

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

An Isolated Integrated Charger for
Electric or Plug-in Hybrid Vehicles

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Division of Electric Power Engineering
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Göteborg, Sweden, 2011

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To my family and friends

Abstract

For electric and hybrid vehicles using grid power to charge the battery, traction circuit components are not normally engaged during the charging time, so there is a possibility to use them in the charger circuit to have an on-board integrated charger.

In this Licentiate thesis, an isolated high power integrated charger is proposed, designed and constructed based on a special ac machine with a double set of stator windings called motor/generator. The charger is capable of unit power factor operation as well as bi-directional power operation for grid to vehicle application.

The mathematical electromechanical model of the motor/generator is derived and presented. Based on the developed model, new controller schemes are developed and designed for the grid synchronization and charge control. The machine windings are re-arranged for the traction and charging by a controllable relay-based switching device that is designed for this purpose.

A laboratory system is designed and implemented based on a 4 pole 25 *kW* interior permanent magnet synchronous motor and a frequency converter considering the integrated charging features for winding re-configuration. The practical results will be added in the next step of the project. The charging power is limited to 12.5 *kW* due to the machine thermal limit (half of the motor full power in the traction mode) for this system.

The whole system is simulated in Matlab/Simulink based on the developed model and controllers to verify the system operation for the charge control. Simulation results show that the system has good performance during the charging time for a load step change. The simulation results show also a good performance of the controllers leading to machine speed stability and smooth grid synchronization. Moreover, the unit power factor operation is achieved for battery charging in the simulations.

Keywords

Integrated Battery Charger, Galvanic Isolation, Vehicle Applications, Grid Synchronization

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Thanks to Lennart Josefson, director of SHC, for his nice support. It was exciting to attend to events conducted by SHC like test drives in Volvo and Scania. I never dream of driving a truck or a bus before! Thanks to our industrial project partners for support and discussions during the project. I would like to mention Robert Eriksson (Volvo Car Corporation), Niklas Edvinsson (Saab Automobile AB), Mats Hilmersson (Saab Automobile AB), Olof Martander (Saab Automobile AB), Anders Kroon (AB Volvo), Jörgen Engström (Scania CV AB), Lars Stenqvist (Scania CV AB), Jonas Hofstedt (Scania CV AB), Svante Bylund (BAE Systems Hägglunds AB) and Viktor Lassila (BAE Systems Hägglunds AB).

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Saeid Haghbin
Göteborg, January 2011

Preface

The Swedish Hybrid Vehicle Center (SHC) was formed in spring 2007 to serve as a center of excellence in Sweden in research and development of sustainable hybrid electric vehicle systems. The mission of the center is to do research and development in hybrid electric vehicles to enhance education and cooperation between industry and academia. Several industrial and academic partners have active participation in the center activities.

The research in the center categorizes to three main themes: the control of the hybrid vehicle, the electric drive line and the energy storage. Theme 2 projects deal with electrical drive systems for the traction system inside the vehicle.

Three projects were defined in theme 2: Sensorless control of the motor in traction, integrated battery chargers (subject of this thesis) and electromagnetic compatibility design. These three projects are running together and share the same target vehicle specifications.

List of Publications and Patents

Appended papers

This thesis is based on the following papers:

- [I] Saeid Haghbin, Sonja Lundmark, Mats Alaküla and Ola Carlson, “Grid-Connected Integrated Battery Chargers in Vehicle Applications: Review and New Solution,”
submitted to the IEEE Transactions on Industrial Electronics, 2011.
- [II] Saeid Haghbin, Sonja Lundmark, Mats Alaküla and Ola Carlson, “An isolated high power integrated charger in electrified vehicle applications,”
submitted to the IEEE Transactions on Vehicular Technology, 2011.
- [III] Saeid Haghbin, Sonja Lundmark and Ola Carlson, “Performance of a Direct Torque Controlled IPM Drive System in the Low Speed Region,”
Proc. of IEEE International Symposium on Industrial Electronics (ISIE), Bari, Italy, July 2010.

Other papers

The following papers are published or submitted but not appended to the thesis, in some cases due to contents overlapping that of appended papers.

- [i] Saeid Haghbin, Sonja Lundmark, Ola Carlson and Mats Alaküla, “A Combined Motor/Drive/Battery Charger Based on a Split-Windings PMSM,”
submitted to the IEEE Vehicle Power and Propulsion Conference (VPPC 2011), 2011.
- [ii] Saeid Haghbin, Kashif Khan, Sonja Lundmark, Mats Alaküla, Ola Carlson, Mats Leksell and Oskar Wallmark, “Integrated Chargers for EVs and PHEVs: Examples and New Solutions,”
Proc. of XIX IEEE International Conference on Electrical Machines (ICEM), ISBN/ISSN: 978-1-4244-4174-7, Rome, Italy, Sep. 2010.
- [iii] Saeid Haghbin, Mats Alaküla, Kashif Khan, Sonja Lundmark, Mats Leksell, Oskar Wallmark and Ola Carlson, ”
An Integrated Charger for Plug-in Hybrid Electric Vehicles Based on a

Special Interior Permanent Magnet Motor,”
Proc. of IEEE Vehicle Power and Propulsion Conference (VPPC 2010),
Lille, France, 1-3 Sep. 2010.

- [iv] Saeid Haghbin and Torbjörn Thiringer, “Impact of inverter switching pattern on the performance of a direct torque controlled synchronous reluctance motor drive,”
Proc. of International Conference on Power Engineering, Energy and Electrical Drives (POWERENG 09), ISBN/ISSN: 978-1-4244-4611-7, 18-20 March 2009, Lisboa, Portugal, pp. 337-341.
- [v] Kashif Khan, Saeid Haghbin, Mats Leksell and Oskar Wallmark, “Design and performance analysis of a permanent-magnet assisted synchronous reluctance machine for an integrated charger application,”
Proc. of XIX IEEE International Conference on Electrical Machines (ICEM), ISBN/ISSN: 978-1-4244-4174-7, Rome, Italy, Sep. 2010.

Patents

The following patent is filed as a result of the current project:

- [i] Saeid Haghbin (Chalmers University of Technology) and Mats Alaküla (Lund University), “Elektrisk Apparat,” Swedish Patent Office, Patent no 1050607-9, filed in 14 June 2010.

Contents

Abstract	v
Acknowledgment	vii
Preface	ix
List of Publications and Patents	xi
1 Introduction	1
1.1 Background and Previous Work	1
1.2 Purpose of the Thesis and Contributions	2
1.3 Thesis Outline	2
2 Electrical Driveline Specification of the Target Vehicle	3
2.1 Plug-in Hybrid Electric Vehicles	3
2.2 Traction System Specification	3
2.3 Charger Specification	4
3 Review of Integrated Chargers in Vehicle Applications	5
3.1 Battery Chargers in Vehicle Applications	5
3.2 Examples of Integrated Chargers	6
3.2.1 A Combined Motor Drive and Battery Recharge System Based on an Induction Motor	6
3.2.2 Non-isolated Integrated Charger Based on a Split-Winding AC Motor	7
3.2.3 An Integral Battery Charger for a Four-Wheel Drive Electric Vehicle	10
3.2.4 An Integrated Charger for an Electric Scooter	10
3.2.5 Isolated Integrated Charger Based on a Wound-Rotor Induction Motor	12
3.2.6 Comparison of Integrated Chargers	13
4 An Integrated Charger Based on a Special ac Machine	15
4.1 Proposed Isolated Integrated Charger	15
4.2 The IPMSM Machine with Split Stator Windings	16
4.2.1 Mathematical Model of the IPMSM with Six Stator Wind- ings	16
4.3 System Operation in Traction and Charging	23

4.3.1	Motor/Generator Grid Synchronization	24
4.3.2	Battery Charge Control	24
4.4	Integrated Charger Simulation Results	29
4.5	Drive System Performance of a DTC Based IPM Machine	37
5	Conclusions and Future Work	43
5.1	Conclusions	43
5.2	Future Work	44
	Bibliography	45
A	Paper I: Grid-Connected Integrated Battery Chargers in Vehicle Applications: Review and New Solution	51
A.1	Introduction	54
A.2	Battery Chargers in Vehicle Applications	54
A.3	Integrated Chargers	55
A.3.1	A Combined Motor Drive and Battery Recharge System Based on Induction Motor	56
A.3.2	Non-isolated Integrated Charger Based on a Split-Winding AC Motor	58
A.3.3	An Integral Battery Charger for a Four-Wheel Drive Electric Vehicle	60
A.3.4	An Integrated Charger for an Electric Scooter	61
A.3.5	An Integrated Charger for a Fork Lift Truck	61
A.3.6	Single-Phase Integrated Charger Based on a Switched Reluctance Motor Drive	62
A.3.7	Single-Phase Integrated Charger Based on a Dual Converter Switched Reluctance Motor Drive	63
A.3.8	Integrated Bidirectional AC/DC and DC/DC Converter for PHEVs	64
A.4	Isolated Integrated Charger Based on the AC Machine Operating as a Motor/Generator Set	65
A.4.1	System Modes of Operation: Traction and Charging	65
A.5	Conclusion	68
B	Paper II: An Isolated High Power Integrated Charger in Electrified Vehicle Applications	75
B.1	Introduction	78
B.2	Integrated Charger Based on a Special Motor Windings Configuration	78
B.2.1	The IPMSM Machine with Split Stator Windings	79
B.2.2	Mathematical Model of the IPMSM with Six Stator Windings	80
B.3	System Modes of Operation: Traction and Charging	85
B.3.1	Motor/Generator Grid Synchronization	86
B.3.2	Battery Charge Control	87
B.4	System Design and Simulation Results	90
B.5	Conclusion	91

C Paper III: Performance of a Direct Torque Controlled IPM Drive System in the Low Speed Region	97
C.1 Introduction	100
C.1.1 Dynamic Model of an IPM	100
C.1.2 The Drive System Diagram	101
C.1.3 The Drive System Simulation	102
C.2 Impact of Switching Pattern on the Drive System Performance	103
C.3 Impact of the Zero Voltage Vector on the IPM Motor Flux and Torque: Analytical Solution	107
C.4 Conclusion	110

Chapter 1

Introduction

The project background and important related results regarding previous works are presented in this chapter. Moreover, the scope of the project and main contributions are also explained.

1.1 Background and Previous Work

The battery has an important role in the development of electric vehicles (EV) or plug-in hybrid electric vehicles (PHEV) [1–5]. The performance of battery modules depends not only on the design of modules, but also on how the modules are used and charged. In this sense, battery chargers play a critical role in the evolution of this technology. Generally there are two types of battery chargers: on-board type and stand-alone (off-board) type [2,3]. The on-board type would be appropriate for nighttime charging from a household utility outlet, or for charging during daytime at workplaces, malls or for emergency charging where no off-board charger is available. On the other hand, the off-board charger can be compared to a gas station used for an internal combustion engine vehicle, thus it is aimed at rapid charging. Because the on-board type of charger always should be carried by the vehicle, the weight and space have to be minimized. Of course, it is very important to minimize charger cost (especially the on-board versions). For on-board chargers, it is difficult to have high power level because of its weight, space and in total cost. Another difficulty is to assure galvanic isolation. Although it is a very favorable option in the charger circuits for safety reasons [6–8], it is usually avoided due to its cost impact on the system.

During charging the vehicle is parked so there is a possibility to use available traction hardware, mainly the electric motor and the inverter, for the charger circuit and thus to have an integrated motor/drive/battery charger to decrease the system weight, space and cost [9]. Several different types of integrated chargers are reported by industry or academia regarding vehicle applications (subject of appended Paper I). For those integrated chargers, the electric motor is used as inductors or as an isolated transformer while the machine is in standstill during charging time. All but one of the reported integrated chargers are non-isolated and they need extensive protection and shielding for safe and proper operation [6]. For the one isolated charger, a

wound rotor induction machine is used as an isolated transformer [9]. So for this solution the system has low efficiency due to the need of a high magnetization current.

So, among the reported integrated chargers, there is no version that combines galvanic isolation and high efficiency features. Moreover, few of them are high power chargers [9].

1.2 Purpose of the Thesis and Contributions

The main objective of the work reported in this thesis is to develop a high power isolated integrated charger for EVs or PHEVs that is 12.5 kW in this case (subject of appended paper II). It is also an objective to investigate the impact of different inverter switching patterns on the performance of a direct torque control (DTC) based drive system (subject of appended paper III). In summary the main contributions can be listed as:

- Proposition, design and implementation of an isolated high power integrated charger based on a special machine winding configuration.
- Mathematical modeling, controllers development and simulation of different system parts including a six terminal electrical machine called motor/generator, grid synchronization and charge control.

1.3 Thesis Outline

The thesis is divided into two parts. The first part gives an introduction to the subject and the second part includes three appended papers. The target vehicle specification including the charging system is presented in the second chapter. The review of integrated chargers is described in chapter 3. The proposed integrated charger with galvanic isolation is described in chapter 4. Chapter 5 is dedicated to conclusions and future work.

Chapter 2

Electrical Driveline Specification of the Target Vehicle

The hybrid electric vehicle (HEV) can, just like the pure electric vehicle (EV), give a higher energy efficiency and reduced emissions when compared with conventional vehicles but compared to the EV, it can also be driven for a longer range by using an internal combustion engine (ICE). A plug-in hybrid means that the HEV can be charged from a power supply off-board. In this project, the electric driveline of a PHEV have been considered with the charger specification. The system configuration and specification is presented in this chapter.

2.1 Plug-in Hybrid Electric Vehicles

Fig. 2.1 shows a schematic diagram of a PHEV with a parallel configuration. The electrical part includes the grid connected battery charger, battery, inverter, motor and control system [1]. During charging time the vehicle is not driven and during driving time the charger is not intended to charge the battery pack. However, it is possible to use the inverter and motor in the charger circuit to reduce the system components, space and weight which means a cost reduction. This is what is referred to as an integrated charger in this thesis.

2.2 Traction System Specification

The traction system specification was set by the project working group and industrial partners. The target vehicle is a passenger car with parallel configuration (PHEV). Table 2.1 shows the traction system specifications.

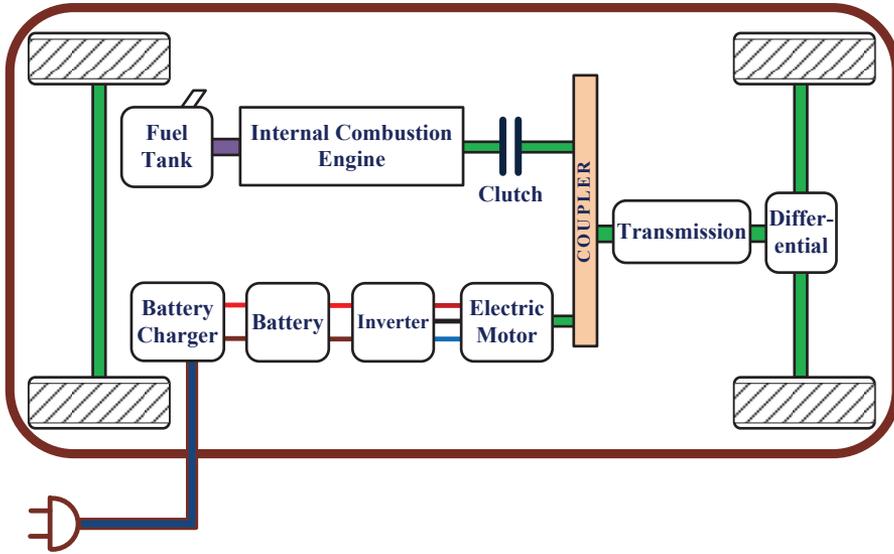


Figure 2.1: Simplified schematic diagram of a PHEV.

