, which is less than the 14 seconds specified for the vehicle. Also the acceleration from 60 to 80 km/h satisfies the requirement of three seconds. These results are
comparable with the acceleration times around 12 seconds from 0 to 60 miles/hour achieved in most new subcompact vehicles. Note in the graph the different acceleration slopes depending on the gear ratio between the motor and the wheels.

Using the simulation, it was verified that the vehicle is capable of maintaining 120 km/h indefinitely on a levelled road and 80 km/h on hills with a 5% grade. In both cases, the engine is started based on the energy manager, recharges the capacitors, and stays on because the power demand from the motor is greater than 15 kW. Figure 7-8 shows the vehicle passing on a 1-km 5%-slope hill at 100 km/h. In a) the initial capacitor voltage is high and the vehicle overtakes the hill while maintaining its speed. In b) the initial capacitor voltage is low and the speed has to be decreased to avoid a deeper capacitor discharge. However, the vehicle overtakes successfully the hill maintaining a speed of over 80 km/h. The initial drop in speed at the beginning of the hill is a result of the speed controller's slow reaction to the new conditions.

Figure 7-9 shows the result for the Federal Urban Driving Cycle test. Comparing the results for the FUDC for the 3:1 prototype (Figure 7-5) and for the full size model (Figure 7-9), it appears like the energy stored in the capacitors is proportionally higher for the full size vehicle since the first engine start happens about 50 seconds later. The reason for such a difference is associated with the resonant tank losses: both models have the same resonant tank losses as they depend on the resonant current ripple and not on the actual converter rating. Therefore, the energy dissipated in losses with respect to the total energy stored is only 33% for the full size vehicle with respect to the prototype. The lower relative losses have a big effect on the engine duty cycle and, therefore, on the vehicle efficiency.
Figure 7-8 Vehicle Climbing a Hill at 100 km/h
Figure 7-9 Vehicle Operation under Federal Urban Driving Cycle

Figure 7-10 Vehicle Operation at 80 km/h Constant Speed
Figure 7-10 presents the results for a test consisting of acceleration to 80 km/h and constant speed after that. Note that the energy manager starts the engine when the voltage drops to a much lower value compared with the previous examples. This verifies the improvement in energy utilisation achieved with the proposed energy management strategy. Also note that even for this relatively high speed the engine duty cycle is less than 50%.

Figure 7-11 shows the simulation results for a more complex driving cycle, namely the FTP75 that includes urban and suburban driving conditions and a more aggressive driving behaviour. The simulation shows that the operating region of the engine is not affected by fast accelerations and decelerations suffered by the vehicle, and that the slow engine power change is maintained under every condition.

### 7.3 Fuel Consumption Estimation

The three driving cycles used in the previous section to verify the energy management and vehicle performance were used to estimate the fuel consumption for the vehicle. To estimate the fuel consumption, the engine map shown in figure 6-2 was divided into a 10x10 square matrix and the fuel efficiency in each of the 100 points was tabulated. Using the simulation results, it is possible to know the exact operation point for the engine at every instant, and an interpolation of

![Figure 7-11 FTP-75 Driving Cycle](image-url)
the table for fuel efficiency gives the fuel consumed at every instant. Then, the total fuel consumed and the travelled distance allow calculating the average consumption in each cycle. A gasoline density of 0.9 gr/cm³, which is typical for unleaded regular gasoline, is used in the calculations. As the engine transients are very slow, the engine operation is assumed to be always in steady state and no additional fuel consumption results from the change in engine conditions. The fuel consumption was also calculated for an aggressive city driving cycle similar to the federal urban cycle but with harder acceleration and braking actions and for 110 km/h constant speed driving. Table 7 presents the results for the fuel consumption for the five cycles simulated.

<table>
<thead>
<tr>
<th>Driving Test</th>
<th>Fuel Consumption (l/100km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal Urban Driving Cycle</td>
<td>3.82</td>
</tr>
<tr>
<td>Aggressive Urban Cycle</td>
<td>4.84</td>
</tr>
<tr>
<td>FTP-75</td>
<td>3.62</td>
</tr>
<tr>
<td>80 km/h Constant Speed</td>
<td>3.84</td>
</tr>
<tr>
<td>110 km/h Constant Speed</td>
<td>4.43</td>
</tr>
</tbody>
</table>

Table 7. Estimated Fuel Consumption for the Proposed Vehicle

Note that the results show a different tendency with respect to the fuel consumption for gasoline vehicles and that is the fact that less fuel is needed in city driving than at highway speeds. Since the air resistance is higher at higher speeds, this is an expected tendency in vehicles; however, the low efficiency of gasoline-only vehicles at low loads increases the fuel consumption in city driving. The high efficiency of well-designed hybrid vehicles allows getting these city consumption numbers considered unachievable before. If the results are compared with values for sub-compact gasoline vehicles such as the Toyota ECO listed in [31] with 7.9 l/100km on the highway and 9.7 l/100km in the city we conclude that improvements of over 50% are expected in gasoline consumption.

7.4 Evaluation of the Vehicle Design

Based on the results for the vehicle performance, an evaluation of the decisions and strategies used in the design process will be presented in this section. The gearbox design and maximum torque and power ratings provide a good acceleration performance for economic small vehicles. An increase in the number of gears would not represent much of an improvement in acceleration and is not justified unless the maximum vehicle speed specification is increased over
160 km/h. A lower number of gears is not recommended as it would limit the maximum vehicle speed and/or increase the rating of the electric components.

The energy capability assigned for the energy storage unit is sufficient to give good vehicle performance and operate the engine in quasi-steady state conditions. However, in all the cycles studied, and especially in the city driving cycles, the engine off time is well over a minute and that indicates that a smaller energy capability is also capable of giving the desired performance. The minimum energy storage capability depends on more extended research on engine on/off operation, but at this point, it is clear that lower energy capability is conceivable. For example, a 900-kWsec energy storage unit would still give engine off intervals of about one minute under most conditions and this time would be shorter only under extreme breaking conditions, which probably would not significantly affect the fuel consumption and emissions resulting from the engine start. The effect of a higher energy capacity on the fuel efficiency would be slim as already in this design the engine operates almost completely at maximum efficiency. Furthermore, the use of a higher energy storage unit would also increase the period of the engine operation and this may result in more emissions since the engine would cool down more during the long off periods. The main advantage of an increase in energy capability rests in the fact that the vehicle would be able to overcome longer and more pronounced hills at high speeds.

The energy manager brings considerable advantages as it provides a much better use of the energy available. The good performance of the energy manager allows the possibility of using a smaller energy storage unit than initially projected [27], and even smaller than the initial estimation in this thesis. However, the energy management consideration may change as a result of new engine operation strategies or different energy storage ratings. It is possible that the improvements in engines for hybrid vehicles may have a considerable effect on energy management strategies.

If the vehicle lifetime is estimated to be 250,000 km, and the driving pattern is divided to be 40% urban (Federal Urban Cycle), 40% sub-urban (FTP-75), and 20% highway (110 km/h constant speed), the capacitor is cycled on average once every 2.56 km. This gives under 100,000 cycles for the capacitors during the vehicle lifetime. With the lifetime specified by the manufacturers of over 500,000 cycles, the capacitor unit would outlive widely the vehicle. The possibility of increasing the maximum and average operating voltage for the capacitor has to be studied. This would result in a higher energy density at the expense of lower lifetimes. This decision has to be taken in combination with the double-layer capacitor manufacturers to evaluate what is the maximum voltage that can be used maintaining a lifetime of over 100,000 cycles.
CHAPTER 8

CONCLUSIONS AND CONTRIBUTIONS

This chapter summarises the conclusions reached during the research and highlights the contributions made to the field of electrical engineering.

8.1 Conclusions

- Neither the electric vehicles with batteries nor the vehicles with internal combustion engine only are able, at this point, to satisfy the requirements for a good performing, low polluting vehicle.

- Hybrid vehicles offer the possibility of reducing the pollution levels considerably while providing excellent performance. The series hybrid configuration is preferable since it decouples the engine operation from the driving and road conditions resulting in a more efficient engine operation. If alternative power sources like fuel cells replace the internal combustion engine as the main energy source, the series configuration would still be used.

- To effectively decouple the engine operation from the driving conditions, an electric energy storage unit is needed to perform load levelling. Such an energy storage unit has to be able to provide high power peaks but needs only to store a limited amount of energy.

- The energy storage devices have been the main obstacles in the development of hybrid electric vehicles. The double-layer power capacitors are attractive for hybrid vehicle designs due to their high specific power and long lifetime.

- The double-layer power capacitors are complex non-linear devices, and many aspects have to be considered when estimating the voltage sharing amongst devices connected in series. However, good voltage sharing in energy storage units using many double-layer capacitors in series can be achieved if some precautions in the devices initial conditions and thermal design are taken into consideration.

- Due to the high power levels needed in a propulsion drive for electric vehicles and the relatively low switching frequency achievable using hard-switched converters, heavy magnetic components are needed in the converters. The use of a soft-switching topology to increase the switching frequency helps to reduce considerably the weight of the converters.
Chapter 8. Conclusions and Contributions

- The actively clamped quasi-resonant DC-link converter is an attractive option in configurations where two or more converters are connected to the same DC-link voltage. This configuration is simple and permits to soft-switch more than one converter using only one resonant tank.
- Overrating of this converter topology due to transient effects can be considerably reduced using intelligent control of the auxiliary resonant circuit.
- Reductions in the order of 50% in fuel consumption appear to be achievable using the proposed configuration.

8.2 Contributions

- A 400-kWsec energy storage unit based on double-layer capacitors and capable of operating at power levels up to 25 kW was designed, implemented, and tested. There is no report of the design and testing of a similar unit in the published English literature. The double-layer power capacitor technology is a new and interesting technology and an energy storage unit like this is attractive not only in automotive applications but also in many other industrial power applications.
- A compact lightweight converter system with a single resonant tank is used to soft-switch simultaneously several converters. Three techniques to reduce the common overrating of the circuit components and improve the converter transient operation have been proposed in and successfully implemented. Such converter topology results in a reduction by a factor of ten in the weight of the magnetic components needed in the power converters.
- A systematic design strategy for series hybrid vehicles that can be used to design larger or more powerful vehicles using a similar configuration was proposed. The strategy represents a valuable reference for engineers involved in the design of electric and hybrid vehicles as it defines clearly the most important considerations and the trade-offs involved in the design decisions.
- A complete accurate model for a series hybrid vehicle using double-layer capacitors has been developed, simulated and verified. The system model will allow researchers to pursue further studies of the vehicle and evaluate new components and new energy management strategies. The model structure allows the designer to change easily the ratings or characteristics of one component without changing the rest of the model.
- An energy manager especially designed for hybrid vehicles using a high-power / low-energy electric storage unit has been proposed. The energy management brings advantages in energy
requirements and is applicable not only to this design but to any load levelling application using a similar configuration and devices.

8.3 Future Work

The double-layer capacitors have continued to evolve quickly as the manufacturing technology improves. The possibility to set energy storage units for larger vehicles is already a possibility. Studies to compare the voltage sharing and thermal behaviour for new devices are required to keep pace with the possibilities associated with this new technology. Lifetime studies are also needed to evaluate the long-term performance of the devices. These studies would also represent an important feedback to the DLCs manufacturers helping them to detect problems and improve the products.

The system design and the model implementation were completed and the goals were achieved. The switching frequency achieved experimentally (60 kHz) was lower than initially desired (100 kHz). An interesting future research would be to investigate the maximum frequency achievable for the proposed converter at the power levels required for a vehicle. It is clear at this point that the 100 kHz intended at the beginning of the thesis would be easily achieved using discreet IGBTs instead of the safer but slower intelligent modules.

Studying and evaluating more complex energy management strategies directed to reduce the energy capability requirements is a possibility for improving the system design. Also intelligent systems capable of learning from the driving behaviour of each user can bring improvements in fuel consumption and emission levels.

For many years the internal combustion engines have been designed and optimised to provide the maximum efficiency and the minimum pollution in normal vehicles. The size and operation of the engines in series hybrid applications are considerably different from the engines used in actual vehicles. A large amount of work is needed to develop internal combustion engines optimised for hybrid vehicles. Improvements in frequent engine on/off operation, wider high efficiency regions close to the maximum power, and smooth engine start are some of the aspects that would be of benefit to hybrid designs. The improvements in engines for hybrid vehicles will have an effect on the energy manager and engine management strategies and especially the operating region and the maximum allowed transients. A close relation between electrical and mechanical engineers to develop simultaneously mechanical components and control strategies would bring a globally more efficient vehicle.

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Studies and ratings estimations for larger and more powerful vehicles such as sport utility vehicles based on the proposed models are a possible continuation of the thesis. These estimations would give an indication of how close the double-layer capacitors are technologically from being applicable in all kinds of vehicles.

Electric vehicles using configurations similar to the one introduced in this thesis, but using new primary energy technologies such as high energy batteries or fuel cells may be a technically attractive possibility for zero emission vehicles. The load-levelling action performed by the double-layer capacitors would reduce considerably the size of the fuel cell as a primary energy source in a vehicle. If used in a system with batteries, it would prolong the life expectancy for the batteries, as they would be used under lower and controlled power demand.
REFERENCES


REFERENCES


REFERENCES


APPENDIX A

DLC EQUIVALENT CIRCUIT MODEL PARAMETERS MEASUREMENTS
IMMEDIATE RESISTANCE (μ OHM)

IMMEDIATE BRANCH FIXED CAPACITANCE
Ci0 (F)
IMMEDIATE BRANCH VARIABLE CAPACITANCE
CI1 (F/V)

TOTAL DLC CAPACITANCE
APPENDIX B

COMPONENTS DATA SHEETS
Electric Double Layer Capacitor

Power Capacitor

Features

- Large capacitance, low resistance
  (Charging possible at current over 100A)
- Because of no chemical reaction, has large charging and discharging capabilities
- Few problems regarding waste treatment
- Suitable for substitution of secondary battery when using it for rapid charging and discharging applications

Specifications

<table>
<thead>
<tr>
<th>Item</th>
<th>EECW2R3A107</th>
<th>EECW2R3A177</th>
<th>EECW2R3A1500</th>
<th>EECW2R3A150N</th>
</tr>
</thead>
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<td>Operating temperature range</td>
<td>-25 °C ~ +70 °C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated working voltage</td>
<td>2.3V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal capacitance range</td>
<td>100F 470F 1500F 1500F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance tolerance</td>
<td>-20% ~ +40%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal resistance</td>
<td>under 60mΩ  under 12mΩ  under 12mΩ  under 5mΩ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Real internal resistance)</td>
<td>25mΩ 6mΩ 4mΩ 2mΩ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Real short circuiting current)</td>
<td>100A 400A 600A 1200A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature characteristic</td>
<td>Capacitance change≤±30% at 20°C Internal resistance≤±4 times at 20°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temperature loading</td>
<td>After applying 70°C, 1000hours rated voltage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shelf life</td>
<td>In accordance with high temperature loading characteristics standard</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dimensions

<table>
<thead>
<tr>
<th></th>
<th>D</th>
<th>L</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>100F</td>
<td>36</td>
<td>53</td>
<td>13</td>
</tr>
<tr>
<td>470F</td>
<td>51</td>
<td>125</td>
<td>23</td>
</tr>
<tr>
<td>1500F/O</td>
<td>77</td>
<td>145</td>
<td>31.8</td>
</tr>
<tr>
<td>1500F/N</td>
<td>64</td>
<td>190</td>
<td>20</td>
</tr>
<tr>
<td>(4 terminals)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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The type 5PT SERIES can meet the critical requirements of series resonant power supplies for higher current carrying capabilities at lower capacitance values, better than any other capacitor on the market today. Now circuit designers are able to build more performance into their systems and realize inherently greater reliability.

To yield these higher current capabilities, Electronic Concepts has developed a new capacitor construction that incorporates heavy metal electrodes in a very densely packed configuration. It is a design exclusive to EC. One that is able to extract significantly more current per MFD at rated voltage than competitive brands.

Its uniquely shaped lugs are mechanically sturdy and able to accommodate higher current with minimum inductance. The termination lugs are also a direct “plug-in” type which adds to overall performance efficiency.

With the advent of the 5PT, the designer can maximize frequency characteristics -- and at the same time simplify system design with miniaturization, reduce assembly work -- plus realize significant overall system cost savings.

SAMPLES FOR EVALUATION AND TESTING AVAILABLE TO QUALIFIED OEMs
CONSTRUCTION
Extended foil.

LIFE TEST
Capacitors can withstand a test potential of rated voltage at 85°C between terminals for a period of 2,000 hours. Failure is defined as a permanent short or open circuit.

HUMIDITY RESISTANCE
Exceeds requirements of MIL-STD-202, Method 103.

HIGH FREQUENCY VIBRATION
Capacitors meet the 2000 cycle vibration test in accordance with Method 204 of MIL-STD-202A, condition B. Vibration is continuous for a four hour period in each of two directions, parallel and perpendicular to the major axis.

Test results show no mechanical damage, and no evidence of intermittent contacts or open short circuiting.

QUALITY CONTROL
Capacitors are 100% tested for:
- CAPACITANCE TOLERANCE
- DISSIPATION FACTOR
- DIELECTRIC WITHSTANDING VOLTAGE
- INSULATION RESISTANCE

Complete process and inspection data is maintained on file and is available on special request.

MARKING
All capacitors are marked with one or more of the following: company initials, "EC", corporate logo or EC trademark – in addition to type 5PT, capacitance, tolerance, rated DC working voltage and date code.

