A Three-Phase Fully-Integrated Battery Charger for Electric Vehicles Offering Galvanic Isolation

by

Milad Keshani

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Graduate Department of Electrical and Computer Engineering
University of Toronto

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Abstract

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Milad Keshani
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Integrated chargers leverage the drivetrain system existing on-board Electric Vehicles (EVs) to minimize dedicated charging circuitry and associated infrastructure cost, thus removing a major barrier to widespread deployment of EVs.

This thesis proposes a fully-integrated charger system for EVs by utilizing a double-stator winding induction machine. The proposed charger uses three-phase AC-grid voltage to provide fast charging feature. Unlike the majority of integrated EV chargers, the proposed topology provides galvanic isolation between the grid and EV battery during the charging processes. The proposed integrated charger is able to regulate the active and reactive power exchange between the utility grid and EV, separately; thereby, it can charge EV battery with unity power factor operation. Moreover, this topology provides bidirectional power transferring capability to support G2V and V2G applications.

The performance of the proposed integrated charger is verified through simulation and experimental results by using two wounded-rotor induction machines with inter-connected rotor windings.
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Chapter 1

Introduction

Fossil fuel shortage, global warming-related problems, and demand for improved driving efficiency have initiated a trend through which internal combustion engine (ICE) vehicles are replaced by electric vehicles (EVs) [1, 2]. The advent of electric vehicles not only provides a clean environment-friendly alternative for ICE vehicles but is also causing a profound transformation in the automotive industry. The differences in manufacturing processes, additional safety concerns, and different requirements for materials involved, have changed the way the car industry operates. These changes are also reflected in different disciplines, such as energy conversion, as power electronics play a pivotal role in both EV traction and battery recharging processes.

In this chapter, after considering some EV technology definitions and expressions, the EV battery chargers as a crucial part of electric vehicle technology are reviewed. Then, some important EV charging challenges and their suggested solutions in literature are presented. Finally, an isolated fully-integrated three-phase battery charger system for charging EVs with dual-stator induction machines or similarly, two coupled wounded-rotor induction machines which their rotor windings are connected together, is proposed.

1.1 Definitions and Terminology

Before delving more into the details of this growing technology, it is beneficial to consider the definitions and terminology to fully understand the context of the dissertation. Although the term EV is often used to designate different vehicle technologies, as Fig.1.1 shows, they have some differences which are explained below [3, 4].

**Electric Vehicle (EV):** EVs, sometimes called Battery EVs (BEVs), are purely electric vehicles use one or more electric motors to run. These motors are supplied by batteries through power electronic converters. Charging the batteries is carried out by plugging in the vehicle to an AC or DC grid.

**Hybrid Electric Vehicle (HEV):** These vehicles have internal combustion engines as well as electric motors for propulsion. In some HEV models, the IEC duty is restricted to
Chapter 1. Introduction

Figure 1.1: Comparison among different types of Electric Vehicle

charge the battery and transmitting power to drive the wheels is performed by electric motor only. The reason behind using electric power for running the vehicle is to achieve higher fuel efficiency. In these vehicles, the electric energy for charging the batteries does not come from any external sources.

Plug-in Hybrid Electric Vehicle (PHEV): This car is a combination of previous two categories. The electric motor is used to run the vehicle and supplied by batteries. Batteries are charged by either ICE or through plugging in the vehicle to AC/DC grid.

In this thesis, the focus is on introducing a new charger for Electric Vehicles; however, the proposed method may be used in PHEVs as well. In the literature, range anxiety is usually mentioned as one of the major barriers to large scale adoption of all-electric vehicles. According to the definition [5], range anxiety defines as:

Range Anxiety: The fear that a vehicle has insufficient range to reach its destination and would thus strand the vehicle’s occupants.

In order to reduce the range anxiety, utilities along with some EV companies have started to build charge stations like ordinary gas stations along the road. Since providing a network of charge stations requires considerable infrastructure and cost, except selected parts of the US and few other countries like Estonia [6], there often exists no such vast charging networks. Electric vehicle manufacturers have sought to quell range anxiety concern through increasing the battery capacity and proposing some new solutions like integrated charging for charging the EV cars.
1.2 Background and Motivation

Due to swift growth in EV sales, totally 3.1 million units as of the end of 2017 [7], many countries including United States (US), China, India, and some European countries have begun to issue and express interest in mandates regarding the future of electric vehicle sales. For example in the US, the state government of California has declared a Zero Emission vehicle (ZEV) mandate as of 2016, which requires auto-makers in the state to sell an increasing amount of ultra-low or zero-emission vehicles year over year. This mandate was later adopted by nine other US states. Similar to the California mandate, China issued its own mandate called the New Energy Vehicle (NEV) mandate, which became effective as of April 2018 [7, 8]. As EVs become more widespread, it is critical for chargers and power system infrastructure to be prepared for this large influx of energy demand and look for new charging solutions to enhance the performance.

1.2.1 Battery Charger Classifications

A crucial part of the operation of EVs is recharging of their battery pack, which can be classified by different aspects. For instance, EV battery chargers can be classified as conductive chargers and inductive chargers [9, 10]. The first charging method uses wires and cords to transfer electrical energy to battery; however, the second method utilizes wireless energy transfer through electromagnetic field coupling, eliminating the plug-in cords. Although wireless charging provides galvanic isolation by nature and more convenience for the users during the charging process, it suffers from relatively low efficiency, low power density, manufacturing complexity, and extra cost [11, 12].

Another classification divides EV battery chargers into two categories: on-board and off-board battery chargers [13]. As illustrated in Fig.1.2, in on-board battery chargers, the charging equipment is mounted on the vehicle and typically it is difficult for on-board chargers to have a high power rating because of their added weight, space, and their total cost limitations. Moreover, providing galvanic isolation during the charging process is challenging for on-board chargers [14, 15]. On the other hand, off-board chargers are comparable to filling stations for ICE cars due to their ability for providing rapid charging. Although off-board chargers are a favorable option regarding the time saving and safety reasons, they require expensive infrastructure which has cost impact on the system as well as negative impacts on environment [16].

In some literature, EV battery chargers are classified based on their power levels into three groups [17, 18]. Level 1 or slow chargers which are usually used for residential garages where they are appropriate for over night charging from a household utility outlet. Level 2 chargers, which offer faster charging rates than level 1 chargers, are typically described as the primary method for public facilities for charging during daytime at work places where no off-board charger is available. Usually single phase solutions are used for level 1 and level 2 chargers.
Figure 1.2: On-board vs. off-board power electronics interfaces for an Electric Vehicles [14]

Level 3 and DC fast chargers, commonly known as Electric Vehicle Supply Equipment (EVSE), are intended for commercial and public applications, operating like a gas station. They can provide the shortest charging time (around 1 hour) among the EV chargers; however, due to their need for special infrastructure, they are more costly [19]. It can be observed in Fig.1.3 that the high cost of EVSE caused the number of residential and public slow chargers (Levels 1 and 2) to considerably exceed the number of installed DC fast charging stations for light duty vehicles (LDV) in recent years [20]. Table 1.1 summarizes the power levels and voltage levels used for each charging group according to SAEJ1772 Standard [10, 16, 21].

Table 1.1: EV Charging Levels based on SAEJ1772 Standard [10, 16, 21]
1.2.2 Integrated Charging

Since the electric vehicle is parked during charge periods, it is possible to use available traction hardware, mainly the electric motor and the converter, in the charging process. Utilizing the vehicle traction system as part of charging process is called integrated charging [22]. Fig.1.4 shows a comparison between conventional charging and integrated charging methods for the electric vehicle. As illustrated in Fig.1.4, integrated on-board chargers leverage the drivetrain system, comprised of motor and drive inverter, to minimize dedicated charging circuitry, resulting in potentially considerable savings both in semiconductors and passive component costs. Due to the reduction in added circuitry, integrated charger topologies can be implemented with minimal additional mass to the vehicle, thus avoiding any range penalty. Furthermore, a substantial decrease in associated charging station costs can facilitate widespread deployment of charging infrastructure, thereby accelerating adoption of this technology [23].

Integrated charging topologies may be designed to offer some of the following characteristics:

1. Minimal additional mass, volume, and cost to the vehicle
2. DC or AC Fast charging capabilities
3. Low switch stress
4. Galvanic isolation
5. Unity power factor operation
6. Improved safety and fault protection
7. Bidirectional power transfer capability
8. Minimum machine redesign requirements
9. Zeroing of the developed torque inside the motor during the charging process
Although integrated charging provides several advantages, there exist some challenges to provide the aforementioned characteristics. The topologies of integrated chargers should be applicable to commercial EVs in the market with minimum manipulation. The integrated charging approaches should not require the access to inaccessible terminals of EVs motors, such as mid-point or neutral point of machine windings [14].

Moreover, multi-phase propulsion systems, such as six-phase or nine-phase propulsion systems, should be avoided in integrated charging approach. This is because the three-phase propulsion systems have proven effective cost in the commercial EVs so far. In addition, the specially designed multi-phase machines and multi-phase converters increase the cost and complexity of overall system [24].

Providing bidirectional power transfer for applications like grid to vehicle (G2V), vehicle to grid (V2G), and vehicle to vehicle (V2V) in integrated charger topologies is also a challenge [25]. Galvanic isolation during the charging process is recommended in EV charging standards due to safety and Electromagnetic Compatibility (EMC) issues [10, 26]; however, most of the integrated chargers suffers from lack of isolation.

Another obstacle usually exists in integrated chargers is unwanted developed torque inside the motor. Current flowing inside the motor winding for charging the batteries can create an unwanted torque inside the motor which is undesired during the charging process and should be addressed. Since the focus of this dissertation is on integrated chargers, a review of previously proposed topologies appearing in the literature is provided in the next section.
1.3 Literature Review

Generally, commercial EVs use three-phase AC-machines for propulsion. These machines are mainly three-phase squirrel-cage induction machines (IM) or permanent magnet synchronous machines (PMSM). For instance, Chevy Volt utilizes a 111kW PMSM, Nissan Leaf uses a 80-kW PMSM, Tesla Model S uses a 310-kW three-phase squirrel-cage IM, and Toyota EV Rav4 utilizes a 115-kW three-phase squirrel-cage IM [27, 28]. Fig.1.5 shows the two induction machines used by Tesla motors for a Tesla Model S car [29].

![Figure 1.5: Location of two induction machines in Tesla Model S EV car [29]](image)

The integration of drivetrain elements into the charging system was first introduced to minimize battery charger costs and weight by D. Thimmesch in 1985 [30]. Since then several circuit topologies and control schemes have been introduced [15, 17, 24, 31]. One can categorize the integrated charger topologies on the basis of the machine and inverter count used.

Numerous integrated battery charger topologies use one AC machine and one converter. Cocconi introduced and patented an integrated charger which utilizes motor windings as a set of inductors [32]. During the charging process, the traction inverter with motor windings constitutes a boost converter and charges the battery with unity power factor. This topology is used for commercial EV cars by AC Propulsion Inc. [33]. In this topology, which is shown in Fig.1.6, a common mode filter is used to eliminate the switching ripple and spikes from
the line side current. Moreover, three relays and significant electrostatic shielding are used to reconfigure the topology for charging mode and decrease the ground current and high-voltage transitions, respectively.

![Diagram of single-phase integrated charger based on one induction machine](image)

Figure 1.6: Single-phase integrated charger based on one induction machine [32, 33]

In [34], two solutions are introduced by Rippel, which use one inverter along with one three-phase AC motor. In the first solution, an inductor is used as the energy storage device; however, the inductance is replaced by the leakage inductance of the motor in the second one.

An integrated charger is shown in Fig.1.7. This topology is based on PM motor and it is used for electric scooter application [35]. As a result of unidirectional current in the motor windings in this topology, no torque is developed during the charging process; nonetheless, it requires access to the neutral point of the motor winding.

A two-channel interleaved boost converter for a PM motor is proposed in [36]. It uses a single/three phase rectifier to inject dc power through the motor winding with reduced conduction losses and low THD. This topology, illustrated in Fig.1.8, is able to charge from either a single-phase or a three-phase grid. The difference between this topology and the electric scooter introduced in [35] is that the DC current is injected through one phase of the motor and there is no need to have access to the neutral point of the machine.

All the previous discussed integrated charger topologies so far are lacking in galvanic isolation; however, galvanic isolation in charging process is recommended by EV charging standards for safety and EMC issues. An isolated integrated charger based on the wounded-rotor induction machine is proposed in [37]. As illustrated in Fig.1.9, the air gap between stator and rotor provides galvanic isolation between grid and battery during the charging process. The disadvantage associated with this topology is the developed torque inside the motor during the
Figure 1.7: The integrated charging topology based on PM motor for Electric Scooter application [35]

Figure 1.8: Integrated charger with two channel interleaved boost converter for a PMSM [36]
charging process; therefore, a mechanical lock is needed to prevent the motor from rotation.

Figure 1.9: Three-phase integrated charger based on wound-rotor induction machine [37]

Other integrated chargers employ two independent inverters for two AC machines [38, 39]. In traction mode, each motor is controlled by its dedicated inverter and then it is reconfigured for charging mode. As illustrated in Fig.1.10, a single-phase AC supply is connected between two motors through EMI filter in charging mode. This topology utilizes the leakage inductance of the two machines to constitute six interleaved boost converters. The patent assignee of this topology is General Motors Inc. [40]. A similar concept is applied by Tang and Su [41], where two inverters drive the main and auxiliary motors. During the charging process, two three-phase motors are used as inductors for converters with neutral points connected to the AC grid. The main disadvantages of these chargers are lack of isolation, large number of extra components, two relays, and complexity of the control method.

The concept of two-motor integrated charging can be merged in one motor with a double set of stator windings [38]. The operational principle is the same as two motors/converters; however, cost and weight are less than the previous one. This arrangement still requires two converters, three contactors and also a special double-stator winding machine.
Figure 1.10: Single-phase integrated charger with two induction machines and two inverters [38, 39, 41]
Shi et al [42] proposed a fast DC charging system which consists of an open-winding motor and a dual-inverter drive through which the system can handle hybrid storage methods. As illustrated in Fig.1.11, the system is able to do charge balancing by tuning different duty-cycles to the top and bottom inverters switches. Although this topology has no relays or contactors, it suffers from lack of isolation and requires a special open-winding machine, which is not compatible with current commercial EV cars in the market.