Table 2.1: Electrical driveline specification of target vehicle in traction mode.

Continuous traction power of the electric motor (kW)	25
Electric motor peak traction power for 3 seconds (kW)	45
Battery voltage level (V)	400
Electric motor speed range (rpm)	0 ... 6500
Electric motor base speed (rpm)	1500
Electric motor maximum speed (rpm)	6500
Electric motor maximum torque (Nm)	270

2.3 Charger Specification

Three-phase supply is available in most residential areas in Sweden. For a three-phase 400 V and 32 A supply, the maximum available power is 22 kW. So the primary level of charging power was set to 22 kW with the three-phase utility grid supply. Later on, the charging power level reduced to half of the traction power due to the integration, that is 12.5 kW in this case.

Although galvanic isolation is not mandatory in the charging circuit according to related standards [10], it is a very interesting option due to the safety and EMC issues. It was thus included in the specifications.

Additionally unit power factor operation was another functionality that was set as mandatory in the specification. Further, bi-directional charger operation, which would allow vehicle to grid (V2G) operation was regarded as an interesting operational feature.

Chapter 3

Review of Integrated Chargers in Vehicle Applications

Different types of integrated chargers are reported by academia or industry [11–14, 19, 20, 20, 21, 21, 22, 22, 23, 27–31, 33–39, 39–43]. Some of them that are more relevant to the current project are reviewed and compared in this chapter.

Different power levels of chargers are briefly presented in the first section and the examples of integrated chargers are described and compared in the second section.

3.1 Battery Chargers in Vehicle Applications

Chargers can be classified in terms of power levels and time of charging [40,41]. The choice of classification depends naturally on nationally available power levels. One example of classification that suits the US residential power source is given in [40]:

Level 1: Common household type of circuit in US rated to 120 V and up to 15 A .

Level 2: Permanently wired electric vehicle supply equipment used specially for electric vehicle charging and it is rated up to 240 V , up to 60 A , and up to 14.4 kW .

Level 3: Permanently wired electric vehicle supply equipment used specially for electric vehicle charging and it is rated greater than 14.4 kW .

Equivalently, above categories are known as emergency charger which charges the battery pack of a vehicle in six to eight hours, standard charger which charges the battery pack in two to three hours, and rapid charger which charges the battery pack in ten to fifteen minutes (fast chargers). Chargers can also be described as either conductive or inductive.

For a conductive charger, the power flow take place through metal-to-metal contact between the connector on the charge port of the vehicle and charger

(off-board charging) or grid (on-board charging). Conductive chargers may have different circuit configurations but the common issues concern safety and the design of the connection interface.

Inductive coupling is a method of transferring power magnetically rather than by direct electrical contact and the technology offers advantages of safety, power compatibility, connector robustness and durability to the users of electric vehicles but on the expense of a lower efficiency and the need of new equipment at charging sites. The electric vehicle user may physically insert the coupler into the vehicle inlet where the ac power is transformer coupled, rectified and fed to the battery, or the charging could be done almost without driver action by wireless charging [42]. For inductive charging, among the most critical parameters are the frequency range, the low magnetizing inductance, the high leakage inductance and the significant discrete parallel capacitance [5, 43].

Different topologies and schemes are reported for both single-phase and three-phase input conductive battery chargers. Usually the three-phase input solutions are used in high power applications [44–47].

3.2 Examples of Integrated Chargers

The electrical system inside a grid-connected hybrid electric vehicle mainly includes the grid connected battery charger, battery, inverter, motor and control system. It is here assumed that during charging time the vehicle is not driven and during driving time it is not possible to charge the battery pack from the grid.

In a classical electrical device arrangement in the vehicle, there are separate inverter and charger circuits for traction and charging from an external source. However, it is possible to integrate both hardware to reduce the system components, space and weight which is equivalent to cost reduction. For instance, the three-phase three-wire boost AC/DC converter that can be used as a battery charger is very similar to the hardware that is available in the traction system. See [44, 45] for different AC/DC rectifier schemes.

Another example of the use of integration is to use the electric motor windings as inductors in the charger circuit. This reduces weight as high current inductors are large components compared to other components like switches for example.

A traction system based on an ac motor and a three-phase inverter is shown in Fig. 3.1. In some schemes a DC/DC converter is used in the system also [48]. The battery power is transferred to the motor through the inverter. Bi-directional operation of the inverter allows energy restoration during braking to the battery. Regarding different drive systems, different types of integrated chargers are reported both within academia and industry and some of them are assessed here.

3.2.1 A Combined Motor Drive and Battery Recharge System Based on an Induction Motor

An integrated motor drive and charger based on an induction machine was patented 1994 by AC Propulsion Inc. [12] and is currently in use in the car

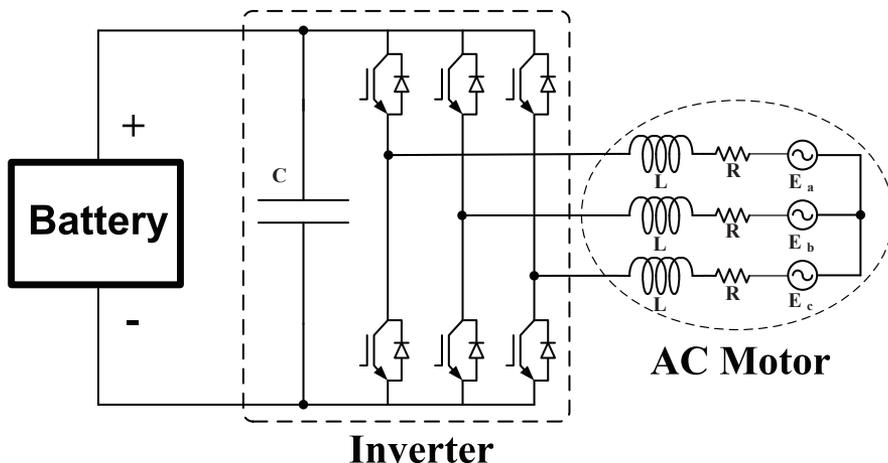


Figure 3.1: Electrical traction in a vehicle.

industry [49]. The main idea is to use the motor as a set of inductors during charging time to constitute a boost converter with the inverter to have unit power factor operation. Fig. 3.2 shows the functional schematic diagram of this non-isolated integrated charger system. By the means of inexpensive relays the machine windings are reconfigured to be inductors in the charging mode.

It is possible to have a three-phase input supply with this scheme, but there will be developed torque in the machine during charging that should be considered. The single-phase charger can charge from any source, $100 - 250 \text{ Vac}$, from 200 W up to 20 kW and can be used for V2G (vehicle to grid) and for backup power and energy transfer to other electric vehicles. The filter bank at the front of the ac supply will smooth the harmonic contents of the charger line current also.

Other similar alternatives have been patented in the US [13, 14]. All of these solutions are bidirectional non-isolated type of chargers with unit power factor operation and single-phase ac supply.

3.2.2 Non-isolated Integrated Charger Based on a Split-Winding AC Motor

A non-isolated high power three-phase integrated charger is reported by Luis De Sousa et al. in Valeo Engine and Electrical Systems in 2010 [19–21]. Fig. 3.3 shows the proposed integrated charger. In traction mode a 3H-bridge topology is used with a DC/DC converter. The DC/DC converter consists of inductor L and two switches. The inverter dc bus voltage is 900 Vdc while the battery voltage is maximum 420 Vdc for the proposed system.

Fig. 3.4 shows the system equivalent circuit in charging mode. For charging, the three-phase supply is connected to the middle point of the stator windings. A small EMI filter is used to improve the grid current waveforms. As is shown in this figure, there are two three-phase boost converters sharing a common dc bus. By using a split-winding configuration and regulating the

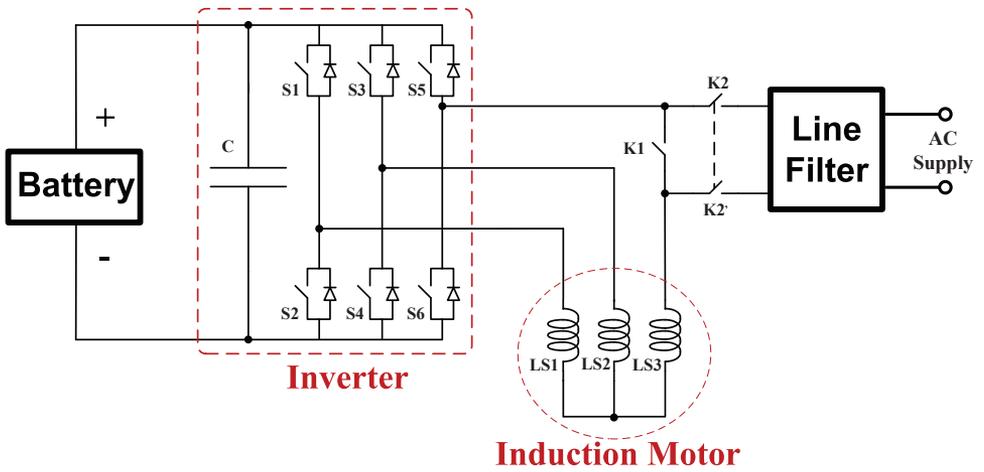


Figure 3.2: Non-isolated single-phase integrated charger based on an induction motor drive system.

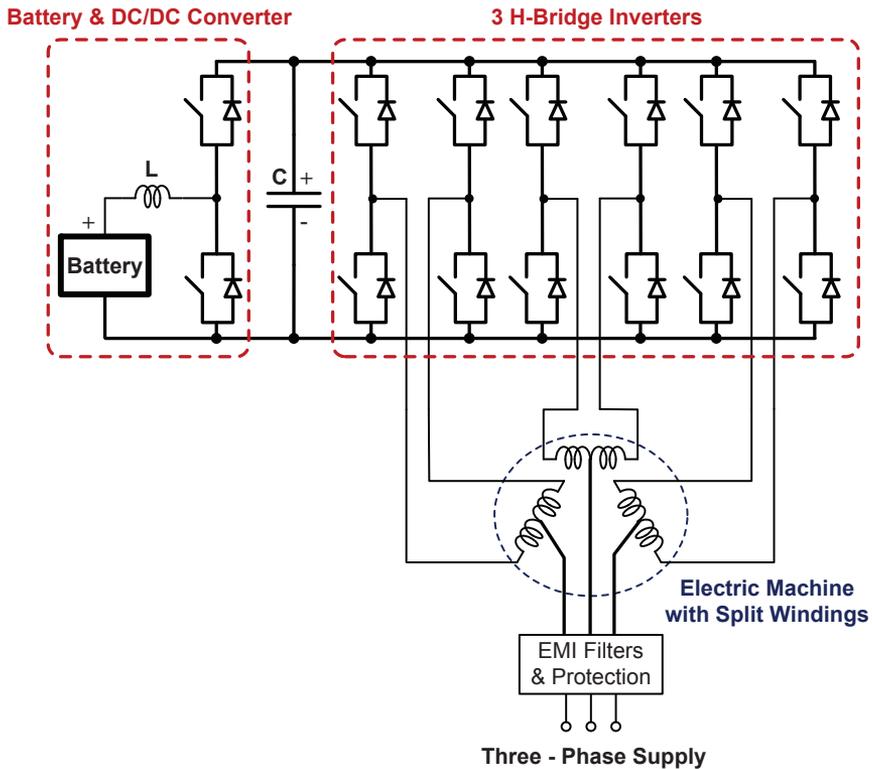


Figure 3.3: Three-phase non-isolated integrated charger based on a split-winding ac motor.

same current in the same phases of the two boost converters, the developed stator magnetomotive force (MMF) of the machine is eliminated so there is not any rotational magnetic field in the motor during charging.

The proposed charger is a high power non-isolated version capable of unit power factor operation. There is no need to use a switch like contactor for the charger to grid connection. A plug can be used for this purpose. Two international patents are received for the proposed scheme [22, 23].

It is shown that it is possible to use the same strategy for a single-phase supply by S. Lacroix et al. [21]. Fig. 3.5 shows the system in charging mode for the single-phase supply. Four legs of bridges in the inverter and inductances of two phases are used in this mode. As is shown in this figure, the third H-bridge inverter is not used. The currents will be regulated to be equal for each phase. Unit power factor operation is possible in this case also due to the boost converter topology.

3.2.3 An Integral Battery Charger for a Four-Wheel Drive Electric Vehicle

An integral battery charger is reported for a four-wheel motor driven EV by Seung-Ki Sul and Sang-Joon Lee [20]. The propulsion system includes four induction motors and four three-leg inverters with a battery on the system dc bus. By the use of an extra transfer switch the whole system is reconfigured to a single-phase battery charger. Fig. 3.6 shows the system configuration in traction and charging mode. In traction mode, four inverters are connected to the system dc bus drive motors (each motor neutral point is float in this mode). In the charging mode (the transfer switch is in position 2) the single-phase ac source is connected between the neutral points of two motors. Utilizing the switches in inverter one and two, this configuration will be a single-phase boost converter with unit power factor operation capability. The third and fourth inverters with the use of two other motors constitute two buck-type converters. Fig. 3.7 shows the system equivalent circuit in charging mode where the motors are used as inductors. For each motor the winding currents are the same for each phase so there is no developed electromagnetic torque in the motors during the charging time. Further, in the charging mode, by controlling the PWM boost converter, the dc link voltage is kept constant. The constant current battery charging profile is achieved by the control of the two buck-type choppers. Of course, this integrated charger solution is a high cost solution and only appropriate for vehicles with four-wheel motors.

3.2.4 An Integrated Charger for an Electric Scooter

A non-isolated single-phase (110 Vac and 60 Hz) integrated charger for an electrical scooter is another example described in [21]. The authors use the three-phase inverter as a single switch in the charging mode, see Fig. 3.8. Thus, the switches S2, S4 and S6 seen in Fig. 3.8 are to be operated all together as a simple switch. In turn, the circuit is a single-phase boost converter. All three windings of the motor are used in the charging process. A power rectifier and line filter are also used as extra components for the charging operation. It is expected to have unit power factor operation as is expected for the boost

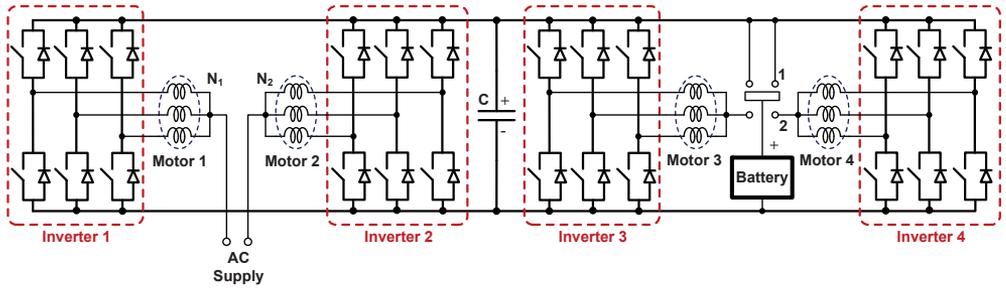


Figure 3.6: Power circuit of integrated battery charger for a four wheel drive.