DATE CODE
The first two digits of the date code represent the year, the second two digits the week, i.e., 9952 is the 52nd week of 1999, 0102 is the second week of 2001.

QUALITY ASSURANCE
Major emphasis is placed on quality assurance. Raw material inspection and the use of SPC manufacturing procedures assure the highest quality standards. Procedures are fully described in the EC Quality Control Manual. Electronic Concepts, Inc. will continue to advance the state-of-the-art by utilizing leading edge technology, compact capacitor designs and establishing reliability procedures.

In constructing the components described, the full intent of the specification will be met. Electronic Concepts, Inc. does, however, reserve the right to depart from detail specifications in order to improve the design of its products. Components made under military approvals will be done so in accordance with specification requirements.

This information is believed to be accurate and reliable. However, Electronic Concepts, Inc. assumes no responsibility for its use, nor for any infringement of patents or other rights of third parties which may result.

SEE PAGE 4 FOR ELECTRICAL SPECIFICATIONS
The tenth character of the part number represents capacitance tolerance: M=±20%, K=±10% and J=±5%
**OPERATING TEMPERATURE RANGE**

From -55°C to +105°C.

**INSULATION RESISTANCE**

When measured at test temperature and rated voltage for a minimum of two (2) minutes, the insulation resistance equals or exceeds the following values:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>25°C</th>
<th>85°C</th>
<th>+105°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Megohms x Microfarads</td>
<td>100,000</td>
<td>10,000</td>
<td>1,000</td>
</tr>
</tbody>
</table>

Insulation resistance in megohms need not exceed: 1,000,000 200,000 20,000

**DISSIPATION FACTOR**

When measured at the frequency specified for capacitance measurement, the dissipation factor will not exceed 0.1%.

**CAPACITANCE CHANGE**

Capacitance change versus temperature for these capacitors shall not exceed the following:

<table>
<thead>
<tr>
<th>Temperature Degrees C.</th>
<th>-55</th>
<th>+25</th>
<th>+105</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Change</td>
<td>+2.0</td>
<td>0</td>
<td>-4.0</td>
</tr>
<tr>
<td>Typical</td>
<td>+1.6</td>
<td>0</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

**DIELECTRIC STRENGTH**

Capacitors withstand a DC potential of 1.5 x rated voltage for one (1) minute without damage or breakdown. Test voltage is applied and discharged through a minimum resistance of 100 OHMS per volt.

**CAPACITANCE TOLERANCE**

Standard tolerance is ±10%. Tolerances of ±5%, ±2% and ±1% are also available.

**NOTE:** Capacitance is measured at 25°C, and at a frequency of 1KHZ for all values.

---

### Electrical Characteristics vs. Temperature (Centigrade)

- **Insulation Resistance vs. Temperature**
- **Dissipation Factor vs. Temperature**
- **Capacitance Change vs. Temperature**

---

**Electronic Concepts, Inc.**

526 Industrial Way West, Eatontown, New Jersey 07724 • TEL (732) 542-7880 • FAX (732) 542-0524
e-mail: sales@eci-capacitors.com
http://www.eci-capacitors.com
Kollmorgen GOLDLINE Series

- 0.62 to 82.0 lb-ft (0.84 to 111.2 N-m)
- 70.0 to 190.0 mm (2.76 to 7.48 inches) Square Frame
- Resolver Feedback
- Maximum Recommended Speed 7500 RPM

Kollmorgen GOLDLINE servomotors incorporate highest energy rare earth neodymium-iron-boron magnets and excellent thermal design to provide exceptional continuous torque and peak torque performance in a compact package.

The brushless lightweight servomotor base models come with integral frameless resolver and industrial grade connectors (B and M models).

These servomotors are available in three basic models to meet the needs of a wide range of applications.

B-Series (low inertia)

The B-Series provides extremely low inertia rotors allowing optimum performance in applications requiring rapid acceleration and deceleration.

M-Series (medium inertia)

The M-Series is an extension of the B-Series. With seven times higher inertia, this motor series offers the advantage of better performance for systems having complaint loads or large inertia mismatches.

EB-Series (explosion proof)

Explosion-Proof Brushless servomotors are listed by UL for use in Class I, Division 1, Groups C and D hazardous locations. This listing includes applications where vapors or gases form flammable or explosive environments.

The EB-Series has been tested and proven capable to withstand internal explosion without bursting or allowing ignition to reach outside the motor frame. Contact your local regional sales office for more information.

FEATURES: B or M Series

- Small (large torque/volume ratio)
- Speeds to 7500 RPM standard
- UL recognized
- Rugged resolver feedback
- Built-in thermostat
- Rear shaft extension
- Class H insulation
- IP-65 sealing

OPTIONS:

- Front mounted gearheads
- IP-67 sealing
- Fail-safe brake
- Encoder feedback
- NEMA mountings
- Mating connectors
### Performance Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Symbol</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cont. Torque at stall</td>
<td>Tc</td>
<td>lb•ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-m</td>
</tr>
<tr>
<td>Peak Torque at stall</td>
<td>Tp</td>
<td>lb•ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-m</td>
</tr>
<tr>
<td>Cont. Power</td>
<td>HP</td>
<td>HP</td>
</tr>
<tr>
<td></td>
<td>kW</td>
<td>kW</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>N</td>
<td>RPM</td>
</tr>
<tr>
<td>Motor Inertia x 10^4 B Series</td>
<td>Jm</td>
<td>lb•ft•s^2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>kg-m^2</td>
</tr>
<tr>
<td>M Series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor Weight B Series</td>
<td>Wt</td>
<td>lb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>kg</td>
</tr>
<tr>
<td>M Series</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>kg</td>
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<tr>
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<td>Tp</td>
<td>lb•ft</td>
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<tr>
<td></td>
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<td>N-m</td>
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<tr>
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<td>RPM</td>
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<td>Motor Inertia x 10^4 B Series</td>
<td>Jm</td>
<td>lb•ft•s^2</td>
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<td></td>
<td></td>
<td>kg-m^2</td>
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<tr>
<td>M Series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor Weight B Series</td>
<td>Wt</td>
<td>lb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>kg</td>
</tr>
<tr>
<td>M Series</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Notes:
1. Motor can be mounted in any position.
2. Shaft seal has been certified to meet IP-65 sealing.
3. Pressure on shaft seal must not exceed 0.21 kg/cm².
4. Motor protection thermostat opens upon temperature rise and should be connected into a latched (locked out) power down type circuit.

Connections:
Motor Receptacle
- Pin A - Phase A (brown)
- Pin B - Phase B (red)
- Pin C - Phase C (white)
- Pin D - Ground (green with yellow stripe)

Resolver Receptacle
- Pin A - S3 (black)
- Pin B - S4 (red)
- Pin C - S4 (blue)
- Pin D - S2 (yellow)
- Pin E - R1 (red/white)
- Pin F - R2 (yellow/white)

SYSTEM INTERCONNECT DIAGRAM
Intellimod™ Modules
Three Phase
IGBT Inverter Output
150 Amperes/600 Volts

Description:
Powerex Intellimod Modules are designed for applications requiring a high frequency (20kHz) output switching inverter. The modules are isolated from the baseplate, consisting of complete drive, control and protection circuitry for the IGBT inverter.

Features:
- Complete Output Power Circuit
- Gate Drive Circuit
- Protection Logic
  - Short Circuit
  - Over-Current
  - Over Temperature
  - Under Voltage

Applications:
- Inverters
- Small UPS
- Motion/Servo Control
- AC Motor Control

Ordering Information:
PM150CSA060

PM150CSA060 Outline Drawing

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Inches</th>
<th>Millimeters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.33 ± 0.04</td>
<td>110.0 ± 1.0</td>
</tr>
<tr>
<td>B</td>
<td>3.74 ± 0.02</td>
<td>95.0 ± 0.5</td>
</tr>
<tr>
<td>C</td>
<td>3.50 ± 0.04</td>
<td>89.0 ± 1.0</td>
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<tr>
<td>D</td>
<td>3.27</td>
<td>83.0</td>
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<tr>
<td>E</td>
<td>2.91 ± 0.02</td>
<td>74.0 ± 0.5</td>
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<tr>
<td>F</td>
<td>2.44</td>
<td>62.0</td>
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<tr>
<td>G</td>
<td>1.28</td>
<td>32.6</td>
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<tr>
<td>H</td>
<td>1.24</td>
<td>31.6</td>
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<tr>
<td>J</td>
<td>1.02</td>
<td>26.0</td>
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<tr>
<td>K</td>
<td>0.94</td>
<td>24.0</td>
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<tr>
<td>L</td>
<td>0.87 ±0.06/0</td>
<td>22.0 ±1.5/0</td>
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<tr>
<td>M</td>
<td>0.79</td>
<td>20.0</td>
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<tr>
<td>N</td>
<td>0.76</td>
<td>19.4</td>
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<tr>
<td>P</td>
<td>0.75</td>
<td>19.0</td>
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<tr>
<td>Q</td>
<td>0.708</td>
<td>17.98</td>
</tr>
<tr>
<td>R</td>
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<table>
<thead>
<tr>
<th>Dimensions</th>
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<th>Millimeters</th>
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<tbody>
<tr>
<td>S</td>
<td>0.67</td>
<td>17.0</td>
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<tr>
<td>T</td>
<td>0.52</td>
<td>13.2</td>
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<tr>
<td>U</td>
<td>0.39</td>
<td>10.0</td>
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<tr>
<td>V</td>
<td>0.32</td>
<td>8.0</td>
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<tr>
<td>W</td>
<td>0.30</td>
<td>7.5</td>
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<tr>
<td>X</td>
<td>0.24</td>
<td>6.0</td>
</tr>
<tr>
<td>Y</td>
<td>0.24 Rad.</td>
<td>Rad. 6.0</td>
</tr>
<tr>
<td>Z</td>
<td>0.22 Dia.</td>
<td>Dia. 5.5</td>
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<tr>
<td>AB</td>
<td>0.127</td>
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<tr>
<td>AC</td>
<td>0.10</td>
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<td>AD</td>
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<td>AE</td>
<td>0.07</td>
<td>1.8</td>
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<tr>
<td>AF</td>
<td>0.06</td>
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<tr>
<td>AG</td>
<td>0.02</td>
<td>0.5</td>
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Absolute Maximum Ratings, $T_J = 25^\circ C$ unless otherwise specified

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Symbol</th>
<th>PM150CSA060</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Device Junction Temperature</td>
<td>$T_J$</td>
<td>-20 to 150</td>
<td>°C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>$T_{stg}$</td>
<td>-40 to 125</td>
<td>°C</td>
</tr>
<tr>
<td>Case Operating Temperature</td>
<td>$T_C$</td>
<td>-20 to 100</td>
<td>°C</td>
</tr>
<tr>
<td>Mounting Torque, MS Mounting Screws</td>
<td>—</td>
<td>20</td>
<td>kg-cm</td>
</tr>
<tr>
<td>Mounting Torque, MS Main Terminal Screws</td>
<td>—</td>
<td>20</td>
<td>kg-cm</td>
</tr>
<tr>
<td>Module Weight (Typical)</td>
<td>—</td>
<td>550</td>
<td>Grams</td>
</tr>
<tr>
<td>Supply Voltage Protected by OC and SC $V_D = 13.5 - 16.5V$, Inverter Part</td>
<td>$V_{CC(prot)}$</td>
<td>400</td>
<td>Volts</td>
</tr>
<tr>
<td>Isolation Voltage, AC 1 minute, 60Hz</td>
<td>$V_{RMS}$</td>
<td>2500</td>
<td>Volts</td>
</tr>
</tbody>
</table>

Control Sector

Supply Voltage Applied between $(V_{NP1}, V_{UPC}, V_{VP1}, V_{URPC}, V_{NP2}, V_{URPC}, V_{NP3}, V_{URPC}, V_{NP4}, V_{URPC})$ | $V_D$ | 20 | Volts |
Fault Output Supply Voltage (Applied between $F_O$ and $V_D$) | $V_{F0}$ | 20 | Volts |
Fault Output Current | $I_{FO}$ | 20 | mA |

IGBT Inverter Sector

Collector-Emitter Voltage | $V_{CES}$ | 600 | Volts |
Collector Current, $\pm$ | $I_C$ | 150 | Amperes |
Peak Collector Current, $\pm$ | $I_{CP}$ | 300 | Amperes |
Supply Voltage (Applied between $P - N$) | $V_{CC}$ | 450 | Volts |
Supply Voltage, Surge (Applied between $P - N$) | $V_{CC(surge)}$ | 500 | Volts |
Collector Dissipation | $P_C$ | 500 | Watts |
### Electrical and Mechanical Characteristics, $T_j = 25^\circ C$ unless otherwise specified

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
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<tbody>
<tr>
<td><strong>Control Sector</strong></td>
<td></td>
<td></td>
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<tr>
<td>Over Current Trip Level Inverter</td>
<td>OC</td>
<td>$-20^\circ C \leq T \leq 125^\circ C$</td>
<td>210</td>
<td>300</td>
<td></td>
<td>Amperes</td>
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<tr>
<td>Short Circuit Trip Level Inverter</td>
<td>SC</td>
<td>$-20^\circ C \leq T \leq 125^\circ C$</td>
<td></td>
<td>420</td>
<td></td>
<td>Amperes</td>
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<tr>
<td>Over Current Delay Time</td>
<td>$t_{woc}$</td>
<td>$V_D = 15V$</td>
<td></td>
<td>10</td>
<td></td>
<td>$\mu$s</td>
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<td>Over Temperature Protection</td>
<td>OT</td>
<td>Trip Level</td>
<td>111</td>
<td>118</td>
<td>125</td>
<td>$^\circ C$</td>
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<tr>
<td></td>
<td>$t_{o_r}$</td>
<td>Reset Level</td>
<td></td>
<td>100</td>
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<td>$^\circ C$</td>
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<tr>
<td>Supply Circuit Under Voltage</td>
<td>UV</td>
<td>Trip Level</td>
<td>11.5</td>
<td>12.0</td>
<td>12.5</td>
<td>Volts</td>
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<tr>
<td>Protection</td>
<td>$t_{u_r}$</td>
<td>Reset Level</td>
<td></td>
<td>12.5</td>
<td></td>
<td>Volts</td>
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<tr>
<td>Supply Voltage</td>
<td>$V_D$</td>
<td>Applied between $V_{upc}, V_{upc}$, $V_{wpd}, V_{wpc}$, $V_{h}, V_{nc}$</td>
<td>13.5</td>
<td>15</td>
<td>16.5</td>
<td>Volts</td>
</tr>
<tr>
<td>Circuit Current</td>
<td>$I_D$</td>
<td>$V_D = 15V, V_{DN} = 15V, V_{IN}, V_{NC}$</td>
<td></td>
<td>40</td>
<td>55</td>
<td>mA</td>
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<tr>
<td></td>
<td></td>
<td>$V_D = 15V, V_{DN} = 15V, V_{XP}, V_{XPC}$</td>
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<td>13</td>
<td>18</td>
<td>mA</td>
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<tr>
<td>Input Bias ON Voltage</td>
<td>$V_{CM(on)}$</td>
<td>Applied between $V_{upc}, V_{wpd}$</td>
<td>1.2</td>
<td>1.5</td>
<td>1.8</td>
<td>Volts</td>
</tr>
<tr>
<td>Input Bias OFF Voltage</td>
<td>$V_{CM(off)}$</td>
<td>$W_p, V_{wpd}, U_p, V_{h}, W_{nc}, V_{nc}$</td>
<td>1.7</td>
<td>2.0</td>
<td>2.3</td>
<td>Volts</td>
</tr>
<tr>
<td>PWM Input Frequency</td>
<td>$f_{PWM}$</td>
<td>3-\phi Sinusoidal</td>
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<td>15</td>
<td>20</td>
<td>kHz</td>
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<tr>
<td>Dead Time</td>
<td>$t_{dead}$</td>
<td>For each Input Pulse</td>
<td>2.5</td>
<td></td>
<td></td>
<td>$\mu$s</td>
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<tr>
<td></td>
<td></td>
<td>Using App. Circuit Optocoupler's</td>
<td>4.5</td>
<td></td>
<td></td>
<td>$\mu$s</td>
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<tr>
<td>Fault Output Current</td>
<td>$I_{FQ}$</td>
<td>$V_D = 15V, V_{FO} = 15V$</td>
<td></td>
<td></td>
<td>0.01</td>
<td>mA</td>
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<tr>
<td>Minimum Fault Output Pulse Width</td>
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<td>$V_D = 15V, V_{FO} = 15V$</td>
<td>1.0</td>
<td>1.8</td>
<td></td>
<td>mS</td>
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### Electrical and Mechanical Characteristics, $T_I = 25^\circ\text{C}$ unless otherwise specified

