

**Versatile Three-Phase Power Electronics Converter based
Real-time Load Emulators**

**A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville**

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August 2015**

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ACKNOWLEDGEMENTS

This dissertation would not have been possible without the help of so many people in so many ways. First of all, my sincerest gratitude goes to my advisor, Dr. Leon M. Tolbert, for his endless support, great patience and numerous advices. Through my six years of journey of Master of Science and Doctor of Philosophy, he has always been there with solid research ideas and profound inspirations for me in the field of power electronics engineering. He shared with me his experience in research and taught me the right attitude towards life.

Also, I am very grateful to Dr. Fred Wang, for his great help in instructing me how to perform and analyze in the research. Since the beginning, he has assisted and supervised me through most of my research projects. I learned and enjoyed his passionate and inspirational ways of conducting research, which will surely benefit me for a life time.

I would like to thank Dr. Kevin Tomsovic, and Dr. Yulong Xing for their invaluable help as my PhD committee members and for their in-depth discussion about the research ideas.

I would like to thank CURENT for its support of my PhD study. This center provides me with a great research atmosphere as well as friendly and helpful colleagues. Here in this big family, I would love to thank Liu Yang (Ms.), Yiwei Ma, Lu Wang (Ms.), Jingxin Wang, Wenchao Cao, Mitch Smith, Bo Liu, Shuoting Zhang, Dr. Xiaonan Lu for team-working with me in the same research project. Also I would like to thank

Yutian Cui (Ms.), Dr. Zheyu Zhang, Weimin Zhang, Dr. Ming Li, Yalong Li, Xiaojie Shi (Ms.), Zhiqiang Wang, Ling Jiang (Ms.), Fei Yang, Ren Ren, Siyao Jiang, Chongwen Zhao, Dr. Lijun Hang, Dr. Xuan Zhang, Dr. Chunshui Du, Dr. Sheng Zheng, Dr. Wanjun Lei, Edward Jones, Brad Trento, Dr. Haifeng Lu, Dr. Wenjie Chen (Ms.) for all the discussions and interactions we had together. Also for the alumnus including Dr. Ben Guo, Dr. Shengnan Li (Ms.), Dr. Dong Jiang, Dr. Bailu Xiao (Ms.), Dr. Lakshmi Reddy Gopi Reddy (Ms.), Dr. Zhuxian Xu (Ms.), Dr. Fan Xu, I would like to express my sincere thanks to you guys for all the memory and valuable industry connections.

Also, I would like to thank staff members, such as Robert Martin, Dana Bryson, Dr. Chien-fei Chen and Erin Wills. They are all very helpful with high dedication to their roles in the center throughout the time.

Last, but not least, I would like to express my deepest love to my parents Chao Wang and Xianhua Meng (Ms.), my sister Yingying Wang (Ms.), and my dearest husband Andrew Morris for their unconditional support. It was such a strong boost of willpower to have the beloved one standing by me when I was depressed and frustrated. Without their support and encouragement, this work is never possible.

This dissertation made use of Engineering Research Center Shared Facilities supported by the Engineering Research Center Program of the National Science Foundation and the Department Of Energy under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

ABSTRACT

This dissertation includes the methodology, implementation, validation, as well as real-time modeling of a load emulator for a reconfigurable grid emulation platform of hardware test-bed (HTB). This test-bed was proposed by Center of Ultra-wide-area Resilient Electric Energy Transmission Network (CURENT) at the University of Tennessee, at Knoxville in 2011, to address the transmission level system challenges posed by contemporary fast changing energy technologies.

Detailed HTB introduction, including design concept, fundamental units and hardware construction, is elaborated. In the development, current controlled three-phase power electronics converter based emulator unit is adopted to create desired power system loading conditions.

In the application, constant impedance, constant current and constant power (ZIP) load has been emulated to represent power system steady state load, with reference to voltage and frequency variations. Also, an induction motor represented dynamic load emulator is developed with a focus on grid-tied starting transient emulation. The technical challenges on the induction motor emulator's hardware and software capabilities to represent the fast varying transient is encountered, analyzed and solved in the development process. They include: emulator hardware tracking bandwidth, real-time digital microprocessor calculation capability, credibility of motor emulator's performance, and electromagnetic/electromechanical transient numerical accuracy.

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CHAPTER 1

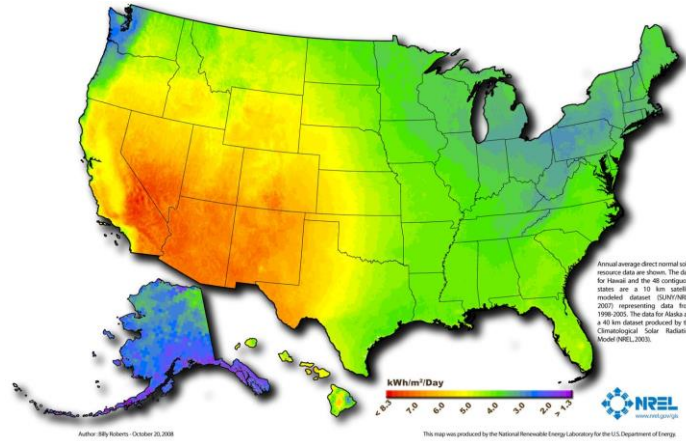
INTRODUCTION

The contemporary challenges posed by a rapidly growing energy need, as well as the emergence of new energy types are confronted by the conventional grid architecture and control system. In this chapter, the various challenges to the power system and the research measures adopted for analyzing possible solutions are discussed. Among the research platforms, the strategic research plan and program proposed by the Center for Ultra-wide-area Resilient Electric Energy transmission Networks (CURENT) at the University of Tennessee, Knoxville, to establish a research test-bed for enabling and testing grid-related technologies are also elaborated in detail.