Figure 1.11: Three-phase integrated charger with open-winding AC machines and two inverters [42]

In the literature, several integrated chargers based on split-phase winding motors have been presented. In these topologies, a relay reconfigures the stator windings as a double set of three-phase windings [43, 44, 45]. A non-isolated three-phase integrated charger based on split-phase motors is shown in Fig.1.12. In traction mode, a three H-bridge topology along with a DC/DC converter is used to supply the 900 Volt DC link from 420 volt battery. On the other hand, as illustrated in Fig.1.13, the system is changed into two three-phase boost converters sharing a common DC bus in charging mode. By using the split-winding configuration and regulating the same current in the same phases of the two boost converters, the developed stator magnetomotive force and consequently the developed torque inside the machine is eliminated. As observed in Fig.1.14, this topology is compatible with both single and three-phase grid supplies. Although there is no contactor or relay to reconfigure the system for charging process,
lack of isolation and requiring special nine-terminal motor are some of the drawbacks associated with this topology. Furthermore, phase current mismatch may arise from the operation and must be actively controlled to avoid torque production.

Figure 1.12: Three-phase non-isolated integrated charger based on split-winding machine [43, 45]

There are other integrated chargers based on split-phase machines such as [40] and [46], where split-phase machines are used as a set of inductors. In [46], the motor rotates at synchronous speed to meet the frequency synchronization requirements while connected to the grid during the charging process. A clutch is needed to disconnect the motor from the mechanical transmission in this mode. The motor winding configuration for the traction and charging modes are shown in Fig.1.15 and Fig.1.16, respectively. Although the proposed topology provides isolation during the charging process and there is no developed torque inside the motor, this topology needs special split-phase machine, and two three-state three-phase high power switches which leads to extra manufacturing costs.
Figure 1.13: Three-phase non-isolated integrated charger based on split-winding machine in charging mode [43, 45]

Figure 1.14: Single-phase charging equivalent circuit for non-isolated integrated charger based on split-winding machine [43, 45]
Figure 1.15: The motor winding configuration for the traction mode [46]

Figure 1.16: The motor winding configuration for the charging mode [46]
1.4 Proposed Integrated Charger

The proposed integrated charger consists of a dual-stator induction machine with identical stator windings. Fig.1.17 shows the winding configuration of a dual-stator induction machine with identical stator windings and mutual squirrel-cage rotor. Similarly, this system can be implemented by two identical wounded-rotor induction machines which are mounted on the same shaft and their rotor windings are connected together. Using one induction machine with dual-stator windings for implementing the proposed charger is cost-effective, more efficient, and more robust than utilizing two identical wounded-rotor induction machines; however, due to the experimental limitations, the idea is presented only for the latter topology.

![Diagram of a dual-stator induction machine with identical stator windings and mutual squirrel-cage rotor](image)

Figure 1.17: The winding configuration of a dual-stator induction machine with identical stator windings and mutual squirrel-cage rotor

Fig.1.18 shows the proposed integrated charging system. For convenience, induction machines are named IM1 and IM2. Each motor is supplied by the battery through separate DC to AC converters during the traction mode. In the charging mode, stator windings of IM1 are connected to the AC grid while rotor terminals are connected to their similar phase in IM2. The grid current flows to the stator of IM1, passes through the common rotor of two machines, then to the stator of IM2, and finally charges the battery by means of the traction converter of IM2, which is called \( \text{VSC}_2 \). During the charging mode, the shaft is mechanically locked to prevent rotation.

As illustrated in Fig.1.18, the proposed charging topology is fully-integrated and uses the
available traction motors and converters which are already mounted on the vehicle. Since, in the charging process, the required energy for charging the battery is transferred from the stator to the rotor magnetically, it provides galvanic isolation between the AC grid and the battery, which is a valuable feature regarding the EV charging standards [10, 26].

The proposed integrated charging topology classifies as fast charger because it can charge EV battery from three-phase AC grid with power at or above 50 kW. Fast chargers can considerably reduce the charging time for electric vehicles; therefore, accelerate adoption of EVs. The proposed integrated charging topology does not require access to inaccessible points of motors like mid-point or neutral point of the motor windings. The proposed charger is easy to adopt and compatible with current EVs in the market as a result of conventional three-phase converters and a single battery pack.

As a result of bidirectional power transferring capability of this system, the proposed topology is able to support applications such as G2V and V2G for trading the energy with grid. As will be demonstrated, the proposed control method for this integrated charger enables the vehicle to control the active and reactive power with the AC grid separately. This feature provides unity power factor operation during the charging mode which is a favorable feature for the utility operator.
1.5 Thesis Objective

The objectives of this thesis are to model, analysis, design and implement a new isolated fully-integrated fast battery charger for electric vehicles using a dual-stator induction machine. The proposed topology should be able to charge EV battery from the three-phase AC grid. The proposed topology should provide bidirectional power transfer for applications such as G2V and V2G. The proposed integrated charger should be able to control the active and reactive power drawn from the grid separately, though charging the battery with unity power factor is of highest importance.

The objectives of this thesis are summarized as follows:

1. To scrutinize existing approaches for integrated charging topologies of electric vehicles and considering pros and cons of each method

2. To propose a new isolated fully integrated charging topology for three-phase fast AC charging

3. To extract the model for a coupled induction machine system in a common ‘qd0’ reference frame

4. To proposed a control method for controlling the active and reactive power separately (unity power factor operation)

5. To evaluate and verify the performance of the proposed method via simulation and laboratory testing on a coupled wounded-rotor induction machine based system
1.6 Thesis Outline

The present dissertation consists of five chapters, which are organized as follows:

Chapter 1 covers the definitions related to EV technology and scrutinizes the existing topologies proposed in literature for integrated chargers with their pros and cons.

Chapter 2 introduces an isolated fully-integrated battery charger for EV along with its model and formulas in ‘qd0’ reference frame.

Chapter 3 describes and discusses in detail the control strategy for proposed circuit topology.

Chapter 4 presents the simulation and experimental results of the proposed topology to verify the theoretical analysis.

Chapter 5 summarizes the main contributions and conclusions of the present work. It also recommends some directions for future works and amendments.
Chapter 2

Proposed Integrated Battery Charger

2.1 Introduction

In this chapter, an isolated fully-integrated three-phase battery charging system for a double-stator induction machine is presented. At first, the equivalent circuit of an induction machine along with its mathematical formulas in both ‘abc’ reference frame and ‘qd0’ reference frame are reviewed. Then, the equivalent circuit for a double-stator induction machine or equivalently, two wounded-rotor induction machines with connected rotor windings is described. The mathematical formulas for the proposed topology in both ‘abc’ reference frame and ‘qd0’ reference frame are derived.

2.2 Induction Machine

The induction machines are without doubt one of the most important means of converting the electric power to mechanical work and vice-versa. Induction machines are used in wide variety of applications, including pumps, steel mills, electric cars, and some household appliances. An induction machine consists of two main parts, namely the stator and rotor. Based on the rotor type, an induction machine can be either wounded type or squirrel-cage type. Rotor windings are accessible in wounded-rotor induction machine; however, there are some conductor bars inside the squirrel-cage motor which are short-circuited together by means of copper rings.

Due to an existing air-gap between the stator and the rotor, induction machines have an intrinsic isolation feature between stator and rotor. The electric current needed in the rotor to produce torque is obtained by electromagnetic induction from magnetic field of the stator winding. We can use this opportunity to build an isolated integrated charger through transferring energy from first stator to the rotor and then out of the second stator.
2.2.1 Equations and Equivalent Circuit in ‘abc’ Reference Frame

For the purpose at hand, the winding arrangement for a two-pole, three-phase, wye-connected, symmetrical induction machine is shown in Fig. 2.1. The stator windings compose of three sinusoidally distributed windings, displaced 120 °, with $N_s$ equivalent turns and resistance $r_s$. Similarly, the rotor windings are identical, sinusoidally distributed windings, displaced 120 °, with $N_r$ equivalent turns and resistance $r_r$. The $\theta_r$ and $\omega_r$ are angular displacement and angular velocity of the rotor with respect to the stator, respectively.

Figure 2.1: Two-pole, three-phase, wye-connected symmetrical induction machine rotor and stator configurations [47]

All the self and mutual inductances for a three-phase induction machine are reviewed in detail in Appendix A.1. By using inductance matrices discussed in Appendix A.1, one can achieve the voltage equations and flux linkages for an induction machine as illustrated in Appendix A.2.
For the convenience, voltage equations and flux linkages are summarized in 2.1, 2.2, and 2.3:

\[ v_{abcs} = r_s i_{abcs} + p \lambda_{abcs} \]  
\[ v_{abcr} = r_r i_{abcr} + p \lambda_{abcr} \]  
\[ \lambda_{abcs} = \begin{bmatrix} \lambda_{abcs} \\ \lambda_{abcr} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr} \\ (L_{sr})^T & L_r \end{bmatrix} \cdot \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix} \]  

The ‘s’ subscript denotes variables and parameters which are associated with the stator circuit while the ‘r’ subscript denotes variables and parameters associated with the rotor circuit. Moreover, all the bold letters denote matrices, for example \( r_s \) and \( r_r \) are both diagonal three by three matrices with common elements along the diagonal. The Laplace variable is illustrated by \( p \), and \( v_{abc} \) and \( i_{abc} \) are voltage and current matrices of the three phase machine.

When expressing the voltage equations for an induction machine, it is convenient to refer all rotor variables to the stator windings by appropriate turns-ratio as:

\[ v_{abcr} = \frac{N_s}{N_r} v_{abcr} \]  
\[ i_{abcr} = \frac{N_r}{N_s} i_{abcr} \]  
\[ \lambda_{abcr} = \frac{N_s}{N_r} \lambda_{abcr} \]  

It is shown in [47] that the referred flux linkages are as:

\[ \lambda_{abcs} = \begin{bmatrix} \lambda_{abcs} \\ \lambda_{abcr} \end{bmatrix} = \begin{bmatrix} L_s & L'_{sr} \\ (L'_{sr})^T & L_r \end{bmatrix} \cdot \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix} \]  

where

\[ L'_{sr} = \left( \frac{N_s}{N_r} \right)^2 L_{sr} \]  
\[ L'_r = \left( \frac{N_s}{N_r} \right)^2 L_r \]  

Thus, the voltage equations of a three-phase induction machine when rotor parameters are referred to the stator side can be expressed as:

\[ \begin{bmatrix} v_{abcs} \\ v'_{abcr} \end{bmatrix} = \begin{bmatrix} r_s + pL_s & pL'_{sr} \\ p(L'_{sr})^T & r'_r + pL'_r \end{bmatrix} \cdot \begin{bmatrix} i_{abcs} \\ i'_{abcr} \end{bmatrix} \]
where the referred rotor resistances are achieved as:

\[
r'_r = \left(\frac{N_s}{N_r}\right)^2 r_r
\]  

Equation 2.10 describes the mathematical behavior of an induction machine. Please note that this equation is written by assuming there exists no phase-shift between the rotor and stator (it is discussed in detail in section 3.4.3). Since the rotor of induction machine is locked during the charging process of the proposed integrated charger, we need to use equivalent circuit of the machine in stand still position. Fig.2.2 shows the equivalent circuit of an induction machine in stand still position when its rotor parameters are referred to the stator side.

\[
\begin{align*}
\ & r_s, L_{ls}, L_m, r'_r, L'_{lr}, i_s, v_s, \ L_{m}, v_r', i'_r, \ v_r' \ \ & \\
\ & +, +, - , -
\end{align*}
\]

Figure 2.2: The equivalent circuit of an induction machine when its rotor parameters are referred to the stator side

### 2.2.2 Equations and Equivalent Circuit in ‘qd0’ Reference Frame

Changes of variables are used in analysis of electrical systems to eliminate time-varying quantities. The "Quadrature-Direct-Zero" transformation which is called ‘qd0’ transformation in abbreviation, is a tensor that rotates the reference frame of a three-element vector or three-by-three element matrix in an effort to simplify analysis. Fig.2.3 shows diagram of ‘abc’ and ‘qd0’ reference frames for this transformation.

The ‘qd0’ transformation, usually known as Park transformation, is often used to rotate the reference frame of AC waveforms such that they become DC signals. Depending on which of \(d\) or \(q\) axes is aligned with magnetic field of phase ‘a’, the transformation matrix would be different. Consistent with [47], \(q\)-axis aligned with magnetic field of phase ‘a’ and \(d\)-axis lags to \(q\)-axis by 90 degrees.

Any three-phase quantity can be transformed from a three phase ‘abc’ stationary reference frame to any arbitrary rotating reference frame by means of a transformation matrix \(K^\omega\) defined as:

\[
K^\omega = \frac{2}{3} \begin{bmatrix}
\cos \omega t & \cos \left(\omega t - \frac{2\pi}{3}\right) & \cos \left(\omega t + \frac{2\pi}{3}\right) \\
\sin \omega t & \sin \left(\omega t - \frac{2\pi}{3}\right) & \sin \left(\omega t + \frac{2\pi}{3}\right) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\]  

(2.12)
such that

\[
(K^\omega)^{-1} = \begin{bmatrix}
\cos \omega t & \sin \omega t & 1 \\
\cos (\omega t - \frac{2\pi}{3}) & \sin (\omega t - \frac{2\pi}{3}) & 1 \\
\cos (\omega t + \frac{2\pi}{3}) & \sin (\omega t + \frac{2\pi}{3}) & 1 \\
\end{bmatrix}
\]  

(2.13)

\[
f_{qd0} = K^\omega f_{abc} 
\]

(2.14)

\[
f_{abc} = (K^\omega)^{-1} f_{qd0} 
\]

(2.15)

\[
\theta = \int \omega dt 
\]

(2.16)

where \(\omega\) and \(\theta\) are the angular velocity and displacement of the arbitrary reference frame with respect to the stator’s a-axis. Therefore, ‘qd0’ voltage and current variables are defined for an induction machine as:

\[
v_{qd0} = K^\omega v_{abc} 
\]

(2.17)

\[
i_{qd0} = (K^\omega)^{-1} i_{abc} 
\]

(2.18)

As illustrated in Appendix A.3, in order to find flux linkage of an induction machine in ‘qd0’ reference frame, we need to apply Park Transform to inductance matrices A.11, A.12, and A.13:

\[
\begin{bmatrix}
\lambda_{qd0s} \\
\lambda'_{qd0r}
\end{bmatrix} = \begin{bmatrix}
K^\omega L_s (K^\omega)^{-1} & K^\omega L_{sr}' (K^\omega)^{-1} \\
K^\omega (L_{sr}')^T (K^\omega)^{-1} & K^\omega L_r' (K^\omega)^{-1}
\end{bmatrix} \cdot \begin{bmatrix}
i_{qd0s} \\
i'_{qd0r}
\end{bmatrix}
\]