<table>
<thead>
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<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
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<tbody>
<tr>
<td>IGBT Inverter Sector</td>
<td></td>
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</tr>
<tr>
<td>Collector Cutoff Current</td>
<td>$I_{CEX}$</td>
<td>$V_{CE} = V_{CEX}, T_I = 25^\circ\text{C}$</td>
<td>—</td>
<td>—</td>
<td>1.0</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{CE} = V_{CEX}, T_I = 125^\circ\text{C}$</td>
<td>—</td>
<td>—</td>
<td>10</td>
<td>mA</td>
</tr>
<tr>
<td>Diode Forward Voltage</td>
<td>$V_{FM}$</td>
<td>$I_C = 150A, V_D = 15V, V_{CIN} = 15V$</td>
<td>—</td>
<td>2.2</td>
<td>3.3</td>
<td>Volts</td>
</tr>
<tr>
<td>Collector-Emitter Saturation Voltage</td>
<td>$V_{CE(max)}$</td>
<td>$V_D = 15V, V_{CIN} = 0V, I_C = 150A$</td>
<td>—</td>
<td>1.8</td>
<td>2.7</td>
<td>Volts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_D = 15V, V_{CIN} = 0V, I_C = 150A, T_I = 125^\circ\text{C}$</td>
<td>—</td>
<td>1.75</td>
<td>2.63</td>
<td>Volts</td>
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<tr>
<td>Inductive Load Switching Times</td>
<td>$t_{on}$</td>
<td>$V_D = 15V, V_{CIN} = 0 - 15V$</td>
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<td>0.4</td>
<td>0.8</td>
<td>2.0</td>
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<tr>
<td></td>
<td>$t_{tr}$</td>
<td>$V_{CC} = 300V, I_C = 150A$</td>
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<td>0.4</td>
<td>1.0</td>
<td>$\mu\text{s}$</td>
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<tr>
<td></td>
<td>$t_{off}$</td>
<td>$T_I = 125^\circ\text{C}$ (Fig. 4, Fig. 5)</td>
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<td>2.0</td>
<td>2.9</td>
<td>$\mu\text{s}$</td>
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<tr>
<td></td>
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<td>$T_I = 125^\circ\text{C}$</td>
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<td>0.6</td>
<td>1.2</td>
<td>$\mu\text{s}$</td>
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### Thermal Characteristics

<table>
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<th>Units</th>
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<tbody>
<tr>
<td>Junction to Case Thermal Resistance</td>
<td>$R_{TJC}$</td>
<td>Inverter IGBT Part</td>
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<td>—</td>
<td>0.25</td>
<td>°C/Watt</td>
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<tr>
<td></td>
<td>$R_{TJC}$</td>
<td>Inverter FWD</td>
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<td>—</td>
<td>0.47</td>
<td>°C/Watt</td>
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<tr>
<td>Contact Thermal Resistance</td>
<td>$R_{TJC}$</td>
<td>Case to Fin, Thermal Grease Applied</td>
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<td>0.027</td>
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### Recommended Conditions for Use

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Condition</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>$V_{CC}$</td>
<td>Applied across P-N Terminats</td>
<td>0 - 400</td>
<td>Volts</td>
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<tr>
<td></td>
<td>$V_D$</td>
<td>Applied between $V_{UP1}$-$V_{UPC}$, $V_{NT}$-$V_{MC}$, $V_{WP1}$-$V_{WPC}$</td>
<td>15 ± 1.5</td>
<td>Volts</td>
</tr>
<tr>
<td>Input ON Voltage</td>
<td>$V_{CIN(on)}$</td>
<td>Applied between $U_P$-$V_{UPC}$</td>
<td>0 - 0.8</td>
<td>Volts</td>
</tr>
<tr>
<td>Input OFF Voltage</td>
<td>$V_{CIN(off)}$</td>
<td>Applied between $U_P$-$V_{UPC}$, $V_{PF}$-$V_{WPC}$, $U_N$-$V_N$, $W_N$-$V_NC$</td>
<td>4.0 - $V_D$</td>
<td>Volts</td>
</tr>
<tr>
<td>PWM Input Frequency</td>
<td>$f_{PWM}$</td>
<td>Using Application Circuit</td>
<td>5 - 20</td>
<td>kHz</td>
</tr>
<tr>
<td>Minimum Dead Time</td>
<td>$t_{DEAD}$</td>
<td>Using Application Circuit Optocoupler’s Input Signal</td>
<td>4.5</td>
<td>$\mu\text{s}$</td>
</tr>
</tbody>
</table>
Description:
Powerex Intellimod Modules are designed for applications requiring a high frequency (20kHz) output switching inverter. The modules are isolated from the baseplate, consisting of complete drive, control and protection circuitry for the IGBT inverter.

Features:
- Complete Output Power Circuit
- Gate Drive Circuit
- Protection Logic
  - Short Circuit
  - Over-Current
  - Over Temperature
  - Under Voltage

Applications:
- Inverters
- Small UPS
- Motion/Servo Control
- AC Motor Control

Ordering Information:
PM150DSA120
### Absolute Maximum Ratings, $T_j = 25^\circ$C unless otherwise specified

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Symbol</th>
<th>PM150DSA120 Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Device Junction Temperature</td>
<td>$T_j$</td>
<td>-20 to 150 °C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>$T_{stg}$</td>
<td>-40 to 125 °C</td>
</tr>
<tr>
<td>Case Operating Temperature</td>
<td>$T_C$</td>
<td>-20 to 100 °C</td>
</tr>
<tr>
<td>Mounting Torque, MS Mounting Screws</td>
<td>—</td>
<td>20 kg-cm</td>
</tr>
<tr>
<td>Mounting Torque, MS Main Terminal Screws</td>
<td>—</td>
<td>20 kg-cm</td>
</tr>
<tr>
<td>Module Weight (Typical)</td>
<td>—</td>
<td>430 Grams</td>
</tr>
<tr>
<td>Supply Voltage Protected by OC and SC ($V_D = 13.5 - 16.5V$, Inverter Part)</td>
<td>$V_{CC(Pro)}$</td>
<td>800 Volts</td>
</tr>
<tr>
<td>Isolation Voltage, AC 1 minute, 60Hz</td>
<td>$V_{RMS}$</td>
<td>2500 Volts</td>
</tr>
</tbody>
</table>

### Control Sector

<table>
<thead>
<tr>
<th>Supply Voltage Applied between ($V_{P1}, V_{PC}, V_{N1}, V_{NC}$)</th>
<th>$V_D$</th>
<th>20 Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage Applied between ($C_{P1}, C_{PC}, C_{N1}, C_{NC}$)</td>
<td>$V_{DH}$</td>
<td>10 Volts</td>
</tr>
<tr>
<td>Fault Output Supply Voltage (Applied between $F_{PO}, V_{PC}$ and $F_{NO}, V_{NC}$)</td>
<td>$V_{FO}$</td>
<td>20 Volts</td>
</tr>
<tr>
<td>Fault Output Current</td>
<td>$I_{FO}$</td>
<td>20 mA</td>
</tr>
</tbody>
</table>

### IGBT Inverter Sector

<table>
<thead>
<tr>
<th>Collector-Emitter Voltage</th>
<th>$V_{CES}$</th>
<th>1200 Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector Current, ±</td>
<td>$I_C$</td>
<td>150 Amperes</td>
</tr>
<tr>
<td>Peak Collector Current, ±</td>
<td>$I_{CP}$</td>
<td>300 Amperes</td>
</tr>
<tr>
<td>Supply Voltage (Applied between P - N)</td>
<td>$V_{CC}$</td>
<td>900 Volts</td>
</tr>
<tr>
<td>Supply Voltage, Surge (Applied between P - N)</td>
<td>$V_{CC(surge)}$</td>
<td>1000 Volts</td>
</tr>
<tr>
<td>Collector Dissipation</td>
<td>$P_C$</td>
<td>960 Watts</td>
</tr>
</tbody>
</table>
**Electrical and Mechanical Characteristics, \( T_j = 25^\circ \text{C} \) unless otherwise specified**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control Sector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over Current Trip Level Inverter Part</td>
<td>OC</td>
<td>(-20^\circ \text{C} \leq T \leq 125^\circ \text{C})</td>
<td>200</td>
<td>320</td>
<td></td>
<td>Amperes</td>
</tr>
<tr>
<td>Short Circuit Trip Level Inverter Part</td>
<td>SC</td>
<td>(-20^\circ \text{C} \leq T \leq 125^\circ \text{C})</td>
<td>280</td>
<td>450</td>
<td></td>
<td>Amperes</td>
</tr>
<tr>
<td>Over Temperature Delay Time</td>
<td>( t_{\text{tr}(OC)} )</td>
<td>( V_D = 15 \text{V} )</td>
<td>—</td>
<td>5</td>
<td>—</td>
<td>( \mu \text{S} )</td>
</tr>
<tr>
<td>Over Temperature Protection</td>
<td>OT</td>
<td>Trip Level</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>( ^\circ \text{C} )</td>
</tr>
<tr>
<td></td>
<td>( t_{\text{R}} )</td>
<td>Reset Level</td>
<td>85</td>
<td>95</td>
<td>105</td>
<td>( ^\circ \text{C} )</td>
</tr>
<tr>
<td><strong>Supply Circuit Under Voltage Protection</strong></td>
<td>UV</td>
<td>Trip Level</td>
<td>11.5</td>
<td>12.0</td>
<td>12.5</td>
<td>Volts</td>
</tr>
<tr>
<td></td>
<td>( t_{\text{R}} )</td>
<td>Reset Level</td>
<td>—</td>
<td>12.5</td>
<td>—</td>
<td>Volts</td>
</tr>
<tr>
<td><strong>Supply Voltage</strong></td>
<td>( V_D )</td>
<td>Applied between ( V_{\text{tr}} ), ( V_{\text{oc}} ), ( V_{\text{nc}} )</td>
<td>13.5</td>
<td>15</td>
<td>16.5</td>
<td>Volts</td>
</tr>
<tr>
<td><strong>Circuit Current</strong></td>
<td>( I_D )</td>
<td>( V_D = 15 \text{V}, V_{\text{tr}} = 5 \text{V}, V_{\text{oc}} = 5 \text{V}, V_{\text{nc}} = 5 \text{V}, V_{\text{pc}} = V_{\text{pc}} )</td>
<td>19</td>
<td>26</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td><strong>Input Bias ON Voltage</strong></td>
<td>( V_{\text{CM(on)}} )</td>
<td>Applied between</td>
<td>1.2</td>
<td>1.5</td>
<td>1.8</td>
<td>Volts</td>
</tr>
<tr>
<td><strong>Input Bias OFF Voltage</strong></td>
<td>( V_{\text{CM(off)}} )</td>
<td>( C_{\text{tr}}, V_{\text{pc}}, V_{\text{nc}} )</td>
<td>1.7</td>
<td>2.0</td>
<td>2.3</td>
<td>Volts</td>
</tr>
<tr>
<td><strong>PWM Input Frequency</strong></td>
<td>( f_{\text{PWM}} )</td>
<td>( 3-\Omega ) Sinusoidal</td>
<td>—</td>
<td>15</td>
<td>20</td>
<td>kHz</td>
</tr>
<tr>
<td><strong>Dead Time</strong></td>
<td>( t_{\text{DEAD}} )</td>
<td>For each Input Pulse</td>
<td>3.5</td>
<td>—</td>
<td>—</td>
<td>( \mu \text{S} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Using App. Circuit Optocoupler's</td>
<td>5.5</td>
<td>—</td>
<td>—</td>
<td>( \mu \text{S} )</td>
</tr>
<tr>
<td><strong>Fault Output Current</strong></td>
<td>( I_{\text{FOP}} )</td>
<td>( V_D = 15 \text{V}, V_{\text{FO}} = 15 \text{V} )</td>
<td>—</td>
<td>—</td>
<td>0.01</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td>( I_{\text{FOLU}} )</td>
<td>( V_D = 15 \text{V}, V_{\text{FO}} = 15 \text{V} )</td>
<td>—</td>
<td>10</td>
<td>15</td>
<td>mA</td>
</tr>
<tr>
<td><strong>Minimum Fault Output Pulse Width</strong></td>
<td>( t_{\text{PO}} )</td>
<td>( V_D = 15 \text{V} )</td>
<td>1.0</td>
<td>1.8</td>
<td>—</td>
<td>mS</td>
</tr>
<tr>
<td><strong>SXN Terminal Output Voltage</strong></td>
<td>( V_{\text{SXN}} )</td>
<td>( T_j &lt; 125^\circ \text{C}, \text{Rin} = 6.8 \Omega (S_{\text{PC}}, S_{\text{NN}}) )</td>
<td>4.5</td>
<td>5.1</td>
<td>5.6</td>
<td>Volts</td>
</tr>
</tbody>
</table>
### Electrical and Mechanical Characteristics, $T_j = 25^\circ C$ unless otherwise specified

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IGBT Inverter Sector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collector Cutoff Current</td>
<td>$I_{CEX}$</td>
<td>$V_{CE} = V_{CED}, T_j = 25^\circ C$</td>
<td>—</td>
<td>—</td>
<td>1.0</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{CE} = V_{CED}, T_j = 125^\circ C$</td>
<td>—</td>
<td>—</td>
<td>10</td>
<td>mA</td>
</tr>
<tr>
<td>Diode Forward Voltage</td>
<td>$V_{FM}$</td>
<td>$I_C = 150A, V_D = 15V, V_{CIN} = 5V$</td>
<td>—</td>
<td>2.5</td>
<td>3.5</td>
<td>V</td>
</tr>
<tr>
<td>Collector-Emitter Saturation Voltage</td>
<td>$V_{CE(sat)}$</td>
<td>$V_D = 15V, V_{CIN} = 0V, I_C = 150A,$</td>
<td>—</td>
<td>2.3</td>
<td>3.2</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_D = 15V, V_{CIN} = 0V, I_C = 150A,$</td>
<td>—</td>
<td>2.1</td>
<td>2.9</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_j = 125^\circ C$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductive Load Switching Times</td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td>1.4</td>
<td>$\mu S$</td>
</tr>
<tr>
<td></td>
<td>$I_{on}$</td>
<td>$V_{D} = 15V, V_{CIN} = 0 - 5V$</td>
<td>—</td>
<td>0.2</td>
<td>0.4</td>
<td>$\mu S$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{CC} = 600V, I_C = 150A$</td>
<td>—</td>
<td>0.4</td>
<td>1.0</td>
<td>$\mu S$</td>
</tr>
<tr>
<td></td>
<td>$t_{hp}$</td>
<td>$T_j = 125^\circ C$</td>
<td>—</td>
<td>2.5</td>
<td>3.5</td>
<td>$\mu S$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>0.6</td>
<td>1.1</td>
<td>$\mu S$</td>
</tr>
<tr>
<td><em><strong>Thermal Characteristics</strong></em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Junction to Case Thermal Resistance</td>
<td>$R_{JQ}$</td>
<td>Inverter IGBT Part</td>
<td>—</td>
<td>—</td>
<td>0.13</td>
<td>°C/Watt</td>
</tr>
<tr>
<td></td>
<td>$R_{DK-Q}$</td>
<td>Inverter FWD</td>
<td>—</td>
<td>—</td>
<td>0.25</td>
<td>°C/Watt</td>
</tr>
<tr>
<td>Contact Thermal Resistance</td>
<td>$R_{DK-Q}$</td>
<td>Case to Fin, Thermal Grease Applied</td>
<td>—</td>
<td>—</td>
<td>0.095</td>
<td>°C/Watt</td>
</tr>
<tr>
<td><em><strong>Recommended Conditions for Use</strong></em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>$V_{CC}$</td>
<td>Applied across C1-E2 Terminals</td>
<td>0 − 800</td>
<td></td>
<td></td>
<td>Volts</td>
</tr>
<tr>
<td>Input ON Voltage</td>
<td>$V_{ON}$</td>
<td>Applied between $V_{P1}, V_{P2}, V_{H1}, V_{HC}$</td>
<td>15 ± 1.5</td>
<td></td>
<td></td>
<td>Volts</td>
</tr>
<tr>
<td>Input OFF Voltage</td>
<td>$V_{ON}$</td>
<td>Applied between $I_{P1}, I_{P2}, I_{H1}, I_{HC}$</td>
<td>0 − 0.8</td>
<td></td>
<td></td>
<td>Volts</td>
</tr>
<tr>
<td>Input OFF Voltage</td>
<td></td>
<td>$V_{CIN(on)}$</td>
<td>4.0 − $V_{EXR}$</td>
<td></td>
<td></td>
<td>Volts</td>
</tr>
<tr>
<td>PWM Input Frequency</td>
<td>$f_{PWM}$</td>
<td>Using Application Circuit</td>
<td>5 − 20</td>
<td></td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>Minimum Dead Time</td>
<td>$I_{DEAD}$</td>
<td>Using Application Circuit Optocoupler's Input Signal</td>
<td>5.5</td>
<td></td>
<td></td>
<td>$\mu S$</td>
</tr>
</tbody>
</table>
APPENDIX C

SIMULATION PROGRAMS
C.1 SAM4 Series-Hybrid Vehicle Simulation

unit enerdef;
   
   Simulation hybrid vehicle. This section includes the complete system from the engine to the driving pattern. However, the resonant converter is not included because the simulation is too slow. The input voltage of the converter is from a DC source (capacitor) instead of a resonant tank. Conduction, switching and resonant losses are included as well as machine losses. The DLCs have an input current given by the power balance at the DC source. The switching frequency is reduced by a factor ten to make the simulation faster

   }

interface
   uses saotype;
      
      saotype defines only types, those are :
      diili = array[l..20] of double;
      diml = array[l..20] of integer;
      name = string[30];
      dimlst = array[l..30] of name;
   }

   const om = 376.99111848;
   pi3 = 1.0471976;
   pi = 3.1415927;

   var inv,ouv : text;

   { ****************** Runge Kutta and math. variables *************** }
   n,ist,ier,ier,errsam : integer;
   x,h,hmax,hmin,toi : double;
   z,y : diml;