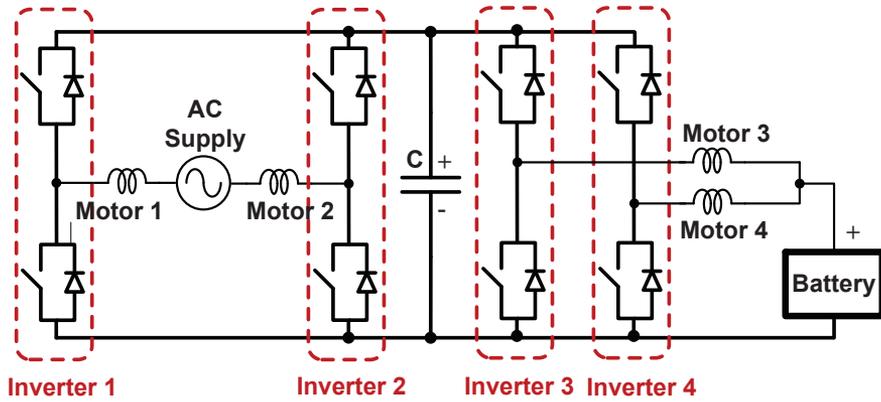


Figure 3.7: System equivalent circuit in charging mode.

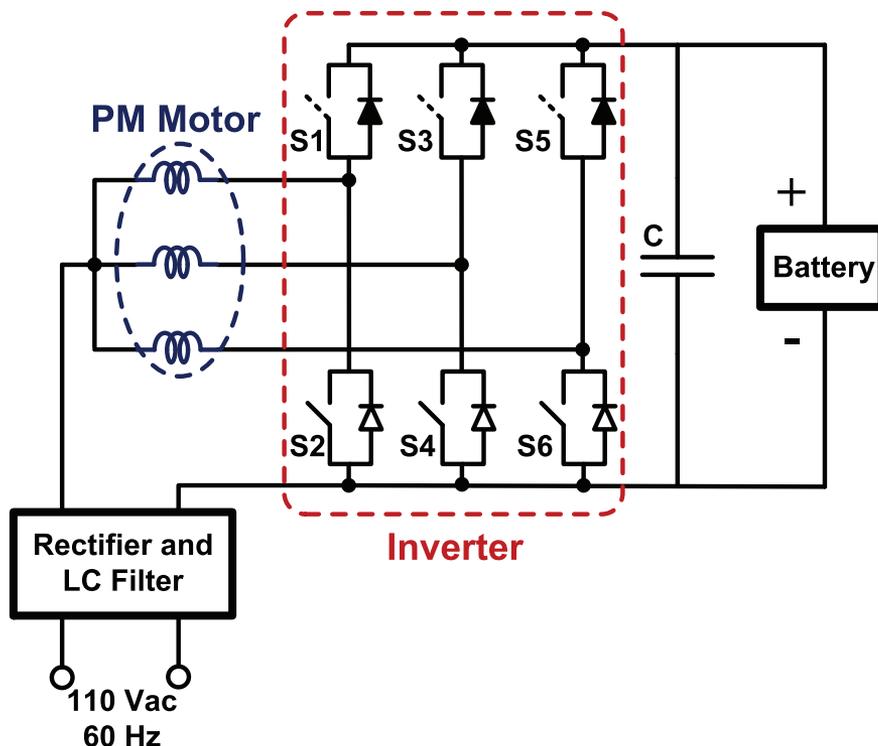


Figure 3.8: Single-phase integrated charger for an electric scooter.

converter and low THD in the ac line current due to use of the line filter. A 180 V_{dc} lead acid battery (12 Ah) is used as the traction power source and the motor is a 6 kW axial flux permanent magnet motor. Moreover, 50 A and 600 V IGBT modules are used with a switching frequency of 25 kHz . At charging mode, the motor is used as three parallel connected 0.1 mH inductances. The currents through the inductances are thus unidirectional, thus no torque is developed in the motor, and the rotor can be at standstill. Of course, only slow, low power charging is possible with this solution.

3.2.5 Isolated Integrated Charger Based on a Wound-Rotor Induction Motor

An integrated drive/charger system has been reported in 2005 for a fork lift truck [22] in which an induction motor is used as a step down transformer in the charging mode. In the traction mode a 6 kW induction machine is used to drive the truck. The battery voltage and rated motor voltage is nominal 48 V . A three-phase inverter is utilized for motor control based on the space vector modulation (SVM) scheme.

In charging mode, the motor is used as a low frequency step-down transformer. A wound-type rotor is used in the drive system and for the charging mode the rotor winding is used as a primary side of the transformer with the secondary side (the stator) connected to the grid (three-phase 400 V_{ac}).

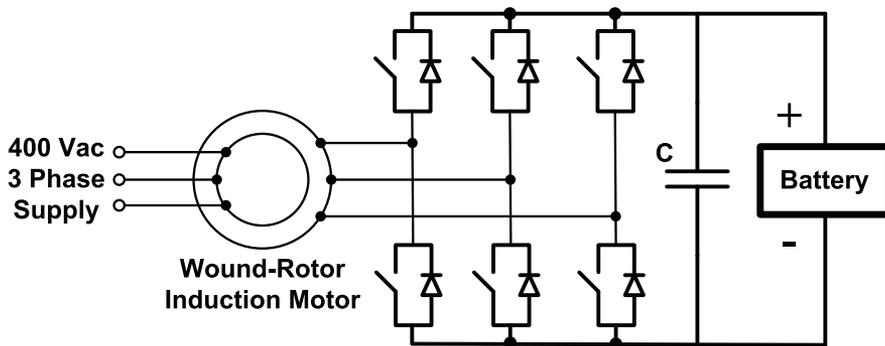


Figure 3.9: Integrated charger based on the operation of an induction machine as a three-phase transformer.

Naturally, there is a galvanic insulation between the grid and battery by the means of this transformer. Fig. 3.9 shows the system in charging mode. The air-gap in the motor (transformer in charging mode) will affect the system performance regarding the loss due to the need of large magnetization currents. Other disadvantages are the extra cost of the wound rotor (compared to a squirrel cage rotor), need of contactors and the need to adapt the motor windings to the charge voltage. Advantages include the possibility of bidirectional power flow, low harmonic distortion and a unit power factor. The rotor is at standstill during charging and a mechanical lock is used.

3.2.6 Comparison of Integrated Chargers

All but one of the presented examples of chargers are non-isolated versions. The presented integrated chargers are compared and summarized in Table 3.1. Type of supply (three-phase or single phase), galvanic isolation of the grid, unit power factor operation capability, efficiency, and extra components for integration are considered in this comparison.

Table 3.1: Comparison of integrated charger examples.

Solution	Supply	Isolation	Efficiency	PFC Operation	Extra Components for Charging	Comments
A Combined Motor Drive and Battery Recharge System Based on an Induction Motor (3.2.1)	single-phase or three-phase	non-isolated	high	feasible	few relays and a line filter	is currently used in car industry
Non-isolated Integrated Charger Based on a Split-Winding AC Motor (3.2.2)	single-phase or three-phase	non-isolated	high	feasible	an extra inverter	will be used in car industry
An Integral Battery Charger for a Four-Wheel Drive Electric Vehicle (3.2.3)	single-phase	non-isolated	high	feasible	a position switch	4 motors and inverters are used in traction mode
An Integrated Charger for an Electric Scooter (3.2.4)	single-phase	non-isolated	high	feasible	a line filter	—
Isolated Integrated Charger Based on a Wound-Rotor IM (3.2.5)	single-phase or three-phase	isolated	low due to the motor air gap	feasible	mechanical rotor lock	feasible for wound type rotor induction motor

Chapter 4

An Integrated Charger Based on a Special ac Machine

A high power isolated integrated battery charger based on a special winding configuration of an ac machine is described in this section. First, the system diagram of the proposed solution is described and then the mathematical model of the machine with double set of stator windings is presented. Further, the system operation in charging mode is explained. Different developed controllers for grid synchronization and charge control are also explained. Simulation results are presented to show the system operation in charging mode for the proposed integrated charger. Moreover, the drive system performance of a DTC based IPM machine is presented as an example that can be applied for the charger grid synchronization and charge control.

4.1 Proposed Isolated Integrated Charger

By reconfiguration of the electric motor windings, an integrated charger scheme is proposed where the machine is used as a special grid connected generator. The main idea is to introduce a multi terminal device called motor/generator set to act like a motor in traction mode and like an isolated generator/transformer in charging mode. The so called motor/generator acts as an isolated three-phase power source after synchronization with the utility grid in charging mode. This rotary three-phase isolated power source constitutes a three-phase boost rectifier (battery charger) with full utilization of the inverter.

All machine windings are used in traction mode and are then reconnected in charging mode through a simple switching device. Fig. 4.1 shows a schematic diagram of the integrated charger for a PHEV first proposed in [11]. Different motor topologies are possible both concerning motor types and winding arrangement. One option with an internal permanent magnet synchronous motor was reported in [11, 50].

Fig. 4.2 shows a simple schematic diagram of the system in the charging mode. This solution has bidirectional capability so it is possible to bring back

power to the grid from the battery. Moreover, unit power factor operation is feasible. Depending on the type of machine and winding configuration, a single-phase solution is also possible. The charging power will be limited by the motor thermal limit and inverter power limit and limit of the supply, so high power charging is feasible in this configuration.

The motor rotates at synchronous speed during charging so a mechanical clutch is used to disconnect the motor from the transmission system. Before connection to the grid, through the inverter-side stator windings, the battery and inverter will synchronize the voltage at the grid-side windings to the grid voltage.

After grid synchronization, the grid-side stator windings are connected to grid voltage. Now the inverter side windings are an isolated three-phase voltage source and the inverter can control the dc voltage and current at the battery side. One control objective is to keep the torque zero during synchronization with the grid. Another control objective is unit power factor operation.

To have proper boost converter operation the dc bus voltage should be more than peak ac line voltage. This can be solved in two ways: using an extra DC/DC converter or $Y - \Delta$ connection of the stator windings to reduce the voltage at the inverter side. The second approach has been selected to reduce the system hardware in this case. The detailed motor design is presented in [50].

4.2 The IPMSM Machine with Split Stator Windings

In a two-pole three-phase IPMSM there are three windings in the stator shifted 120 electrical degrees [51]. Assume that each phase winding is divided into two equivalent parts and moreover they are shifted symmetrically around the stator periphery. Basically there will be six windings inside the stator instead of three for a two pole machine. Fig. 4.3 shows the cross section of the motor in this configuration.

As is shown in this figure, there are six windings shifted 30 electrical degrees while the rotor has a two-pole configuration. Other number of pole pairs are also possible for the machine with this integrated charger.

These six windings can be considered as two sets of three-phase windings. Let say a_1, b_1 and c_1 are the first set of windings (the same as classical three-phase windings). Consequently, a_2, b_2 and c_2 are the second set of three-phase windings. These two sets of three-phase windings are shifted 30 electrical degrees (angle between magnetic axis of $a'_1 a_1$ and $a'_2 a_2$) in this configuration to have a symmetric winding placement around the stator periphery.

4.2.1 Mathematical Model of the IPMSM with Six Stator Windings

A mathematical model of this machine is developed based on the assumption that all windings and rotor magnets magnetomotive forces are sinusoidally distributed. To model this machine with six stator windings, the inductance matrix is first calculated (a 6×6 matrix including self inductances and mutual

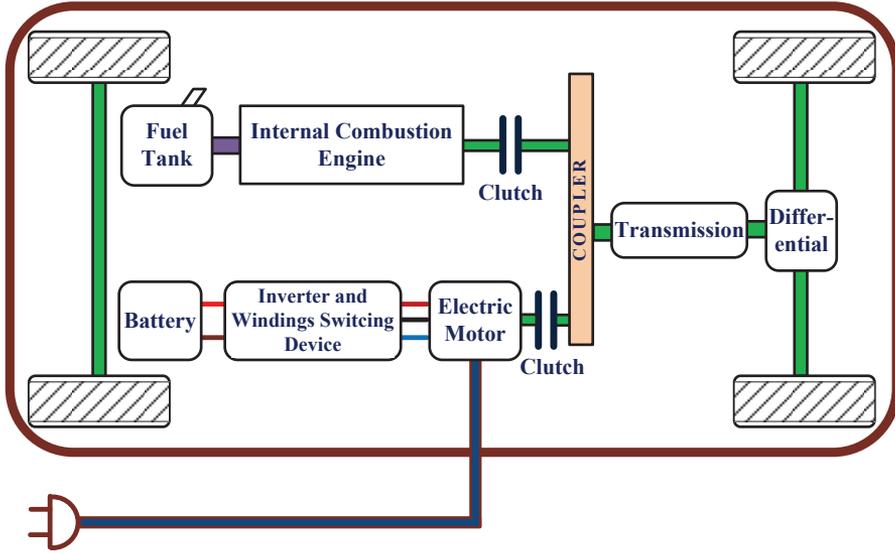


Figure 4.1: Integrated charger based on the special electric motor configuration.

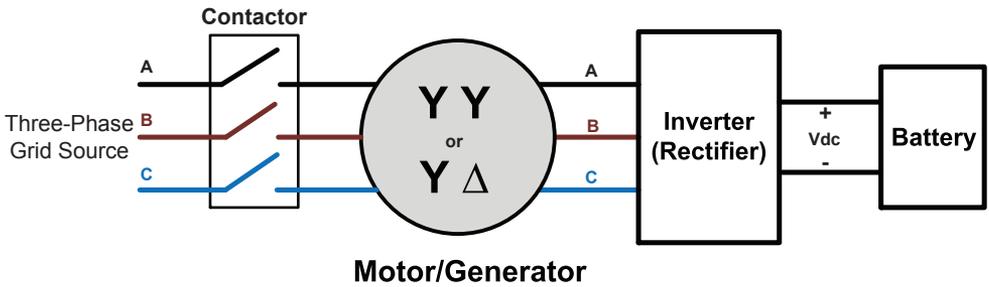


Figure 4.2: Simplified system diagram of the proposed integrated charger.