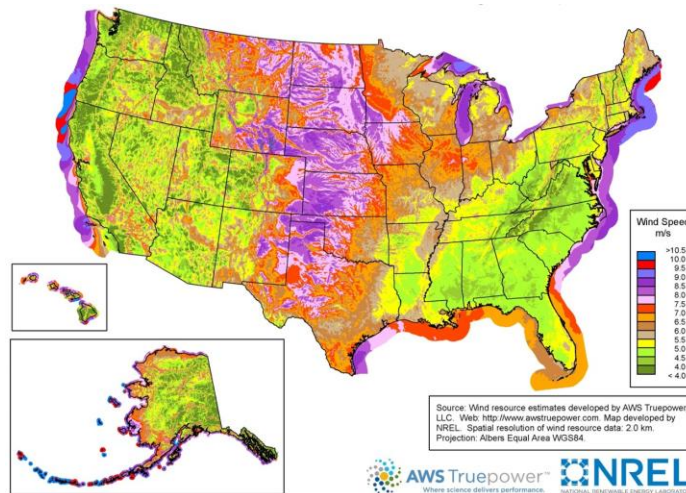
1.1 Application Background

The transition trend of energy sources from fossil fuels to renewables, the operation mode of power grid shifting into a more local basis, the trend of reducing carbon footprint via electrified transportation, as well as so many other energy roadmaps, are challenging the conventional energy generation, transmission, and distribution infrastructure.

As illustrated with the maps in Figure 1-1 (a) and (b), most of the concentrated solar energies are distributed in southern California and Nevada, Arizona and New Mexico, while places with most ideal conditions of wind resources are offshore, lake areas, and the Great Plains in the United States.



(a)



(b)

Figure 1-1 Maps of (a) solar and (b) wind natural resources distribution in United States [2][3].

Due to geographical reason, renewables such as wind and solar energies, are located in remote areas, while the population dense areas are concentrated in western coastline, as well as eastern US. In order to go through the transition from traditional fossil fuel based energy sources to renewable energy sources, delivery of the electricity from the renewables dense area to the population dense areas poses big challenges to the conventional transmission systems. Fundamental breakthroughs are needed to control interconnection

wide dynamics and manage resources across vast geographical distances, widely varying time scales, and diverse production sizes.

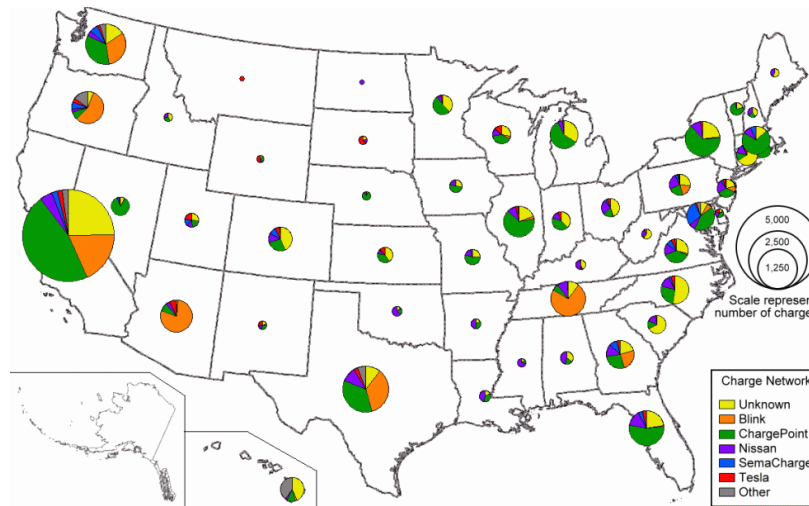


Figure 1-2 Electric Vehicle (EV) charger map by network at 01/2015 [4].

From the power system transmission level such as HVAC and HVDC, to consumer level such as EV load charger distribution (shown in Figure 1-2) and household smart metering concept, electricity delivery issues with complex electric network with numerous transmission lines, buses and control points, are awaiting to be addressed.

CURRENT, Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks, is a National Science Foundation Engineering Research Center that is jointly supported by NSF and the US Department of Energy. Its efforts are contributing to monitor and control the transmission grid dynamically (in real time) for high efficiency, high

reliability, low cost, better accommodation of renewable sources, full utilization of storage and responsive load.

Among the challenges to the electric grid system in the US, CURENT has proposed research goals of realizing black-out events reduction by 80%, increasing current transmission capacity by 30%, accommodating the penetration of 50% and higher of renewable energy to the existing power system, controlling in wide-area responsive load, and enhancing nation-wide grid situational awareness at all control centers [1].