   { *************** Variables spec. program *********************** }
   band : boolean;
   state,stp,stdc,stpdc,stag : integer;
   drvmod,sel,gep : integer;
   Iqref,Idref : double;
   Vam,Vbm,Vcm,Vdm,Vgs: double;
   Vag,Vbg,Vcg,Vdq,Vqq: double;
   Vbe,Val,Valfa,Valf: double;
   Idm,Iqm,Iam,Ibm,lc: double;
   Idg,Iqg,Ibg,Icg: double;
   Ial,Ibe,ila,ib: double;
   Idcom,IdcomI,Idcomb,Idcomc: double;
   Idconm,IdconmI,Idconm: double;
   fldm,flmg,lg,lgm,lgm: double;
   Irm,IrmI,erm: double;
   Ieg,IegI,erq: double;
   Iqg,IqgI,Idg,IdgI: double;
   jw,jl,Jm,Jg : double;
   vs,js,fs,Rs,ldq,tdq,fig,figd,npp: double;
   vba,iba,wa,gb,gb,gb : double;
   Ldq,rdq,rdq: double;
   Iqprem,Ipqaux,erm,erp,erpkm,spref,kp: double;
   Iqprem,Ipqaux,erm,erp,erpkm,spref,kp: double;
   Vcap,comvcap,Pref: double;
   spmax,spmin,tmax,tmn,chnp,chtq: double;
   desap,vesp,veps,grade: double;
   vma,volores,aero,tire,fric,airres: double;
   Tloadm,Tloadg,Tlossg,Tlossm: double;
   Mloss,Tfric,Tdamp: double;
   Iloadm,Iloadg,Iloadm1,Iloadm2,Iloadg1,Iloadg2: double;
   Vdcref,Vdcref,Vcapa : double;
   tx,txl: double;

   { engine shutdown flag }
   { switches cond }
   { control mode }
   { open loop motor curr }
   { motor voltages }
   { generator volt }
   { motor currents }
   { conversion volt }
   { conversion curr }
   { motor control curr }
   { generator control curr }
   { Power limit }
   { error signals motor }
   { error signals gener }
   { electric positions }
   { inertias }
   { machines constants }
   { base values }
   { per unit values }
   { motor speed control }
   { generator speed cont }
   { energy management }
   { engine condit }
   { driving cond }
   { mech car const }
   { Machine load torques }
   { Mechanical Losses }
   { DC link currents }
   { DC link/DLC voltage }
   { controllers period }
\texttt{R1}, \texttt{R2}, \texttt{R3}, \texttt{Rleu}: \texttt{double}; \quad \text{(branch resistances)}
\texttt{Rlpu}, \texttt{R2pu}, \texttt{R3pu}, \texttt{Rleapu}: \texttt{double}; \quad \text{(per unit resistances)}
\texttt{C0}, \texttt{C1}, \texttt{C2}, \texttt{C3}: \texttt{double}; \quad \text{(branch capacitances)}
\texttt{C0pu}, \texttt{C1pu}, \texttt{C2pu}, \texttt{C3pu}: \texttt{double}; \quad \text{(per unit capacitances)}
\texttt{Igbt}, \texttt{Idio}, \texttt{Vosw}, \texttt{Vod}, \texttt{Rsw}, \texttt{Rod}: \texttt{double}; \quad \text{(Conduction losses)}
\texttt{Cr}, \texttt{Crpu}, \texttt{tf}: \texttt{double}; \quad \text{(resonant parameters)}
\texttt{Psw}, \texttt{Plosses}, \texttt{Iswlo}, \texttt{Irripple}: \texttt{double}; \quad \text{(switching losses)}
\texttt{gear}, \texttt{gearl}, \texttt{gear2}: \texttt{double}; \quad \text{(transmission gears)}
\texttt{L}, \texttt{Lpu}, \texttt{Cdc}, \texttt{Cdcpu}, \texttt{V1}, \texttt{Isw}, \texttt{Iswp}: \texttt{double}; \quad \text{(chopper conditions)}
\texttt{Tqf, Tqfpre, Tqp, Ener, Pdt}: \texttt{double}; \quad \text{(power control)}
\texttt{Vdc, Vdcip, Vdcpre, Vdlc, Vcapip, Vdlcpre}: \texttt{double}; \quad \text{(voltage control)}
\texttt{Tqf, Tqfpre, Tqp, Ener, Pdt}: \texttt{double}; \quad \text{(voltage filters)}

\{ *************** Procedures declaration *********************** \}
\begin{verbatim}
procedure conv23(v1l,v12:double;var v21,v22,v23:double);
procedure cotr(vll,vl2,anq:double;var v21,v22:double);
procedure fcn (n:integer; var z2:double;var z3:double;var xtdouble);
procedure rkm(ntinteger; var ytdim1r;var x,htdouble; toltdoub1e;ist:inteqer; var ierrinteger);
procedure enerinit;
procedure calstep (pvaltdimls; puritdimli; setflgtbaolean; var yytàimïr; var xxtdouble);
\end{verbatim}

\{ ****************程序的声明 ******************* \}

\texttt{procedure conv32(v11,v12,v13:double;var v21,v22,double);}
\begin{verbatim}
procedure conv23(v1l,v12:double;var v21,v22,v23:double);
procedure cotr(vll,vl2,anq:double;var v21,v22:double);
procedure fcn (n:integer; var z2:double;var z3:double;var x:double; toltdouble;ist:inteqer; var ierrinteger);
procedure enerinit;
procedure calstep (pvaltdimls; puritdimli; setflgtbaolean; var yytàimïr; var xxtdouble);
\end{verbatim}

\texttt{implementation}
\begin{verbatim}
procedure conv32; \{conversion from 3 phase to s frame\}
const w3 : double = 1.7320508;
const w2 : double = 1.41421356;
begin
  v21:= (w2*vll - v12/w2 - v13/w2)/w3;
  v22:= (v12 - v13)/w2;
end;

procedure conv23; \{conversion from s frame to 3 phase\}
const w3 : double = 1.7320508;
const w2 : double = 1.41421356;
begin
  v21:= v11*w2/w3;
  v22:= (-v11/w3 + v12)/w2;
  v23:= (-v11/w3 - v12)/w2;
end;

procedure cotr; \{conversion from frame to frame\}
var cn,sn : double;
begin
  cn:= cos(ang); sn:= sin(ang);
  v21:= v11*cn - v12*sn;
  v22:= v11*sn + v12*cn;
end;

procedure fcn; \{state variables formulation\}
\begin{verbatim}
{ \texttt{z[1]} is the engine power. The change in engine power } \texttt{is limited by the maximum change in speed and/or torque } \texttt{\texttt{chsp} and \texttt{chtq}. the reference speed for the controller } \texttt{is calculated to get the desired \texttt{Tq} vs \texttt{speed} trajectory. } z[2] \texttt{to } z[12] \texttt{are defined beside the diff equation.}\}
begin
  if \texttt{z[1]>Preq}+0.001 then begin
    if \texttt{z[1]<trqmin}+\texttt{spmax} then begin
\end{verbatim}

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\[
\begin{align*}
&\text{else if} \ (\text{Freq} < z[1] - 0.001) \ \text{then} \begin{align*}
&\text{if} \ (z[1] > \text{tqmin} * \text{spmax}) \ \text{then} \begin{align*}
&z[1] := -\text{spmax} * \text{chtq}; \\
&s\text{prefg} := \text{spmax}; \\
&\text{end}; \\
&\text{end} \text{ else } \begin{align*}
&z[1] := -\text{tqmin} * \text{chsp}; \\
&s\text{prefg} := z[1] / \text{tqmin}; \\
&\text{end}; \\
&\text{end}; \\
&\text{else } z[1] := 0; \\
\end{align*}
\end{align*}
\]

\[
\{ \text{functions} \}
\]

\[
\begin{align*}
&z[2] := (T\text{loadg} - T\text{loss}_g - (z[3] * Iqg - z[4] * Idg)) / Tg; \quad \{\text{generator speed}\} \\
&z[3] := (Vd\text{g} - \text{ramp} * \text{Idg} + z[2] * z[4]) / \text{wba}; \quad \{\text{generator flux}\} \\
&z[4] := (Vqg - \text{ramp} * Iqg - z[2] * z[3]) / \text{wba}; \quad \{\text{generator field}\} \\
&z[5] := (Vdm - \text{ramp} * \text{Idm} + z[7] * z[6]) / \text{wba}; \quad \{\text{motor flux}\} \\
&z[6] := (Vqm - \text{ramp} * Iqm - z[7] * z[5]) / \text{wba}; \quad \{\text{motor field}\} \\
&z[8] := \text{wba} * VL / \text{Lpu}; \quad \{\text{DC-link currs}\} \\
&z[9] := \text{wba} * (\text{In} + T\text{load}_g / \text{Cdpu}); \quad \{\text{DC-link volt}\} \\
&z[10] := \text{wba} * (V\text{capa} - z[10]) / (R\text{pu} * (C\text{dpu} * C\text{lpu} * z[10] * 100 / \text{vba})); \quad \{\text{DLC model}\} \\
&z[11] := \text{wba} * (V\text{capa} - z[11]) / (C\text{dpu} * R\text{pu}); \quad \{\text{DLC model}\} \\
&z[12] := \text{wba} * (V\text{capa} - z[12]) / (R\text{pu} * C\text{dpu}); \\
&\text{end}; \\
&\text{end functions}
\end{align*}
\]

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\[
\text{procedure enerinit;}
\]

\[
\begin{align*}
&\text{begin} \begin{align*}
&\{ \text{initial values} \} \begin{align*}
&\text{readln}\ (\text{inv}, \ h, \text{hmax}, \text{hmin}, \text{tol}, \text{ist}); \\
&\text{writeln}(\text{ouv}); \\
&\text{writeln}(\text{ouv}, \ 'h\ hmax\ hmin\ tol\ ist'); \\
&\text{writeln}(\text{ouv}, \ h:12, \ ',hmax:12, \ ',\text{hmin:12,} \ ',\text{tol:12,ist:3}); \\
&\end{align*} \\
&\end{align*}
\end{align*}
\]

{initial values}

\[
\begin{align*}
&\text{readln}\ (\text{inv}, \ \text{vs}, \\text{is}, \\text{f0}); \quad \{\text{base values}\} \\
&\text{writeln}(\text{ouv}); \\
&\text{writeln}(\text{ouv}, \ 'Vs\ Is\ fre'); \\
&\text{writeln}(\text{ouv}, \ \text{vs:8:3, is:8:3, f0:8:3}); \\
&\text{readln}\ (\text{inv}, \ \text{Rs, Ldq, fifmag, jm, jw, npp, Pmax}); \quad \{\text{machine param}\} \\
&\text{writeln}(\text{ouv}); \\
&\text{writeln}(\text{ouv}, \ 'Rs\ Ldq\ fifmag\ jm\ jw\ npp\ Pmax'); \\
&\text{write}(\text{ouv}, \ \text{Rs:8:3, Ldq:8:3, fifmag:8:3, jm:8:3, jw:8:3, npp:8:3, Pmax:5}); \\
&\text{readln}\ (\text{inv}, \ \text{vms}, \\text{rolres}, \\text{aero}, \\text{tire}, \\text{gear}'); \quad \{\text{vehicle param}\} \\
&\text{writeln}(\text{ouv}, \ 'veh\ mass\ rol\ coef\ aerodin\ coef\ tire\ rad\ gear\ rat'); \\
&\text{write}(\text{ouv}, \ \text{vms:8:3, rolres:8:3, aero:8:3, tire:3:8, gear:3:8}); \\
&\text{readln}\ (\text{inv}, \ \text{spmax, spmin, tmax, tmmin}); \quad \{\text{engine conditions}\} \\
&\text{writeln}(\text{ouv}); \\
&\text{write}(\text{ouv}, \ 'max\ speed\ min\ speed\ max\ torque\ min\ torque'); \\
&\text{write}(\text{ouv}, \ \text{spmax:8:3, spmin:8:3, tmax:8:3, tmmin:8:3}); \\
&\text{readln}\ (\text{inv}, \ \text{jg, chsp, chtq}); \\
&\text{writeln}(\text{ouv}); \\
&\text{write}(\text{ouv}, \ 'J\_eng\ dw/dt\_max\ dtq/dt\_max'); \\
&\text{write}(\text{ouv}, \ \text{jg:8:3, chsp:8:3, chtq:8:3}); \\
&\text{readln}(\text{inv}, \ \text{Mloss, Tfric, Tdamp});
\end{align*}
\]

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writeln(ouv);
writeln(ouv, 'Ilossg Tfricm Tdampm');
writeln(ouv, 'L083,Tfric83,Tdamp83');
readln(inv, C0,C1,C2,C3);  {DLC model}
writeln(ouv);
writeln(ouv, 'C0 C1 C2 C3');
writeln(ouv, C0:83,C1:83,C2:83,C3:83);
readln(inv, R1,R2,R3,Rlea);
writeln(ouv, 'R1 R2 R3 Rlea');
writeln(ouv, 'Vosw, Vod, Rosw, Rod');
writeln(ouv, 'Vosw83, Vod83, Rosw83, Rod83');
readln(inv, L, Cdc);  {IGBTs parameters}
writeln(ouv, 'L Cdc');
writeln(ouv, R183, C283, R383, Rlea83);
readln(inv, tf, Cr, Iripple);  {switching cond}
writeln(ouv);
writeln(ouv, 'IGBT_tf Res_Cap IVS_ripple_current');
writeln(ouv, tf:5, Cr:5, Iripple:83);

/* *************** Base and initial values calculation *************** */

vba:= v5*sqrt(2/3);  iba:= is*sqrt(2.0);
wba:= 2.0*pi*f0;  zba:= vba/iba;
Pba:= 1.5*vba*iba;  tqba:= Pba/(vba/npp);
Ldqpu:= wba*Ldq/zba;  rsp:= Rs/zba;
Pmax:= Pmax/Pba;
J1:= (jw+vmas*tire*tire)/(gear*gear);
tm:= wba*vba*(j1+jm)/(1.5*vba*iba*npp*npp);
tg:= wba*vba*jg/(1.5*vba*iba*npp*npp);
Mloss:= Mloss/tqba;  Tfric:= Tfric/tqba;
Tdp:= Tdp/tqba;
Crpu:= Cr*zba*wba;  Iripple:= Iripple/tqba;
Lpu:= wba*L/zba;  Cdcps:= Cdc*zba*wba;
Voswp:= Voswp/vba;  Vod:= Vod/vba;
Roswp:= Roswp/zba;  Rod:= Rod/zba;
C0pu:= C0*zba/wba;  C1pu:= C1*zba/wba;
C2pu:= C2*zba/wba;  C3pu:= C3*zba/wba;
R1pu:= R1/zba;  R2pu:= R2/zba;
R3pu:= R3/zba;

/* *************** Other program variables init *************** */

tx1:=0.0;  tx1:= 0.0;
ang:=0.0;  angm:=0.0;
syam:=0.0;  ggap:=1;
gear1:=gear;  gear2:= gear/2;
errm:=0.0;  errq:=0.0;
errreg:=0.0;  errdc:=0.0;
Iqaxm:=0.0;  Ivol:=0;
Idconm:=0.0;  Iqcomm:=0.0;
Idconq:=0.0;  Iqcomq:=0.0;
smp:=0;  stmpd:=1;
Vcap:=400/vba;  Vdcpre:=400/vba;
Vcapip:=190/vba;  Vdcpr:=190/vba;
Tqp:=0.0;  Tqfpre:=0.0;
sprq:=0.0;  Iswp:=0.0;
Ilom:=0.0;  Ilog1:=0.0;
state:=0;  stateg:=1;
Preq:=0.0;  Ener:=0.0;
Pdir:=0.0;

/* *************** Initialize diff. equations variables *************** */

n:= 12;  ierr:= 0;
x:= 0.0;  h:= hmin;
[1]:=0.0;  x[2]:=0.0;
[3]:=0.0;  z[4]:=0.0;
[5]:=0.0;  z[6]:=0.0;
[7]:=0.0;  z[8]:=0.0;
[9]:=400/vba;  z[10]:=190/vba;
[11]:=190/vba;  z[12]:=190/vba;
{ No assignment of variable parameters required as the
d parameters are assigned in the SAM before the first
calculation takes place (paflig true → setflag true)
The first plot point is set to 0.0 for all variables,
this is fixed in SBSRSAM and should not be altered to
ensure a save start up; if the first step is kept
small, it does not matter and usually the initial step
for the Runge Rutta Routine starts with bmin.
}
end; {end initialization}

procedure calstep;
{calculations every step}
procedure assignpar;
begin
  Iqref := pval[1];  Iqref := pval[1];
slope := pval[3];    slope := pval[3];
Vdcref := pval[5];  Vdcref := pval[5];
drvmod := pari[1];  drvmod := pari[1];
end; {end assignpar}

begin
if setflg then assignpar;
{ *********************** Changes mech. losses and angle update *********************** }
Tlossg := Miross*z[2];
Tlossm := Tfric+Tdammp*z[7];
syman := syman'h+wba;
angg := angg'z[2]*h'wba;
angm := angm'z[7]*h'wba;

{ *********************** Limiting the angles to [-pi,pi] *********************** }
If (syman>pi) then syman := syman-2*pi;
If (angg>pi) then angg := angg-2*pi;
If (angg<-pi) then angg := angg+2*pi;
If (angm>pi) then angm := angm-2*pi;
If (angm<-pi) then angm := angm+2*pi;

{ *********************** Motor currents from rotor frame to abc *********************** }
Idm := (z[5]-flmag)/Ldqpu;
Iqm := z[6]/Ldqpu;
ang := angm'syman;
cotr(Idm, Iqm, ang, Ialpha, Ibeta);
ang := syman;
cotr(Ialpha, Ibeta, ang, Ialpha, Ibeta);
conv23(Ialpha, Ibeta, Ialpha, Ibeta, Ialpha, Ibeta);