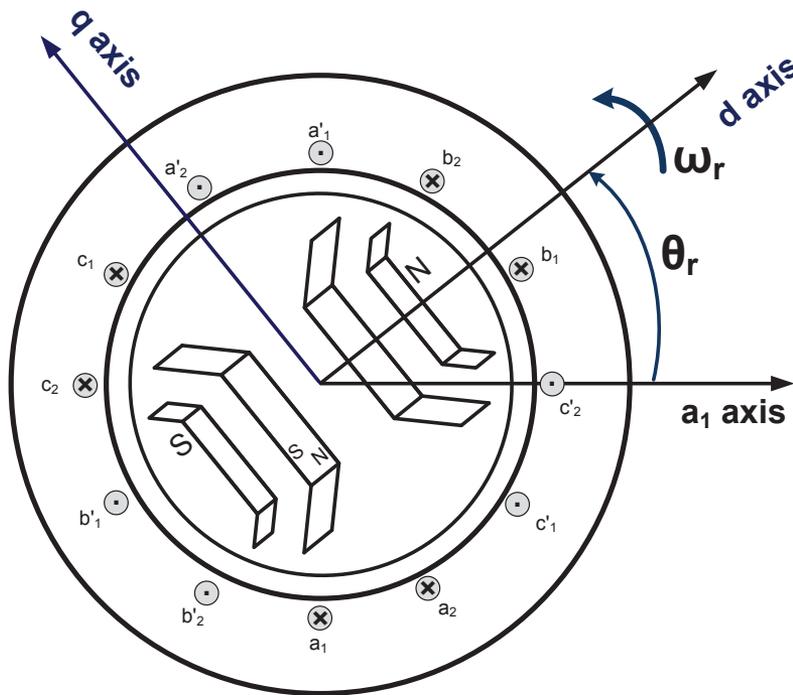


Figure 4.3: Cross section of a IPMSM with split stator windings.

inductances). Afterwards, the flux and voltage equations are written to model the electrical system [51]. The derivative of the co-energy is calculated to obtain the developed electromagnetic torque. The order of system is eight that is six electrical equations and two mechanical equations in the phase domain.

A special abc to dq transformation is used that is based on the Park transformation but an extended version for six variables instead of three. The system equations in the dq frame is reduced to a six order system while all sin and cos terms are eliminated from the equations.

The voltage equations for six windings can be described by the following equations:

$$v_{a_1} = r_s i_{a_1} + \frac{d}{dt} \psi_{a_1} \quad (4.1)$$

$$v_{b_1} = r_s i_{b_1} + \frac{d}{dt} \psi_{b_1} \quad (4.2)$$

$$v_{c_1} = r_s i_{c_1} + \frac{d}{dt} \psi_{c_1} \quad (4.3)$$

$$v_{a_2} = r_s i_{a_2} + \frac{d}{dt} \psi_{a_2} \quad (4.4)$$

$$v_{b_2} = r_s i_{b_2} + \frac{d}{dt} \psi_{b_2} \quad (4.5)$$

$$v_{c_2} = r_s i_{c_2} + \frac{d}{dt} \psi_{c_2} \quad (4.6)$$

where $v_{a_1}, v_{b_1}, v_{c_1}, v_{a_2}, v_{b_2}, v_{c_2}, i_{a_1}, i_{b_1}, i_{c_1}, i_{a_2}, i_{b_2}, i_{c_2}, \psi_{a_1}, \psi_{b_1}, \psi_{c_1}, \psi_{a_2}, \psi_{b_2}, \psi_{c_2}$ and r_s are windings voltages, currents, flux linkages and resistance.

The windings flux linkages can be expressed as:

$$\begin{aligned} \psi_{a_1} = & L_{a_1a_1}i_{a_1} + L_{a_1b_1}i_{b_1} + L_{a_1c_1}i_{c_1} + L_{a_1a_2}i_{a_2} + \\ & L_{a_1b_2}i_{b_2} + L_{a_1c_2}i_{c_2} + \psi_{pm}\cos(\theta_r) \end{aligned} \quad (4.7)$$

$$\begin{aligned} \psi_{b_1} = & L_{b_1a_1}i_{a_1} + L_{b_1b_1}i_{b_1} + L_{b_1c_1}i_{c_1} + L_{b_1a_2}i_{a_2} + \\ & L_{b_1b_2}i_{b_2} + L_{b_1c_2}i_{c_2} + \psi_{pm}\cos(\theta_r - \frac{2\pi}{3}) \end{aligned} \quad (4.8)$$

$$\begin{aligned} \psi_{c_1} = & L_{c_1a_1}i_{a_1} + L_{c_1b_1}i_{b_1} + L_{c_1c_1}i_{c_1} + L_{c_1a_2}i_{a_2} + \\ & L_{c_1b_2}i_{b_2} + L_{c_1c_2}i_{c_2} + \psi_{pm}\cos(\theta_r + \frac{2\pi}{3}) \end{aligned} \quad (4.9)$$

$$\begin{aligned} \psi_{a_2} = & L_{a_2a_1}i_{a_1} + L_{a_2b_1}i_{b_1} + L_{a_2c_1}i_{c_1} + L_{a_2a_2}i_{a_2} + \\ & L_{a_2b_2}i_{b_2} + L_{a_2c_2}i_{c_2} + \psi_{pm}\cos(\theta_r - \frac{\pi}{6}) \end{aligned} \quad (4.10)$$

$$\begin{aligned} \psi_{b_2} = & L_{b_2a_1}i_{a_1} + L_{b_2b_1}i_{b_1} + L_{b_2c_1}i_{c_1} + L_{b_2a_2}i_{a_2} + \\ & L_{b_2b_2}i_{b_2} + L_{b_2c_2}i_{c_2} + \psi_{pm}\cos(\theta_r - \frac{2\pi}{3} - \frac{\pi}{6}) \end{aligned} \quad (4.11)$$

$$\begin{aligned} \psi_{c_2} = & L_{c_2a_1}i_{a_1} + L_{c_2b_1}i_{b_1} + L_{c_2c_1}i_{c_1} + L_{c_2a_2}i_{a_2} + \\ & L_{c_2b_2}i_{b_2} + L_{c_2c_2}i_{c_2} + \psi_{pm}\cos(\theta_r + \frac{2\pi}{3} - \frac{\pi}{6}) \end{aligned} \quad (4.12)$$

where $L_{a_1a_1}, L_{b_1b_1}, L_{c_1c_1}, L_{a_2a_2}, L_{b_2b_2}$ and $L_{c_2c_2}$ are windings self inductances. Moreover, $L_{a_1b_1}, L_{a_1c_1}, L_{a_1a_2}, L_{a_1b_2}, L_{a_1c_2}, L_{b_1b_1}, L_{b_1c_1}, L_{b_1a_2}, L_{b_1b_2}, L_{a_2c_2}$ and $L_{b_2c_2}$ are windings mutual inductances. ψ_{pm} is the permanent magnet flux (the rotor flux) and θ_r is the angel between the rotor d axis and the magnetic axes of winding a'_1a_1 .

The inductance values are calculates as (see appended paper II):

$$L_{a_1a_1} = L_{ls} + \bar{L}_m - L_{\Delta m}\cos(2\theta_r) \quad (4.13)$$

$$L_{a_1b_1} = L_{b_1a_1} = -\frac{1}{2}\bar{L}_m - L_{\Delta m}\cos2(\theta_r - \frac{\pi}{3}) \quad (4.14)$$

$$L_{a_1c_1} = L_{c_1a_1} = -\frac{1}{2}\bar{L}_m - L_{\Delta m}\cos2(\theta_r + \frac{\pi}{3}) \quad (4.15)$$

$$L_{a_1a_2} = L_{a_2a_1} = \frac{\sqrt{3}}{2}\bar{L}_m - L_{\Delta m}\cos2(\theta_r - \frac{\pi}{12}) \quad (4.16)$$

$$L_{a_1b_2} = L_{b_2a_1} = -\frac{\sqrt{3}}{2}\bar{L}_m - L_{\Delta m}\cos2(\theta_r - \frac{\pi}{3} - \frac{\pi}{12}) \quad (4.17)$$

$$L_{a_1c_2} = L_{c_2a_1} = L_{\Delta m}\sin2\theta_r = L_{\Delta m}\cos2(\theta_r - \frac{\pi}{4}) \quad (4.18)$$

$$L_{b_1b_1} = L_{ls} + \bar{L}_m - L_{\Delta m}\cos2(\theta_r - \frac{2\pi}{3}) \quad (4.19)$$

$$L_{b_1c_1} = L_{c_1b_1} = -\frac{1}{2}\bar{L}_m - L_{\Delta m}\cos2\theta_r \quad (4.20)$$

$$L_{b_1 a_2} = L_{a_2 b_1} = L_{\Delta m} \cos 2(\theta_r + \frac{\pi}{12}) \quad (4.21)$$

$$L_{b_1 b_2} = L_{b_2 b_1} = \frac{\sqrt{3}}{2} \bar{L}_m + L_{\Delta m} \cos 2(\theta_r - \frac{\pi}{4}) \quad (4.22)$$

$$L_{b_1 c_2} = L_{c_2 b_1} = -\frac{\sqrt{3}}{2} \bar{L}_m - L_{\Delta m} \cos 2(\theta_r - \frac{\pi}{12}) \quad (4.23)$$

$$L_{c_1 c_1} = L_{l_s} + \bar{L}_m - L_{\Delta m} \cos 2(\theta_r + \frac{2\pi}{3}) \quad (4.24)$$

$$L_{c_1 a_2} = L_{a_2 c_1} = -\frac{\sqrt{3}}{2} \bar{L}_m - L_{\Delta m} \cos 2(\theta_r + \frac{\pi}{4}) \quad (4.25)$$

$$L_{c_1 b_2} = L_{b_2 c_1} = L_{\Delta m} \cos 2(\theta_r + \frac{5\pi}{12}) \quad (4.26)$$

$$L_{c_1 c_2} = L_{c_2 c_1} = \frac{\sqrt{3}}{2} \bar{L}_m + L_{\Delta m} \cos 2(\theta_r + \frac{\pi}{12}) \quad (4.27)$$

$$L_{a_2 a_2} = L_{l_s} + \bar{L}_m - L_{\Delta m} \cos 2(\theta_r - \frac{\pi}{6}) \quad (4.28)$$

$$L_{a_2 b_2} = L_{b_2 a_2} = -\frac{1}{2} \bar{L}_m - L_{\Delta m} \cos 2(\theta_r - \frac{\pi}{2}) \quad (4.29)$$

$$L_{a_2 c_2} = L_{c_2 a_2} = -\frac{1}{2} \bar{L}_m - L_{\Delta m} \cos 2(\theta_r + \frac{\pi}{6}) \quad (4.30)$$

$$L_{b_2 b_2} = L_{l_s} + \bar{L}_m - L_{\Delta m} \cos 2(\theta_r - \frac{2\pi}{3} - \frac{\pi}{6}) \quad (4.31)$$

$$L_{b_2 c_2} = L_{c_2 b_2} = -\frac{1}{2} \bar{L}_m - L_{\Delta m} \cos 2(\theta_r - \frac{\pi}{6}) \quad (4.32)$$

$$L_{c_2 c_2} = L_{l_s} + \bar{L}_m - L_{\Delta m} \cos 2(\theta_r + \frac{2\pi}{3} - \frac{\pi}{6}) \quad (4.33)$$

where \bar{L}_m , $L_{\Delta m}$ and L_{l_s} are average values of magnetization inductance, half-amplitude of the sinusoidal variation of the magnetization inductance and the leakage inductance of each winding. It is assumed that all windings have the same number of turns.

If we define the vectors and matrixes for the inductances, currents, voltages, fluxes, and resistance as following:

$$\mathbf{L}_s = \begin{bmatrix} L_{a_1 a_1} & L_{a_1 b_1} & L_{a_1 c_1} & L_{a_1 a_2} & L_{a_1 b_2} & L_{a_1 c_2} \\ L_{b_1 a_1} & L_{b_1 b_1} & L_{b_1 c_1} & L_{b_1 a_2} & L_{b_1 b_2} & L_{b_1 c_2} \\ L_{c_1 a_1} & L_{c_1 b_1} & L_{c_1 c_1} & L_{c_1 a_2} & L_{c_1 b_2} & L_{c_1 c_2} \\ L_{a_2 a_1} & L_{a_2 b_1} & L_{a_2 c_1} & L_{a_2 a_2} & L_{a_2 b_2} & L_{a_2 c_2} \\ L_{b_2 a_1} & L_{b_2 b_1} & L_{b_2 c_1} & L_{b_2 a_2} & L_{b_2 b_2} & L_{b_2 c_2} \\ L_{c_2 a_1} & L_{c_2 b_1} & L_{c_2 c_1} & L_{c_2 a_2} & L_{c_2 b_2} & L_{c_2 c_2} \end{bmatrix},$$

$$\mathbf{i}_s = [i_{a_1} \quad i_{b_1} \quad i_{c_1} \quad i_{a_2} \quad i_{b_2} \quad i_{c_2}]^T,$$

$$\mathbf{v}_s = [v_{a_1} \quad v_{b_1} \quad v_{c_1} \quad v_{a_2} \quad v_{b_2} \quad v_{c_2}]^T,$$

$$\boldsymbol{\psi}_s = [\psi_{a_1} \quad \psi_{b_1} \quad \psi_{c_1} \quad \psi_{a_2} \quad \psi_{b_2} \quad \psi_{c_2}]^T \text{ and}$$

$$\mathbf{R}_s = \begin{bmatrix} r_s & 0 & 0 & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 & 0 & 0 \\ 0 & 0 & r_s & 0 & 0 & 0 \\ 0 & 0 & 0 & r_s & 0 & 0 \\ 0 & 0 & 0 & 0 & r_s & 0 \\ 0 & 0 & 0 & 0 & 0 & r_s \end{bmatrix}$$

the voltage and flux equations can be written as [51]:

$$\mathbf{v}_s = \mathbf{R}_s \mathbf{i}_s + \frac{d}{dt} \psi_s. \quad (4.34)$$

The developed electromagnetic torque in the machine can be calculated as [51]:

$$T_e = \frac{P}{2} \left(\frac{1}{2} \mathbf{i}_s^T \frac{\partial \mathbf{L}_s}{\partial \theta_r} \mathbf{i}_s + \mathbf{i}_s^T \frac{\partial \psi_{\mathbf{pm}}}{\partial \theta_r} \right) \quad (4.35)$$

where P is the machine number of poles. $\psi_{\mathbf{pm}}$ is stator winding fluxes due to rotor magnets. The mechanical dynamical equations describing the machine are:

$$\frac{d\omega_r}{dt} = \frac{P}{2J} \left(T_e - \frac{2B_m}{P} \omega_r - T_L \right) \quad (4.36)$$

$$\frac{d\theta_r}{dt} = \omega_r \quad (4.37)$$

where J , B_m , T_L and ω_r are the moment of inertia, viscous friction coefficient, load torque and speed of the machine.