(2.19)
Similarly, in order to find voltage equations of an induction machine in \( 'qd0' \) reference frame, we use transformation matrices 2.12 and 2.13 for equation 2.10. After mathematical simplification, the voltage equations are achieved as:

\[
\begin{align*}
v_{qs} &= r_s i_{qs} + \omega \lambda_{ds} + p \lambda_{qs} \\
v_{ds} &= r_s i_{ds} - \omega \lambda_{qs} + p \lambda_{ds} \\
v_{0s} &= r_s i_{0s} + p \lambda_{0s} \\
v'_{qr} &= r'_r i'_{qr} + (\omega - \omega_r) \lambda'_{dr} + p \lambda'_{qr} \\
v'_{dr} &= r'_r i'_{dr} - (\omega - \omega_r) \lambda'_{qr} + p \lambda'_{dr} \\
v'_{0r} &= r'_r i'_{0r} + p \lambda'_{0r}
\end{align*}
\]

where flux linkages are as:

\[
\begin{align*}
\lambda_{qs} &= L_{ls} i_{qs} + L_M \left( i_{qs} + i'_{qr} \right) \\
\lambda_{ds} &= L_{ls} i_{ds} + L_M \left( i_{ds} + i'_{dr} \right) \\
\lambda_{0s} &= L_{ls} i_{0s} \\
\lambda'_{qr} &= L'_{lr} i'_{qr} + L_M \left( i_{qs} + i'_{qr} \right) \\
\lambda'_{dr} &= L'_{lr} i'_{dr} + L_M \left( i_{ds} + i'_{dr} \right) \\
\lambda'_{0r} &= L'_{lr} i'_{0r}
\end{align*}
\]

In above equations, \( \omega_r \) is the angular velocity of the rotor and magnetizing inductance is defined as:

\[
L_M = \frac{3}{2} L_{ms}
\]

Now one can use equations 2.20 to 2.31 to achieve the equivalent circuit of induction machine in an arbitrary \( 'qd0' \) reference frame. Fig.2.4 shows the equivalent circuit of an induction machine when its rotor parameters are referred to the stator side.
Figure 2.4: The arbitrary equivalent circuit of an induction machine when its rotor parameters are referred to the stator side


2.3 Coupled Induction Machines Model

The proposed isolated fully-integrated charger system is shown in Fig.1.18. For the convenience, the proposed integrated charging system is again illustrated in 2.5a. As observed in Fig.2.5, the proposed system has two modes of operation: traction mode and charging mode. In the traction mode, each inverter drives its assigned motor and the system works as a conventional motor drive vehicle with stator power shared between two motors (Fig.2.5b). Since control and drive of the induction motor have been explained well in literature [48, 49, 50, 51], we skipped discussing the proposed circuit in traction mode.

In charging mode, a three-phase AC grid charges the EV battery with passing energy through the two induction machines. In the experimental work, two identical wounded-rotor type induction machines are used. These machines are mounted on the same shaft their rotor windings are connected together. As illustrated in Fig.2.5c, the grid current enters to the stator of IM1, induced on the rotor windings, and flows toward the rotor of IM2. The rotor of IM2 is now energized and induces voltage on stator of IM2 which is connected to voltage source converter VSC2. Finally, the grid current charges the battery through VSC2.

The proposed integrated charger not only uses the leakage inductances of two traction machines as a set of filter inductors but also uses the air-gap between the stator and rotor of machines to provide galvanic isolation between the battery and grid during the charging process. In order to design a controller for charging system, a model must be developed for the proposed circuit, as presented in the following sections.

2.3.1 Equations and Equivalent Circuit in ‘abc’ Reference Frame

Regarding the model discussed in section 2.2 for a symmetrical three-phase induction machine, we can derive a referred equivalent circuit and accordingly, the voltage equations for the dual-stator induction machine or equivalently two coupled wounded rotor induction machines of the proposed charger. Since two induction machines used for experimental validation are identical and connected together from the rotor side, it is possible to merge both rotor resistances and rotor leakage inductances of two machines together.

Fig.2.6 shows the referred equivalent circuit of two stationary induction machines where their rotors are connected together. As illustrated in Fig.2.6, the equivalent circuit is obtained through combining two referred equivalent circuits of induction machines (shown in Fig.2.2) in stand still position.

By applying the Kirchhoff’s Voltage and Current laws (KVL and KCL) to equivalent circuit shown in Fig.2.6, we have voltage equations in ‘abc’ reference frame as:

\[ v_{s1} = r_s i_{s1} + p (L_{ls} + L_m) i_{s1} + pL_m i'_r \]
\[ 0 = 2r'_r i'_r + 2pL'_r i'_r + pL_m i_{s1} - pL_m i_{s2} \]
\[ v_{s2} = r_s i_{s2} + p (L_{ls} + L_m) i_{s2} - pL_m i'_r \]
Figure 2.5: The proposed three-phase isolated integrated charger system
Figure 2.6: The ‘abc’ equivalent circuit of the proposed charger when their rotor parameters are referred to the stator side

where ‘s1’ and ‘r1’ subscripts denote variables and parameters which are associated with the stator and rotor circuits of the first machine (IM1), while the ‘s2’ and ‘r2’ denote variables and parameters associated with the stator and rotor circuits of the second machine (IM2). \( L_m, L_{ls}, \) and \( L_{lr} \) are the magnetizing inductance, the leakage inductance of the stator, and the referred leakage inductance of the rotor, respectively. The Laplace operator is illustrated by \( p \), and \( v \) and \( i \) are voltage and current of the three phase machine.

### 2.3.2 Equations and Equivalent Circuit in ‘qd0’ Reference Frame

Similar to what was discussed in section 2.2.2, we can express the equations and equivalent circuit for two rotor-connected induction machines in ‘qd0’ reference frame. A single squirrel-cage induction machine with double stator windings have the same model but the parameter values may be different. Before extracting the mathematical model and deriving formulas for the proposed system, the following assumptions and clarifications are made:

1. The induction machines are assumed to be identical and symmetrical.

2. The proposed charger is expected to connect to a balanced three-phase voltage source such as the AC utility grid. In a balanced three-phase supply, the zero-component of the currents and voltages achieved from Park transform are zero. Therefore, the equivalent circuit and voltage equations associated with zero-components are discarded.

3. Since the rotors of the induction machines are mechanically locked during the charging mode, angular velocity of the rotors is zero (\( \omega_r=0 \)).

4. The rotating ‘qd0’ reference frame is assumed to rotate with grid synchronous speed. In other words, the angular velocity used in the Park transform is equal to the grid angular velocity (\( \omega=\omega_s \)).
By considering the above assumptions, we can express voltage equations of the proposed two coupled induction machines in ‘qd0’ reference frame as:

\[
\begin{align*}
v_{qs1} &= r_s i_{qs1} + \omega \lambda_{ds1} + p \lambda_{qs1} \quad (2.36) \\
v_{ds1} &= r_s i_{ds1} - \omega \lambda_{qs1} + p \lambda_{ds1} \quad (2.37) \\
0 &= 2 r_s' i_{qr} + \omega \lambda_{dr}' + p \lambda_{dr}' \quad (2.38) \\
v_{qs2} &= r_s i_{qs2} + \omega \lambda_{ds2} + p \lambda_{qs2} \quad (2.39) \\
v_{ds2} &= r_s i_{ds2} - \omega \lambda_{qs2} + p \lambda_{ds2} \quad (2.40) \\
0 &= 2 r_s' i_{dr}' - \omega \lambda_{qr}' + p \lambda_{dr}' \quad (2.41)
\end{align*}
\]

where the flux linkages are as:

\[
\begin{align*}
\lambda_{qs1} &= L_{ls} i_{qs1} + L_M \left( i_{qs1} + i_{qr}' \right) \quad (2.42) \\
\lambda_{ds1} &= L_{ls} i_{ds1} + L_M \left( i_{ds1} + i_{dr}' \right) \quad (2.43) \\
\lambda_{qr}' &= 2 L_{lr}' i_{qr}' + L_M \left( i_{qs1} - i_{qs2} + 2 i_{qr}' \right) \quad (2.44) \\
\lambda_{qs2} &= L_{ls} i_{qs2} + L_M \left( i_{qs2} - i_{qr}' \right) \quad (2.45) \\
\lambda_{ds2} &= L_{ls} i_{ds2} + L_M \left( i_{ds2} - i_{dr}' \right) \quad (2.46) \\
\lambda_{dr}' &= 2 L_{lr}' i_{dr}' + L_M \left( i_{ds1} - i_{ds2} + 2 i_{dr}' \right) \quad (2.47)
\end{align*}
\]

Fig. 2.7 shows the ‘qd’ equivalent circuit of the two induction machines connected together from rotor side when their rotor parameters are referred to the stator sides.

Figure 2.7: The \(qd\) equivalent circuit of the two induction machines connected together from rotor side when their rotor parameters are referred to the stator sides.
2.4 Integrated Voltage Source Converter

The equivalent circuit and mathematical model for two rotor-connected induction machines were introduced in Section 2.3. As illustrated in Fig.2.5c, stator of the second machine (IM2) is connected to a three-phase voltage source converter (VSC2). The converter topology usually serves as the basis for most of three-phase variable speed drive systems is a three-phase two-level converter. The converter in Fig.2.8 is a two-level converter because it can generate only two voltage levels, $\frac{1}{2}V_{dc}$ and $-\frac{1}{2}V_{dc}$ at the output phases ‘a’, ‘b’, and ‘c’, relative to the supply mid-point ‘$v = 0$’. In the proposed topology, $V_{dc}$ connects to the battery and $i_{as}$, $i_{bs}$, and $i_{cs}$ are supplied from the stator of IM2. In the charging process, leakage inductances of the two induction machines serves as a set of inductor.

As illustrated in Fig.2.8, a three-phase two-level converter is compromised of six controllable switches. The voltage source converter is controlled through gating signals which are sent to switches by controller unit. There are different methods to generate gating signals such as Square-wave modulation, Selective Harmonic Elimination (SHE) modulation, Sinusoidal Pulse Width modulation (SPWM), and Space Vector Modulation (SVM). In this project, Sinusoidal Pulse Width Modulation method is used to generate the gating signal for the converter. The reference signal for the SPWM unit is generated by the controller unit, which is discussed in detail in the next chapter.

Figure 2.8: The three-phase full-bridge converter topology
Chapter 3

Control Strategy

3.1 Introduction

In this chapter, a controller is designed to regulate the grid currents flowing into the proposed integrated charging system to desired values for charging the battery. The controller should be able to control the exchange of active and reactive power between the grid and vehicle separately, and be operational in both G2V and V2G modes. As a result, the controller is supposed to control the grid currents \(i_{qs1}\) and \(i_{ds1}\), individually.

Before describing the control approach, we need to rewrite the system equations, derived in 2.36 to 2.47, in state-space representation. The state-space formulation not only eases designing the controller for the multi-input, multi-output system (MIMO), but also offers advantages of using computer-aided control system design (CACSD) tools for system analysis and disturbance rejection goals. Later in this chapter, a full state feedback regulator method combined with integral action is described to be used as the controller unit. Finally, after a discussion about the features and characteristics of the practical system, the general control strategy of the proposed system is presented.

3.2 State-Space Representation

The general state-space form of the proposed MIMO system is expressed as:

\[
\frac{d}{dt}X = AX + BU + d \quad (3.1)
\]
\[
Y = CX + DU \quad (3.2)
\]

where \(X\) is matrix of state variables, \(U\) is matrix of inputs, \(Y\) is vector of outputs, and \(d\) is vector of disturbances entered to the system. On this basis, the equations achieved in 2.36 to 2.47 are clustered in state-space representation for further analysis of the system.
By considering the flux linkages as state variables and converter voltages as input, we have:

\[
X = \begin{bmatrix}
\lambda_{qs1} \\
\lambda_{qs2} \\
\lambda_{qr} \\
\lambda_{ds1} \\
\lambda_{ds2} \\
\lambda_{dr}
\end{bmatrix},
\]

(3.3)

\[
U = \begin{bmatrix}
v_{qs2} \\
v_{ds2}
\end{bmatrix},
\]

(3.4)

For the coefficient matrix \(A\), we have:

\[
A = \begin{bmatrix}
-2r_s D - L_M^2 r_s & L_M^2 r_s & L_M r_s & -\omega & 0 & 0 \\
2L_M r_s & -2r_s D - L_M^2 r_s & -L_M r_s & 0 & -\omega & 0 \\
2r_s L_M & -2r_s L_M & -2r_s L_M & 0 & 0 & -\omega \\
\omega & 0 & 0 & -2r_s D - L_M^2 r_s & L_M^2 r_s & L_M r_s \\
0 & \omega & 0 & 2L_M r_s & -2r_s D - L_M^2 r_s & 0 \\
0 & 0 & \omega & 2r_s L_M & -2r_s L_M & -2r_s L_M
\end{bmatrix},
\]

(3.5)

where

\[
\omega = 2\pi f_s
\]

(3.6)

\[
L_{ss} = L_{ls} + L_M
\]

(3.7)

\[
L_{rr} = L_{lr} + L_M
\]

(3.8)

\[
D = L_{ss} L_{rr} - L_M^2
\]

(3.9)

For the coefficient matrix \(B\), we have:

\[
B = \begin{bmatrix}
0 & 0 \\
1 & 0 \\
0 & 0 \\
0 & 0 \\
1 & 0 \\
0 & 0
\end{bmatrix},
\]

(3.10)
While the state variables comprise of flux linkages, the measurable outputs are system currents. Considering the system currents as outputs, and grid voltages as disturbance, we have:

\[
Y = \begin{bmatrix} \dot{i}_{qs1} \\ \dot{i}_{qs2} \\ \dot{i}_{qs} \\ \dot{i}_{qr} \\ \dot{i}_{ds1} \\ \dot{i}_{ds2} \\ \dot{i}_{dr} \end{bmatrix}_{6 \times 1} \tag{3.11}
\]

\[
d = \begin{bmatrix} v_{qs1} \\ 0 \\ 0 \\ v_{ds1} \\ 0 \\ 0 \end{bmatrix}_{6 \times 1} \tag{3.12}
\]

The coefficient matrix \( C \) is given by:

\[
C = \begin{bmatrix}
\frac{2D+L_M^2}{2L_{ss}D} & -\frac{L_M^2}{2L_{ss}D} & -\frac{L_M}{2D} & 0 & 0 & 0 \\
\frac{L_M^2}{2L_{ss}D} & \frac{L_M^2}{2D} & L_M & 0 & 0 & 0 \\
-\frac{L_M}{2D} & \frac{L_M}{2D} & \frac{L_M}{2D} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{2D+L_M^2}{2L_{ss}D} & -\frac{L_M^2}{2L_{ss}D} & -\frac{L_M}{2D} \\
0 & 0 & 0 & -\frac{L_M^2}{2L_{ss}D} & \frac{L_M}{2D} & L_M \\
0 & 0 & 0 & -\frac{L_M}{2D} & L_M & L_{ss} \\
\end{bmatrix}_{6 \times 6} \tag{3.13}
\]

Since the outputs have no direct relation with inputs, for the coefficient matrix \( D \), we have:

\[
D = [0]_{6 \times 2} \tag{3.14}
\]

### 3.3 Control Approach

As illustrated in equation (3.5), the proposed topology has multiple coupling terms between its ‘q’ and ‘d’ axes. In order to control the grid active and reactive powers flowing into the system individually, we need a controller to regulate the input currents \( i_{qs1} \) and \( i_{ds1} \) to desired reference values, separately. By this means, a full-state feedback controller with integral action method is used. Fig.3.1 shows the block diagram of the controller unit [52].