{ *********************** Generator currents from rotor frame to abc *********************** }
Idg := (z[3]-0.7)/Ldqpu;
Iqg := z[4]/Ldqpu;
ang := angg'syman;
cotr(Idg, Iqg, ang, Ialpha, Ibeta);
ang := syman;
cotr(Ialpha, Ibeta, ang, Ialpha, Ibeta);
conv23(Ialpha, Ibeta, Ialpha, Ibeta, Ialpha, Ibeta);

{ *********************** Control currents to abc frame *********************** }
ang := angm'syman;
cotr(Idconn, Iqconn, ang, Ialpha, Ibeta);
ang := syman;
cotr(Ialpha, Ibeta, ang, Ialpha, Ibeta);
conv23(Ialpha, Ibeta, Ialpha, Ibeta, Ialpha, Ibeta);

{ *********************** DLC bank terminal voltage calculation *********************** }
/(1.0/Ripu + 1.0/R2pu + 1.0/R3pu + 1.0/Rleapu);
{ *************** Motor load torque calculation *************** }

vesp= z[7]*f0*2*pi*tire/(npp*gear);
fric= rolres*vmas*9.8;
if z[7]=0.0 then fric=-0.0 else
if z[7]<0 then fric=-fric;
airres= aero*vesp*vesp;
grade= vmas*9.8*sin(slope*pi/180);
Tloadm= fric+airres+grade;
Tloadm= Tloadm/tire/gear;
Tloadm= Tloadm/tqba;
vesp= vesp*3.6/100;

{ *************** Gear change at 50 km/h *************** }

if ((gep=1)AND(vesp>0.52)) then {gear change accel}
begin
  gear:=gear2;
  z[7]=z[7]/2;
  j1= (jw*vmas*tire)/(gear*gear);
  tm= (wbawba*(jwr+j1))/(1.5*vba*iba*npp*npp);
  gep=2;
end;
if ((gep=2)AND(vesp<0.48)) then {gear change break}
begin
  gear:=gear1;
  z[7]=z[7]*2;
  j1= (jw*vmas*tire)/(gear*gear);
  tm= (wbawba*(jwr+j1))/(1.5*vba*iba*npp*npp);
  gep=1;
end;

{ *************** Generator load torque calculation *************** }

if (z[2]>spmin) then Tloadg=(z[1]+z[2]) else Tloadg=0;

{ *************** Generator load current averaging *************** }

case state of
  0: Ilom2=0;
  1: Ilom2=Iam;
  2: Ilom2=Iam+Ibm;
  3: Ilom2=Ibm;
  4: Ilom2=Ibm+Icm;
  5: Ilom2=Icm;
  6: Ilom2=Iam+Icm;
end; {cases}
Iloadm=(Ilom1+Ilom2)/2; {initial + final /2}

{ *************** Generator load current averaging *************** }

case state of
  1: Ilog2=Iag;
  2: Ilog2=Ibg;
  3: Ilog2=Iag+Ibg;
  4: Ilog2=Icg;
  5: Ilog2=Iag+Icg;
  6: Ilog2=Ibg+Icg;
end; {cases}
Iloadg=(Ilog1+Ilog2)/2; {initial + final /2}

{ *************** Generator load current averaging *************** }

Igbt=0.0; {cond losses init}
Idio=0.0;

if (stdc = 0) then
begin
  if (z[8]<0) then Igbt:=Igbt+z[8]
  else Idio:=Idio+z[8];
  Isw:= (z[8]+Iswp)/2;
end
else
begin
  if (z[8]<>0) then Igbt:=z[8]
  else Idio:=z[8];

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if sw = 0; end;

{ ************** Speed control and current calculation ************** }
if x = tx then {25 Hz section}

{ ************** Drive mode selection and speed reference ************** }
if (sel = 0) then begin

if drvmod = 0 then spref := desp
else if drvmod = 1 then

begin
spref := 0.0;
if x = 20 then spre := 0.25;
if x = 65 then spre := 0.0;
if x = 70 then spre := 0.25;
if x = 96 then spre := 0.0;
if x = 98 then spre := 0.25;
if x = 145 then spre := 0.0;
if x = 165 then spre := 0.35;
if x = 200 then spre := 0.0;
if x = 210 then spre := 0.35;
if x = 225 then spre := 0.0;
if x = 228 then spre := 0.35;
if x = 270 then spre := 0.0;
if x = 290 then spre := 0.4;
if x = 320 then spre := 0.0;
if x = 325 then spre := 0.4;
if x = 350 then spre := 0.0;
if x = 352 then spre := 0.4;
if x = 370 then spre := 0.0;
if x = 395 then spre := 0.5;
if x = 415 then spre := 0.0;
if x = 425 then spre := 0.5;
if x = 440 then spre := 0.0;
if x = 442 then spre := 0.5;
if x = 455 then spre := 0.0;

end;

{ ************** Motor speed control and curr ref calculation ************ }
spc = (gear * 100 * npp) / (3.6 * f0 + 2 * pi * tire); {km/h -> rpm}
errp := errm;
erm := (spc - z[7]);
Iqkm := Iqauxm;
Iqaux := Iqkm + 10 * errm - 9.9955 * errp;
Idcon := 0;
end else begin
Iqaux := Iqref;
Idcon := Idref;
end;
If Iqaux > 2 then Idcon := 2 else If Iqaux < 2 then Idcon := -2 else Iqcon := Iqaux;

{ *********************** Maximum power limitation *********************** }
flq := Ldcpu * Iqcon;
{flux calc}
fl := Ldcpu * Idcon + flmag;
If ((z[7] > 0) and (Iqcon > 0)) then (driving power)
begin
Iqmax := (Pmax * npp / z[7]) + (flq * Idcon) / fl;
If (Iqmax < Iqcon) then Iqcon := Iqmax;
end else If ((z[7] > 0) and (Iqcon < 0)) then (braking power)
begin
Iqmax := (-Pmax * npp / z[7]) + (flq * Idcon) / fl;
If (Iqmax > Iqcon) then Iqcon := Iqmax;
end;

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/* Generator speed control and curr ref calculation */
err2preg=errpreg;
errpreg=errg;
errg=(sprefg-z[2]);
Iqpreg=Iqcong;
Iqcong=(Iqpreg-121*errg+42*errpreg-4.12+errg);
If Iqcong>2 then Iqcong=2;
If Iqcong<-2 then Iqcong=-2;
Idcong=Idref;

/* Energy Management Section */
if (vesp<=1.0) then comvcap=68*vesp*vesp*vesp
else comvcap=68;
comvcap=(186+6.25*Pd-comvcap)/vba;
if (z[0]<comvcap) then Preq=0.8;
else if (z[0]>=230/vba) then Preq=0.0;
if (Preq<0.2) and (z[1]<=0.2) and (band=false) then
begin
Preq=0.0;
z[1]=0.0;
sprefg=z[2];
end;

if (Preq>0.2) and (band) then
begin
band=false;
z[1]=0.2;
z[2]=spmin;
sprefg=z[2];
end;

end; {speed control}

{ CALCULATIONS EVERY SWITCHING PERIOD }
if (x=tx1) then
begin

{ Motor controller switch state selection }
erram=Iam-Iacong;
errbm=Ibm-Ibconm;
errcm=Icm-Iconm;
if (erram<0) AND (errbm>0) AND (errcm>0) then state:=1 else
if (erram<0) AND (errbm<0) AND (errcm>0) then state:=2 else
if (erram<0) AND (errbm<0) AND (errcm<0) then state:=3 else
if (erram<0) AND (errbm>0) AND (errcm<0) then state:=4 else
if (erram<0) AND (errbm<0) AND (errcm<0) then state:=5 else
state:=0;
if (step=0) then state:=state else
if (state=0) then state:=state else
if (ABS(state-step)<=1) then state:=state else
if (ABS(state-step)=5) then state:=state else
state:=0;

{ generator controller switch selection }
errag=Iaq-Iacong;
errbg=Ibg-Iacong;
errcg=Icg-Iccong;
if (Iaq<Iacong) then stateg=1 else stateg=0;
if (Iaq>Iacong) then stateg=2;
if (Ibg<Ibcong) then stateg=4;
if (stateg=0) then
begin
if (errag<errbg) AND (errag<errcg) then stateg=1;
if (errbg<errag) AND (errbg<errcg) then stateg=2;
if (errcg<errag) AND (errcg<errbg) then stateg=4;
end;

if (stateg=7) then
begin
if (errag<errbg) AND (errag<errcg) then stateg=6;
if (errbg<errag) AND (errbg<errcg) then stateg=5;
end;
*/
if (errcp>=errag) AND (errcp>=errbg) then stateg:=3;
end;

************** Digital Filters for Voltages **************
Vdc:=(z[9]+Vdcip+21.27*Vdcpre)/23.27;
Vdcpre:=Vdc;
Vdcp:=Vdcp+21.27*Vdcpre;
Vcp:=Vcp+21.27*Vdcpre;
Vdc:=Vdc;

************** PI voltage controller **************
Icon:=(Pd-z[1])/Vdc;
Irr:=(Vdc-z[1])/errcp;
Irr:=(Vdc-z[1])/errtp;
Ivol:=Ivol;
Ivol:=(Ivol+5*errdc-4.9871*errcp);
if (Icon>5.4) then Icon:=5.4; {max curr 500A}
if (Icon<5.4) then Icon:=-5.4;

********* Current control and switch state selection *********
if (z[8]>Icon) then stdc:=0
else stdc:=1;

************** Switching losses calculation **************
Iswlo:=0.0;
if ((state=0) OR (state=5) OR (state=3)) AND
((stp=6) OR (stp=1) OR (stp=2)) AND (Iam>0)
then Iswlo:=Iswlo+Iam*Iam else
if ((state=1) OR (state=2) OR (state=6)) AND
((stp=3) OR (stp=4) OR (stp=5) OR (stp=0)) AND
(Iam>0) then Iswlo:=Iswlo+Iam*Iam;
if ((state=0) OR (state=1) OR (state=5)) AND
((stp=2) OR (stp=3) OR (stp=4)) AND
(Iam>0) then Iswlo:=Iswlo+Iam*Iam else
if ((state=2) OR (state=3) OR (state=4)) AND
((stp=1) OR (stp=5) OR (stp=6) OR (stp=0)) AND
(Iam>0) then Iswlo:=Iswlo+Iam*Iam;
if ((state=0) OR (state=3) OR (state=1)) AND
((stp=4) OR (stp=5) OR (stp=6)) AND
(Iam>0) then Iswlo:=Iswlo+Iam*Iam else
if ((state=4) OR (state=5) OR (state=6)) AND
((stp=1) OR (stp=2) OR (stp=3) OR (stp=0)) AND
(Iam>0) then Iswlo:=Iswlo+Iam*Iam;

stp:=state;
if ((stdc=0) AND (stpd=1) AND (z[8]>0))
then Iswlo:=Iswlo+z[8]*z[8] else
if ((stdc=1) AND (stpd=0) AND (z[8]<0))
then Iswlo:=Iswlo+z[8]*z[8];

stpd:=stdc;
Psw:=Iswlo*tf*z[7]/(24*crpu*15e-6);

************** Digital filter for motor torque **************
Tqfa:=(z[5]*1gm-z[6]*1dm)*Tqfa+212*Tqfa/214;

Tq:= (z[5]*1gm-z[6]*1dm);
end; {controller}

********** Motor phase voltages and conduction losses **********
case state of
0: begin
Vam:=0;
Vbmr:=0;
Vcmt:=0;
If Iam>0 then Idio:=Idio+Iam else Igbt:=Igbt-Iam;
If Ibm>0 then Idio:=Idio+Ibm else Igbt:=Igbt-Ibm;
If Icm>0 then Idio:=Idio+Icm else Igbt:=Igbt-Icm;
Iloml:=0;
end;

1: begin
Vam:=z[9];
Vbm:=0;
Vcm:=0;
If Iam>0 then Igbt:=Igbt+Iam else Idio:=Idio-Iam;
If Ibm>0 then Igbt:=Igbt+Ibm else Idio:=Idio-Ibm;
If Icm>0 then Igbt:=Igbt+Icm else Idio:=Idio-Icm;
Iloml:=Iam+Ibm;
end;

2: begin
Vam:=z[9];
Vbm:=0;
Vcm:=0;
If Iam>0 then Igbt:=Igbt+Iam else Idio:=Idio-Iam;
If Ibm>0 then Igbt:=Igbt+Ibm else Idio:=Idio-Ibm;
If Icm>0 then Igbt:=Igbt+Icm else Idio:=Idio-Icm;
Iloml:=Ibm+Icm;
end;

3: begin
Vam:=0;
Vbm:=z[9];
Vcm:=0;
If Iam>0 then Idio:=Idio+Iam else Igbt:=Igbt-Iam;
If Ibm>0 then Idio:=Idio+Ibm else Igbt:=Igbt-Ibm;
If Icm>0 then Idio:=Idio+Icm else Igbt:=Igbt-Icm;
Iloml:=Idio+Iam;
end;

4: begin
Vam:=0;
Vbm:=z[9];
Vcm:=0;
If Iam>0 then Idio:=Idio+Iam else Igbt:=Igbt-Iam;
If Ibm>0 then Idio:=Idio+Ibm else Igbt:=Igbt-Ibm;
If Icm>0 then Idio:=Idio+Icm else Igbt:=Igbt-Icm;
Iloml:=Idio-Iam;
end;

5: begin
Vam:=0;
Vbm:=0;
Vcm:=z[9];
If Iam>0 then Idio:=Idio+Iam else Igbt:=Igbt-Iam;
If Ibm>0 then Idio:=Idio+Ibm else Igbt:=Igbt-Ibm;
If Icm>0 then Idio:=Idio+Icm else Igbt:=Igbt-Icm;
Iloml:=Ibm;
end;

6: begin
Vam:=z[9];
Vbm:=0;
Vcm:=z[9];
If Iam>0 then Igbt:=Igbt+Iam else Idio:=Idio-Iam;
If Ibm>0 then Igbt:=Igbt+Ibm else Idio:=Idio-Ibm;
If Icm>0 then Igbt:=Igbt+Icm else Idio:=Idio-Icm;
Iloml:=Idio-Icm;
end;
end; {cases}

{ *********************** Generator phase voltages *********************** }

case state of
1: begin
Vag:=z[9];
Vbg:=0;
Vcg:=0;
Ilogl:=Iag;
end;

2: begin
Vag:=0;
Vbg:=z[9];
Vcg:=0;
Ilogl:=Ibg;
end;

3: begin
Vag:=z[9];
Vbg:=z[9];
Vcg:=0;
Ilogl:=Iag+Ibg;
end;

4: begin
Vag:=0;
Vbg:=0;
Vcg:=z[9];
Ilogl:=Icg;
end;

5: begin
Vag:=z[9];
Vbg:=0;
Vcg:=z[9];
Ilogl:=Iag+Icg;
end;

6: begin
Vag:=0;
Vbg:=z[9];
Vcg:=z[9];
Ilogl:=Ibg+Icg;
end;

{ cases }

{ ********************** Chopper output ********************** }
if (stdc = 0) then begin
  Iswp:= z[8];
  Vl:= Vcapa-z[9];
end else begin
  Iswp:=0.0;
  Vl:= Vcapa;
end;

{ ********************** Conduction losses calculation ********************** }
Plosses:= Vosw*Igbt+Rosw*Igbt*Vod+Idio*Rod+Idio*Idio;

{ ********************** Auxiliary resonant switch losses ********************** }
if (x=txl) then begin
  If (Ilom2-Isw-Iwml+Iwmp>Irripple) then
    Iswlo:=(Ilom2-Isw-Iwml+Iwmp)/2
  else Iswlo:=Irripple/2;
Psw:= Psw+(Iswlo*Vosw+Rosw*Iswlo*Iswlo+Iwlo);
Psw:= Psw+(Iswlo*Vod+8*Iswlo*Iswlo);
Psw:= Psw+(Iwlo*tf*tf*tf*tf)/((24*crpu*15e-6));
Plosses:=Plosses+Psw;
tx1:=tx1+150e-6;
end;
Iloadm:= Iloadm+(Plosses/z[9]);
Ener:= Ener+Iloadm*z[9]*h*wba;

{ *************** motor input voltages to rotor frame *************** }
conv32(Vam,Vbm,Vcm,Val,Vbe);
ang:=syman;
cotr(Val,Vbe,ang,Valfa,Vbeta);
ang:=syman-angm;
cotr(Valfa,Vbeta,ang,Vdm,Vqm);

{ *************** generator input voltages to rotor frame *************** }
conv32(Vag,Vbg,Vcg,Val,Vbe);
ang:=syman;
cotr(Val,Vbe,ang,Valfa,Vbeta);
ang:=syman-angg;
cotr(Valfa,Vbeta,ang,Vdg,Vqg);

{ *************** Solution mathematical problem, prev step *************** }
if ist = 0 then h:= 0.25E-4;  
{ slow down 386 }
rm(n,z,x,h,tol,ist,ier);

{ ******************* Error handling ******************* }
if ierr <>0 then ierr:= ierr+1;
if h < hmin then ierr:= 5;
if ierr > 3 then errsm := ierr;
if h > hmax then h:= hmax;