1.2 Grid Study Analysis Tool

1.2.1 Computer Simulation Software

Power system analysis and simulation software are applied widely in power engineering practice. When the power system analysis target is beyond the capability of an analytical form, digital numerical calculation is the only possibility to yield a solution [1].

Computer simulation tools are typically programs that formulate and solve nonlinear differential equations of the power network [1][36]. Initially they were applied to solve the nonlinear power flow problem and calculate short circuit fault currents, but their usage has gradually expanded to many other areas such as power system stability, protection and coordination, contingency / reliability, economic modeling, etc.

Commercial or non-commercial software packages such as Powerfactory, CAPE, EMTP-RV, ETAP, SimPowerSystems, DSATools, PowerWorld, PSS/E, OpenDSS, ATP-EMTP and PSAT, are designed to provide algorithms for calculating steady state power

flow or electromagnetic, electromechanical or other transients, with additional specific expertise on system protection scheme (CAPE), system model in matrices, eigenvalues in frequency domain (DSATools), analysis of large system (PSS/E), small systems (PSCAD) or distribution level (ETAP, OpenDSS), etc.

Power System Simulation for Engineering (PSS/E) is one of the most applied power system analysis software. It contains probabilistic analysis and dynamic modeling capabilities. Its primary analysis goals include areas of steady state and dynamic simulations. Major capabilities of steady state system analysis and optimization include balanced/unbalanced power flow, PV/PQ analysis, contingency analysis, restoration of supply, short circuit calculation, multiple faults, steady state network reduction, state estimation, optimal power flow, V/Var optimization, compensation placement and optimization, load balancing, load assignment, generation and load profiles, feeder evaluation/optimal branching and geomagnetic induced currents [10]. While in terms of dynamic analysis capability, it contains motor start scenario, stability calculation, electromagnetic transient stability, eigenvalue/modal analysis, dynamic network reduction, parameter identification/optimization, real-time test of protection/control devices and standard and user-defined models [10].

EMTP was first developed by Prof. Hermann Dommel in the 1960s [6] to analyze electromagnetic transients. After decades of evolution, its commercial computer software package by POWERSYS, features a wide variety of modeling capabilities encompassing electromagnetic, electromechanical and control systems transients in multiphase electric power systems [8].

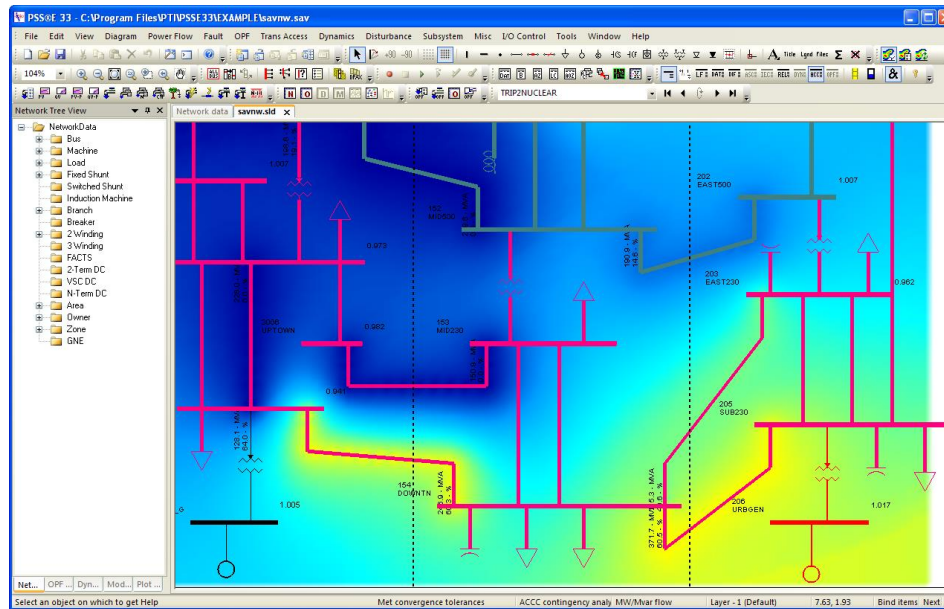


Figure 1-3 PSS/E simulation results on a one line diagram [10].

Dynamic Security Assessment Software (DSATools), as another commonly adopted tool, contains the four key components: Powerflow & Short circuit Analysis Tool (PSAT), Voltage Security Assessment Tool (VSAT), Transient Security Assessment Tool (TSAT), and Small Signal Analysis Tool (SSAT) [9]. It provides a computer software application for power system planning and operation studies, involving voltage decline/rise assessment, reactive power planning, stability assessment (transient, small signal and voltage), design of special protection systems, coordination and tuning of controls, and determination of security limits [9]. On-line application is also included in its analysis target: assessment of power system security for current operating state, determination of critical contingencies, determination of security limits and determination of remedial measures [9]. The simulated model handling capability could be up to 100,000 buses and 8000 generators [9].

Evolving towards the direction of involving as many buses as possible, the advantages of power system simulation software are: strong computation capabilities on complexities of system structure and events, and flexible options of various scenarios. However, as ideal/user-defined models in signal scale, simulation software can provide neither real-time capability nor power amplifying platform for testing. Also, research about how to optimize system simulation models for more realistic results is an on-going topic in power system studies [20]-[27].