To simplify the machine equations a special version of the Park transformation (it is called extended Park transformation here) is used to reduce the system order and remove all sinusoidal terms. The transformation matrix, \mathbf{K}_s , is applied to machine equations to transform them to the synchronous dq0 reference frame. This matrix is defined as:

$$\mathbf{K}_s = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) & \dots \\ -\sin\theta_r & -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) & \dots \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \dots \\ 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & \dots \\ \cos(\theta_r - \frac{\pi}{6}) & \cos(\theta_r - \frac{2\pi}{3} - \frac{\pi}{6}) & \cos(\theta_r + \frac{2\pi}{3} - \frac{\pi}{6}) & \dots \\ -\sin(\theta_r - \frac{\pi}{6}) & -\sin(\theta_r - \frac{2\pi}{3} - \frac{\pi}{6}) & -\sin(\theta_r + \frac{2\pi}{3} - \frac{\pi}{6}) & \dots \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \dots \end{bmatrix}.$$

The inverse of the matrix $\mathbf{K}_s, \mathbf{K}_s^{-1}$, can be calculated as:

$$\mathbf{K}_s^{-1} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r & 1 & \dots \\ \cos(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r - \frac{2\pi}{3}) & 1 & \dots \\ \cos(\theta_r + \frac{2\pi}{3}) & -\sin(\theta_r + \frac{2\pi}{3}) & 1 & \dots \\ 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & \dots \end{bmatrix}$$

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \cos(\theta_r - \frac{\pi}{6}) & -\sin(\theta_r - \frac{\pi}{6}) & 1 \\ \cos(\theta_r - \frac{2\pi}{3} - \frac{\pi}{6}) & -\sin(\theta_r - \frac{2\pi}{3} - \frac{\pi}{6}) & 1 \\ \cos(\theta_r + \frac{2\pi}{3} - \frac{\pi}{6}) & -\sin(\theta_r + \frac{2\pi}{3} - \frac{\pi}{6}) & 1 \end{bmatrix}.$$

By transforming the phase variables to the rotor reference frame by applying the transformation matrix \mathbf{K}_s , the machine equations will be simplified with reduced number of equations. In the rotor reference frame the variables are superscripted by letter r and are defined as:

$$\mathbf{i}_s^r = [i_{d_1} \quad i_{q_1} \quad i_{0_1} \quad i_{d_2} \quad i_{q_2} \quad i_{0_2}]^T,$$

$$\mathbf{v}_s^r = [v_{d_1} \quad v_{q_1} \quad v_{0_1} \quad v_{d_2} \quad v_{q_2} \quad v_{0_2}]^T \text{ and}$$

$$\psi_s^r = [\psi_{d_1} \quad \psi_{q_1} \quad \psi_{0_1} \quad \psi_{d_2} \quad \psi_{q_2} \quad \psi_{0_2}]^T.$$

The indexes d , q and 0 denote the direct axis, quadrature axis and zero component of the variables. Moreover, there are two set of three-phase quantities that are denoted by the numbers 1 and 2 respectively. For example the voltage can be transformed from the abc domain to the dq domain by $\mathbf{v}_s^r = \mathbf{K}_s \mathbf{v}_s$.

By transforming machine voltage, flux linkage and torque equations to the dq reference frame, the following equations describe the electrical system dynamics:

$$v_{d_1} = r_s i_{d_1} + \frac{d}{dt} \psi_{d_1} - \omega_r \psi_{q_1} \quad (4.38)$$

$$v_{q_1} = r_s i_{q_1} + \frac{d}{dt} \psi_{q_1} + \omega_r \psi_{d_1} \quad (4.39)$$

$$v_{d_2} = r_s i_{d_2} + \frac{d}{dt} \psi_{d_2} - \omega_r \psi_{q_2} \quad (4.40)$$

$$v_{q_2} = r_s i_{q_2} + \frac{d}{dt} \psi_{q_2} + \omega_r \psi_{d_2} \quad (4.41)$$

$$\psi_{d_1} = L_d i_{d_1} + L_{md} i_{d_2} + \psi_{pm} \quad (4.42)$$

$$\psi_{q_1} = L_q i_{q_1} + L_{mq} i_{q_2} \quad (4.43)$$

$$\psi_{d_2} = L_{md} i_{d_1} + L_d i_{d_2} + \psi_{pm} \quad (4.44)$$

$$\psi_{q_2} = L_{mq} i_{q_1} + L_q i_{q_2} \quad (4.45)$$

where L_d , L_q , L_{md} , L_{mq} are direct and quadrature axis winding self and mutual inductances respectively. Moreover, $L_d = L_l + L_{md}$ and $L_q = L_l + L_{mq}$. It is assumed that the zero components are zero due to symmetrical three-phase quantities.

The developed electromagnetic torque can be expressed as:

$$T_e = \frac{3P}{2} [\psi_{pm}(i_{q_1} + i_{q_2}) + (L_d - L_q)(i_{d_1} i_{q_1} + i_{d_1} i_{q_2} + i_{d_2} i_{q_1} + i_{d_2} i_{q_2})]. \quad (4.46)$$

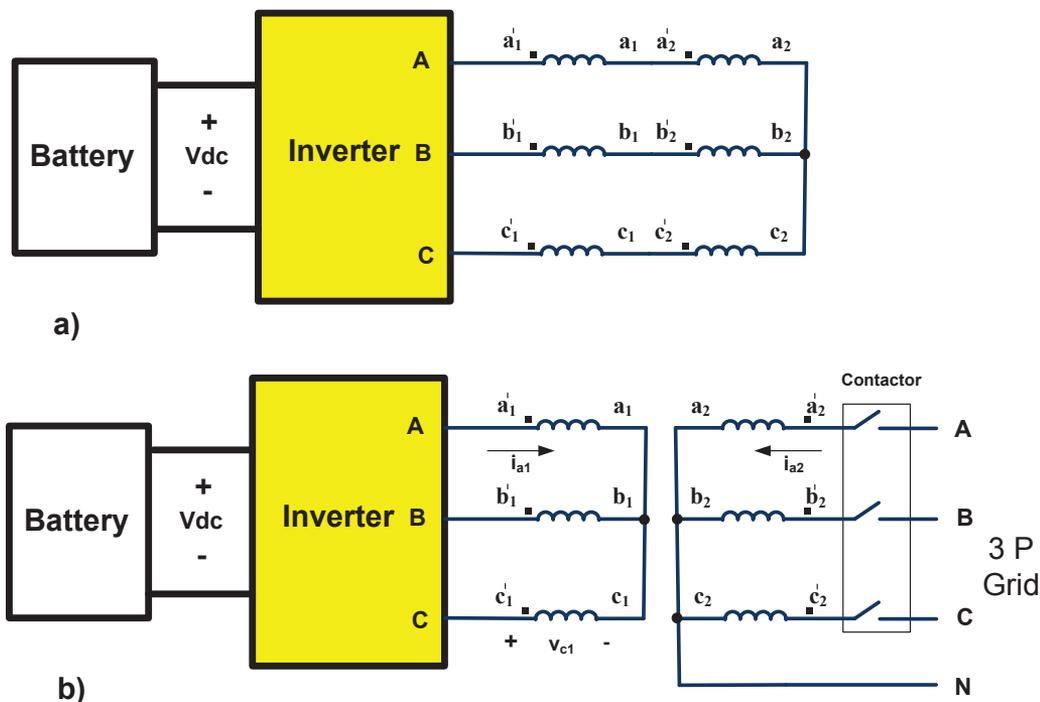


Figure 4.4: System modes of operation: a) traction and b) charging.

4.3 System Operation in Traction and Charging

As mentioned before, the system has two modes of operation: traction and charging. In traction mode, each two windings are connected to each other in series to constitute a three-phase winding set. These three windings can be connected to each other in Δ or Y to form a classical three-phase machine. Moreover, the motor is powered by the battery through the inverter. Fig. 4.4.a shows the system diagram in this mode. Sensorless schemes for example can be employed to run the motor in traction mode [52].

For charging, the system is reconfigured according to the scheme shown in Fig. 4.4.b. A simple relay based device re-connects the windings and a contactor is needed to connect the system to the utility grid.

If the machine would be kept in standstill as in [22], the magnetization current will be high due to the air-gap. So it is expected to have lower system efficiency depending on the air-gap length. However, if the machine rotates with the grid synchronous speed, the magnets will induce voltages in the inverter-side windings that emulates an isolated PM ac generator for the inverter. The idea is thus to connect the machine to the grid via the grid-side three-phase windings, a_2 , b_2 and c_2 . These three windings can be used to run the machine as a classical motor. The inverter side windings, a_1 , b_1 and c_1 pick up the induced voltage due to the developed flux inside the machine (since they are located on the same pole-pair as are the grid-side windings). The inverter uses

this isolated voltage source to charge the battery by the means of machine leakage inductances as the converter energy storage component (yielding a three-phase boost converter).

4.3.1 Motor/Generator Grid Synchronization

At first, the inverter-side windings are used to drive the motor by the means of the battery and proper inverter operation while the grid-side windings are open connected. The electric machine must be rotated at the synchronous speed and produce the same voltage as the grid does (both amplitude and phase) for the grid connection. Before closing the contactor, the dc link voltage, motor/generator primary side currents and the rotor position/speed are measured to have a classical field oriented speed control of the IPM motor [53]. The position/speed can be estimated instead of using a sensor, but here for simplicity it is assumed that the position and speed signals are available.

Both grid-side winding voltages, and grid voltages are measured and transformed to the dq reference frame. Both voltage vectors magnitude and angle of the grid voltage and motor/generator grid-side windings should be equal as an index of synchronization. The magnitude of voltage is a function of the motor speed and flux (refer to motor/generator equations), so by controlling the flux, the voltage level can be adjusted. In a classical IPM motor usually the reference value for the d component of the machine is zero (for flux weakening operation this value will be modified), but at this scheme this value is used as a control parameter to change the induced voltage magnitude. The d component of the voltage is close to zero so the angle error is replaced by the voltage d components error ($v_{dg} - v_{d2}$) in the controller for the phase synchronization.

The motor/generator will rotate at the synchronous speed to meet the frequency synchronization requirement. So the speed reference will be $2\pi 50 \text{ rad/s}$ for a grid with 50 Hz frequency supply. Moreover, to match the voltage angles, a PI controller is used to adjust the motor/generator speed reference due to the angle error signal. This speed reference will be tracked by the field oriented speed control part of the system. Fig. 4.5 shows the schematic diagram of the control system in the synchronization phase.

When both voltage magnitude and angle error signals are small values within predefined bands, the motor/generator set is synchronized and the contactor is closed. Now the system is ready for the charge operation.

4.3.2 Battery Charge Control

Fig. 4.6 shows a basic diagram of a three-phase boost converter. This scheme is very similar to the proposed integrated charger system. The voltage equations describing the converter in the dq reference frame are [54]:

$$u_{Ld} = Ri_{Ld} + L \frac{d}{dt} i_{Ld} - \omega L i_{Lq} + u_{Id} \quad (4.47)$$

$$u_{Lq} = Ri_{Lq} + L \frac{d}{dt} i_{Lq} + \omega L i_{Ld} + u_{Iq} \quad (4.48)$$

where u_{Ld} , u_{Lq} , u_{Id} and u_{Iq} are line and inverter dq voltage components respectively. R , L and ω are the resistance, inductance and source frequency

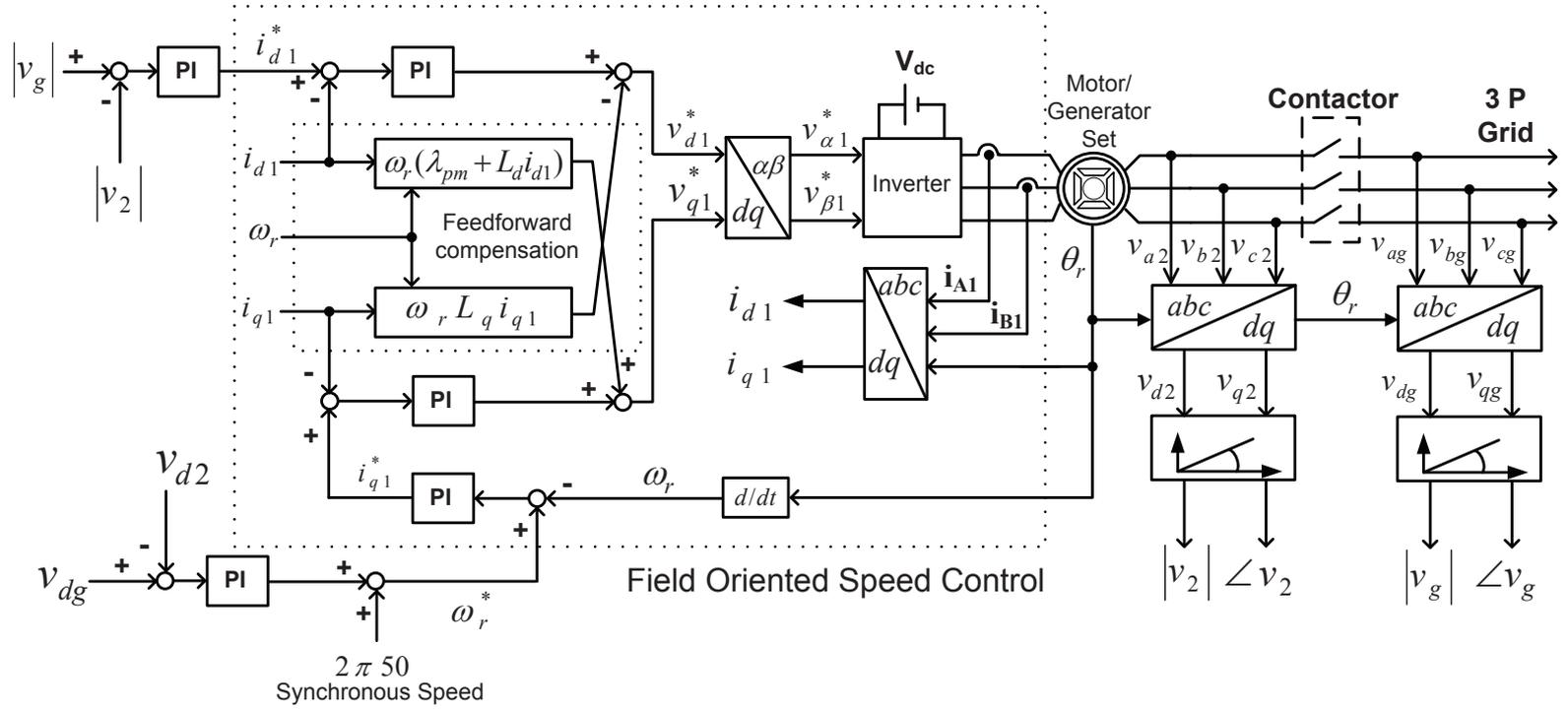


Figure 4.5: Grid synchronization scheme of IPM motor/generator set.

also. i_{Ld} and i_{Lq} are d and q components of the line currents. The active and reactive power going to the converter from the grid can be written as [54]:

$$p = \frac{3}{2}(u_{Ld}i_{Ld} + u_{Lq}i_{Lq}) \quad (4.49)$$

$$q = \frac{3}{2}(u_{Lq}i_{Ld} - u_{Ld}i_{Lq}) \quad (4.50)$$

Different control strategies have been proposed for this three-phase boost converter operation [12]. If $i_{Lq} = 0$ and $u_{Lq} = 0$ in the equations above, then the active and reactive power will be simplified to $p = \frac{3}{2}u_{Ld}i_{Ld}$ and $q = 0$. Based on these equations, the feedforward current control method is one of the widely used schemes for power control. Fig. 4.7 shows the basic diagram of the controller. The dq current control and feedforward compensation are the main parts of this decoupled control scheme. The controller has an outer loop for the dc bus voltage regulation. This controller output sets the reference value for the d component of the current that controls the power. Two independent PI controllers have been used to generate reference values for the converter, u_α and u_β . The feedforward terms are added to this reference values to the decoupled system in d and q axes to improve the system performance.