Since we are interested in controlling the grid currents entering to the system, the feedback path from output to the reference values includes only the two currents \( i_{qs1} \) and \( i_{ds1} \). Accordingly, the coefficient matrix \( K_i \) is a square matrix with dimension of two. The integral block ensures zero steady state error in case of existing any parameter inaccuracy between the actual
system and the modeled one.

The machine fluxes can not be measured directly; therefore, we need an estimator to extract these state variables from the measured output currents. Since the $C$ matrix described in 3.13 is invertible, the estimates of the state variables are found by using the inverse of $C$ matrix as the estimator block. Both coefficient matrices $K$ and $K_i$ are achieved by using the Linear Quadratic Regulator (LQR) method, which will be discussed in detail in the next section.

The $N_x$ block is a coefficient matrix which generates the reference state variables from the desired output references. By defining $R$ as the desired reference values for the intended outputs, we have:

$$R = \begin{bmatrix} i_{qs1}^* \\ i_{ds1}^* \end{bmatrix}$$  \hspace{1cm} (3.15)$$

Considering $X_r$ as desired values for the state variables, and $Y_r$ as measured outputs of the system, we have:

$$N_x R = X_r$$ \hspace{1cm} (3.16)

$$CX_r = Y_r = R$$ \hspace{1cm} (3.17)

Therefore, by substituting 3.16 into 3.17, one can achieve the $N_x$ matrix through solving the following equation:

$$CN_x = I$$ \hspace{1cm} (3.18)$$

where $I$ is identical matrix. Please note that since we are interested in controlling the two input currents entering the system from grid, we should only consider the two corresponding columns of matrix $N_x$. 
3.4 Controller Design

3.4.1 System Analysis

Before designing a controller for the system, it is important to analyze it from different aspects such as stability, controllability, and observability. For this purpose, we need to obtain the coefficient matrices of the system including $A$, $B$ and $C$ based on the actual motor parameters used in this project. Table 3.1 shows the parameters of each motor deployed in the test setup according to the datasheet provided by the motor manufacturer [53].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Stator Voltage (Y/Δ)</td>
<td>360/208</td>
<td>V$_{rms}$</td>
</tr>
<tr>
<td>Nominal Stator Current (Y/Δ)</td>
<td>2/3.5</td>
<td>A$_{rms}$</td>
</tr>
<tr>
<td>Nominal Speed (Synchronous/asynchronous)</td>
<td>1800/1680</td>
<td>rpm</td>
</tr>
<tr>
<td>Nominal Power</td>
<td>800</td>
<td>W</td>
</tr>
<tr>
<td>$\cos(\phi)$</td>
<td>1/0.75</td>
<td>-</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>60</td>
<td>Hz</td>
</tr>
<tr>
<td>Turns ratio (Y/Y)</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>8</td>
<td>Ω</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>0.81</td>
<td>Ω</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>46.4</td>
<td>mH</td>
</tr>
<tr>
<td>Rotor leakage inductance</td>
<td>5.2</td>
<td>mH</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
<td>511.9</td>
<td>mH</td>
</tr>
</tbody>
</table>

After substituting the above values in matrices 3.5, 3.10, and 3.13 for the controlability and observability tests, we have:

Controllability:

$$\text{Rank} \left( \begin{bmatrix} B & AB & A^2B & A^3B & A^4B & A^5B \end{bmatrix} \right) = 6 \quad (3.19)$$

Observability:

$$\text{Rank} \left( \begin{bmatrix} C & CA & CA^2 & CA^3 & CA^4 & CA^5 \end{bmatrix}^T \right) = 6 \quad (3.20)$$

As observed, the proposed system is fully controllable and observable. Furthermore, the six conjugate eigenvalues of the system are:

$$Eign \ (A) = \begin{pmatrix} -4.82 \pm 377i \\ -9.82 \pm 377i \\ -164.35 \pm 377i \end{pmatrix} \quad (3.21)$$

As illustrated, all the eigenvalues are in the left half plane, which means the system is open-loop stable.
3.4.2 Integral Action

Implementing the introduced controller Fig.3.1 without the integrator does not guarantee zero steady state error; thus, adding the integral action to the system is inevitable. This integrator is implemented as part of the controller equations. To accomplish the design of the feedback gains for both the integral and original state vector, we augment the model of the plant with two integrators. In other words, we add two error integrals as two new state variables to the existing plant states variables [52]. Equation 3.22 defines these two error integrals as:

\[ \frac{d}{dt} X_i = \frac{d}{dt} \begin{bmatrix} x_{i1} \\ x_{i2} \end{bmatrix} = \begin{bmatrix} e_{qs1} \\ e_{ds1} \end{bmatrix} \]  \hspace{1cm} (3.22)

where

\[ \begin{bmatrix} e_{qs1} \\ e_{ds1} \end{bmatrix} = \begin{bmatrix} i^*_{qs1} - i_{qs1} \\ i^*_{ds1} - i_{ds1} \end{bmatrix} \]  \hspace{1cm} (3.23)

Considering \( Y_1 \) as the measured output currents containing only the two intended currents \( i_{qs1} \) and \( i_{ds1} \), one can rewrite the system equations by adding the augmented integral states to 3.1 and 3.2 as:

\[ \frac{d}{dt} \hat{X} = \frac{d}{dt} \begin{bmatrix} X \\ X_i \end{bmatrix} = \begin{bmatrix} AX + BU \\ R - Y_1 \end{bmatrix} = \begin{bmatrix} AX + BU \\ R - C_1 X \end{bmatrix} \]  \hspace{1cm} (3.24)

\[ \frac{d}{dt} \hat{X} = \hat{A} \hat{X} + \hat{BU} \]  \hspace{1cm} (3.25)

Note that \( C_1 \) comprises only the rows of \( C \) matrix corresponding to two intended output currents.

\[ C_1 = \begin{bmatrix} \frac{2D+L^2_m}{2L_{ss}D} & -\frac{L^2_m}{2L_{ss}D} & -\frac{L_M}{2D} & 0 & 0 & 0 \\ 0 & \frac{2D+L^2_m}{2L_{ss}D} & -\frac{L^2_m}{2L_{ss}D} & -\frac{L_M}{2D} & 0 & 0 \end{bmatrix}_{2 \times 6} \]  \hspace{1cm} (3.27)

Ordinary \( LQR \) method is used to calculate the feedback control gains \( K \) and \( K_i \) for the new system as:

\[ J = \frac{1}{2} \int (\hat{X}^T Q \hat{X} + \hat{U}^T L \hat{U}) dt \]  \hspace{1cm} (3.28)

\[ \hat{U} = -\begin{bmatrix} K & K_i \end{bmatrix} \begin{bmatrix} X - X_r \\ X_i \end{bmatrix} \]  \hspace{1cm} (3.29)

\[ \hat{X} = \begin{bmatrix} X \\ X_i \end{bmatrix} \]  \hspace{1cm} (3.30)
The $Q$ matrix is chosen in such a way that all states have equal weights. Similarly, matrix $L$ is chosen with equal weights for both axes. Constant coefficient $k$ is determined by trial and error method to meet the voltage limits of the converter.

$$Q = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}_{8 \times 8}$$  \hspace{1cm} (3.31)

$$L = k \times \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}_{2 \times 2}$$  \hspace{1cm} (3.32)

### 3.4.3 Discussion about the Phase-Shifts

As illustrated in Fig.2.1, there may exist a phase-shift between voltage/current of the stator and their counterparts on the rotor. This phase-shift appears when the rotor quantities of the machine are transferred to stator side. Fig.3.2 shows the phase-shift between reference frames of the rotor and the stator of induction machine.

![Phase-shift diagram](image)

Figure 3.2: The phase-shift between reference frames of the rotor and stator in an induction machine

Since the first stator in the proposed integrated charger with double-stator windings machine may not be aligned with the second stator, there exists another phase-shift in the charging system. Similarly, in the two wounded-rotor induction machines topology that rotors are interconnected, there exists this phase-shift between stator of the first machine and stator of the
second machine.

Fig.3.3 illustrates the phase-shift between the two stator reference frames in the double-stator induction machine (coupled-induction machines with inter-connected rotors) in proposed integrated charging system.

![Diagram showing phase-shift between two stator reference frames](image)

Figure 3.3: The phase-shift between two stator reference frames in the proposed charging system

It is critical for practical implementation of the proposed charger to transform all the system parameters from their 'abc' reference frames to one 'qd0' reference frame, which the stator 'qd0' reference frame of the IM2 is chosen in this thesis. Therefore, we need to know the phase differences between the rotor and stator axes as well as the phase-shift between the two stator axes to transform their stator and rotor quantities to the stator 'qd0' reference frame of the IM2.

If we assume that the rotor reference frame leads stator reference frame by $\theta_{sr}$, one can refer voltage and current quantities of the rotor to the stator reference frame as:

$$V'_{abcr} = \frac{N_s}{N_r} V_{abcr} \angle + \theta_{sr}$$

$$I'_{abcr} = \frac{N_r}{N_s} I_{abcr} \angle + \theta_{sr}$$

Since the relative position of the two stator windings are fixed, the phase-shift between the two stators in the proposed integrated charger always stays unchanged. Thus, by doing a simple test, one can measure this phase-shift and import it into the 'qd0' transform calculation part.
Likewise, if we assume that the stator axis of the second machine leads the stator axis of the first machine by $\theta_{off}$, one can express the stator voltage and current quantities of the first machine in the stator ‘$abc$’ reference frame of the second machine as:

\[
\begin{align*}
V'_{abcs1} &= V_{abcs1} \angle -\theta_{off} \\
I'_{abcs1} &= I_{abcs1} \angle -\theta_{off}
\end{align*}
\] (3.35) (3.36)

Fig.3.4 summarizes the phase-shifts exist between two stators and between the stator and rotor of each machine in the proposed integrated charger.

Figure 3.4: The phase-shifts between two stators and between the stator and rotor of each machine in the proposed integrated charging system

Fig.3.5 shows the detail control strategy for the proposed isolated integrated charger with considering the effects of both phase-shifts existing between the rotors and stators as well as between the two stators in one diagram.
Figure 3.5: The detail control strategy for the proposed isolated integrated battery charger system
3.5 Chapter Summary

This chapter investigates the control mechanism of the proposed integrated charging system for either a double-stator windings machine or two wounded-rotor induction machines. The state-space formulation of the system is achieved and it is observed that the practical system is stable, fully controllable, and observable. In order to regulate the $q$-axis and $d$-axis grid currents flowing into the system to their reference values separately, a full-state feedback control method combined with integrator parts are introduced. The integral action in the control unit guarantees the zero error for the steady state response of the system.

Moreover, a discussion about the phase-shifts in the proposed charging system and their effects on referring the parameters to the stator side of the second machine is presented. The phase-shift between the stator and the rotor frames only affects the rotor parameters when they are referred to the stator side. On the contrary, the phase-shift between two stators appears when the stator voltage and current quantities of the first machine are referred to the stator side of the second machine.
Chapter 4

Simulation and Experimental Results

This chapter aims to validate the charging functionality of the proposed isolated fully-integrated battery charger system. For this purpose, the proposed system is simulated and also implemented in practice through the experimental setup compromising two identical wounded-rotor induction machines. After describing the simulated system and the experimental setup specifications, performance of the proposed system in charging mode is evaluated in two different parts including steady state operation and dynamic response.

In the first part, the simulation and practical results shall verify the current regulation feature of the system. This feature is shown by regulating the grid current flowing to the system to the desired values specified by the user with zero steady state error. The proposed integrated charging system also has bidirectional power transferring capability. It is able to supply active power to the utility grid from its battery in V2G mode. This feature is shown by setting a negative reference current for $i_{qs1}^*$. 

The proposed integrated charging system also provides the ability to control the active and reactive power exchanges between the grid and electric vehicle, separately. This ability is demonstrated by setting different values for $i_{qs1}^*$ and $i_{ds1}^*$. As a result, the proposed integrated charger can charge the battery with unity power factor, which is a favorable option from the utility operator point of view.

It is important to study the dynamic response of the proposed isolated integrated charger to external changes. Section 4.3 presents dynamic behavior of the proposed charger in some different cases when its reference values have changed.
4.1 Simulation and Experimental Setup Specifications

Fig.4.1 shows the proposed integrated charging system which is simulated in MATLAB/Simulink. As illustrated in Fig.4.1, the simulated system in charging mode consists of four main blocks including: ‘Circuit’, ‘Controller’, ‘VSC2’, and ‘PWM Unit’. The first three are ‘PLECS Blockset’ inside MATLAB. Fig.4.2, Fig.4.3, and Fig.4.4 show inside of these three blocks, respectively. The ‘qd’ equivalent circuit of the coupled induction machines (delivered in Section 2.3.2) along with the three-phase grid are modeled in the ‘Circuit’ block.

![Figure 4.1: Simulation of the proposed isolated integrated charging system](image)

All the parameter values used in simulation are similar to the experimental ones, which are summarized in Table.4.1.