1.2.2 Mini Grid Test Bed

Targeting at smaller scale grid, real equipment with scaled power ratings system test-beds were proposed for addressing issues associated with distribution and control of a ‘micro-grid’ (examples as [11]-[15]). They are usually rated at tens to hundreds of kW.

One example as reported in [11], in 1989, a real hardware based project of NASA is trying to mimic the real power flow conditions in the space station to secure the users’ electricity availability, power quality, and load independence at any situation. Its support facility includes air-driven turbo alternator (18.75 kVA), solar array simulators (75 kW), dc power supply (11 kW), 20 kHz load bank (30 kW) and programmable load banks (32 kW), and controller and monitoring equipment. The test-bed itself contains dc and ac remote bus isolator, inverter (10 kW), transformers (25 kVA), ac load converter (1.5 kW), dc load converter (1 kW), switching assembly, power distribution and control units, distribution system, etc [11].

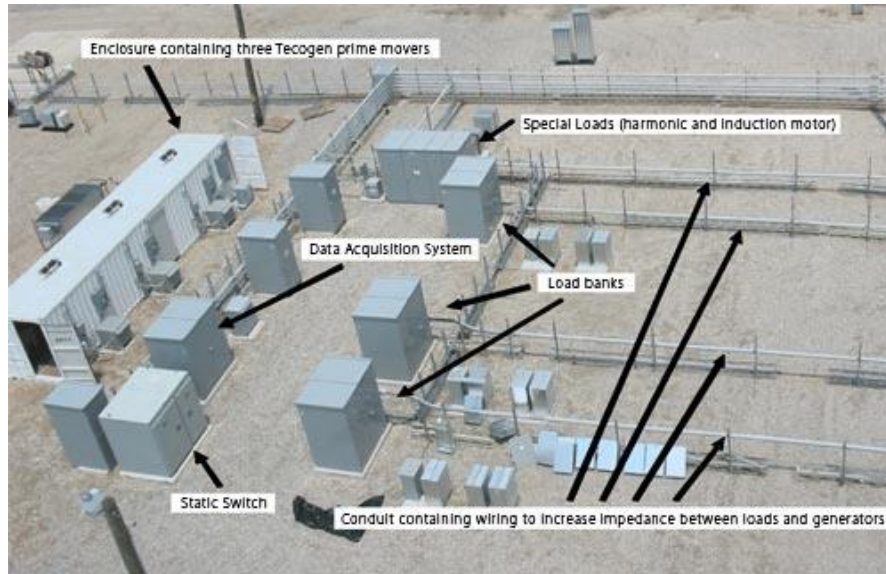


Figure 1-4 CERTS microgrid test-bed (in courtesy of American Electric Power) [15].

In 2008, a micro-grid test-bed developed by CERTS in California, US, was constructed for the purpose of studying how to enhance the ease of integrating distributed energy sources (less than 100 kW) into a micro-grid [15]. The system contains real hardware of prime movers, special loads including harmonics and induction motor (0-20 hp), data acquisition system, load banks (0-90 kW and 0-45 kVar), static switch and transmission impedance represented by conducting wires.

A 200 kW micro-grid test-bed called Micro-grid with Multi-Energy Generators (TB-MMEG) was developed by Hefei University of Technology, China in 2008 [13]. The system consists of real hardware of (30 kW), battery (300 Ah), fuel cell (5 kW) and ultra-capacitor storages (1800F x 110), renewables generations (40 kW PV generators, 60 kW wind generators), passive and active electronic load banks, communication and central

controllers. This system is proposed to solve reliability and power quality due to decentralization of supply [13].

Reference [14] discusses a micro-grid laboratory built by scientists from CSIRO in Australia 2011, serving the purpose of studying the micro-grid patterns to increase the reliability, security and cost effectiveness while studying the stability with high penetration of renewables. With total rated generation of 326 kW and storage of 726 kWh, the complete design of the experimental scenario includes a minigrid with the real hardware of wind turbine, battery storage, solar PV arrays, gas turbine, test load bank and virtual power station micro-grid. The microrgid is attached to minigrid through power switches, and the minigrid central room is the interaction interface between testing setup and real grid facility, with functions of real-time monitor and control [14].

Real equipment based micro-grid test-bed has the advantages of real power involved and no modeling induced inaccuracies. It is more representative of an actual system. However, limited by cost, flexibility and research purposes, it is not as popular in the field of power system study and research.

1.2.3 Real-time Simulation/Emulation Platform

The development of simulation technology has close connection to the development of computing technologies and hardware. Real-time calculation is a study on the data processing and estimation that are subject to the real time constraint, limited hardware resources and complexity of computation model. It is implemented under the

given time frame; the next time step behavior needs to be estimated based on the mathematical model before the ‘deadline’ [63].

A real-time application consists of multiple co-operating tasks; their actions are usually invoked at regular (or irregular) period time instants, provided with sensed input signals at the time interval, and the tasks are completed before the next ‘input’ time constant [63]. Compared with computer software simulation, more processors with distributed computation are used to guarantee the calculation accuracy and time-restraint requirements of real-time calculation.