At grid synchronization the contactor is closed and the grid voltages are applied to the grid-side motor/generator windings. Thus it is a constant voltage source over the windings. The motor/generator voltage equations can be written as below after some mathematical manipulations:

$$v_{d_2} = r_s(i_{d_2} - i_{d_1}) + L_l \frac{d}{dt}(i_{d_2} - i_{d_1}) - \omega_r L_l (i_{q_2} - i_{q_1}) + v_{d_1} \quad (4.51)$$

$$v_{q_2} = r_s(i_{q_2} - i_{q_1}) + L_l \frac{d}{dt}(i_{q_2} - i_{q_1}) + \omega_r L_l (i_{d_2} - i_{d_1}) + v_{q_1}. \quad (4.52)$$

The equations above are very similar to (4.47) and (4.48) that describe the classical three-phase boost converter. The difference is that currents are replaced by the difference of the primary and secondary winding currents. So the same control strategy is adopted with small modifications (adjusting the currents by the current differences). Moreover, due to existence of a battery in the dc link, the dc bus voltage controller is eliminated from the scheme.

Fig. 4.8 shows the proposed control system diagram in charging mode. This scheme is an extension of the classical control (Fig. 4.7) with some modifications. Two sets of three-phase machine currents and rotor position are measured and used in the controller. The grid voltage is also measured and used in the controller for proper operation (feed-forward compensation). When the system starts to charge, there are some mechanical oscillations in the rotor. The rotor speed error (the difference between the synchronous speed and true speed) is added to the controller by the means a proportional controller to reduce these oscillations.

With assumption of the symmetrical three-phase currents and voltages for the inverter-side and grid-side windings, each three-phase quantity can be represented by a classical two-dimensional vector with the extended dq transformation (there is no coupling in the matrix transformation between the two systems).

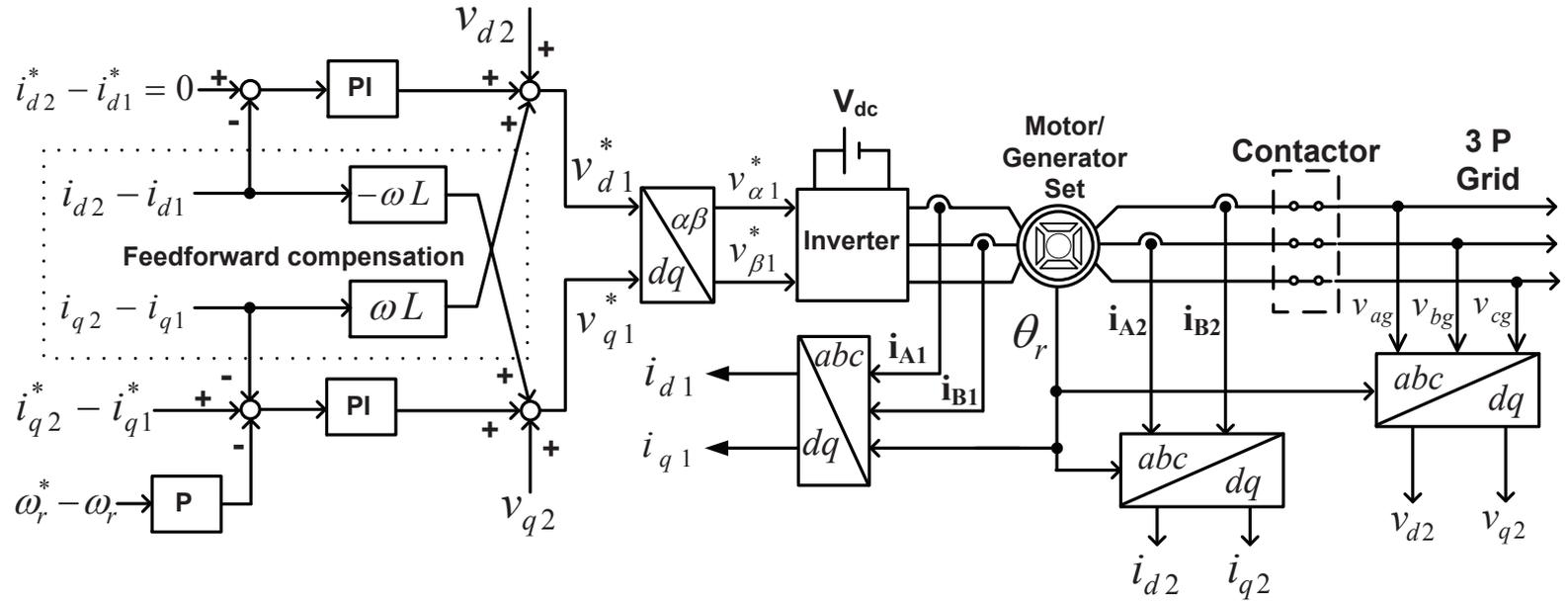


Figure 4.8: Block diagram for the charge control of proposed integrated charger.

The system has a bidirectional power flow capability that is inherent in the system because of the bidirectional operation of the three-phase inverter. Moreover, by changing the set point of the d component of the current, there is also a possibility of production/generation of reactive power. The system power limitation is mainly a thermal limitation of the machine in the classical vehicle drive systems. Half of the machine's full power can be used in the charging mode (the converter withstands this power level because it is designed for machine full power operation).

4.4 Integrated Charger Simulation Results

A 4 pole IPM machine is designed, optimized and constructed for a 25 kW traction system with a possibility to reconnect the windings for charging [50]. Fig. 4.9.a shows the windings configuration (in delta) in traction mode. The dc bus voltage (battery voltage) is 400 Vdc in this case. The machine base speed is 1500 rpm while the maximum speed is 6500 rpm. For charging, the windings are re-arranged according to Fig. 4.9.b. The charge power is limited to 12.5 kW due to the machine thermal limit. The motor parameters are shown in Table 4.1. The whole system has been simulated by the use of

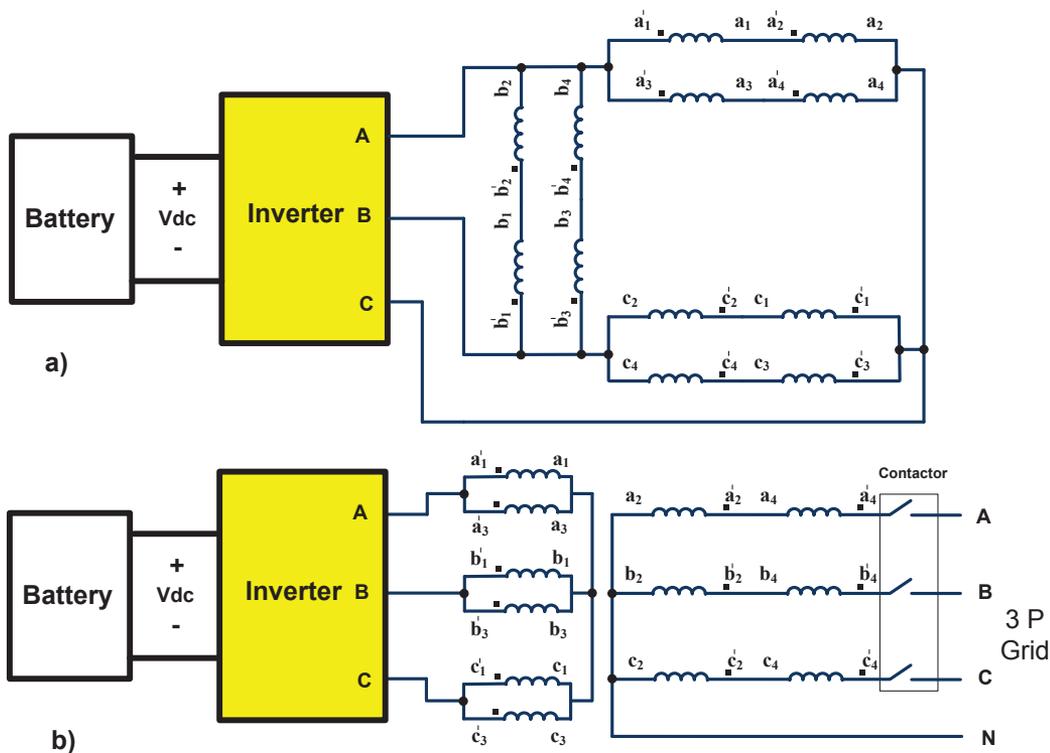


Figure 4.9: 25 kW system modes of operation: a) traction and b) charging.

Matlab/Simulink software based on the before mentioned system equations. The ideal converter is used in the simulation (no PWM or SVM is used for

Table 4.1: IPM motor parameters.

Rated power (kW)	25
Rated line voltage (V)	270
Rated phase current (A)	30
Rated speed (rev/min)	1500
No of poles	4
Permanent magnet flux (Wb)	0.6
Stator resistance (Ohm)	0.45
d axis inductance (mH)	12
q axis inductance (mH)	42
Inertia (Kg.m ²)	0.1
Viscous friction coefficient (Nms/rad)	0.002

the inverter). Before simulation starts, it is assumed that the system is re-configured for charging but the grid contactor is open. The charging process starts with that the inverter starts to rotate the motor by the means of the battery and inverter side motor windings. The motor will then rotate at grid synchronous speed.

When the motor speed is close to synchronous speed, the voltage level of the grid-side winding is adjusted by controlling the motor flux level (d component of the current). Afterwards, the voltage angle is adjusted by speed control of the motor (equivalently torque control) by the means of the q component of the current in this case. After synchronization, both voltage amplitude and angle adjustment, the contactor is closed and the machine grid-side windings are directly connected to the grid. One second after closing the contactor (the system continues the synchronization while the contactor is closed for more stability), the charge control is started for a power level of 12.5 kW. In order to show the system transient response, the charge power is reduced to 7 kW after two seconds.

System operation during different time intervals can be summarized as:

- $t = 0$ s till $t = 0.5$ s: The speed is regulated close to the synchronous speed, $2\pi 50$ rad/s. The system is in synchronization mode and the contactor is open.
- $t = 0.5$ s till $t = 0.9$ s: The grid side windings voltage amplitudes are adjusted. The system is in synchronization mode and the contactor is open.
- $t = 0.9$ s till $t = 3.6$ s: The grid side windings voltage angles are adjusted. The system is in synchronization mode and the contactor is open.
- $t = 3.6$ s till $t = 5$ s: Synchronization is finished and the contactor is closed, but the charging is not started.
- $t = 5$ s till $t = 7$ s: The system is charging full power (12.5 kW).
- $t = 7$ s till $t = 9$ s: The system is charging with 7 kW power.

Fig. 4.10 shows the power from the grid to the charger system. At first, while the motor/generator is in synchronization mode (the first 3.6 seconds), the grid power is zero. Then the contactor is closed and charging is started after 1.4 seconds ($t=5$ s). After additional two seconds ($t=7$ s), the charging power is reduced to 7 kW. The electrical speed is shown in Fig. 4.11. As is shown in this figure, the rotor speed oscillations are damped quickly by the proper operation of the controller as it was expected. The system efficiency is around 89%. However, the machine iron losses and inverter losses are neglected in this simulation. This efficiency level is acceptable compared to a similar isolated version of integrated charger. Even though motor losses are the same and inverter losses are lower in charging mode compared to traction mode, the efficiency of the system in charging mode is lower than the efficiency of the system in traction mode since with the same amount of losses the output power in charging is half that of traction. Thus, with improved design of the motor it is possible to increase the system efficiency for both charging and traction.

The motor/generator torque is shown in Fig. 4.12. The machine develops constant torque in the first 0.35 seconds to increase the speed to become close to the synchronous speed ($2\pi 50$ rad/s in this case). Then there are some oscillations around times $t = 0.5$ s and $t = 0.9$ s. First the voltage magnitude is adjusted and then the voltage angle is adjusted for synchronization. Moreover, there are some oscillations in torque around the times that the contactor is closed ($t = 3.6$ s), start of charging ($t = 5$ s) and step changes of the charge power level ($t = 7$ s). The developed torque compared to its nominal value is almost negligible (less than 1%) because there is no mechanical load connected to the machine during charging.

As is mentioned before, unit power factor operation is possible for the charger. Fig. 4.13 shows grid side phase A winding voltage and current. The voltage is scaled to half its value for more figure clarity.

Grid side and inverter side windings are shifted 30 electrical degrees (refer to Fig. 4.3). Therefore, phase shifted voltages for grid side and inverter side windings are expected. This phase shift can be seen in Fig. 4.14 which shows phase A voltages for the grid side and inverter side windings.

Fig. 4.15 shows the phase A current of the grid during the charge operation. For more clarity, the three-phase currents are shown in Fig. 4.16, 4.17 and 4.18 during the time when the contactor is closed, at full power charging and at the step change in charging power. As is shown in these figures, the system has good dynamic performance.

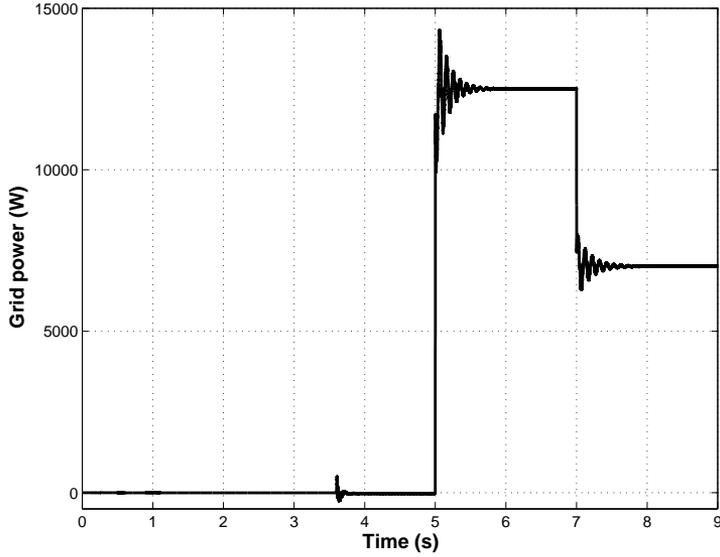


Figure 4.10: Grid power to the charger system.