Table 4.1: The parameter values used in both simulation and experimental setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage</td>
<td>208</td>
<td>$V_{\text{rms}}$</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>60</td>
<td>Hz</td>
</tr>
<tr>
<td>DC side voltage</td>
<td>380</td>
<td>$V_{dc}$</td>
</tr>
<tr>
<td>Stator Nominal current ($\Delta$)</td>
<td>3.5</td>
<td>$A_{\text{rms}}$</td>
</tr>
<tr>
<td>Nominal Speed (Synchronous/asynchronous)</td>
<td>1800/1680</td>
<td>rpm</td>
</tr>
<tr>
<td>Nominal Power</td>
<td>800</td>
<td>W</td>
</tr>
<tr>
<td>Cos($\phi$)</td>
<td>1/0.75</td>
<td>-</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>10</td>
<td>kHz</td>
</tr>
<tr>
<td>Turns ratio</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>8</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>0.81</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>46.4</td>
<td>$mH$</td>
</tr>
<tr>
<td>Rotor leakage inductance</td>
<td>5.2</td>
<td>$mH$</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
<td>511.9</td>
<td>$mH$</td>
</tr>
</tbody>
</table>
Figure 4.2: Simulation of ‘qd’ reference frame equivalent circuit of the coupled induction machines (inside the ‘Circuit’ block)

Figure 4.3: Simulation of the controller unit (inside the ‘Controller’ block). The ‘C’ language code inside the ‘C – Script’ block is provided in Appendix B
Figure 4.4: Simulation of the voltage source converter and the DC grid (inside the ‘VSC2’ block)
The stator and rotor of both machines are in \textit{delta} (\(\Delta\)) and \textit{star} (\(Y\)) configurations, respectively; therefore, the value of stator voltage of the first machine (\(V_{s1}\)) is equal to the grid line-to-line voltage. The controller unit shown in Fig. 4.3 is implemented by ‘C’ language code (provided in Appendix B) inside the ‘C – Script’ block.

Fig. 4.5 shows the experimental test setup for the implemented proposed charging topology. As shown in Fig. 4.6, the two induction machines are identical and wounded-rotor type. They are mounted on the same shaft which is locked by a PMSM dynamometer. The data sheet of the motors are given in Appendix A.4.

![Figure 4.5: The implemented test setup](image1)

![Figure 4.6: The coupled induction machines and the PMSM dynamometer](image2)

Fig. 4.7 shows the two-level three-phase voltage source converter used in experimental setup. A bidirectional DC supply is used as the electric vehicle battery. Both three-phase ac grid voltage and bidirectional DC supply are provided through the panel shown in Fig. 4.8. This panel is able to provide a three-phase voltage 208 \([V_{\text{rms}}]\) and an assignable DC voltage up to 800 \([V_{\text{dc}}]\).
Figure 4.7: The two-level three-phase voltage source converter

Figure 4.8: The DC-AC voltage panel
4.2 Steady State Operation

In order to validate the performance of the proposed integrated charger in the steady state operation, the reference values for the grid currents flowing into the integrated charging system are set as:

\[ i_{qs}^* = 1A \]  \hspace{1cm} (4.1)
\[ i_{ds}^* = 1A \]  \hspace{1cm} (4.2)

Fig.4.9 shows the simulation and experimental waveforms of the three-phase voltages along with their ‘qd’ reference frame values at the Point of Common Coupling (PCC), where the stator of the first machine connects to the grid for charging the battery. These voltages are measured and used in the controller unit for synchronization purpose.

(a) Simulation, y-axis: Voltage [V], x-axis: Time [20 msec]

(b) Experiment, based on the data extracted from RT-Linux

Figure 4.9: The three-phase voltages along with ‘qd’ reference frame values at the PCC
Fig. 4.10a and Fig. 4.10b show the steady state currents of the grid flowing into the stator of first machine in ‘abc’ reference frame in simulation and experiment, respectively. As illustrated, the controller regulated the three-phase currents to the desired reference values, as readily observable by looking at ‘qd’ reference frame variables.

Figure 4.10: The line to neutral voltage of the phase ‘a’ and the steady state currents of the grid flowing into ∆-connected stator of the first machine in ‘abc’ reference frame
Fig. 4.11 shows the simulation and experimental waveforms of the currents flowing into the system in ‘qd’ reference frame at the PCC. As observed, there exists some noise on experiment waveforms; however, these currents are regulated to their reference values without any steady state error.

(a) Simulation, y-axis: Current [A], x-axis: Time [sec]

(b) Experiment, based on the data extracted from RT-Linux

Figure 4.11: The simulation and experimental waveforms of the currents flowing into the system in ‘qd’ reference frame at the PCC
As discussed in section 3.4.3, there exist two phase-shifts in the system, which need to be considered for ‘qd’ transformation of the rotor and converter side quantities. The first phase-shift is between the rotor and stator of the induction machine ($\theta_{sr}$) and the second one exists between the two rotors ($\theta_{off}$). Fig.4.12 shows the generated $\theta_r$ and $\theta_2$ required for ‘qd’ transformation of the rotor and converter side quantities by considering these two phase-shifts.

Figure 4.12: The $\theta_r$ and $\theta_2$ required for ‘qd’ transformation of the rotor and converter side quantities
4.2.1 Unity Power Factor Operation

In order to show the performance of the system in unity power factor operation, we set the reference values as:

\[
i_{qs1} = 1A \quad (4.3) \\
i_{ds1} = 0A \quad (4.4)
\]

Fig.4.13 shows the line to neutral voltage of the phase ‘a’ along with three-phase grid currents flowing to the system at the PCC. As observed, the voltage and current of the phase ‘a’ are ‘in-phase’, which verifies the unity power factor operation of the proposed integrated charger.

Figure 4.13: The line to neutral voltage of the phase ‘a’ and the steady state currents of the grid flowing into Δ-connected stator of the first machine in ‘abc’ reference frame
4.2.2 Vehicle to Grid Operation (V2G)

In order to show the performance of the system in Vehicle to Grid Operation (V2G), we should inject active power from the battery (DC power supply) to the grid. This is carried out by setting a negative value for \(i_{qs}^*\) as:

\[
\begin{align*}
  i_{qs}^* &= -1A \\
  i_{ds}^* &= 1A
\end{align*}
\]  

(4.5)  
(4.6)

Fig.4.14 shows the steady state three-phase currents of the grid flowing into the stator of first machine in \(\text{abc}\) reference frame for the V2G mode. As illustrated, the controller regulated the three-phase currents to the desired reference values, as readily observable by looking at \(\text{qd}\) reference frame variables shown in Fig.4.15.

![Graph](image_url)

(a) Simulation, y-axis: Voltage [25 volt] and Current [A], x-axis: Time [20 msec]

(b) Experiment-oscilloscope

Figure 4.14: The line to neutral voltage of the phase ‘a’ and the steady state grid currents flowing into \(\Delta\)-connected stator of the first machine in \(\text{abc}\) reference frame in V2G mode
Figure 4.15: The simulation and experimental waveforms of the grid currents flowing into the system in ‘qd’ reference frame at the PCC in V2G mode.
### 4.3 Dynamic Response

For evaluating the dynamic response of the proposed integrated charger, three different dynamic tests have been carried out in both simulation and practice.

In the first case, the dynamic response of the system to a step change in active power when the charger is working with unity power factor operation is examined. This experiment is implemented through a step change in \( i_{qs1}^* \) while \( i_{ds1}^* \) (reactive power) is kept constant. The reference current \( i_{qs1}^* \) is changed from \( i_{qs1}^* = 0 [A] \) to \( i_{qs1}^* = 1 [A] \) while \( i_{ds1}^* \) is kept constant at 0 [A]. Fig.4.16 shows the transient response of the system to this step change for both simulation and experimental setup.

![Simulation and Experimental Results](image)

(a) Simulation, y-axis: Voltage [30 volt] and Current [A], x-axis: Time [100 msec]

(b) Experiment-oscilloscope data, y-axis: Voltage [30 volt] and Current [A], x-axis: Time [100 msec]

Figure 4.16: Dynamic response of the system to a step change in \( i_{qs1}^* \), the line to neutral voltage of the phase ‘a’ along with the three-phase grid currents flowing into the system in ‘abc’ reference frame

Fig.4.17 shows the transient response of the system to this step change for both simulation and experimental setup in ‘qd’ reference frame at the PCC.
Figure 4.17: Dynamic response of the system to a step change in \(i_{qs1}^*\), the simulation and experimental waveforms of the grid currents flowing into the system in ‘qd’ reference frame at the PCC
In the second case, the dynamic response of the system to a step change in $i_{ds1}^*$ is examined while $i_{qs1}^*$ is kept constant. This experiment corresponds to changing the reactive power while the active power is kept constant. The reference current $i_{ds1}^*$ is changed from $i_{ds1}^* = 0$ A to $i_{ds1}^* = 1$ A while $i_{qs1}^*$ is kept constant at 1 [A]. Fig. 4.18 shows the transient response of the system to this step change for both simulation and experimental setup. As observed, the proposed integrated charger shows relatively a fast response to this reference change.

Figure 4.18: Dynamic response of the system to a step change in $i_{ds1}^*$, the line to neutral voltage of the phase ‘a’ along with the three-phase grid currents flowing into the system in ‘abc’ reference frame.
Fig. 4.19 shows the transient response of the system to this step change for both simulation and experimental setup in ‘qd’ reference frame at the PCC.

(a) Simulation, y-axis: Current [A], x-axis: Time [sec]

(b) Experiment, based on the data extracted from RT-Linux

Figure 4.19: Dynamic response of the system to a step change in ‘\(i_{ds1}^*\)’, the simulation and experimental waveforms of the grid currents flowing into the system in ‘qd’ reference frame at the PCC.
In the final case, the dynamic response of the system for the transition from V2G mode to G2V mode is examined. In other words, we evaluate the transient response of the proposed integrated charger while it is switched from grid supplying mode to EV charging mode. For this purpose, a step change in \( i_{qs1}^* \) is applied while \( i_{ds1}^* \) is kept constant. Therefore, value of the reference current \( i_{qs1}^* \) is changed from \( i_{qs1}^* = -1 \text{A} \) to \( i_{qs1}^* = 1 \text{A} \) while \( i_{ds1}^* \) is kept constant at 1 [A]. Fig.4.20 shows the transient response of the system to this step change for both simulation and experimental setup. As observed, the proposed integrated charger shows relatively a fast response to this reference change.

(a) Simulation, y-axis: Voltage [30 volt] and Current [A], x-axis: Time [100 msec]

(b) Experiment-oscilloscope

Figure 4.20: Dynamic response of the system for switching from V2G mode to G2V mode, the line to neutral voltage of the phase ‘a’ along with the three-phase grid currents flowing into the system in ‘abc’ reference frame
Fig. 4.21 shows the transient response of the system to this step change for both simulation and experimental setup in ‘qd’ reference frame at the PCC.

(a) Simulation, y-axis: Current [A], x-axis: Time [sec]

(b) Experiment, based on the data extracted from RT-Linux

Figure 4.21: Dynamic response of the system to a step change in ‘$i_{qs1}^*$’, the simulation and experimental waveforms of the grid currents flowing into the system in ‘qd’ reference frame at the PCC
Chapter 5

Conclusion

Electric vehicle technology has been introduced as an effective solution to alleviate fossil fuel shortages and global warming-related problems. Moreover, the demand for improved driving efficiency has drawn global interest toward this growing technology. One of the major barriers to widespread deployment of electric vehicles is range anxiety. Utilities along with some EV companies have started to build charging stations along the roads; however, due to their expensive infrastructure costs, charging networks remain sparse.

Recently, integrated charge and drive solutions have been turning into a focus of research especially for the passenger vehicle market. The integrated charging concept directly charges the on-board energy sources of the electric vehicles through using part or all of the traction system. As a result, a significant portion of the dedicated charging hardware can be eliminated and considerable saving in both semiconductor and passive component costs is achieved. Avoiding the external charging system not only facilitates charging the electric vehicle but also quells any range penalty by minimizing the additional mass to the vehicle. Although integrated charge and drive systems offer some beneficial features, they are often lacking in providing galvanic isolation between the utility grid and the battery, which is recommended by most of the EV charging standards.

This thesis presents a new fully-integrated charging system suitable for dual-stator induction machines. Due to utilizing three-phase AC-grid, the proposed charging topology is a fast charger which is able to charge the EV battery much faster than single-phase on-board chargers. The proposed charging topology not only provides a galvanic isolation between the AC-grid and the battery but also offers a separate control of the active and reactive power exchange between the grid and electric vehicle. Thus, the proposed charger is able to operate with unity power factor. Additionally, the proposed integrated charger has bidirectional power transferring capability and has been demonstrated to support both G2V and V2G applications.
5.1 Contributions

The key contribution of this thesis is to introduce an isolated integrated fast battery charger topology and control for a dual-stator induction machine. The concept is to eliminate the need for an external voltage source converter, its input and output filters, isolation transformers, controls, and cooling system by using the traction motor, its converter, and other existing components. As a result, the EV battery can be charge through using the existing traction system in cost-effective manner. Cost-reduction of the fast charging hardware is crucial to increase deployment and accessibility of fast charging systems for EV users.

Another key contribution of this thesis is that the control method used for the proposed integrated charging topology provides the ability to control the active and reactive power exchange between the AC-grid and the EV battery, separately. This feature is shown by regulating the \( q \) and \( d \) components of the input currents flowing to the machine to their desired reference values, separately. Therefore, charging the electric vehicle can be done in unity power factor operation, which is a favorable option from the grid operator point of view. Due to the bidirectional capability of the proposed topology, the integrated charge and drive system is able to supply power for the distribution grid which is known as V2G application.

The equivalent model and equations of the proposed system in both \( qd \) and \( abc \) reference frames are achieved and the control strategy for regulating the currents flowing into the system is introduced. Finally, the performance of the proposed isolated integrated charger along with its features are demonstrated through simulation and experimental verification using two wounded-rotor induction machines and three-phase voltage source converter.

5.2 Future Work

As an extension to this thesis, the following presents the potential research areas related to this isolated integrated battery charger:

1. The experimental setup consists of two wounded-rotor induction machines, where each has brushes with considerable resistances. It is recommended for future work to implement the proposed integrated charger with a double-stator squirrel-cage induction machine and liquid cooling system so that machine parameters become more realistic.