For example, a motor real-time simulation model uses the periodic sensed terminal voltage as input signals, calculates within the time interval before next sampling point the status of the next time constant electrical parameters, including the stator current, flux, and rotor angles, etc. However, due to the calculation interval between discrete sampling time instants of input and output, such real-time technique may introduce high frequency poles and zeros close to simulation sampling frequency [47].

Since the 1990s, digital simulators have been used for steady state, dynamic and transient simulation and modeling of grid study [32][34] and equipment testing [35]. In the last decade, the concept of micro-grid [29] and small-distributed generation systems [30] have gained popularity due to their higher operating efficiencies and lower emission levels [42]. Requiring high resolution device modeling capabilities as well as simulation environment including distribution, transmission and power electronics, micro-grid simulation tools bifurcate from ‘sequential’ (computer simulation software) to the other

branch with paralleled calculation capabilities: real-time digital simulators [36]. Being able to simulate with high resolutions with high convergence, a real time digital simulator is able to interface and communicate with other simulation platforms in a micro-grid platform [36].

Small distributed generation systems, among which each individual component is typically rated around hundreds of kW, are investigated with the tools of real-time digital simulation (control hardware-in-the-loop CHIL) (examples as [36][44][52]), power converter emulator (power hardware-in-the-loop PHIL) / hybrid power emulation (examples as [42][43][45][47][48][49][50][53][51][54]). Some platforms are based on commercially available real time digital simulators, including RTDS [38] and OPAL-RT [39], while some are establishing their own digital hardware emulation system by building real-time electromagnetic transient models of machine and transmission line [52].

To investigate microgrid with hardware-in-the-loop (HIL) system, some test-beds have implemented a mixture of real hardware and emulators of distributed generation resources such as batteries, fuel cells, photovoltaic systems or wind turbines. The PHIL system in [47] investigated a dc microgrid with both inverters representing interface with ac network and dc-dc converter representing dynamic load and fuel cell emulators. While in [53], a new approach to interface an ultra-capacitor with a fuel cell as secondary source of energy is implemented on a digital signal processor controlled dc-dc converter emulating the fuel cell. In [54], in order to characterize the distributed generation interactions with the grid, single-phase inverter based PV simulator, motor generator set emulated wind power generator, and fuel cell simulators are implemented for establishing the validation

platform. References [43] (example system picture shown in Figure 1-5), [47] and [48] adopted similar concepts of emulators as part of their test-bed systems.

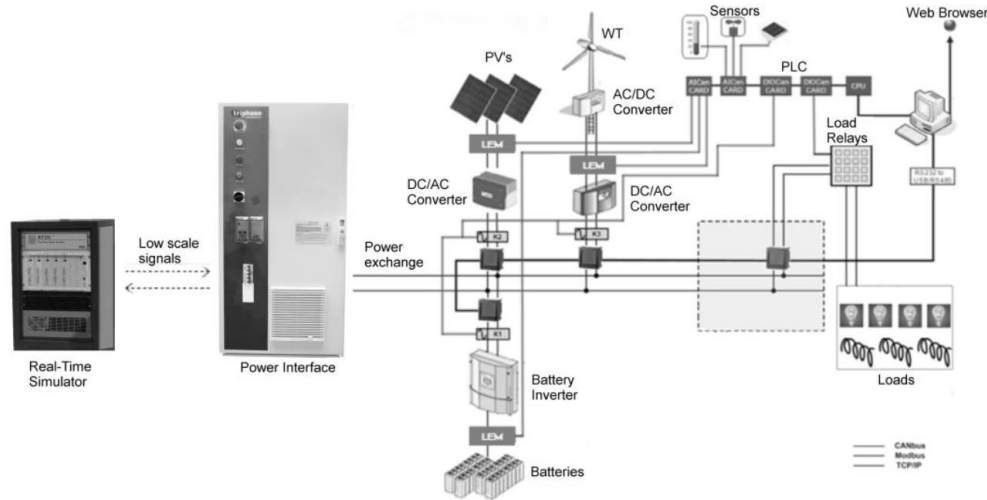


Figure 1-5 Overview of an example hybrid PHIL test-bed system for microgrid [43].

Proposing a unified controller for regulating real and reactive power sharing between DG in grid-connected and islanding modes, [42] verified the strategy through simulation with Real Time Digital Simulator (RTDS) as well as a scaled hardware prototype with power electronics representing a distributed generation system. Similarly, references [45][46] validated the control strategy prototype for regulating power flow, defining voltage set points based on fast power flow analysis as well as frequency synchronization scheme, on the hardware platform of three inverter represented distributed energy resources.

As indicated in [36], HIL simulation has its widespread influence on modeling and simulation, control based HIL simulation, hardware testing, PHIL simulation, hardware test bed experiments, and for field testing of installed equipment. However, the major errors and challenges, in the application of PHIL, are attributed to limited converter bandwidth, sensor noise, time delays and ripple in the interface amplifier [37][90]. Also as a simulation tool, the validity of HIL experiments is challenged by how well the models represent the real system [36]. Nevertheless, with the rapid growing computation technology, real-time simulation / emulation will be the future trend for solving and analyzing many systems.

1.2.3.1 Hardware Test-bed (HTB)

CURRENT is developing a scaled universal reconfigurable grid emulator hardware test-bed for testing and demonstrating various proposed key technologies related with electric grid. As the integration platform for prototyping the proposed solutions to the power delivery challenges, it is the actuation interface between outcomes and system requirements.