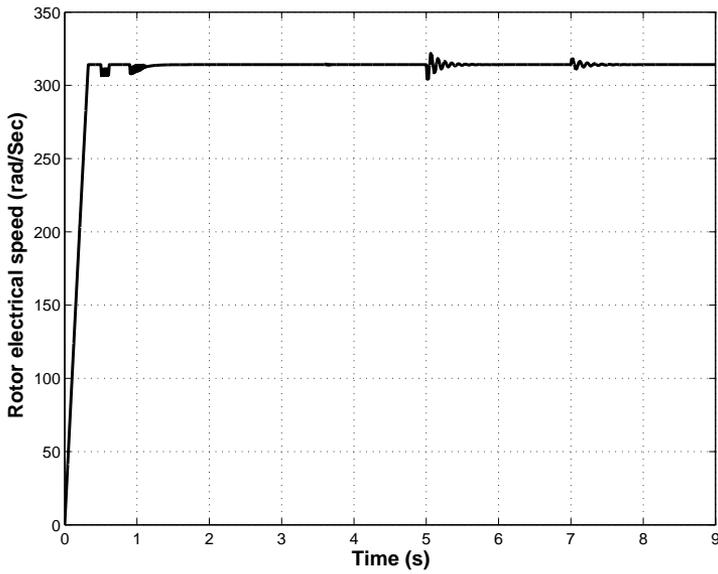


Figure 4.11: Electrical speed of the motor/generator.

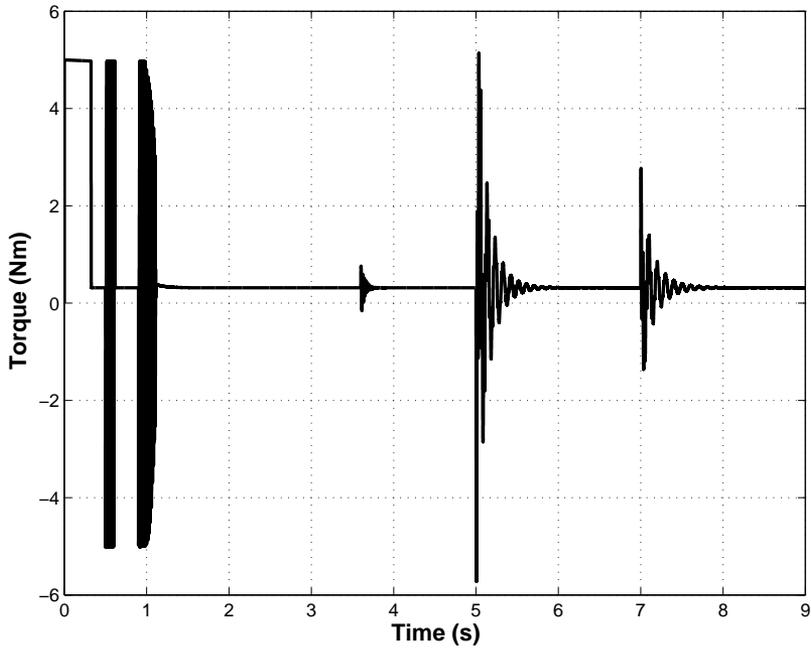


Figure 4.12: Motor/generator torque during charge time.

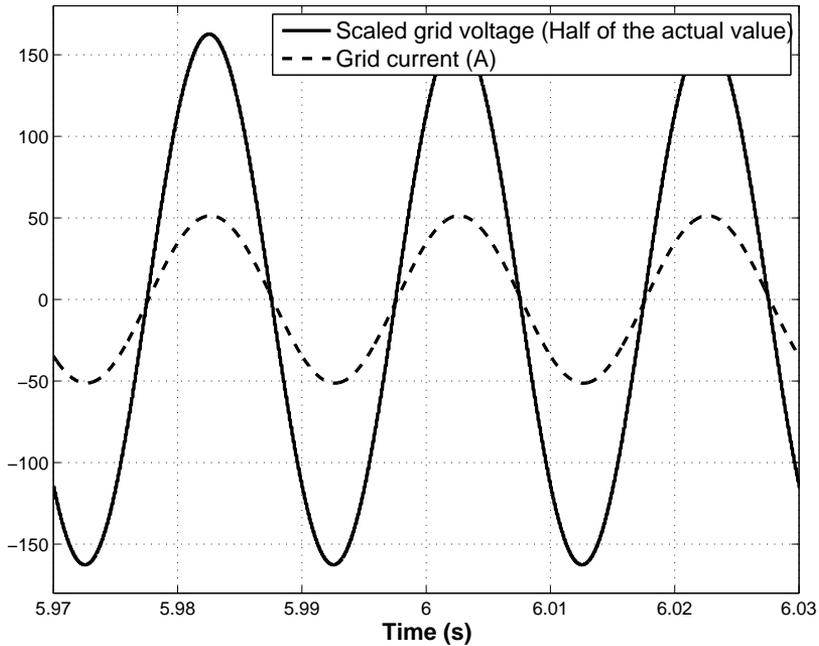


Figure 4.13: Grid side phase A voltage and current: unit power factor operation.

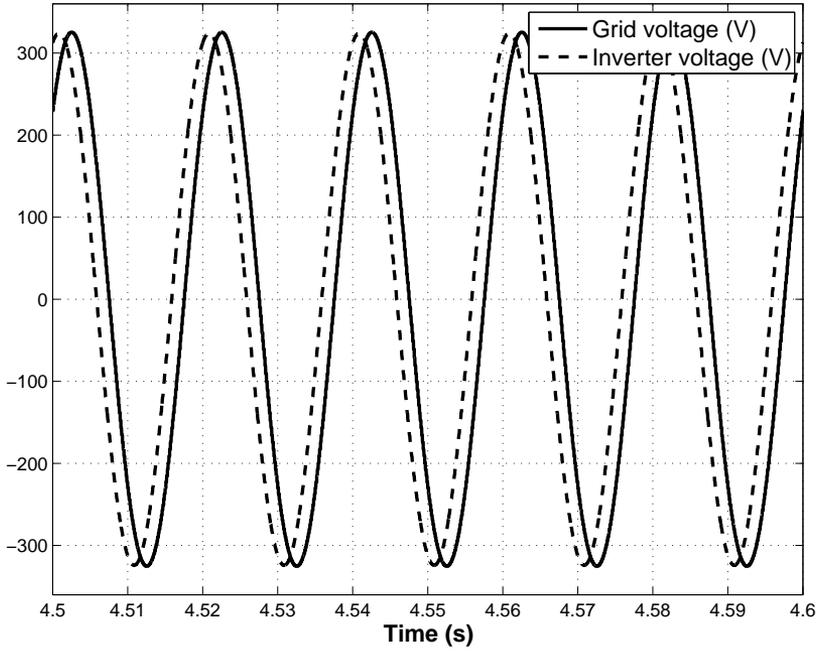


Figure 4.14: Grid side and inverter side winding voltages for phase A.

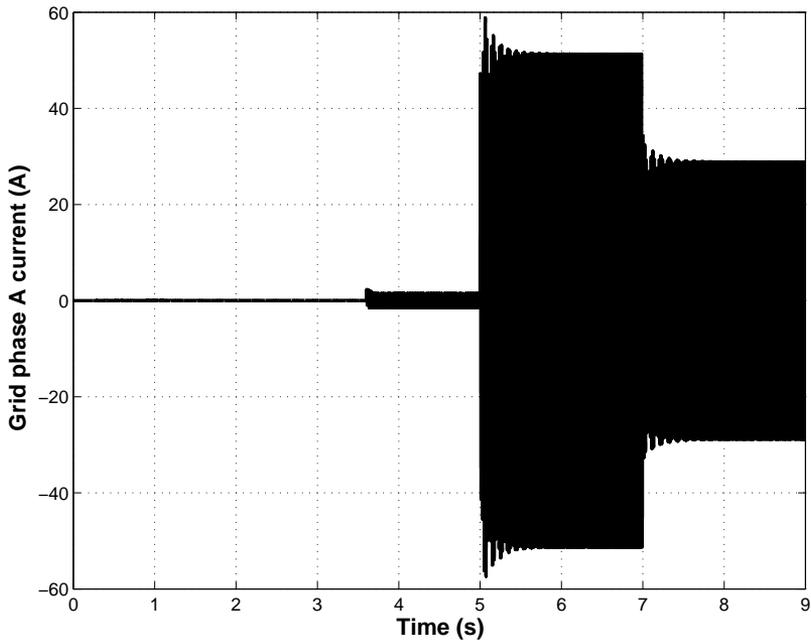


Figure 4.15: Grid side phase A current during charge time.

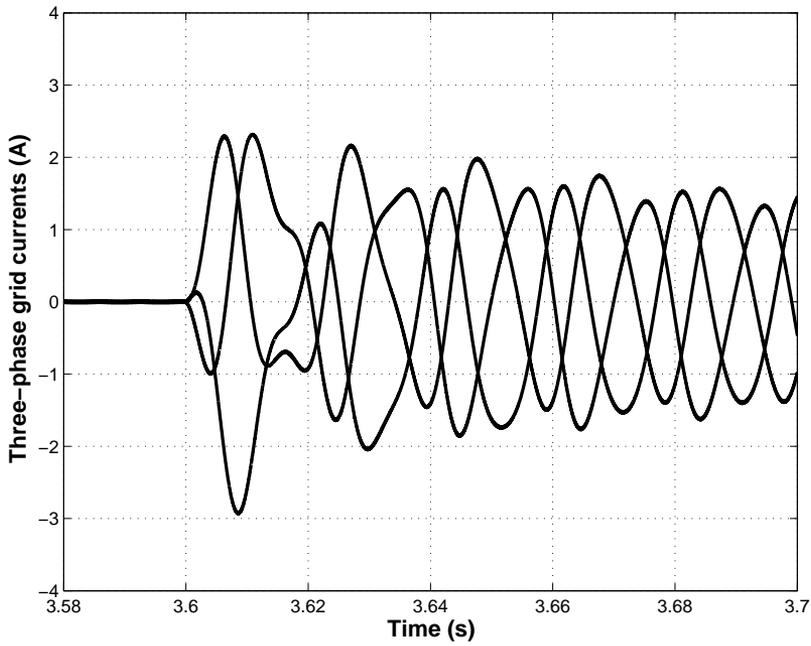


Figure 4.16: Grid three-phase currents during closing the contactor and before charge start-up.

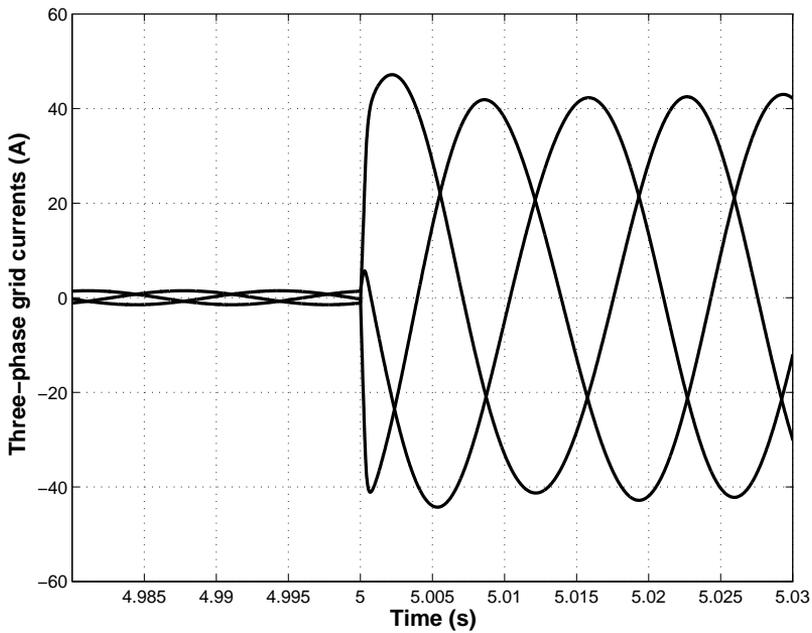


Figure 4.17: Grid three-phase currents after closing the contactor and during charge start-up.

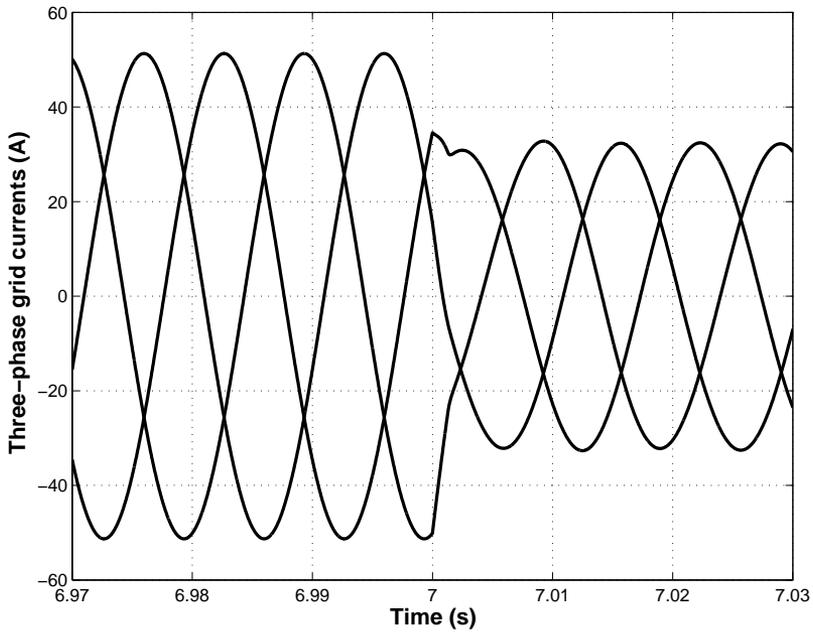


Figure 4.18: Grid three-phase currents during the step change of the charging power.

4.5 Drive System Performance of a DTC Based IPM Machine

As mentioned in previous sections, the field-oriented control method used for both synchronization and charge control is a widely-used method [55]. Other alternatives can be employed to improve the overall system performance like system response time or improved dynamic behavior. Direct torque control is one of these techniques gained a lot of interest due to its simplicity and fast dynamic response [56]. A 25 kW IPM machine is used in this project as traction motor and motor/generator device in charging mode. The drive system performance for a IPM machine is introduced in this section while the detail discussions are presented in appended paper [III].

Direct torque control method first introduced by Takahashi [57] and Depenbrock [58] gained a lot of attentions thanks to its simple structure and fast torque dynamics. In the DTC method, six non-zero and two zero voltage vectors generated by the inverter are selected to keep the motor flux and torque within the limits of two hysteresis bands [59]. The DTC method has been widely studied for induction machines. For the induction machines there are four different switching patterns for the selection of the inverter voltage vector [52]. Each switching method affects the drive system performance [60]. The same concept is applied to the IPM synchronous machine [56], so most of the methods developed for DTC based induction motor drive systems can be applied for the DTC based IPM synchronous motor drives.

The impact of different inverter switching patterns on the performance of a DTC based IPM drive system is investigated in terms of torque ripple, flux ripple, current ripple and inverter switching frequency at low speeds. Applying a zero voltage vector by the inverter has an important role on the overall drive system performance that will be addressed in the sequel.