2. Although fast charging is able to charge the EV battery in shorter time, it would be beneficial for future work to consider the single-phase charging possibility. The reason behind this is that some residential garages do not have access to the three-phase AC grid; therefore, by providing the single-phase charging possibility for the proposed charger, one can charge the EV at home.
Appendices
Appendix A

Induction Machine

A.1 Inductance

The winding inductance of the induction machine is achieved based on the inductance relationship given for the salient-pole synchronous machine in [47]. However, in the case of induction machine, the air-gap is uniform and $2\theta_r$ variation in the self- and mutual inductances do not occur. Fig.A.1 shows a two-pole, three-phase, wye-connected symmetrical induction machine along with its rotor and stator windings [47]. The $\theta_r$ and $\omega_r$ are angular displacement and velocity of the rotor with respect to the stator.

For a symmetrical induction machine, all the stator self-inductances and similarly all the rotor self-inductances are equal for three phases with value of:

\[
L_{asas} = L_{hsbs} = L_{cscs} = L_{ls} + L_{ms}
\]

\[
L_{arar} = L_{brbr} = L_{crcr} = L_{lr} + L_{mr}
\]

where $L_{ms}$, and $L_{ls}$, are magnetizing and leakage inductances of the stator and $L_{mr}$, and $L_{lr}$ are magnetizing and leakage inductances of the rotor, respectively. If we assume that the uniform air-gap between stator and rotor has length of $g$, one can express the magnetizing inductances as:

\[
L_{ms} = \left(\frac{N_s}{2}\right)^2 \frac{\pi \mu_0 r l}{g}
\]

\[
L_{mr} = \left(\frac{N_r}{2}\right)^2 \frac{\pi \mu_0 r l}{g}
\]
Figure A.1: Two-pole, three-phase, wye-connected symmetrical induction machine rotor and stator configurations [47]
Likewise, all the stator to stator and rotor to rotor mutual inductances are equal with the value of:

\[ L_{asbs} = -\frac{1}{2}L_{ms} \]  
\[ L_{arbr} = -\frac{1}{2}L_{mr} \]  

Expressions for mutual inductances between stator and rotor windings for each phase have equal value as phase 'a' and are as:

\[ L_{asar} = L_{sr}\cos\theta_r \]  
\[ L_{asbr} = L_{sr}\cos\left(\theta_r + \frac{2\pi}{3}\right) \]  
\[ L_{ascr} = L_{sr}\cos\left(\theta_r - \frac{2\pi}{3}\right) \]  

where \( \theta_r \) is angular displacement of the rotor and \( L_{sr} \) is

\[ L_{sr} = \left(\frac{N_s}{2}\right)\left(\frac{N_r}{2}\right)\pi\mu_0\gamma l \]  

Therefore, winding inductances for a symmetrical three-phase induction machine are derived as:

\[
L_s = \begin{bmatrix}
L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\
-\frac{1}{2}L_{ms} & L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} \\
-\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls} + L_{ms}
\end{bmatrix}
\]  
\[
L_r = \begin{bmatrix}
L_{lr} + L_{mr} & -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} \\
-\frac{1}{2}L_{mr} & L_{lr} + L_{mr} & -\frac{1}{2}L_{mr} \\
-\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} & L_{lr} + L_{mr}
\end{bmatrix}
\]  
\[
L_{sr} = L_{sr} \begin{bmatrix}
cos\theta_r & cos\left(\theta_r + \frac{2\pi}{3}\right) & cos\left(\theta_r - \frac{2\pi}{3}\right) \\
cos\left(\theta_r - \frac{2\pi}{3}\right) & cos\theta_r & cos\left(\theta_r + \frac{2\pi}{3}\right) \\
cos\left(\theta_r + \frac{2\pi}{3}\right) & cos\left(\theta_r - \frac{2\pi}{3}\right) & cos\theta_r
\end{bmatrix}
\]
A.2 Flux Linkage and Voltage Equations

Based on the machine inductances achieved in section A.1, the flux linkage and voltage equation for phase ’a’ of a three-phase magnetically linear system such as an induction machine can be expressed as:

\[ \lambda_{as} = L_{asas}i_{as} + L_{asbs}i_{bs} + L_{ascas}i_{cs} + L_{asar}i_{ar} + L_{asbr}i_{br} + L_{ascr}i_{cr} \] (A.14)

\[ v_{as} = r_{s}i_{as} + \frac{d\lambda_{as}}{dt} \] (A.15)

Since the induction machine is symmetrical, flux linkages and voltage equations for phases ’b’ and ’c’ can be achieved similarly. Equations A.16 and A.17 represent the mathematical model for a three-phase induction machine.

\[ v_{abcs} = r_{s}i_{abcs} + p\lambda_{abcs} \] (A.16)
\[ v_{abcr} = r_{r}i_{abcr} + p\lambda_{abcr} \] (A.17)

where the flux linkages are:

\[
\begin{bmatrix}
\lambda_{abcs} \\
\lambda_{abcr}
\end{bmatrix} = 
\begin{bmatrix}
L_{s} & L_{sr} \\
(L_{sr})^T & L_{r}
\end{bmatrix}
\cdot
\begin{bmatrix}
i_{abcs} \\
i_{abcr}
\end{bmatrix}
\] (A.18)

In all the above equations, ’s’ subscript denotes variables and parameters associated with the stator circuit and ’r’ subscript denotes variables and parameters associated with the rotor circuit. Moreover, all the bold letters denotes the matrices, for example \( r_{s} \) and \( r_{r} \) are both diagonal three by three matrices that each has equal non-zero elements. The derivative operator is illustrated by \( p \), and \( v_{abc} \) and \( i_{abc} \) are voltage and current matrices of the three phase machine.

A.3 Park Transform for Induction Machine

By using Park Transform, inductances and accordingly all the flux linkage and voltage equations of an induction machine can be transformed from a three phase ”abc” stationary reference frame to any arbitrary rotating reference frame and vice versa.

Depending on which of ”d” or ”q” axes is aligned with the magnetic field of phase ”a”, the transformation matrices would be different. According to [47], ”q” axis is aligned with magnetic flux of phase ”a”; therefore, Park Transform matrices are defined as below:

\[ f_{qd0} = K^\omega f_{abc} \] (A.19)
\[ f_{abc} = (K^\omega)^{-1} f_{qd0} \] (A.20)
\[ \theta = \int \omega dt \] (A.21)
\[ K^\omega = \frac{2}{3} \begin{bmatrix} \cos \omega t & \cos \left( \omega t - \frac{2\pi}{3} \right) & \cos \left( \omega t + \frac{2\pi}{3} \right) \\ \sin \omega t & \sin \left( \omega t - \frac{2\pi}{3} \right) & \sin \left( \omega t + \frac{2\pi}{3} \right) \end{bmatrix} \]  

(A.22)

\[ (K^\omega)^{-1} = \begin{bmatrix} \cos \omega t & \sin \omega t & 1 \\ \cos \left( \omega t - \frac{2\pi}{3} \right) & \sin \left( \omega t - \frac{2\pi}{3} \right) & 1 \\ \cos \left( \omega t + \frac{2\pi}{3} \right) & \sin \left( \omega t + \frac{2\pi}{3} \right) & 1 \end{bmatrix} \]  

(A.23)

where \( \omega \) and \( \theta \) are the angular velocity and angular displacement of the arbitrary reference frame.

Equation 2.10 expresses the voltage relations in "abc" reference frame for a three-phase induction machine while rotor parameters are referred to stator side. In order to find voltage equations of an induction machine in "qd0" reference frame, we need to apply Park Transform to inductance matrices A.11, A.12, and A.13:

\[
\begin{bmatrix} \lambda_{qd0s} \\ \lambda'_{qd0r} \end{bmatrix} = \begin{bmatrix} K^\omega L_s (K^\omega)^{-1} & K^\omega L_{sr}' (K^\omega)^{-1} \\ K^\omega \left(L_{sr}'\right)^T (K^\omega)^{-1} & K^\omega L_r' (K^\omega)^{-1} \end{bmatrix} \cdot \begin{bmatrix} i_{qd0s} \\ i'_{qd0r} \end{bmatrix}
\]  

(A.24)

which results in:

\[ K^\omega L_s (K^\omega)^{-1} = \begin{bmatrix} L_s + L_M & 0 & 0 \\ 0 & L_s + L_M & 0 \\ 0 & 0 & L_s \end{bmatrix} \]  

(A.25)

\[ K^\omega L_{sr}' (K^\omega)^{-1} = \begin{bmatrix} L_{sr}' + L_M & 0 & 0 \\ 0 & L_{tr}' + L_M & 0 \\ 0 & 0 & L_{tr}' \end{bmatrix} \]  

(A.26)

\[ K^\omega \left(L_{sr}'\right)^T (K^\omega)^{-1} = K^\omega L_r' (K^\omega)^{-1} = \begin{bmatrix} L_M & 0 & 0 \\ 0 & L_M & 0 \\ 0 & 0 & 0 \end{bmatrix} \]  

(A.27)

where

\[ L_M = \frac{3}{2} L_{ms} \]  

(A.28)
By substituting A.25, A.26, and A.27 into A.24, voltage equations of an induction machine in "qd0" reference frame is achieved as:

\[
v_{qs} = r_s i_{qs} + \omega \lambda_{ds} + p \lambda_{qs} \tag{A.29}
\]
\[
v_{ds} = r_s i_{ds} - \omega \lambda_{qs} + p \lambda_{ds} \tag{A.30}
\]
\[
v_{0s} = r_s i_{0s} + p \lambda_{0s} \tag{A.31}
\]
\[
v'_{qr} = r'_r i'_{qr} + (\omega - \omega_r) \lambda'_{dr} + p \lambda'_{qr} \tag{A.32}
\]
\[
v'_{dr} = r'_r i'_{dr} - (\omega - \omega_r) \lambda'_{qr} + p \lambda'_{dr} \tag{A.33}
\]
\[
v'_{0r} = r'_r i'_{0r} + p \lambda'_{0r} \tag{A.34}
\]

where \( \omega_r \) is the angular velocity of the rotor and the flux linkages are as:

\[
\lambda_{qs} = L_{ls} i_{qs} + L_M (i_{qs} + i'_{qr}) \tag{A.35}
\]
\[
\lambda_{ds} = L_{ls} i_{ds} + L_M (i_{ds} + i'_{dr}) \tag{A.36}
\]
\[
\lambda_{0s} = L_{ls} i_{0s} \tag{A.37}
\]
\[
\lambda'_{qr} = L'_{lr} i'_{qr} + L_M (i_{qs} + i'_{qr}) \tag{A.38}
\]
\[
\lambda'_{dr} = L'_{lr} i'_{dr} + L_M (i_{ds} + i'_{dr}) \tag{A.39}
\]
\[
\lambda'_{0r} = L'_{lr} i'_{0r} \tag{A.40}
\]
A.4 Induction Machine Datasheet

**Nominal values:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage (Y/delta)</td>
<td>360/208 V</td>
</tr>
<tr>
<td>Nominal current</td>
<td>2/3.5 A</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Nominal speed (synchronous/asynchronous):</td>
<td>1800/1680 min⁻¹</td>
</tr>
<tr>
<td>Nominal power</td>
<td>0.8 kW</td>
</tr>
<tr>
<td>Cos phi</td>
<td>1/0.75</td>
</tr>
<tr>
<td>Exciter voltage</td>
<td>130~/24= V</td>
</tr>
<tr>
<td>Exciter current</td>
<td>0.4~/11A=</td>
</tr>
</tbody>
</table>

In case that the nominal values deviate from the name plate, the data of the name plate shall prevail.

**Additional data:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum of inertia</td>
<td>0.0066 kgm²</td>
</tr>
</tbody>
</table>

**Equivalent circuit:**

![Equivalent circuit diagram](image)

**Circuit**

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 phase resistor (20°)</td>
<td>8 Ω</td>
</tr>
<tr>
<td>X1s reactance stator</td>
<td>17.5 Ω</td>
</tr>
<tr>
<td>U1 phase voltage</td>
<td>360 V</td>
</tr>
<tr>
<td>R2 rotor resistance (20°)</td>
<td>7.3 Ω</td>
</tr>
<tr>
<td>X2s reactance rotor</td>
<td>17.6 Ω</td>
</tr>
<tr>
<td>Xh main reactance</td>
<td>193 Ω</td>
</tr>
</tbody>
</table>

Figure A.2: Wounded-Rotor Induction Machine Datasheet
Appendix B

Controller Code

B.1 ‘C’ Block in the Simulation
#include <math.h>

// Voltages
float vab = 0;
float vbc = 0;
float vca = 0;
float V = 0;
float uabs2 = 0;
float ubcs2 = 0;
float valf = 0;
float vbet = 0;
float vqs1 = 0;
float vds1 = 0;
float ualf = 0;
float ubet = 0;
float uqs2 = 0;
float uds2 = 0;
float ua = 0;
float ub = 0;
float uc = 0;
float theta = 0;
const double Ts = 0.0002;

// Currents
float iqs1 = 0;
float ids1 = 0;
float iqr = 0;
float idr = 0;
float iqs2 = 0;
float ids2 = 0;
float ialfs1 = 0;
float ibets1 = 0;
float ialfr = 0;
float ibetr = 0;
float ialfs2 = 0;
float ibets2 = 0;
float ia1 = 0;
float ib1 = 0;
float ic1 = 0;
float iar = 0;
float ibr = 0;
float icr = 0;
float ia2 = 0;
float ib2 = 0;
float ic2 = 0;
float iqs1_ref = 0;
float ids1_ref = 0;

// Integration
const double k11 = 5*282.414890;
const double k12 = 5*142.273784;
static double X1d_1 = 0, X1q_1 = 0, E1d_1 = 0, E1q_1 = 0;
static double X1d_0 = 0, X1q_0 = 0, E1d_0 = 0, E1q_0 = 0;

// States
float lamqs1 = 0;
float lamds1 = 0;
float lamqr = 0;
float lamdr = 0;
float lamqs2 = 0;
float lamds2 = 0;

// Xr
float xr1 = 0;
float xr2 = 0;
float xr3 = 0;
float xr4 = 0;
float xr5 = 0;
float xr6 = 0;

// U
float u1 = 0;
float u2 = 0;
float u11 = 0;
float u22 = 0;
float uqr = 0;
float uad = 0;
float uas2 = 0;
float ubs2 = 0;
float ucs2 = 0;

// Inputs
vab = Input(0);
vbc = Input(1);
ias1 = Input(2);
ibs1 = Input(3);
iar = Input(4);
ibr = Input(5);
ias2 = Input(6);
ibs2 = Input(7);
inqs1_ref = Input(8);
ids1_ref = Input(9);

// creating third phase currents
ics1 = -(ias1 + ibs1);
icr = -(iar + ibr);
ics2 = -(ias2 + ibs2);
vca = -(vab + vbc);