Communication and networking support for power systems, as another research topic, also utilizes the platform of HTB, for addressing the issues and improving performances with: information survivability, security, and access during power system data transmission. Strategies for confidentiality and authentication specifically suited for data delivery and replication needs of power systems will be demonstrated on the HTB [1].

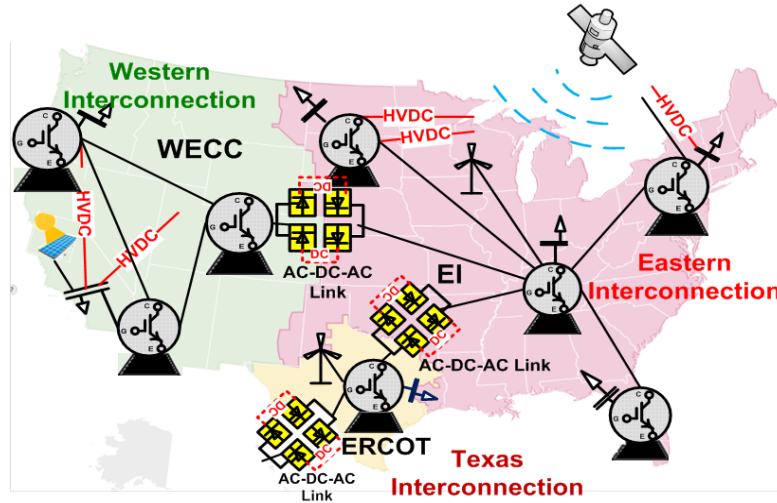


Figure 1-6 United States large scale power system network with transmission architecture.

Step by step, the initial stage of proposed HTB system has the functionalities of standard protection and control, and real time measurement and communication algorithms. After the hardware platform was established, the grid system model was incorporated with fault-tolerant measures to evaluate the ability of the system controllers to recognize missing or bad data and to make decisions that maintain the security of the power system network. The third stage will emphasize the flat control structures' ability to integrate the synchronized data measurement and real-time communication and control processes, such that, the emulation network can maintain stability even in the event of large disturbances [1].

Generators, loads, other energy sources as well as the necessary power system components would be emulated by power electronics based programmable sources and loads to match the dynamic characteristics of the real generators and loads. The

transmission line distance effect can be realized through adjustable line impedance of the interconnections and frequency scaling, which is also implemented by power electronic converters. With HTB, renewable energies, high voltage system architectures (HVDC and HVAC), responsive loads and energy storage could be evaluated.

Including the actual sensing and monitoring system such as FNET and PMU, real time communication networks, real-time control, protection and actuation, HTB ties the hardware platform with state-of-art technologies. On top of the hardware realization, a universal application controller will be developed which includes the higher layer functions of real power flow regulation, reactive power control, voltage regulation, frequency regulation, harmonic compensation, damping of transients, fault detection and limiting [1].

Figure 1-7 shows the current status of HTB universal reconfigurable grid emulator built by the CURENT research center from University of Tennessee at Knoxville, USA in 2014. By reconfiguring the grid component emulators for different scenarios, the emulation network could be monitored and studied for different dynamics. The network contains emulator units of: synchronous generator emulator [85], composite load emulator [92], PV farm emulator [87], wind farm emulator unit [86], transmission emulator unit [88], and a RTDS amplified network representing wider-area grid background with HTB is under development.



(a)



(b)

Figure 1-7 HTB photographs of (a) hardware structure of power electronic converters and (b) central control and visualization room (Mar. 2015) developed by HTB team, CURENT at the University of Tennessee, Knoxville, US.

1.3 Motivation and Strategy

In order to establish a transmission network test-bed by interconnected generation sources and loads as well as being able to produce flexible power system scenarios, the

design of grid emulator adopts the idea of constructing stand-alone power electronic dynamic emulator units, and connects them together in the shape of desired grid network [109]. For easy structure rearrangement and flexible scenario component, each individual component emulator inside grid emulator shares the same power converter topology. Details about overall structure and individual unit are discussed in CHAPTER 3.

In order to provide the grid emulator with options for both static and dynamic characteristics, load emulators are desired with the behaviors of static real and reactive power system loads, as well as dynamic loads. The load emulators are designed to resemble that of power system loading conditions in steady state, such as the voltage and frequency dependent power system load flow, and that of strong electromagnetic transients, such as the heavy industry induction motors starting up.

Three-phase static power loading conditions, with characteristics of constant impedance, current, and power, with features of variations with voltage, and frequency, and with capability of bi-directional power flow, are critical of real-time power system HTB in steady state power flow emulation.

Three-phase dynamic power loading conditions, representing large industrial motor online starting transients, as well as full details of stator, and rotor dynamics including induced higher frequency oscillations on the load currents, are crucial in the real-time power system HTB transient stability events evaluation.

1.4 Dissertation Outline

This research presents the methodology for design, development, implementation, and analysis of three-phase regenerative power electronic emulator, functioning as power system composite load.