{ *************** Step calculated - assign display variables *************** }
xx:= x;
yy[1]:= z[1];
yy[2]:= z[2];
yy[3]:= Tloadg;
yy[4]:= Pd;
yy[5]:= Tqf;
yy[6]:= Tloadm;
yy[7]:= Iqm;
yy[8]:= z[8]*Vcapa;
yy[9]:= Icon;
yy[10]:= Vdc;
yy[11]:= z[10];
yy[12]:= vesp;
end;  
{calstep}
end.  
{enerdef}
C.2 Matlab Resonant Transient Simulation

clear;
Vs=350;
Vclamp=1.3*Vs;
Iload=75;
Iloads=75;
Tload=40e-6;
Tloads=40e-6;
igl=10;
ig2=60;
Cres=100E-9;
Cc=10e-6;
L=10E-6;
dt=5e-9;

x=1;
x1=1;
tt(1)=0;
tts(1)=0;
Vres(1)=1;
Vress(1)=1;
i(1)=Iload;
ias(1)=Iloads;
Iloadx(1)=Iload;
Ieloads(1)=Iloads;
Vclamp=Vclamp;
w1=1/sqrt(L*Cres);
w2=1/sqrt(L*(Cres+Cc));

for counter = 0:20
    counter

    while (Vress(xs) < Vclamp & Vress(xs) >= 0)
        xs=xs+1;
        Vress(xs)=Vs+(Vresas-Vs)*cos(w1*ts)+sqrt(L/Cres)*(ias-Iloads)*sin(w1*ts);
        ias(xs)=Iloads+(ias-Iloads)*cos(w1*ts)-sqrt(Cres/L)*(Vresas-Vs)*sin(w1*ts);
        ts=ts+dt;
        tts(xs)=tts(xs-1)+dt;
        Iloadx(xs)=Iloads;
    end
    Vresas = Vress(xs);
    ias=ias(xs);
    ts=0;

    while (Vress(xs) >= Vclamp)
        xs=xs+1;
        Vress(xs)= Vs+(Vresas-Vs)*cos(w2*ts)+(ias-Iloads)*sqrt(L/(Cres+Cc))*sin(w2*ts);
        ias(xs)= Iloads+(ias-Iloads)*cos(w2*ts)-sqrt((Cres+Cc)/L)*(Vresas-Vs)*sin(w2*ts);
        ts=ts+20*dt;
        tts(xs)=tts(xs-1)+20*dt;
        Iloadx(xs)=Iloads;
    end
    Vresas=Vress(xs);
    ias=ias(xs);
    ts=0;

    while (ias(xs) < Iloads+igl & Vress(xs)<=0)
        xs=xs+1;
        Vress(xs)=0;
        ias(xs)=ias+Vs*ts/L;
        ts=ts+10*dt;
        tts(xs)=tts(xs-1)+10*dt;
        if (tts(xs)>=Tloads)
            Iload= -Iloads;
            Tloads= Tloads+40e-6;
        end
$$I_{load}(x) = I_{loads};$$

end

$$V_{ress}(x) = V_{res}(x);$$

$$i_{s} = i_{s}(x);$$

$$t_{s} = 0;$$

while ($V_{res}(x) < V_{clamp} & V_{res}(x) >= 0$)

$$x = x + 1;$$

$$V_{res}(x) = V_{s} + (V_{ress} - V_{s}) \cdot \cos(w_{1} \cdot t) + \sqrt{L/C_{res}} \cdot (i_{s} - I_{load}) \cdot \sin(w_{1} \cdot t);$$

$$i(x) = I_{load} + (i_{s} - I_{load}) \cdot \cos(w_{1} \cdot t) - \sqrt{C_{res}/L} \cdot (V_{ress} - V_{s}) \cdot \sin(w_{1} \cdot t);$$

$$t = t + dt;$$

$$t_{t}(x) = t_{t}(x-1) + dt;$$

$$I_{load}(x) = I_{load};$$

end

$$V_{ress} = V_{res}(x);$$

$$i_{s} = i(x);$$

$$t = 0;$$

while ($V_{res}(x) > V_{clamp}$)

$$x = x + 1;$$

$$V_{clamp} = V_{clamp};$$

$$V_{res}(x) = V_{s} + (V_{ress} - V_{s}) \cdot \cos(w_{2} \cdot t) + \sqrt{L/(C_{res} + C_{c})} \cdot \sin(w_{2} \cdot t);$$

$$i(x) = I_{load} + (i_{s} - I_{load}) \cdot \cos(w_{2} \cdot t) - \sqrt{(C_{res} + C_{c})/L} \cdot (V_{ress} - V_{s}) \cdot \sin(w_{2} \cdot t);$$

if ($i(x) < I_{load} - ig_{2}$)

$$V_{clamp} = V_{res}(x);$$

if ($V_{clamp} < 1.35 \cdot V_{s}$)

$$ig_{2} = 60;$$

$$ig_{1} = 10;$$

else

$$ig_{1} = 0;$$

$$ig_{2} = 75;$$

end

end

$$t = t + 20 \cdot dt;$$

$$t_{t}(x) = t_{t}(x-1) + 20 \cdot dt;$$

$$I_{load}(x) = I_{load};$$

end

$$V_{ress} = V_{res}(x);$$

$$i_{s} = i(x);$$

$$t = 0;$$

while ($i(x) < (I_{load} + ig_{1}) & V_{res}(x) <= 0$)

$$x = x + 1;$$

$$V_{res}(x) = 0;$$

$$i(x) = i_{s} = V_{s} \cdot t;$$

$$t = t + 10 \cdot dt;$$

$$t_{t}(x) = t_{t}(x-1) + 10 \cdot dt;$$

if ($t_{t}(x) > t_{load}$)

$$t_{load} = t_{load} + 40 \cdot e^{-6};$$

$$I_{load} = -I_{load};$$

$$ig_{1} = 10 - (V_{clamp} - V_{clamp})/3;$$

end

$$I_{load}(x) = I_{load};$$

end

$$t = 0;$$

$$V_{ress} = V_{res}(x);$$

$$i_{s} = i(x);$$

end

figure(1)

subplot(2,1,1);

hold on;

title('Voltage V(Cres)');

plot(tt, Vres, 'r', t, Vress, 'y--');

axis([0 max(tt) min(Vres) max(Vress)+10]);

subplot(2,1,2);

hold on;

title('Currents i(L), Iload');

plot(tt, i, 'r', t, is, 'g--');

axis([0 max(tt) min(is) max(is)+10]);
C.3 SAM4 Soft-Switched Converter System Simulation

unit convdef;
{
Simulation hybrid vehicle. This section includes the
Resonant DC link and the converters Chopper and VSI
with current control section in both cases.
The input Cont enables the techniques to reduce the
transient time for the resonant circuit:
Cont = 0 No control modification
Cont = 1 Adds zero state utilization for the DC/AC
Cont = 2 Adds switch synchronization between converters
Cont = 3 Adds division of the transient pulse.
The control AC load currents are perfect sinewaves of
peak value GAIN (pu). The control DC current is input Idc.
Vdc is the value of the DC source and Vover is the
clamping voltage in the resonant DC link.
}

interface
uses samtype;
{
samtype defines only types, those are :
di1r = array[1..20] of double;
di1i = array[1..20] of integer;
name = string[30];
di1st = array[1..30] of name;
}

const om = 376.99111848;
pj3 = 1.0471976;
pj = 3.1415927;

var
inv,ouv : text;

{ **************** Runge Kutta and math. variables **************** }
n,iis,ier,ierr,erream : integer;
x,h,hmax,hmin,tol : double;
z,y : di1r;

{ **************** Variables spec. program **************** }
state,stdc : integer;
stp,stacp,stdcp,Cont : integer;
flag,zvc,rip,ovup : boolean;
vs,is,f0 : double;
va,ib,wb,tcba,zeba : double;
C1,C2,L,Cpu,C2pu,Lpu : double;
Vdc,Vd1c,Vdcpu,Vd1cpu : double;
Vclamp,Vover,Voverpu : double;
erra,erbr,ercc : double;
Lload,Lldcpu,Gain,Iload : double;
Icona,Iconb,Iconc : double;
Ldc,Ldcpu,Idcon : double;
xep,Iacs : double;

{ **************** Procedures declaration **************** }
procedure fcn (n:integer; var zpr:di1r; z:di1r; x:double);
procedure rkm(n:integer; var y:di1r; var x,h:double;
tol:double; var ier:integer);
procedure convinit;
procedure calstep (palectimr; paridi1i; setflg:boolean;
var yy:di1r; var xx:double);

{ *********************** PROGRAM *********************** }

implementation
procedure fcn;
{
  Differential equations formulation. \( z[1], z[2], z[3] \)
  represent the capacitor voltages and inductor current
  in the resonant link. \( z[4], z[5], z[6] \) are the output
  line currents of the voltage source inverter. \( z[7] \) is
  the DCC bank's current
}
begin
  if \((z[1]<0)\) then \(z[1]:=0;\)
  if \((z[1]<=Vclamp)\) then
    begin
      zpr[1] := wba*(z[3]-Iload)/Clpu;
      zpr[2] := 0;
      zpr[3] := wba*(Vdcpu-z[1])/Lpu;
    end;
  if \((z[1]=0)\) AND \((z[3]<Iload+0.4)\) then
    begin
      zpr[1] := 0;
      zpr[2] := 0;
      zpr[3] := wba*Vdcpu/Lpu;
    end;
  if \((z[1]>Vclamp)\) then
    begin
      if \((z[3])\) AND \((z[3]<Iload-1)\) then
        begin
          zpr[1] := wba*(z[3]-Iload)/Clpu;
          zpr[2] := 0;
          zpr[3] := wba*(Vdcpu-z[1])/Lpu;
        end
      else
        begin
          zpr[1] := wba*(z[3]-Iload)/(Clpu+C2pu);
          zpr[2] := wba*(z[3]-Iload)/(Clpu+C2pu);
          zpr[3] := wba*(Vdcpu-z[1])/Lpu;
        end;
    end;
  Case state Of {branch currents calc}
  0:
    begin
      zpr[4] := 0.0;
      zpr[5] := 0.0;
      zpr[6] := 0.0;
      Iload:= 0.0;
    end;
  1:
    begin
      zpr[4] := wba*(2*z[1])/(3*Lloadpu);
      zpr[5] := wba*(-z[1])/(3*Lloadpu);
      zpr[6] := wba*(-z[1])/(3*Lloadpu);
      Iload:= z[4];
    end;
  2:
    begin
      zpr[4] := wba*(z[1])/(3*Lloadpu);
      zpr[5] := wba*(z[1])/(3*Lloadpu);
      zpr[6] := wba*(-2*z[1])/(3*Lloadpu);
      Iload:= z[4]+z[5];
    end;
  3:
    begin
      zpr[4] := wba*(-z[1])/(3*Lloadpu);
      zpr[5] := wba*(2*z[1])/(3*Lloadpu);
      zpr[6] := wba*(-z[1])/(3*Lloadpu);
    end;
end;
Iload := z[5];

begin
zpr[4] := wba*(-2*z[1])/(3*Iloadpu);
zpr[5] := wba*(z[1])/(3*Iloadpu);
zpr[6] := wba*(z[1])/(3*Iloadpu);
Iload := z[5]+z[6];
end;

begin
zpr[4] := wba*(-z[1])/(3*Iloadpu);
zpr[5] := wba*(-z[1])/(3*Iloadpu);
zpr[6] := wba*(2*z[1])/(3*Iloadpu);
Iload := z[6];
end;

begin
zpr[4] := wba*(z[1])/(3*Iloadpu);
zpr[5] := wba*(-2*z[1])/(3*Iloadpu);
zpr[6] := wba*(z[1])/(3*Iloadpu);
Iload := z[4]+z[6];
end;

{ functions }

procedure convinit;  { initial values }
begin
{ *************** Read integration routine var. *************** }
readln(inv, h, hmax, hmin, tol, ist);
writeln(ouv);
writeln(ouv, 'h hmax hmin tol ist');
writeln(ouv, h:12,' ',hmax:12,' ',hmin:12,' ',tol:12,ist:3);

{ *************** Read input special variables *************** }
readln(inv, C1,C2,L,Load,Ldc);
writeln(ouv);
writeln(ouv, 'C1 C2 L Load Ldc');
writeln(ouv, C1:8:3,C2:8:3,L:8:3,Load:8:3,Ldc:8:3);
readln(inv, vs,is,f0);
writeln(ouv);
writeln(ouv, 'Vs Is fzr');
writeln(ouv, vs:8:3,is:8:3,f0:8:3);

{ *************** Base and per unit values calculations *************** }
vba := vs; ia := is;
wba := 2.0*pi*f0; zba := vba/iba;
C1pu := C1*zba*vba; C2pu := C2*zba*vba;
Lpu := L*vba/zba; Lloadpu := Load*wba/zba;
Ldcpu := Ldc*vba/zba;

end;
flag:=false; zvc:=false; rip:=false; ovup:=false;
state:=5; Iload:=0; stdc:=1; stdcp:=0;
stacp:=5; stp:=0; Iacs:=0; Vclamp:=1.3;

{ ************** Initialize diff. equations variables ************** }
n:=7;
ier:=0; ierr:=0;
h:=hmin;
x:=0.0;
z[1]:=0.0; z[2]:=0.3; z[3]:=0.0; z[4]:=0.0;
z[5]:=0.0; z[6]:=0.0; z[7]:=0.0;

{ No assignment of variable parameters required as the parameters are assigned in the SAM before the first calculation takes place (flag true -> setflg true) 
The first plot point is set to 0.0 for all variables, this is fixed in SBRSAM and should not be altered to ensure a save start up; if the first step is kept small, it does not matter and usually the initial step for the Runge Kutta Routine starts with hmin. 
}
end;   {end initialization}

procedure calstep;
procedure assignpar;
begin
Vdc:= pval[1]; Vover:= pval[2];
Vdc:= pval[3]; Gain:= pval[4];
Idc:= pval[5]; hmax:=pval[6]*1e-3;
Cont:= pari[1];
end;

begin
if setflg then assignpar;

{ ************** Possible change in source and overvoltage ************** }
Vdcpu:=Vdc/vba;
Voverpu:=Vover/vba;
Vdclpu:=Vdcpu/vba;

{ ************** Clamping voltage update for transients ************** }
if (z[1]>Vclamp) then begin
ovup:=true;
Vclamp:=Voverpu;
end;
if (z[1]<Vdcpu) AND (ovup) then begin
Vclamp:=Vdcpu+z[2];
ovup:=false;
end;

{ ************** Desired output currents update ************** }
Icona:=Gain*cos(wba*x);
Iconb:=Gain*cos((wba*x)-2*pi3);
Iconc:=Gain*cos((wba*x)+2*pi3);

{ ***** Zero voltage detection and switch state selection ***** }
if (z[1]<=0.01) AND (flag) then zvc:=true;
if (z[1]>0.05) then flagt:=true;
if zvc then 
begin
if (z[7]>Idc) then stdc:=1  { DC/DC current control }
else stdc:=2;
erra:= z[4]-Icona;     { DC/AC current control }
errb:= z[5]-Iconb;
errc:= z[6]-Iconc;
if (erra<0)AND(errb>0)AND(errc>0) then state:=1 else
if (erra>0)AND(errb<0)AND(errc>0) then state:=2 else
if (erra<0)AND(errb<0)AND(errc>0) then state:=3 else

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if (error>0) AND (error<0) AND (error<0) then state:=4 else
if (error>0) AND (error>0) AND (error<0) then state:=5 else
if (error<0) AND (error>0) AND (error<0) then state:=6 else
state:=0;

if (Cont>0) then
    { Zero vector is used }
begin
    if (stp=0) then state:=state else
    if (state=0) then state:=state else
    if (ABS(state-stp)<=1) then state:=state else
    if (ABS(state-stp)=5) then state:=state else
    state:=0;
end;

if (Cont>1) then
    { Switching synchronization }
begin
    if (Cont>1) then
        { If Idlc > 100 A (2 pu) }
    case state OF
    0:  Iexp:=0.0;
    1:  Iexp:=z[4];
    2:  Iexp:=z[4]+z[5];
    3:  Iexp:=z[5];
    4:  Iexp:=z[5]+z[6];
    5:  Iexp:=z[6];
    6:  Iexp:=z[4]+z[6];
end;
If ((stdcp=1) AND (stdc=2) AND (z[7]<2)) then
begin
    if (Iexp>Iacs) then state:=stacp;
    Iexp:=Iacs;
end;
else If (stdcp=1) AND (stdc=2) AND (z[7]>2)) then
begin
    if (Iexp>Iacs) then state:=stacp;
    Iexp:=Iacs;
end;
if (stdc=2) then Iexp:=Iexp + z[7];

if (Cont>2) then
    { Clamping division }
begin
    { if load_step > 70A (1.4 pu) }
    rip:=false;
    If (load-I.exp>1.4) then rip:=true;
end;

stacp:=state;
stdcp := stdc;
stp := state;
zvc:=false;
flag:=false;
end;
{ zero voltage cond }

{ ************** Solution mathematical problem, next step ************** }
if ist = 0 then h:= 0.25E-4;  { slow down 386 }

{ ************** Error handling ************** }
if ier <=0 then ierr:=ierr+1;
if h < hmin then ierr:= 5;
if ierr > 3 then errsum := ierr;
if h > hmax then h:= h/2;

{ ************** Step calculated - assign display variables ************** }
xx:= x;
yy[1]:= z[1]*x;
yy[2]:= z[2];
yy[3]:= z[3];
yy[4]:= z[4];
yy[5]:= z[5];
yy[6]:= z[6];
yy[7]:= z[7];
yy[8]:= Icons;
yy[9]:= Iconb;
yy[10]:= Iconc;
yy[11]:= Idcon;
yy[12]:= Iload;
end;
end.