// generating quasi synchronization
valf = (0.66666667 * vab) - (0.33333333 * vbc) - (0.33333333 * vca);
vbet = (0.577350269 * vca) - (0.577350269 * vbc);
V = sqrt((valf * valf) + (vbet * vbet));
theta = -atan2(vbet, valf);
vqs1 = valf * cos(theta) - vbet * sin(theta);
vids1 = valf * sin(theta) + vbet * cos(theta);
ialfl1 = -(0.66666667 * ias1) - (0.33333333 * ibs1) - (0.33333333 * ics1);
ibetl1 = -(0.577350269 * ics1) + (0.577350269 * ibs1);
ialfr1 = -(0.66666667 * iar) + (0.33333333 * ibr) + (0.33333333 * icr);
ibetr1 = -(0.577350269 * icr) - (0.577350269 * ibr);
ialfl2 = -(0.66666667 * ias2) - (0.33333333 * ibs2) - (0.33333333 * ics2);
ibetl2 = -(0.577350269 * ics2) + (0.577350269 * ibs2);
ialfr2 = -(0.66666667 * iar) + (0.33333333 * ibr) + (0.33333333 * icr);
ibetr2 = -(0.577350269 * icr) - (0.577350269 * ibr);

// Generating States
lamqs1 = 0.814399999999999 * iqs1 + 0.000000000000001 * iqs2 + 0.767999999999998 * iqr;
lamqs2 = 0.000000000000001 * iqs1 + 0.814399999999999 * iqs2 - 0.767999999999998 * iqr;
lamqr = 0.767999999999998 * iqs1 - 0.767999999999998 * iqs2 + 1.629399999999997 * iqr;
Appendix B. Controller Code

\[
\begin{align*}
\text{lamds1} &= 0.814399999999999 \cdot \text{idsl} + 0.000000000000001 \cdot \text{idss} + 0.767999999999998 \cdot \text{idr}; \\
\text{lamds2} &= 0.000000000000001 \cdot \text{idsl} + 0.814399999999999 \cdot \text{idss} - 0.767999999999998 \cdot \text{idr}; \\
\text{lamdr} &= 0.767999999999998 \cdot \text{idsl} + 0.767999999999998 \cdot \text{idss} + 1.629399999999997 \cdot \text{idr};
\end{align*}
\]

// Generating \(Xr=P*W\)

\[
\begin{align*}
\text{xr1} &= 0.000000012957189 \cdot \text{iqs1\_ref} + 0.021220212811471 \cdot \text{ids1\_ref} - 0.000000000175753 \cdot \text{vqs1} - 0.002652519856277 \cdot \text{vds1}; \\
\text{xr2} &= -0.202299231032401 \cdot \text{iqs1\_ref} + 0.070068815200429 \cdot \text{ids1\_ref} - 0.000141836892264 \cdot \text{vqs1} + 0.003315110127174 \cdot \text{vds1}; \\
\text{xr3} &= -0.001070064907079 \cdot \text{iqs1\_ref} - 0.041066625214281 \cdot \text{ids1\_ref} + 0.00013755198532 \cdot \text{vqs1} + 0.000000000075950 \cdot \text{vds1}; \\
\text{xr4} &= -0.01220212811471 \cdot \text{iqs1\_ref} + 0.000000012957189 \cdot \text{ids1\_ref} - 0.002652519856277 \cdot \text{vqs1} - 0.0000000000175753 \cdot \text{vds1}; \\
\text{xr5} &= -0.070068815200429 \cdot \text{iqs1\_ref} - 0.202299231032401 \cdot \text{ids1\_ref} + 0.003315110127174 \cdot \text{vqs1} - 0.000141836892264 \cdot \text{vds1}; \\
\text{xr6} &= 0.041066625214281 \cdot \text{iqs1\_ref} - 0.001070064907079 \cdot \text{ids1\_ref} + 0.000000000075950 \cdot \text{vqs1} + 0.00013755198532 \cdot \text{vds1};
\end{align*}
\]

// Generating \(Un = K*e = K*(Xr - X)\)

\[
\begin{align*}
\text{u1} &= -17.054245 \cdot (\text{xr1} - \text{lamqs1}) + 302.448936 \cdot (\text{xr2} - \text{lamqs2}) - 129.886596 \cdot (\text{xr3} - \text{lamqr}) + 3.112246 \cdot (\text{xr4} - \text{lamds1}) - 3.558555 \cdot (\text{xr5} - \text{lamds2}) - 3.112247 \cdot (\text{xr6} - \text{lamdr}); \\
\text{u2} &= -3.112247 \cdot (\text{xr1} - \text{lamqs1}) + 3.558555 \cdot (\text{xr3} - \text{lamqr}) - 17.054245 \cdot (\text{xr4} - \text{lamds1}) + 302.448936 \cdot (\text{xr5} - \text{lamds2}) - 129.886596 \cdot (\text{xr6} - \text{lamdr});
\end{align*}
\]

// Generating \(E = Y - R\)

\[
\begin{align*}
\text{E1q\_1} &= \text{iqs1\_ref} - \text{iqs1}; \\
\text{E1d\_1} &= \text{ids1\_ref} - \text{ids1};
\end{align*}
\]

// Integration \(Ui\)

\[
\begin{align*}
\text{X1q\_1} &= \text{X1q\_0} + \text{Ts} / 2 \cdot (\text{E1q\_1} + \text{E1q\_0}); \\
\text{X1d\_1} &= \text{X1d\_0} + \text{Ts} / 2 \cdot (\text{E1d\_1} + \text{E1d\_0}); \\
\text{u11} &= \text{k11} \cdot \text{X1q\_1} - \text{k12} \cdot \text{X1d\_1}; \\
\text{u22} &= \text{k12} \cdot \text{X1q\_1} - \text{k11} \cdot \text{X1d\_1};
\end{align*}
\]

// Updating variables

\[
\begin{align*}
\text{X1q\_0} &= \text{X1q\_1}; \\
\text{X1d\_0} &= \text{X1d\_1}; \\
\text{E1q\_0} &= \text{E1q\_1}; \\
\text{E1d\_0} &= \text{E1d\_1};
\end{align*}
\]

// Generating \(U=Ui+Un\)

\[
\begin{align*}
\text{uq} &= \text{u1} + \text{u11}; \\
\text{ud} &= \text{u2} + \text{u22}; \\
\text{if} (\text{uq} \geq 350) \\
\text{uq} &= 350; \\
\text{if} (\text{ud} \geq 350) \\
\text{ud} &= 350; \\
\text{if} (\text{uq} \leq -350) \\
\text{uq} &= -350; \\
\text{if} (\text{ud} \leq -350) \\
\text{ud} &= -350; \\
\text{ualf} &= \text{uq} \cdot \cos(\theta) + \text{ud} \cdot \sin(\theta); \\
\text{ubet} &= \text{ud} \cdot \cos(\theta) - \text{uq} \cdot \sin(\theta); \\
\text{uas2} &= \text{ualf} / 1.732; \\
\text{ubs2} &= (-0.5 \cdot \text{ualf} - 0.8660254038 \cdot \text{ubet}) / 1.732; \\
\text{ucs2} &= (-\text{uas2} - \text{ubs2}); \\
\text{uabs2} &= \text{uas2} - \text{ubs2}; \\
\text{ubcs2} &= \text{ubs2} - \text{ucs2};
\end{align*}
\]

// Outputs

\[
\begin{align*}
\text{Output(0)} &= \text{uq}; \\
\text{Output(1)} &= \text{ud}; \\
\text{Output(2)} &= \text{iqs1}; \\
\text{Output(3)} &= \text{ids1}; \\
\text{Output(4)} &= \text{uas2}; \\
\text{Output(5)} &= \text{ubs2}; \\
\text{Output(6)} &= \text{ucs2};
\end{align*}
\]
Appendix B. Controller Code

B.2 ‘C’ Code in the RT-Linux System for the Practical Setup

```
// Milad Keshani-Research Thesis - RT-Linux Control Program
// Prof. Peter Lehn-Energy system lab, University of Toronto
// Last Update: 24 August 2018

//******************************************************************************
// ECE Dept: BEGIN - DEFINE GRAPHICAL USER INTERFACE
//******************************************************************************

// rtce_boolean_param gating_on false "Gating on"
// rtce_line
// rtce_boolean_param filter_c false "current filters"
// rtce_boolean_param filter_v false "voltage filter"
// rtce_line
// rtce_scalar_slider thetaoff 3.1 2.5 3.5 "offset phase of rotor"
// rtce_scalar_slider thetaSR 0.0 -0.5 0.5 "phaseshift stator/rotor"
// rtce_scalar_slider thetadel 0.5236 -1 1 "phaseshift Delta/Wye"
// rtce_scalar_slider slider 0.0 -0.5 0.5 "slide_offset"
// rtce_scalar_param Vdc_ref 300 300 400 "Vdc_ref"
// rtce_scalar_param Iq_ref 1.0 -3.0 3.0 "Iq_ref"
// rtce_scalar_param Id_ref 1.0 -3.0 3.0 "Id_ref"
// rtce_new_column
// rtce_scalar_meter meter_vDC "%0.0f V" "Vdc"

//******************************************************************************
// ECE Dept: END - DEFINE GRAPHICAL USER INTERFACE
//******************************************************************************

#define __VERBOSE // for output of PRINTF

#include "rtce_module.h"
#include "rtce_control.h"
#include "acromag.h"
#include "../fpga/pwm.h"

#include automatically created parameter definitions
#include "parser_output.h"

// get the shared memory support for parameter exchange
#include "rtce_shared_mem_param.h"
#include "rt_math.h"
#include "math_tools.h"
#include "control_tools.h"

// excitation- and booster- VSIs
#define SET_PWM_G24(value) SET_PWM_Q1(value)
#define SET_PWM_G28(value) SET_PWM_Q1(value)
```
Appendix B. Controller Code

```c
#define SET_PWM_G2C(value) SET_PWM_Q3(value)
#define SET_PWM_G1A(value) SET_PWM_P1(value)
#define SET_PWM_G1B(value) SET_PWM_P2(value)
#define SET_PWM_G1C(value) SET_PWM_P3(value)

static float signal[64];
#define SIGNAL(i) signal[i]

static int rtce_create_sharedmem(void) { 
    int result = rtce_create_sharedmem_for_this_number_of_items(
        RTC_NUM_SCALAR_PARAMS,
        RTC_NUM_BOOLEAN_PARAMS,
        RTC_NUM_SCALAR_METERS,
        RTC_NUM_SCALAR_SLIDERS);

    // only the control-module may reset the select-index on startup,
    // if the userinterface resets this index on startup,
    // it changes the parameter that might be used by a running controller
    if ((result==0) && (RTC_NUM_CONFIRM_PARAMS!=0)) {
        *rtce_ctrl_memory_block_select_index = 0;
    }
    return result;
}

// ----------------------------------------------------------------------
// module section
//
// this controller can be built as a module
// in this case only this file needs to be recompiled
// ----------------------------------------------------------------------
#ifdef MODULE
// ATTENTION: no floating point in these functions !!!!

int init_module(void) {
    PRINTF("init_module - begin\n");
    PRINTF(" $Id: test_control.c,v 3.0 2002/04/23 19:20:27 martin Exp martin $\n");

    rtce_create_sharedmem();

    rtce_pwm_set_ts_for_pwm_and_AD(200);
    PRINTF("init_module - end\n");
    return 0;
}

void cleanup_module(void) {
    PRINTF("cleanup_module - begin\n");
    rtce_reset_control();
    PRINTF("cleanup_module - end\n");
```
Appendix B. Controller Code

RT_linux_Code.c

}
#endif

// -----------------------------------------------------------------------
// CONTROL FUNCTIONS
//
// is started when the thread is created
// floating point and all symbol support
// -----------------------------------------------------------------------

static hrtime_t t_ns_start; // time in ns between bootup and controller start
RTCE_SCALAR_TYPE ts;        // sampling period in s, set in init_control()

void rtce_init_control(void) {
    PRINTF("init_control - begin\n");

    {
        int i;
        for (i=0; i<32; i++) ROUTE(i+ 0) = &SIGNAL(i);
        for (i=0; i<16; i++) ROUTE(i+32) = &IN(i);
        for (i=0; i<16; i++) ROUTE(i+48) = &OUT(i);
        for (i=0; i<64; i++) rbi->route[i] = i;
    }

    rtce_route = &(rbi->route[0]);
    rtce_pwm_set_gating_mode(DCAC);
    t_ns_start = gethrtime();
    PRINTF("init_control - end\n");
    return;
}

// reset global variables if necessary ...
void rtce_reset_control(void) {
}

// stop the controller if it has it's own timing
void rtce_stop_control(void) {
    rtce_pwm_stop();
}

// calc the time that has elapses since t_ns and show it
static void ___inline___ update_execution_time_meter(hrtime_t t_ns) {
    hrtime_t t_delta;

    // that's aprox. the time the control loop needs
    // to execute in ns:
    t_delta = gethrtime() - t_ns_start-t_ns;
}

// turn the gating on according to switch_var and some security issues
static void __inline__
gating_main_switch(char switch_var, RTCE_SCALAR_TYPE v_DC) {
    #define V_DC_MIN (100.0) // mainly to ensure the DC voltage sensor is working
    #define V_DC_MAX (400.0) // to ensure the VSI is not operated overrated
    // keep a margin to the maximum sensor value

    // old_gating_on = TRUE on init ensures that
    // the gating on controller startup can not be on by default
    static char old_gating_on = TRUE;
    if (old_gating_on!=switch_var)
    {
        old_gating_on= switch_var;
        if ( switch_var ) rtce_pwm_start();
        else rtce_pwm_stop();
    }

    if ( V_DC_MIN > v_DC || v_DC > V_DC_MAX) rtce_pwm_stop();
}

void rtce_run_control(void) {
    // DEFINE GLOBAL VARIABLES
    hrtimer_t t_ns; // time in ns since start of controller
    RTCE_SCALAR_TYPE t; // time in s since start of controller
    int T_sample; // sample period in microseconds
    RTCE_SCALAR_TYPE v_DC; // required name of the dc bus voltage variable

    // ********************************************
    // ECE Dept: BEGIN - DO NOT MODIFY OR ADD **ANY** CODE BEFORE THIS POINT !!!
    // ********************************************

    // ********************************************
    // VARIABLE DECLARATIONS
    // ********************************************