Fig. 4.19 shows the block diagram of a IPM synchronous motor drive system based on the DTC method. During each sample interval the stator currents, i_A and i_B , are measured along with the dc bus voltage V_{dc} . Using the inverter switching states ($S_A S_B S_C$), the stator voltage and current vector components in the stationary reference frame can be calculated as [52]:

$$u_\alpha = \frac{2}{3}V_{dc}(S_A - \frac{S_A + S_B}{2}) \quad (4.53)$$

$$u_\beta = \frac{1}{\sqrt{3}}V_{dc}(S_B - S_C) \quad (4.54)$$

$$i_\alpha = i_A \quad (4.55)$$

$$i_\beta = \frac{i_A + 2i_B}{\sqrt{3}} \quad (4.56)$$

where u_α , u_β , i_α and i_β are α and β components of the stator voltage and current in the stationary reference frame. The α and β components of the stator flux, ψ_α and ψ_β , can be obtained by the integration of the stator voltage minus the voltage drop in the stator resistance as:

$$\psi_\alpha = \int_0^t (u_\alpha - Ri_\alpha)dt + \psi_{\alpha|t=0} \quad (4.57)$$

$$\psi_\beta = \int_0^t (u_\beta - Ri_\beta)dt + \psi_{\beta|t=0}. \quad (4.58)$$

The electromagnetic torque, T_e , can be written in terms of quantities in the stationary reference frame as:

$$T_e = \frac{3}{2}P(\psi_\alpha i_\beta - \psi_\beta i_\alpha). \quad (4.59)$$

This equation is used in the drive system to estimate the developed electromagnetic torque [52]. The stator flux vector magnitude and phase are given by:

$$|\overline{\psi}_s| = \sqrt{\psi_\alpha^2 + \psi_\beta^2} \quad (4.60)$$

$$\angle \overline{\psi}_s = \arctan\left(\frac{\psi_\beta}{\psi_\alpha}\right). \quad (4.61)$$

As shown in Fig. 4.19, estimated values of the stator flux vector magnitude, $|\overline{\psi}_s|$, and the electromagnetic torque, T_e , are compared with their reference values. Afterwards, the errors are provided to the flux and torque hysteresis controllers. The goal of the control system is to limit the flux and torque within the hysteresis bands around their reference values. By using the torque error, flux error and stator flux position the control can be done by applying a proper inverter voltage. For a three phase inverter, there are 6 power switches. It is not possible to turn on the upper and lower switches in a leg simultaneously. So there are 8 possible switching configurations where each state defines a voltage space vector. Fig. 4.20 shows six non-zero inverter voltage space vectors (there are two zero voltage vectors, \overline{u}_7 and \overline{u}_8 , that are not shown in this figure). Moreover the $\alpha\beta$ plane can be divided into 6 sectors ($k=1, 2, 3, 4, 5$ and 6) in which the controller needs to know in what sector the stator flux is located. If two level hysteresis controllers are used for the flux and torque control, there will be four switching strategies for the selection of the appropriate stator voltage vector (these possible switching strategies are proposed for the DTC of induction motors originally). Assume that the stator flux vector is located in sector k , then these four switching strategies are listed in Table 4.2 [59]. Effects of the applied voltage vector on the motor flux and torque are summarized in Table 4.2 as well. For the DTC system based on the IPM synchronous motor mainly solution A and D are used [61].

Assume that the flux is located in sector k ; then, to increase the torque the voltage vectors \overline{u}_{k+1} or \overline{u}_{k+2} will be applied (depending on if the flux increases or decreases, one of the two voltage vectors will be selected). Different voltage vectors can be applied to decrease the torque in different switching possibilities. \overline{u}_k , \overline{u}_{k-1} , \overline{u}_{k-2} , \overline{u}_{k+3} , \overline{u}_7 and \overline{u}_8 can be applied according to Table 4.2. As is seen in Table 4.2, different switching patterns are only different in the torque decrement case, regardless of the flux increase or decrease demand in the motor. To decrease the torque, the simplest way is applying a zero voltage (solution A). The main difference between switching algorithms is in applying the zero vector or non-zero vector to decrease the torque. The motor current ripple, torque ripple and inverter switching frequency will vary for each switching strategy. This will affect the whole drive system performance for each switching method.

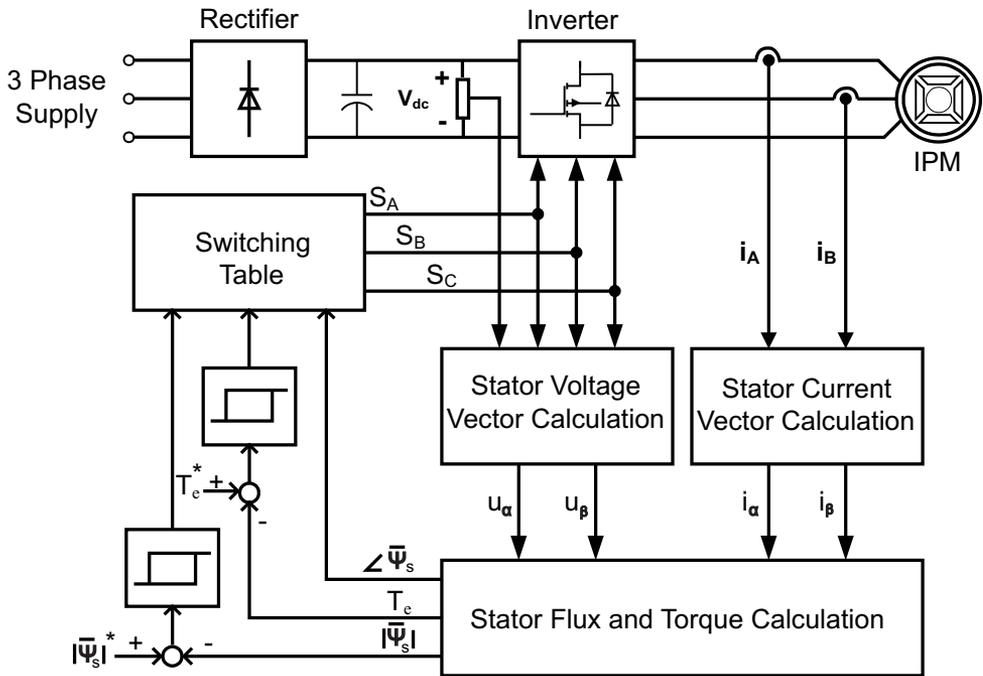


Figure 4.19: Block diagram of the direct torque control of IPM synchronous motor.

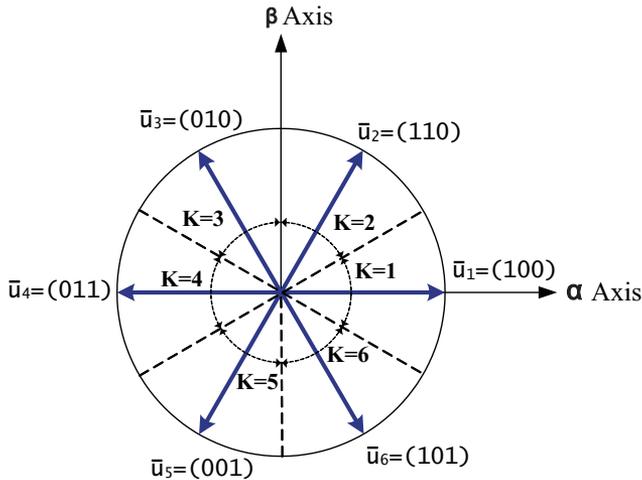


Figure 4.20: Inverter voltage space vectors.

To evaluate the drive system performance at low speed for different inverter switching algorithms according to Table 4.2, the motor torque ripple, stator current ripple, stator flux ripple and inverter switching frequency have been considered. Using the same motor, controller and load parameters, simulations have been conducted for different inverter switching patterns. The normalized torque ripple, normalized stator current ripple, normalized stator flux ripple and average inverter switching frequency have been determined.

Thus, after removing the average part of the signals (torque, magnitude of the stator current and flux vectors), the root mean square (rms) values are calculated. Moreover, the values are normalized by dividing with the related average values. The results are presented in Table 4.3.

As is presented in Table 4.3, the torque ripple and average inverter switching frequency are lower in solution A compared to the other switching patterns. For solution D, the inverter switching frequency is the highest, making inverter loss higher than those of the other switching algorithms. Thus, high values of the torque ripple and inverter switching frequency make this solution (solution D) an unfavorable choice for the drive system at low speeds. The inverter switching pattern A which employs the zero voltage vector to reduce the torque has better performance compared to the other switching methods at low speeds.

Table 4.2: Inverter switching strategies for the DTC system.

	$T_e \uparrow \bar{\psi}_s \uparrow$	$T_e \uparrow \bar{\psi}_s \downarrow$	$T_e \downarrow \bar{\psi}_s \uparrow$	$T_e \downarrow \bar{\psi}_s \downarrow$
Solution A	\bar{u}_{k+1}	\bar{u}_{k+2}	\bar{u}_7, \bar{u}_8	\bar{u}_7, \bar{u}_8
Solution B	\bar{u}_{k+1}	\bar{u}_{k+2}	\bar{u}_k	\bar{u}_7, \bar{u}_8
Solution C	\bar{u}_{k+1}	\bar{u}_{k+2}	\bar{u}_k	\bar{u}_{k+3}
Solution D	\bar{u}_{k+1}	\bar{u}_{k+2}	\bar{u}_{k-1}	\bar{u}_{k-2}

Table 4.3: Impact of switching algorithm on the drive system performance.

Switching algorithm	Normalized torque ripple (%)	Normalized stator current ripple (%)	Normalized stator flux ripple (%)	Inverter switching frequency [kHz]
Solution A	5.31	6.81	7.54	0.35
Solution B	11.15	10.36	7.50	0.27
Solution C	10.11	7.81	8.91	1.46
Solution D	8.84	7.48	7.57	2.47

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this Licentiate thesis, it is shown and thoroughly explained how it is possible to use the electric drive system components in a plug-in vehicle for fast high power charging, with charging power restricted to half the traction power. The electric motor stator windings are re-configured for the traction and charging modes by the means of a relay-based switching device which together with a clutch, due to the machine rotation in charging mode, are the only extra components needed to yield a very cost-effective and compact on-board three-phase insulated charger with unit power factor capability. All motor windings are used in both traction and charging so there is no extra winding in the motor. Bi-directional power operation for the grid to vehicle application is possible also.

By the use of an exclusive Park type transformation, a mathematical electromechanical model of the electric machine is derived and presented. Also, new controller schemes are developed and designed for the necessary grid synchronization and for the charge control. The torque reference is zero, as the machine is rotating in the charging mode, and the torque ripple is shown to be less than 1% of rated torque. It is also shown that smooth grid synchronization can be achieved and that the system has good performance during the charging time, also for a load step change.

To verify the system operation for the modeled integrated charger, a practically designed system is simulated, with 25 kW traction power and with an IPM motor with double set of windings. The charge power is thus limited to 12.5 kW in this case and the system efficiency was found to be 89%, neglecting iron losses and converter losses. The efficiency of the system in charging mode is lower than the efficiency of the system in traction mode since with the same amount of losses the output power in charging is half that of traction.

A patent is filed as a result of the current project [62].

5.2 Future Work

Basically there are two areas that will be focused on for the continuation of the current study: theory development and practical implementation.

Further development can be done in the theoretical side by applying the principle to different machines with different winding configurations. Moreover, the overall system can be optimized by considering the impact of the integration on the system performance to have a more efficient system in charging mode.

The machine rotation is the key point in the proposed integrated charger, because it will avoid high magnetization currents compared to the methods employing the machine as a stationary transformer. A IPM machine is analyzed in this thesis as an example, but it is possible to apply the method to other type of machines like PMSM with different winding arrangements. For example in the IPM machine two set of windings are shifted $\pi/6$ degree in the stator periphery. It is possible to have double set of windings without space shift.

When the machine is rotating at the synchronous speed in the charging mode, the machine produced voltage should be the same as the grid voltage in the synchronization. With the d component of the current it is possible to adjust the voltage level. By an accurate machine design it is possible to have very low d component current that is equivalent to more system efficiency. So, with better machine design the system efficiency can be improved.

For the grid synchronization and charge control more advanced controllers can be employed to improve system performance. Another example is controlling the reactive power during the charging that can broaden the application of the proposed charger concerning grid issues like reactive power compensation.

The grid supply is assumed to be three-phase. It is possible to investigate system operation for the single-phase supply also. More theoretical development is needed to address the system operation for the single-phase supply.

And finally the system validation will be checked in an experimental set up developed for this purpose.

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Appendix A

Paper I: Grid-Connected Integrated Battery Chargers in Vehicle Applications: Review and New Solution

Saeid Haghbin, Sonja Lundmark, Mats Alaküla and Ola Carlson

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The layout has been revised.

Abstract

For vehicles using grid power to charge the battery, traction circuit components are not engaged during the charging time, so there is a possibility to use them in the charger circuit to have an on-board integrated charger. The battery charger can be galvanic isolated from the grid or non-isolated. Different examples of isolated or non-isolated integrated chargers are reviewed and explained. Moreover, a novel isolated high power three-phase battery charger based on a special ac motor design and its winding configuration is presented in this paper. The proposed charger is a bi-directional charger with unit power factor operation capability that has high efficiency.

Appendix B

Paper II: An Isolated High Power Integrated Charger in Electrified Vehicle Applications

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The layout has been revised.

Abstract

For vehicles using grid power to charge the battery, traction circuit components are not engaged during the charging time, so there is a possibility to use them in the charger circuit to have an on-board integrated charger. One solution of an isolated high power integrated charger is based on a special electrical machine with a double set of stator windings: By reconfiguration of the motor stator windings in the charging mode, a six-terminal machine is achieved. The so called motor/generator acts as an isolated three-phase power source after synchronization with the utility grid in the charging mode. This rotary three-phase isolated power source constitutes a three-phase boost rectifier (battery charger) with full utilization of the inverter. The motor windings are reconfigured by a relay-based switching device for the charging and traction modes. This paper presents the mathematical model of the motor/generator and explains the system functionality for the traction and charging modes. Further, the charger grid synchronization and charge control are described. Finally, simulation results are presented for a practically designed system with a traction power of 25 kW and with a possible charge power of 12.5 kW.

Appendix C

Paper III: Performance of a Direct Torque Controlled IPM Drive System in the Low Speed Region

Saeid Haghbin, Sonja Lundmark and Ola Carlson

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Abstract

High power density, high speed operation, high efficiency and wide speed range made the interior permanent magnet (IPM) synchronous motors an interesting choice for ac drive systems. Different control strategies have been proposed to reach a high performance drive system. Direct torque control (DTC) is one of these widely used methods which has fast torque dynamic and a simple structure. Different motor, inverter and controller parameters affect the drive system performance in this scheme. The drive system performance is investigated for four possible inverter switching patterns in terms of the torque ripple, stator current ripple, flux ripple and inverter switching frequency in the low speed region. The results show that the switching pattern in which zero voltage is applied to reduce the torque has better performance compared to the other switching patterns. The analytic solution is provided to quantify the effects of the inverter zero voltage vector on the flux and torque of the machine and how they change when the speed varies.