To provide an overall picture of the dissertation background, this chapter discusses the research focus and vision of CURENT research center for addressing transmission grid issues by means of enabling grid related state-of-art monitoring and control technologies. The current grid study analysis tools could be categorized as computer software simulation, scaled physical components based mini grid, real-time simulation/emulation platform. The real-time emulation platform of HTB is established to integrate the technologies with physical power as well as the close-to-real scenario with implementation flexibility.

The rest of dissertation chapters are organized as follows:

To discuss the context of application options from previous researchers during development of grid research power platform, CHAPTER 2 does a thorough literature review for the previous researchers' work on providing / creating power loading conditions. The challenge proposed to developers about the numerical issues facing real-time highly dynamic system is also surveyed and discussed.

To define the fundamental hardware, structure network, and software of the emulator, CHAPTER 3 talks about the basic emulator unit topology and its connection structure within HTB. Focuses have been stressed on current controlled dynamic load

emulator design and development, in terms of its control structure, dynamic tracking capability, hardware design, and related concerns.

To equip HTB with highly detailed power load emulator programmed with flexible and desired profiles, CHAPTER 4 defines the power system static load emulator used in HTB. Not only providing constant impedance, constant current, constant power load characteristics, voltage amplitude and frequency variation dependences are also presented in the emulator behavior.

To reproduce the behavior of induction motor starting up, the full details of stator dynamics of induction motor represented dynamic load emulator is also included in the emulator reference model as discussed in CHAPTER 5. Overall performance and technical implementation details of a composite load emulator represented PQ bus functionality are demonstrated as well.

To validate and prove the credibility of induction motor emulator's dynamic details, CHAPTER 6 presents the improvement on the induction motor model with saturation characteristics. The upgraded induction motor emulator is then compared with the real motor test result on startup transients.

To address the challenge on the numerical performance conflicts with limited controller computation resource, CHAPTER 7 aims at analyzing the proposed discrete numerical induction motor models in real-time emulator application. Implementation and stability regions of the numerical methods, and accuracy sensitivity evaluation with reference to time steps are compared, and illustrated with details.

To conclude the previous work and provide future research ideas, CHAPTER 8 concludes the dissertation, proposes future work and points out the HTB induction motor emulator limitations.

CHAPTER 2

LITERATURE REVIEW

2.1 Power Loading Options

During the power system models, the load representation has remained the least accurate of all – its random and stochastic characteristics remain a significant challenge for the design and implementation of appropriate power control solutions [21]. Load model accuracy is often considered the key to accuracy in power system analysis.

The system load model could reflect the seasonal change and area substation load class (agricultural, commercial, industrial or residential) by adjusting the percentages between and within static load models [110].

However, lack of dynamic motor models are suspected to be one of the most important reason contributing to mismatch between simulation and real measurements during dynamic and transient system analysis. One example could be found in [20]: combination of induction motor and various static loads are used to replace the previous constant current model in the transient stability evaluation, after discrepancies between simulated and measured data obtained during the widespread power outage that happened in western North America on August 10th, 1996.

Although it is impossible to define a fixed load model for universal power distribution system, standard multiple load models for power flow and dynamic simulation programs are recommended in [25], where static as well as induction motor models are

combined as a composite load model for loading profiles per bus in power system study in the areas of transient stability, long-term dynamics and small-disturbance stability programs.

During the design and development of the CURENT HTB, flexible and representative power loading characteristics are desired for designing scenarios.

2.1.1 Passive and Scaled Physical Load

Physical power loads consist of resistors, capacitors and inductors, ac and dc motors and load converters, (as shown in Figure 2-1) have been previously mixed and applied to provide controllable load options, in order to provide power loading conditions for grid / power distribution study test beds [11]-[15][42]-[45] [47][48][53]. As the most widely adopted method to represent power load profiles in the test-beds, physical electric load is easy to operate and stable in terms of its passive characteristics.

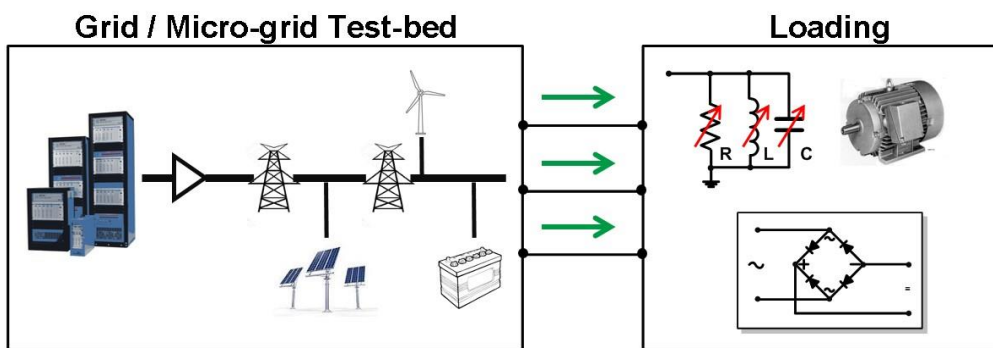


Figure 2-1 Passive and physical loads in grid/micro-grid test-bed.

Aiming at investigating issues of integrating distributed generation, including renewable energies into the electric-network in the mini-grid [14], a custom-built passive load bank installed in a micro-grid laboratory provides up to 64 kVA in resistive, inductive and capacitive loads in discrete values of 1, 2, 4, 8, 16 and 32 kVA.