{Control curr b}
{Control curr c}
{DC curr reference}
{DC Link Current}
{end calstep}
{end convdef}
APPENDIX D

EXPERIMENTAL IMPLEMENTATION
D.1 M68332 CONTROL PROGRAM

/** engine.c */
/** 03/01/2000 L.ZUBIETA */

#include "memap332.h" /* hardware memory map */
#include "hetable.h" /* function tables */

/* ----------------- CONSTANTS, VARIABLES ----------------- */

/* ----- Variables for data transfer from interrupt routines ---- */
unsigned short ka,loopflg,ilpcnt;
signed int in0,in4,in5,in6,in7,aux2;
signed int out2,out3,out4,out5,out6,out7,out8,out9;
unsigned int sllcnt;

/* ----------- Variables for ch8 encoder reset ----------- */
signed short pos,cont,cntd;
unsigned short turn;
static unsigned short openfl = 0;

/* ---------- Variables for Table Look Up ---------- */
unsigned int tabpos;
signed short tabres;

/* ----------------- External functions ----------------- */
extern void pr_setup(),qsms58(),keybl_io();

/* ----------- FUNCTIONS & INTERRUPT ROUTINES ----------- */

#pragma interrupt()
void intch8()
{
    *pCHPrf6 = 0x0000; /* reset channel F */
    cont = 0;
    cntd = 0;
    pos = 0;
    turn = turn+1;
    if (turn == 2) /* two open loop turns */
        if (openfl = 1) /* close loop */
            ka = *pCISR;
        ka = ka & 0xFFFE;
    *pCISR = ka;
    /* end intch8 */
}

#pragma interrupt()
void dio_samp()
{
    /* interrupt TPU ch 1 for transfer of pwm data for next
interval timing of sampling and I/O through QSPI */
    analog input last cycle,
    analog output and telegrams in next cycle
    analog I/O data format:
    for fxp 1.0 p.u. -> read signed short var = *pRXDF >> 3;
    write fxp to ch *pTXDE = (signed short var fxp)>> 1;
    if program qsms582 is used, then :
    analog in :  ch7..6..5..4,  ch0
        *pRXDF..C..9..6  *pRXD3
    analog out : ch7..6..5..4..3..2,  ch9..8
        *pTXDE..D..B..A..8..7  *pTXD5..4
    telegr :  *pTXD0..1
}
ilpcnt = ilpcnt + 1;
switch(ilpcnt)
{
    case 2:
        /* Ts = 500 usec */
        /* pwm data transfer */
        *pCH3p46 = swllcnt; /* switch data next per */
        /* telegrams dummy */
        *pTXD0 = 0xAAAA;
        *pTXD1 = 0x5555;
        /* analog in */
        in7 = *PRXDF >> 3; /* ch7 */
        in6 = *PRXDC >> 3; /* ch6 */
        in5 = *PRXD9 >> 3; /* ch5 */
        in4 = *PRXD6 >> 3; /* ch4 */
        in0 = *PRXD3 >> 3; /* ch0 */
        /* analog out */
        *pTXDS = out9 >> 1; /* out to ch 9 */
        *pTXDA = out7 >> 1; /* out to ch 7 */
        *pTXDB = out5 >> 1; /* out to ch 5 */
        *pTXD8 = out4 >> 1; /* out to ch 4 */
        *pTXD7 = out3 >> 1; /* out to ch 3 */
        *pSPCRl = 0x9010; /* start QSM single shot */
        loopflg = 0x1111; /* set flag algorithm loop */
        ilpcnt = 0; /* reset loop counter */
        break;
    }
    /* end switch ilpcnt */
    } /* clear int ch1 */
    /* end dio_samp */
}

/* ------------------------------------------------ PROGRAM ------------------------------------------------ */

main(void)
{
    /* ---------- Variables General Infrastructure ---------- */
    /* for keyb_io */
    static unsigned char kbflg = 0x55;
    static signed int val,valf;
    static unsigned char letter;
    /* for Loop and QSM sync flag */
    static unsigned short mlo,TEflg;
    /* for PI current controller */
    static signed int klcu,k2cu,encu,e0cu,uncu,u0cu;
    static signed int aux,LPcu,LNcu;
    static unsigned short piflg;
    /* for PI voltage controller */
    static signed int klvo,k2vo,envo,e0vo,unvo,u0vo;
    static signed int kpvo,LPvo,LNvo,Iff;
    /* for PI speed controller */
    static signed int ksp,k2sp,ensp,e0sp,unsp,u0sp;
    static signed int LPsp,LNsp;
    static unsigned short spct,spinp,spref;
    static unsigned int time;
    /* for resonant converter reference values */
    static signed int ibase,vbase;

    /* for keyb_io */
    static unsigned char kbflg = 0x55;
    static signed int val,valf;
    static unsigned char letter;
    /* for Loop and QSM sync flag */
    static unsigned short mlo,TEflg;
    /* for PI current controller */
    static signed int klcu,k2cu,encu,e0cu,uncu,u0cu;
    static signed int aux,LPcu,LNcu;
    static unsigned short piflg;
    /* for PI voltage controller */
    static signed int klvo,k2vo,envo,e0vo,unvo,u0vo;
    static signed int kpvo,LPvo,LNvo,Iff;
    /* for PI speed controller */
    static signed int ksp,k2sp,ensp,e0sp,unsp,u0sp;
    static signed int LPsp,LNsp;
    static unsigned short spct,spinp,spref;
    static unsigned int time;
    /* for resonant converter reference values */
    static signed int ibase,vbase;
static signed int chref,dcref,clref,zvref,itref,imain;
static signed int vav1,vav2,vav3;

/* for open loop motor operation */
static unsigned int xl,ama,fmax,phi1,phi2,phi3,phiincr;

/* for chopper PWM */
static unsigned int swpercent,swcnt,pwlcnt;
static signed int pwcon;

/* for position calculation */
static signed short sinr,cosr;
static unsigned int ang,rot,
static unsigned short airb,dir,dflg;

/* for speed calculation */
static unsigned short posold,spbase,spflg;
static unsigned int deltan,sp,spold;

/* for closed loop currents */
static signed int Iqcmd,Iq,Id,Ialfa,Ibeta,rt3;

/* for power limitation */
static signed int Pmax,Iqlim;

/* for energy management */
static signed int em0,em1,em2,emh,emmin,ienmi,ienma;
static signed short sftflg;

/* operation modes flags */
static unsigned short short modesel,spmod,emilq;

/* base and reference values */
static signed int Vdcref,Iref,Vba,Iba,Vmax;

/* data collection */
static unsigned short datcol,sent,carac;
static signed short tinuaer,kbstat,stwd;

static signed int chref,dcref,clref,zvref,itref,imain;
static signed int vav1,vav2,vav3;

/* for open loop motor operation */
static unsigned int xl,ama,fmax,phi1,phi2,phi3,phiincr;

/* for chopper PWM */
static unsigned int swpercent,swcnt,pwlcnt;
static signed int pwcon;

/* for position calculation */
static signed short sinr,cosr;
static unsigned int ang,rot;
static unsigned short dirb,dir,dflg;

/* for speed calculation */
static unsigned short posold,spbase,spflg;
static signed int deltan,sp,spold;

/* for closed loop currents */
static signed int Iqcmd,Iq,Id,Ialfa,Ibeta,rt3;

/* for power limitation */
static signed int Pmax,Iqlim;

/* for energy management */
static signed int em0,em1,em2,emh,emmin,ienmi,ienma;
static signed short sftflg;

/* operation modes flags */
static unsigned short short modesel,spmod,emilq;

/* base and reference values */
static signed int Vdcref,Iref,Vba,Iba,Vmax;

/* data collection */
static unsigned short datcol,sent,carac;
static signed short tinuaer,kbstat,stwd;

 /*-------------------------------------------------------------------------*/

/* setup port P pin 3-0 for PLD control of gating */
*pPfpar = 0x00FO;  /* set pin 3-0 up as port P */
*pDdrf = 0x000F;  /* pin 3-0 out */
/* IRQ 7-4 still operative */

/* setup parallel port M68230 on GPC-board */
p_setup();  /* PA out,PB in,PC out */

/* programing of PLD U14 controls of ch2..D 
see chopper program */
*pPortf = 0x03;  /* gating off (0x0D => on) */
*pPCDR = 0x00;

/* initialize and start QSM */
int ID $10, intv $50 -> $140 offset. No interrupts used */
qss582();  /* Ts = 180 + 0x25*1.9 = 250 usec */

/* init output data. Run one cycle to set flag, get 1. data */
*pTXDE = 0;  /*pTXDD = 0; */  /*pTXDB = 0; */
*pTXDA = 0;  /*pTXD8 = 0; */  /*pTXD7 = 0; */
*pTXD5 = 0;  /*pTXD4 = 0; */
*pTXD0 = 0;  /*pTXD1 = 0; */
*pSPCR1 = 0x9010;  /* start QSM */
TEflg = *pSPSR;  /* test end of QSM cycle */
while ((TEflg & 0x80) == 0 ) { TEflg = *pSPSR;}

/* --------------- TPU set up ------------- */
/* general set up */
*pTMCR = 0x00C1;  /* 0.24 usec; int ID $1, presc = 1 */

160
/*
  fnt  req 6, intv $4x -> $100 offset */
  /* CAUTION 332Bug trap at $108 !!! */

/* description of channel functions:
  ch 0 SPWM mode 2 links
  ch 1 SPWM mode 0 or 1 sync to ch 0
  ch 3 SPWM mode 1
  ch 2,4,5,6,7 DIO set to zero!
  ch 8,E,F ITC for encoder
  ch A DIO for enable */

/* values for setup of timing pattern: PWM & control */
  swpercnt = 1048;
  /* 4194 = 1 kHz = fsw  
      2097 = 2 kHz, 
      1048 = 4 kHz */
  pwcon = 0x0EA0;
  /* start pw 100% Vi = Vo */
  swotcnt = 26;
  /* 7 usec switch over time */
  pwlcnt = (swpercnt + (0x0PPP + pwcon)) >> 13;
  /* (swpercnt + pwcon)/2 */
  swlcnt = ((pwlcnt + swotcnt) << 16)
           + ((swpercnt-pwlcnt-swotcnt) >> 1); /* set up parameter registers */

/* ch0 SPWM mode 2, switch interval timing */
  *pCH0prO = 0x0092; /* f low, TCR1 */
  *pCH0p46 = ((swpercnt >> 1) << 16) + swpercnt;
      /* coherent write, hightime = swpercnt/2 */
  *pCH0p8 = 0x660E; /* L st L cnt, dummy adr */
  *pCH0pRA = 0;
      /* delay, only on start */

/* ch1 SPWM mode 1, QSM algorithm timing */
  *pCH1pr0 = 0x0092; /* f low, TCR1 */
  *pCH1p46 = (0x00640000 + (swpercnt-200));
      /* coherent write, hightime 25 usec, 
         delay -50 usec. Check whether int 
         finishes before ch0 rising edge */
  *pCH1p8 = 0x0200;
      /* adr1, adr2 ch 0 */

/* ch3 = switch 11, SPWM mode 1 linked */
  *pCH3pr0 = 0x0092; /* f low, TCR1 */
  *pCH3p46 = swlcnt;
      /* coherent write, pw, del */
  *pCH3p8 = 0x0200;
      /* adr1, adr2 of ch 0 */

/* ch 8 = ITC Encoder reset detection */
  *pCH8pr0 = 0x0007;
  *pCH8p2 = 0x010E;
  *pCH8p46 = 0x00010000;

/* ch F = ITC Encoder pulses counter */
  *pCHFpr0 = 0x000B;
  *pCHFpr2 = 0x010E;
  *pCHFp46 = 0x0F000000;

/* ch E = DIO Encoder direction */
  *pCHEpr0 = 0x0003;

/* ch 2,4,5,6,7 & A DIO, no parameter reg. */

/* channel function registers group ch F..8 */
  *pCFSR0 = 0xA800; /* ch E DIO, F ITC */
  *pCFSR1 = 0x080A; /* ch A DIO, 8 ITC */
  *pCFPR0 = 0xF013; /* ch E,F,8 high pri */
  *pHSPR0 = 0x6021; /* ch A,E upd on HSR, F,8 no links */

/* channel function registers group ch 7..0 */
  *pCFSR2 = 0x8888; /* ch 7,6,5,4 DIO */
/* ch A low stop inverter */
/* set ch 2,4,5,6,7 low no gating */
/* caution ch5,6 inv */
/* set up int -> ch1 low-high (dio-samp) */
*pCISR = 0x0000;
/* clear interrupts */
*pCIER = 0x0102;
/* enable chl,8 int */

kpv = 0xBFFF;
k1cu = 0x6000; /* gain 70, Tr 0.005, Ts 0.5 msec */
k2cu = 0x0E7A;
k1vo = 0x146B; /* gain 40, Tr 0.065, Ts 0.5 msec */
k2vo = 0x0F20;
k1sp = 0x1000; /* gain , Tr 2.78, Ts 20 msec */
k2sp = 0x0FPP;
LPcu = 0x0EAO << 12; /* old 0xF0F000; 96% */
LNcu = -(0x0EAO) << 12; /* old 0xF0F00000; -54% */
LPvo = 0x0AAA << 12; /* 67% = -100 A */
LNvo = -(0x0AAA) << 12; /* 67% = -100 A */
LPsp = 0x0888 << 12; /* 47% = 80 A */
LNsp = -(0x0666) << 12; /* 60% = 60 A */
uOcu = LPcu; uncu = 0; eOcu = 0; encu = 0;
uOvo = 0; unvo = 0; eOvo = 0; envo = 0;
uOsp = 0; unsp = 0; eOsp = 0; ensp = 0;

/* ------------------ Initial reference values for res. converter --- */

zvref = (((30*10)<<16)/vbase)>>4;
dcref = 0;
c1ref = (((400*10)<<16)/vbase)>>4;
itref = (((15*10)<<16)/vbase)>>4;
imin = (((35*10)<<16)/vbase)>>4;

/* Other Initializations */

spmax = 600; /* in Hz fmax = 100 */
fsmax = 100; /* phi per unit = 0xFFFF. Each phase 120 degrees apart */

Vba = 400; /* base values engine */
Vmax = (((250<<16)/Vba)>>4); /* shut down at 350 V */
em0 = (((180<<16)/Vba)>>4); /* constant part for e. man */
emmin = (((115<<16)/Vba)>>4); /* min DLC voltage */
emb = (((232<<16)/Vba)>>4); /* max DLC voltage */
ienmin = (((15<<16)/Iba)>>5); /* 15/2 = 7.5 A min engine curr */
ienma = (((29<<16)/Iba)>>4); /* 30 A maximum engine current */
Pmax = 0x740;
emflg = 0; /* no Id required */
rt3 = 0x1BB6; /* sqrt(3) = 1.732 */
sfplg = 0; /* speed flags */
dflg = 0; /* direction flag */
modelsel = 2; /* initialy do nothing */
spmod = 0; /* current control */
Iba = 50; /* base values engine */
Vmax = (((250<<16)/Vba)>>4); /* shut down at 350 V */
em0 = (((180<<16)/Vba)>>4); /* constant part for e. man */
emmin = (((115<<16)/Vba)>>4); /* min DLC voltage */
emb = (((232<<16)/Vba)>>4); /* max DLC voltage */
ienmin = (((15<<16)/Iba)>>5); /* 15/2 = 7.5 A min engine curr */
ienma = (((29<<16)/Iba)>>4); /* 30 A maximum engine current */
Pmax = 0x740;
emflg = 0; /* no Id required */
time = 0; /* turn-off */
cont=0;  cntd = 0;  spold = 0;
pos = 0;  posold = 0;  dir = 0;
 DATCOL = 1;  sent = 1;  timer = 1;
carac = 1;
/* ------------------------------- */
/* === program loop ===== */
alo = 2; /* LOOP */
while (alo == 2) /* test for end of dio_samp int */
{ while (loopflg == 0X8888) { }
  loopflg = 0x8888;
  TFeflg = *pSPSR;
  if ((TFeflg & 0x80) == 0 )
  { letter = 'E'; }
  *pSPSR = 0x7F;
/* exit to monitor */
/* cycle finished, clear bit */
/* --------------------------- Rotor Position and Current Vector Calculation ------------------- */
/* cont = *pCHFpr6; */
/* Read TPU pulse counter */
if ( (dflg==4) && (cont-cntd==1)) /* check direction */
{ *PHSRR0 = 0x3000;
dirb = *pCHBr2 & 0xC000;
if (dirb==0x000) (dir = 1;)
else if (dirb==0) (dir = 0;)
}
if (cont==cntd) /* check at very low speed only */
{ *PHSRR0 = 0x3000;
dflg = dflg+1;
if (dflg==4) { dflg=4;}
}
else (dflg = 0;)
if (dir==0) (pos = pos+cont-cntd;)
else (pos = pos-cont+cntd;)
while (pos>1050) { pos = pos - 1000; }
while (pos<50) ( pos = pos + 1000; )
cntd = cont;
ang = (0xC49C*pos)>>8; /* 1000 pulses = 3*FFFF */
rot = ang+0xA000; /* Encoder in phase with Va */
/* 240 degrees for current vector */
if (openfl == 1) /* closed loop section */
{
  tabpos = rot & 0xFFFF;
  asm( " move.l _tabpos,D0 " );
  asm( " TBLSW_sintab,D0 " );
  asm( " move.w D0,_tabres " );
  sinr = tabres; /* sin curr vector */
  asm( " move.l _tabpos,D0 " );
  asm( " TBLSW_costab,D0 " );
  asm( " move.w D0,_tabres " );
  cosr = tabres; /* cos curr vector */
  Ialfa = (Id*cosr-Iq*sinr)>>12; /* current to stator frame */
  Ibeta = (Id*sinr+Iq*cosr)>>12;
  vavl = Ialfa;
  /* from 2 phase to 3 phase */
  vav2 = ((rt3*Ibeta)-(Ialfa<<12))>>13;
  vav3 = ((-Ialfa<<12)-(rt3*Ibeta))>>13;
}
else /* open loop section */
{
  phil = phil + phiincr;
  tabpos = phil;
  asm( " move.l _tabpos,D0 " );
  asm( " TBLSW_sintab,D0 " );
  asm( " move.w D0,_tabres " );
  vavl = (asm * tabres) >> 12; /* phase a current reference */
phi2 = phi2 + phincr;
tabpos = phi2;
asm( "move.l _tabpos,DO " );
asm( " TBL.W _sintab,DO " );
asm( " move.w DO,_tabres" );
vav2 = (ams * tabres) >> 12; /* phase b current reference */