    // HELPFUL HINTS:
    // USE "STATIC" for variable that need to be initialized at time t=0 and need
    // to keep their old value from sample period to sample period.
    // e.g. history terms in PI-controllers
    //
    // USE "FLOAT" for values that can be purged at the end of each loop
    //
    // USE "CONST" to define parameters. These parameters will be substituted with
    // their numeric value at compile time.
    // ********************************************

double vab, vbc, vca, V;
double vabs2, vbcas2;
double valf, vbet, vqs1, vds1, vqss1, vdss1;
double ualf, ubet;
double ualfss, ubetss, uqss2, udss2, uass2, ubss2, ucss2;
double Vta, Vtb, Vtc, Vtab, Vtbc;
double ias1, ibs1, ics1, iqs1, ids1;
double iar, ibr, icro, icqr, idr;
double ias2, ibs2, ics2, iqrs2, ids2;
double ialfs1, ibets1, ialfr, ibetr, ialfs2, ibets2;

    // *** Filter ***

double vqs1_f;
double iqsf1_f, ids1_f, icr_f, idr_f, iqrs2_f, ids2_f;

    // *** Integration ***

const double k11 = 282.414890;
const double k12 = 142.273784;
static double X1d_1 = 0.0, X1q_1 = 0.0, E1d_1 = 0.0, E1q_1 = 0.0;
static double X1d_0 = 0.0, X1q_0 = 0.0, E1d_0 = 0.0, E1q_0 = 0.0;

    // *** States ***
double lamqs1;
double lamds1;
double lamqr;
double lamdr;
double lamqs2;
double lamds2;

    // *** Xr ***
double xr1;
double xr2;
double xr3;
double xr4;
double xr5;
double xr6;

    // **** U ***
double u1;
double u2;
double u11;
double u22;
double uq;
double ud;
double uas2;
double ubs2;
double ucs2;

    // *** Thetas ***

double thetas1;
double thetar;
double thetas2;
double thet;
double thetas2_act;
double thetar_act;
double M_a, M_b, M_c;

const double pi = 3.14159265;
const double Ts = 0.0002; // Sampling time
const double R = 0.25;
const double L_F = 0.0016; // L of the Filter
const double L_T = 0.000053; // L of the Transformer
const int f = 60;
const double w = 376.9911184;

// -----------------------------Current LPF-----------------------------
//const double taw1 = 0.0002; // Id and Iq filter time constant
//const double a1 = 0.36787944; // exp(-Ts/taw1) For Current feedback LPF

const double a1 = 0.333333; // For bilinear (2*taw1/Ts - 1)/(2*taw1/Ts + 1)
const double b1 = 0.333333; // 1/(2*taw1/Ts + 1)

// -----------------------------Current LPF-----------------------------
static double I_df = 0, I_qf = 0; // Filtered feedback current Idf and Iqf
static double I_d_1 = 0, I_q_1 = 0; //Id(k-1) Iq(k-1), set for the feedback current LPF

// *******************************************************
// BEGIN - DATA AQUISITION & CONVERSION
// *******************************************************

vab = IN(0) * 50.0 + 0.24;
vbc = IN(1) * 50.0 + 0.24;
ias1 = IN(2) * 5.0;
ibs1 = IN(3) * 5.0 + 0.065;
ias = IN(4) * (-5.0) - 0.05; // current sensor 5A/V - modify gain if necessary
ibr = IN(5) * (-5.0) - 0.071;
ias2 = IN(6) * 5.0 + 0.002;
ibs2 = IN(7) * 5.0 + 0.071;

v_DC = IN(8)*50.0; // voltage sensor 50.0V/V ** DO NOT CHANGE THE NAME OF THIS VARIABLE **

// *******************************************************
// END - DATA AQUISITION & CONVERSION
// *******************************************************

// ASSIGN SAMPLING RATE & SWITCHING RATE
// *******************************************************
Tsample = 200; // This assigns the sample period in microseconds (integer number)
rtce_pwm_set_ts_for_pwm_and_AD(Tsample);
// ******************************************************************************************
// BEGIN - YOUR CONTROL ALGORITHM
// ******************************************************************************************

// creating third phase currents and voltage

v_DC = 380.0;
ics1 = -(ias1 + ibs1);
icro = -(iar + ibr);
ics2 = -(ias2 + ibs2);
va = -(vab + vbc);

// Quasi Synchronization of S1

//valf = (0.66666667* vab )+(0.33333333* vbc );
//vbet = -(0.577350269* vbc );
valf = (0.66666667* vab ) - (0.33333333* vbc ) - (0.33333333* vca);
vbet = (0.577350269* vca ) - (0.577350269* vbc );
V = sqrt((valf * valf ) + (vbet * vbet));
theetas1 = -atan2(vbet,valf);
vs = valf * cos( theetas1 ) - vbet * sin( theetas1 );
vs = vs;
second_order_low_pass(vs, 30.0, 0.0002);
vs = 0.0;

ialf = (0.66666667* has1 ) - (0.33333333* hbs1 ) - (0.33333333* ics1 );
ibets1 = (0.577350269* ics1 ) - (0.577350269* hbs1 );

ics = (ialf * cos( theetas1 ) - ibets1 * sin( theetas1 ));
ids = (ialf * sin( theetas1 ) + ibets1 * cos( theetas1 ));

// Finding phase-shifts between voltages

//valfs2 = (0.66666667* vab2 )+(0.33333333* vbc2 );
//vbet2 = -(0.577350269* vbc2 );
//theetas2_act = -atan2(vbet2,valfs2);
//theetas2 = theetas1 + thetas;
//thetaoff is the phase shift of two machines rotor in Rad
//if (theetas2 > 3.1415926536)
// thetas2 = thetas2 - 6.28318531;

//vqs = valfs2 * cos( theetas2 ) - vbet2 * sin( theetas2 );
//vds = valfs2 * sin( theetas2 ) + vbet2 * cos( theetas2 );

//ialfr = (0.66666667* iar )+(0.33333333* ibr );
//ibetr = -(0.577350269* ibr );
//thetar_act = -atan2(ibetr,ialfr);
// thetar = thetas1 + thetaSR; // thetaSR is the phase shift between stator and rotor of each machine
// if (thetar > 3.1415926536)
// thetar = thetar - 6.28318531;

// iqr = (ialfr * cos(thetar) - ibetr * sin(thetar));
// idr = (ialfr * sin(thetar) + ibetr * cos(thetar));

// Quasi Synchronization of r
ialfr = 0.3269774 * ((0.666666667* iar ) - (0.33333333* ibr ) - (0.33333333* icr ));
ibetr = 0.3269774 * ((0.577350269* icr ) - (0.577350269* ibr ));

// Quasi Synchronization of s2
ialfs2 = (0.666666667* ias2 ) - (0.33333333* ibr2 ) - (0.33333333* ics2 );
ibets2 = (0.577350269* ics2 ) - (0.577350269* ibr2 );

// current filters
iqs1_f = iq1;
id1_f = id1;
qs2_f = iq2;
ids2_f = id2;

// ************** Controller Unit **************
// Generating States X from Observer

lamq1 = 0.8143999999999999 * iqs1_f + 0.00000000000001 * iqs2_f + 0.7679999999999999 * 
         lqr_f;

lamq2 = 0.00000000000001 * iqs1_f + 0.8143999999999999 * iqs2_f - 0.7679999999999999 * 
         lqr_f;

lamqr = 0.7679999999999999 * iqs1_f - 0.7679999999999999 * iqs2_f + 1.6293999999999999 * 
         lqr_f;

lamds1 = 0.8143999999999999 * ids1_f + 0.00000000000001 * ids2_f + 0.7679999999999999 * 
         ldr_f;

lamds2 = 0.00000000000001 * ids1_f + 0.8143999999999999 * ids2_f - 0.7679999999999999 * 
         ldr_f;

lamdr = 0.7679999999999999 * ids1_f - 0.7679999999999999 * ids2_f + 1.6293999999999999 * 
         ldr_f;

// Generating state references Xr=P*W

xr1 = 0.000000012957189* iqs1_ref + 0.021220212811471* ids1_ref - 0.00000000175753 * 
      vqs1_f - 0.002652519856277* vds1;
xr2 = -0.20229231032401* iqs1_ref + 0.070068815200429* ids1_ref - 0.000141836892264 * 
      vqs1_f - 0.003315110127174* vds1;
xr3 = -0.00107064907079* iqs1_ref - 0.04106625214281* ids1_ref + 0.000133755198532 * 
      vqs1_f - 0.000000000875950* vds1;
xr4 = -0.021220212811471* iqs1_ref + 0.000000012957189* ids1_ref + 0.002652519856277 * 
      vqs1_f - 0.00000000175753* vds1;
xr5 = -0.070068815200429* iqs1_ref - 0.20229231032401* ids1_ref + 0.003315110127174 * 
      vqs1_f - 0.000141836892264* vds1;
xr6 = 0.04106625214281* iqs1_ref - 0.00107064907079* ids1_ref + 0.000000000875950 * 
      vqs1_f + 0.000133755198532* vds1;

// Generating Un = K*e = K*(Xr - X)

u1 = -17.0544245 * ( xr1 - lamq1 ) + 302.448936 * ( xr2 - lamq2 ) - 129.88656 * ( xr3 - 
     lamqr ) + 3.112246 * ( xr4 - lamds1 ) - 3.558555 * ( xr6 - lamdr );
u2 = -3.112247 * ( xr1 - lamq1 ) + 3.558555 * ( xr3 - lamqr ) - 17.054245 * ( xr4 - 
     lamds1 ) + 302.448936 * ( xr5 - lamds2 ) - 129.88656 * ( xr6 - lamdr );

// Generating E = Y - R

E1q_1 = iqs1_ref - iqs1_f;
E1d_1 = ids1_ref - ids1_f;

// Integration U1

if (!gating_on) {
    X1q_1 = 0.0;
    X1q_0 = 0.0;
    E1q_1 = 0.0;
```c
RT_linux_Code.c

E1q_0 = 0.0;
X1d_1 = 0.0;
X1d_0 = 0.0;
E1d_1 = 0.0;
E1d_0 = 0.0;

else {

X1q_1 = X1q_0 + Ts / 2 * ( E1q_1 + E1q_0 );
X1d_1 = X1d_0 + Ts / 2 * ( E1d_1 + E1d_0 );

u11 = - k11 * X1q_1 - k12 * X1d_1;
u22 = k12 * X1q_1 - k11 * X1d_1;
}

// Updating variables

X1q_0 = X1q_1;
X1d_0 = X1d_1;
E1q_0 = E1q_1;
E1d_0 = E1d_1;

// Generating U=Ui+Un

uq = u1 + u11;
uq = u2 + u22;

if ( uq > 350 )
uq = 350;
if ( ud > 350 )
ud = 350;
  if ( uq < -350 )
uq = -350;
if ( ud < -350 )
ud = -350;

walf = uq * cos( thetas2 - thetadel ) + ud * sin( thetas2 - thetadel );
ubet = ud * cos( thetas2 - thetadel ) - uq * sin( thetas2 - thetadel );

uas2 = walf;
ubs2 = -0.5* walf - 0.8660254038* ubet;
ucs2 = - uas2 - ubs2;

//**************************// Modulation indices creation
// Modulation indices creation
//Vtd = Vsd - w * (L_F + L_T) * I_q + Ud;
```
// Vtq = Vsq + w * (L_F + L_T) * I_d + Uq; // decoupling feedforward and feedforward compensation.

// Quasi Synchronization dq to alpha/beta
// Vtalpha = (Valpha*Vtd - Vbeta*Vtq) / Vsd;
// Vtbeta = (Valpha*Vtq + Vbeta*Vtd) / Vsd;

// alpha/beta to abc transformation
// Vta = Vtalpha;
// Vtb = -0.5*Vtalpha + 0.866025*Vtbeta;
// Vtc = -0.5*Vtalpha - 0.866025*Vtbeta;

Vta = uas2 / 1.732;
Vtb = usb2 / 1.732;
Vtc = ucs2 / 1.732;

M_a = Vta / (v_DC/2.0);
M_b = Vtb / (v_DC/2.0);
M_c = Vtc / (v_DC/2.0);

// Only for testing
Vtab = Vta - Vtb;
Vtbc = Vtb - Vtc;

// *****************************************************
// BEGIN - SEND OUT SPWM REFERENCES
// *****************************************************
SET_PWM_G1A(M_a); // Values M_a through M_c are normalized values between -1 and +1
SET_PWM_G1B(M_b); // A value of +1 yields +Vdc/2 on the respective phase
SET_PWM_G1C(M_c); // A value of -1 yields -Vdc/2 on the respective phase

// *****************************************************
// END - SEND OUT SPWM REFERENCES
// *****************************************************

// *****************************************************
// BEGIN - GATING On/Off WITH PROTECTION
// *****************************************************
SET_PWM_SWITCH(PWM_Q, PWM_OFF); // uses gating output 1 only
gating_main_switch( gating_on, v_DC ); // gating will be disabled if v_DC is excessively high or low

// *****************************************************
// END - GATING On/Off WITH PROTECTION
// *****************************************************

// *****************************************************
// BEGIN - PREPARE VALUES FOR TALK & SCOPE - YOU MAY ADD SIGNAL/METERS
// *****************************************************

// Output to METERS in "TALK", using a build in 2nd order 10Hz low pass filter
#define display_cut_off_freq (10.0)
meter_vDC = v_DC; //second_order_low_pass(meter_vDC, display_cut_off_freq, ts);

// Output up to 12 signals to the SCOPE
// SIGNAL( 0)= v_DC;

SIGNAL( 0)= thetas1;  // define up to 12 signals here for viewing on

RT-oscilloscope
SIGNAL( 1)= vqs1;
SIGNAL( 2)= vds1;
SIGNAL( 3)= iqs1;
SIGNAL( 4)= ids1;
SIGNAL( 5)= - iqr;
SIGNAL( 6)= - idr;
SIGNAL( 7)= - iqs2;
SIGNAL( 8)= - ids2;
SIGNAL( 9)= ias1;
SIGNAL(10)= uq;
SIGNAL(11)= ud;

// ***************************************************************************
// END - PREPARE VALUES FOR TALK & SCOPE - YOU MAY ADD SIGNAL/METERS
// ***************************************************************************

// ***************************************************************************
// ECE1065: END - DO NOT MODIFY OR ADD **ANY** CODE AFTER THIS POINT !!!
// ***************************************************************************

}

// Routing table support function
void rtce_assign_data(void) {
    int i;
    for(i=0; i< MAX_DATA_BUF; i++)
    {
        SHOW(i) = *(ROUTE( rbi->route[i] ));
    }
}
reference