phi3 = phi3 + phincr;
tabpos = phi3;
asm( "move.l _tabpos,DO " );
asm( " TBL.W _sintab,DO " );
asm( " move.w DO,_tabres" );
vav3 = (ams * tabres) >> 12; /* phase c current reference */

spflgl = spflgl+1;
if (spflgl >= 20) /* calc every 10 msec (20 loops) */
{
  if (dir==0) /* counterclock calc */
  {
    if (pos < posold) {deltan = 1000-posold+pos;}
    else {deltan = pos - posold;}
  }
  else /* clockwise calc */
  {
    if (pos > posold) {deltan = pos-posold-1000;}
    else {deltan = poslas - posold;}
  }
  /* First option when counter is reseted, second option is the normal case */
  sp = (deltan * Ox3C0)>>12; /* speed 1 pu = 2000 rpm */
  if (abs(sp-spold)>>=0xCC) {sp=spold;} /* possible misreading */
  spold = sp;
  spflgl = 0;
  posold = pos;
  specr = spctr+1; /* flag for PI speed cont */
  if (spsmod==0) {Iq = Iqcmd; /* Torque Control */
    else if (spsmod==1) /* Speed command */
    { time = time + 1;
      if (time>=1000) {spref = spinp;}
      else {spref = 0;}
    }
    else if (spsmod==2) /* FUDC speed command */
    {
      time = time + 1;
      if (time>=45500) {spref = 0;}
      else if (time>=44200) {spref = 500;}
      else if (time>=44000) {spref = 0;}
      else if (time>=42500) {spref = 500;}
      else if (time>=41500) {spref = 0;}
      else if (time>=39500) {spref = 500;}
      else if (time>=37000) {spref = 0;}
      else if (time>=35200) {spref = 400;}
      else if (time>=35000) {spref = 0;}
      else if (time>=32500) {spref = 400;}
      else if (time>=32000) {spref = 0;}
      else if (time>=29000) {spref = 400;}
      else if (time>=27000) {spref = 0;}
      else if (time>=22800) {spref = 350;}
      else if (time>=22500) {spref = 0;}
      else if (time>=21000) {spref = 350;}
      else if (time>=20000) {spref = 0;}
      else if (time>=16500) {spref = 350;}
      else if (time>=14500) {spref = 0;}
      else if (time>=9800) {spref = 250;}
      else if (time>=9600) {spref = 0;}
      else if (time>=7000) {spref = 250;}
      else if (time>=6500) {spref = 0;}
      else if (time>=2000) {spref = 250;}
      else {spref = 0;}
    }
else if (spmod==3)  /* Pulsed speed command */
{
    time = time + 1;
    if (time>=24000) {spref = 0;}
    else if (time>=22000) {spref = 400;}
    else if (time>=20000) {spref = 0;}
    else if (time>=18000) {spref = 400;}
    else if (time>=16000) {spref = 0;}
    else if (time>=14000) {spref = 400;}
    else if (time>=12000) {spref = 0;}
    else if (time>=10000) {spref = 400;}
    else if (time>=8000) {spref = 0;}
    else if (time>=6000) {spref = 400;}
    else if (time>=4000) {spref = 0;}
    else if (time>=2000) {spref = 400;}
    else {spref = 0;}

    if ((spmod>0) && (spctr>=2))  /* PI speed cont every 20 msec */
    {
        spref = ((spref<<16)/spbase) >> 4;
        spctr = 0;
        ensf = spref - sp;
        aux = (kisp*ensf)-(kisp*e0sp);  /* begin 8.24 section */
        e0sp = ensf;
        uosp = u0sp + aux;
        if (uosp > LPsp) {unsp = LPsp;}
        if (uosp < LNsp) {unsp = LNsp;}
        uosp = unsp;  /* end 8.24 section */
        Iq = (unsp >> 12);
    }
    if (sp>0xA00)  /* power limitation */
    {
        Iqlim = ((Pmax<<16)/sp)>>4;
        if (Iq > Iqlim) {Iq = Iqlim;}
        else if (Iq<Iqlim) {Iq = Iqlim;}
    }
    
    /* --------------------- Energy Management ------------------------------- */
    eml = (((0x98*sp)>>12)*((sp*sp)>>12))>>12;  /* Speed feedback */
    em2 = (0x120*(Iq*sp)>>12);  /* Power feedforward */
    eml = em0+em2-em1;  /* Engine start setpoint */
    if (eml<emmin) {eml=emmin;}  /* Minimum 115 V */

    /* --------------------- Safety shut down if DC link overvoltage ---------- */
    if (in6 > Vmax) { *pPCDR = 0x00; chref = 200; modesel = 2;}

    /* ------------------------- Mode 0. Start up. Engine builds DC link --------- */
    if (modesel == 0)  /* Prop. voltage regulator */
    {
        chref = dcref;  /* charge DLC manually */
        envo = Vdcref - in6;
        Iref=(kpv+envo)>>12;
        if (Iref>ienma) {Iref=ienma;}  /* max 30 A */
    }

    /* ----------------------------- Mode 1. DC link controlled using DLCs --------- */
    else if (modesel == 1)  /* PI voltage regulator */
    {
        if ((in5 < eml) && (emflg == 0))
        {
            Iref = ienma;
            sftflg = 1;
            emflg = 1;
            *pPCDR = 0x0F;
        }
        else if ((in5 < emh) && (emflg == 1))
        {
            sftflg = -1;  /* stop engine (slowly) */
            emflg = 0;
        }
        if (sftflg==1)
        {
            if (sftflg==4)  /* slow engine start */
        }
```c
{  sftflg = 1;
   Iref = Iref+1;
}
else if (sftflg == 1)
{  sftflg = sftflg+1;
   if (Iref>=iemmi) /* increase up to max curr */
   sftflg = 0;
}
else if (sftflg<=-1)
{  if (sftflg<=-4) /* slow engine stop */
     sftflg = -1;
     Iref = Iref-1;
   else if (sftflg <= iemmi) /* when min curr stop eng */
     sftflg = 0;
     piflg = 0;
     Iref = 0;
     *pPCDR = 0x00;
  }
}
Iff = 0xA02*(Iq*sp)>>12; /* Power feedforward for faster */
Iff = (((Iff-Iref*0x300)<<4)/in5)>>4; /* response */
envo = Vdcref - in6;
aux = envo - ((k2vo*e0vo) >> 12);
e0vo = envo;
aux = (kivo*aux); /* begin 8.24 section */
unvo = u0vo + aux;
if (unvo > LPvo) { unvo = LPvo; }
if (unvo < LNvo) { unvo = LNvo; }
u0vo = unvo; /* end 8.24 section */
chref = (unvo >> 12) + Iff;
}
/* ------------------------ Engine current control ------------------------ */
if (((modesel == 0)||(modesel == 1)&(piflg == 1)))
{  /* PI current regulator */
   encu = in7 - Iref;
   aux = encu - ((k2cu*e0cu) >> 12);
   e0cu = encu;
   aux = (kcu*aux); /* begin 8.24 section */
   uncu = u0cu + aux;
   if (uncu > LPCu) { uncu = LPCu; }
   if (uncu < LNCu) { uncu = LNCu; }
u0cu = uncu; /* end 8.24 section */
   pwcon = (uncu >> 12); /* end current regulator */
}
/* ------------------------ CHOPPER PULSEWIDTH ------------------------ */
/* update chopper pulsewidth, pwcon must be limited to */
/* max to avoid malfunction of pulse width modulator */
pwlcnt = (swpercnt * (0x0FF + pwcon)) >>13;
swllcnt = ((pwlcnt + swotcnt) << 16)
   + ((swpercnt-pwlcnt-swotcnt) >> 1);
/* ------------------------ Data aquisition section ------------------------ */
if ((datcol==7)&(sent==7))
{  timer = timer-1;
   if (timer<=0) /* send every second */
   {  kbstat = *pSCSR;
      if (kbstat & 0x0100)
      {  switch(car8c)
          {  case 1: /* send speed pu */
              stdw = sp;
              *pSCDR = 0x30+(stwd & 0xF);
              carac = 2;
              break;
              case 2:
              break;
          }
      }
  }
```
```c
*pSCDR = 0x30+((stwd & 0x0F0)>>4);
carac = 3;
break;
case 3:
*pSCDR = 0x30+((stwd & 0x0F00)>>8);
carac = 4;
break;
case 4:
*pSCDR = 0x30+((stwd & 0x0F000)>>12);
carac = 5;
break;
case 5:  /* send Vcap pu */
  stwd = in5;
*pSCDR = 0x30+(stwd & 0xF);
carac = 6;
break;
case 6:
*pSCDR = 0x30+((stwd & 0x0F0)>>4);
carac = 7;
break;
case 7:
*pSCDR = 0x30+((stwd & 0x0F00)>>8);
carac = 8;
break;
case 8:
*pSCDR = 0x30+((stwd & 0x0F000)>>12);
carac = 9;
break;
case 9:  /* send Ieng pu */
  stwd = Iref;
*pSCDR = 0x30+(stwd & 0xF);
carac = 10;
break;
case 10:
*pSCDR = 0x30+((stwd & 0x0F0)>>4);
carac = 11;
break;
case 11:
*pSCDR = 0x30+((stwd & 0x0F00)>>8);
carac = 12;
break;
case 12:
*pSCDR = 0x30+((stwd & 0x0F000)>>12);
carac = 1;
timer = timer+2000;
break;
}

/* ----------------- Start sequence selection ----------------- */
if (((kbflg == 0xAA) && (letter == 'f')))
{
  if (val == 0)  /* Build up DLink from engine */
  {
    modesel = 0;
    Vdcref = ((300<~16)/Vba)>>4;
    *pPCDR = 0x0F;
  }
  else if (val == 1)  /* Energy Management */
  {
    modesel = 1;
    u0vo = 0; unvo = 0; e0vo = 0; envo = 0;
    u0cu = LPcu; uncu = 0; e0cu = 0; encu = 0;
    Iref = 0;
    *pPCDR = 0x00;
  }
  else if (val == 2)  /* Motor in open loop */
  {
    openfl = 0;
    turn = 0;
  }
  else if (val == 3)  /* Torque control */
  {
```
{  
    spmod = 0;
    usp = 0; usp = 0; esp = 0; esp = 0;
}
else if (val == 4) /* Speed reference */
{  
    spmod = 1;
    time = 0;
}
else if (val == 5) /* PUDC */
{  
    spmod = 2;
    time = 0;
}
else if (val == 6) /* Pulsed Speed */
{  
    spmod = 3;
    time = 0;
}

/* ----------------------------- Reset to Open Loop for Restart ----------------------------- */
if ((kbflg == 0xAA) && (letter == 'S'))
{  
    if (val == 1) { "PSSRRO = 0x0010;" /* Engine enable high */
    else
        "PSSRRO = 0x0020;" /* Disable Engine */
    *PPCDR = 0x00;
    modesel = 2;
    u0cu = LFcu; uncu = 0; e0cu = 0; encu = 0;
    pwcon = (LFcu>>>12);
    chref = 0;
    emflg = 0;
    piflg = 0;

    /* ----------------------------- Quadrature Current Amplitude Control ----------------------------- */
    if ((kbflg == 0xAA) && (letter == 'a'))
    {  
        if (val > 150) { val = 150; }
        if (val < (-150)) { val = (-150);}
        lqcmd = (val*10+valf) << 16;
        lqcmd = (lqcmd/ibase) >> 4;
    }

    /* ----------------------------- DC/DC Converter Current Reference ----------------------------- */
    if ((kbflg == 0xAA) && (letter == 'c'))
    {  
        if (val>149) {val=149;}
        if (val<150) {val=-150;}
        val = -val;
        dcref = (val*10-valf) << 16;
        dcref = (dcref/ibase) >> 4;
    }

    /* ----------------------------- Clamping Voltage Reference ----------------------------- */
    if ((kbflg == 0xAA) && (letter == 'k'))
    {  
        if (val>999) {val=999;}
        if (val<0) {val=0;}
        val = -val;
        clref = (val*10-valf) << 16;
        clref = (clref/ibase) >> 4;
    }

    /* ----------------------------- "zero" Voltage Reference ----------------------------- */
    if ((kbflg == 0xAA) && (letter == 'b'))
    {  
        if (val>999) {val=999;}
        if (val<0) {val=0;}
        val = -val;
        zvref = (val*10-valf) << 16;
        zvref = (zvref/ibase) >> 4;
    }

    /* ----------------------------- Minimum Short Current Reference ----------------------------- */
    if ((kbflg == 0xAA) && (letter == 'D'))
    {  
        if (val>999) {val=999;}

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if (val<0) {val=0;)
val = -val;
itref = (val*10-valf) << 16;
itref = (itref/ibase) >> 4;
}

/*================================================================----------
* Minimum Clamp Current Reference
================================================================----------*/
if {{(valf == 0xAA) & (letter == 'p'))}
{ if (val>149) {val=149;}
  if (val<0) {val=0;}
  val = -val;
imin = (val*10-valf) << 16;
imin = (imin/ibase) >> 4;
}

/*================================================================----------
* Motor Speed Reference
================================================================----------*/
if ((kflag == 0xAA) & (letter == 'G'))
{ if (val > 55) { val = 55; }
  if (val < 0) { val = 0; }
  spinp = (val*10+valf);
}

out9 = -val1;
out8 = -val2;
out7 = -val3;
out6 = chref;
out5 = clref;
out4 = svref;
out3 = itref;
out2 = imin;
out4 = lq;

/*================================================================----------
* Exit the program
================================================================----------*/
if {letter == 'E')
{ mlo = 0;
  letter = 0xEE;
}

/*================================================================----------
* read keyboard, clear flag
================================================================----------*/
if {{(kflag == 0xAA)&&(kflag == 0x11)&&(kflag == 0x33))
{ kflag = 0x55;
keybl_io(kflag,letter,val,valf);
if (kflag == 0x33)
{ datcol = 7;
sent = 7;
}
else if (kflag == 0x11)
{ datcol = 1;
sent = 1;
carac = 1;
}
} /* end program LOOP mlo == 2 */
/* end main */

/*================================================================----------
* END MAIN PROGRAM
================================================================----------*/
HIGH FREQUENCY MEASUREMENTS

Vres & Vcla (800V INPUT => 15 V OUTPUT)

5 Current inputs: ilr, ia, ib, ic & Idc (150A INPUT => 15 V OUTPUT)

R1 = 1 K
R2 = 50 K
R3 = 1.5 K
R = 10 K
REFERENCE SIGNALS AMPLIFICATION

EIGHT SIGNALS FROM THE GPC 68332 BOARD
Vciref, zvref, iaref, ibref, idref, idcref, lmin, ltr

REFERENCE SIGNAL

TWO MEASUREMENTS FROM THE ALTERA BOARD

SIGNAL FROM ALTERA BOARD

OVER VOLTAGE SHUT DOWN

A1 (Vrej)  

<table>
<thead>
<tr>
<th>REFERENCE INPUTS AMPLIFICATION</th>
<th>SIZE</th>
<th>FSCM NO</th>
<th>DWG NO</th>
<th>REV</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPLEX RESONANT B</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

DRAWN  LUIS ZUBIETA  SCALE  1 : 1  28/08/99  SHEET  1 OF 1
CONVERTER SWITCHES CONTROL LOGIC (DC)

Interface

Alterna board

R = 10 K
Rc = 1 K

A1 (Vres)

B1 (vref)

B1 (Idccon)

A3 (Idc)
LOGIC FOR ZERO VOLTAGE USE AND INVERTER NON-SWITCHING CONDITION
HOLDING SWITCH SELECTION AND GATING SIGNALS

RESET

C2

E2

E3

C1

D12

D13

S1

S4

S3

S6

S5

S2

Sc

Sdc1

Sdc2

G1

G4

G3

G6

G5

G2

Si

s4

S3

S6

s2

Sc

sdc1

sdc2

Si

s4

S3

S6

s2

Sc

sdc1

sdc2

Si

s4

S3

S6

s2

Sc

sdc1

sdc2

Si

s4

S3

S6

s2

Sc

sdc1

sdc2
ZVELIM: Logic to eliminate the zero vector output in case of current sensors DC offset.
ZVINC: Logic to introduce zero vector switching state in the DC/AC converter to improve the resonant tank transient response.
SYNCH: Logic to coordinate the switching of the DC/AC converter with the switching of the DC/DC converter to improve the resonant tank transient response.
PROTEC: Logic to safely shut down the converter if the resonance stops or the conditions for the correct circuit operation are not satisfied.