However, due to the size, ratings and limitations in the laboratory environment, [42] proposed three RL fixed value passive loads (rated 110 W, 120 W, 200W and 90 Var, 65 Var, 145 Var) as substitutes for critical loads in the scenario of ensuring proper operation of micro-grid running in island mode during grid fault conditions while sharing and providing the critical loads.

During development of the hardware-in-the-loop simulation system for testing operation and control functions of micro-grid in [48], the electric load is represented by fixed $9\ \Omega$ resistive and 12 mH inductive loads controlled by separate transformers equipped with on-load tap changers for achieving different load profiles.

Because of its large power consumptions and fixed settings, a passive RLC load can not provide the power test platform with compact design (it requires a massive cooling system for higher rating) nor flexible loading profiles. Not being able to represent the exact power system PQ bus time-variant changing load profiles is one of the most important disadvantages of a physical load.

In the research [15], in order to test the micro-grid operation modes of islanding and grid-connected, as well as the transition algorithms between these two modes as designed, the four load banks of the test bed could be remotely controlled from 0-90 kW

and 0-45 kVar with designated fault loads such as bolted faults to high impedance faults (60 kW and 83 kW). However, for creating the loading profile of a difficult motor starting load conditions for testing operational limits of the micro-grid, an induction motor rated at 20 hp is also part of the loading scenario. What's more, in order to provide nonlinear loading condition, a six-pulse power rectifier is also included in some scenarios in this micro-grid test-bed.

During evaluating the performance of power management and distribution dc test-bed shown in [11], four types of power converters (under 208 V, 32 kW operating frequency from dc to 20 k Hz) including series resonant, zero voltage switched, series inductor and switching full-bridge, are utilized in order to provide a spectrum of load converter types. Apart from the load converter units, six fixed resistance heater element loads (30 kW, water cooled, made up of eight power absorption modules and two power control modules) are also part of the loading system for the dc test-bed.

By adding scaled physical loads, such as induction motor, rectifier and other types of power electronics converters, the complexity of loading profiles are improved to provide the desired scenarios. However, similar as the disadvantage of mini-grid discussed in section 1.2.2, the scaled physical loads are limited in representing different scenarios.

2.1.2 Regenerative Electronic Load

Electronic controllable load by power electronics is another way to provide loading conditions in the power test-bed [54][92]. This technology is not first applied in the field

of grid-related testing; it has its wide applications in the area of testing power devices and applications.

Universally accepted as a simple and efficient way of testing dc applications, the power ratings of dc commercial electronic loads could vary from as small as 200 W to as large as 250 kW, with different cooling technologies (air or liquid cooling). Higher power rated dc load could be attained by paralleling the modular electronic loads. Hierarchical control among the modular loads could enable master/follower algorithm and communication between modules [18].

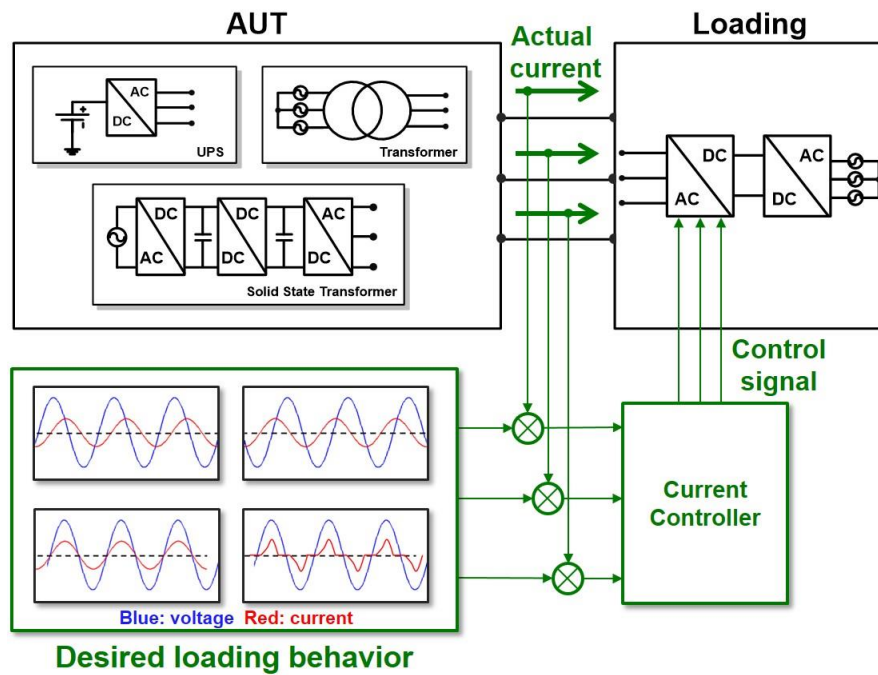


Figure 2-2 Basic principle of three-phase converter based ac electronic load (AUT: Application Under Test).

In the design of commercially available ac electronic loads, various loading options (as illustrated in Figure 2-2), depending on software control algorithms and target references applied on the controller, include constant current (CC), constant power (CP), constant impedance (CZ), constant voltage (CV), and variable power factor programmable modes [17]-[19].

With input voltage ranging from 50-500 V_{rms}, the commercial ac electronic load power ratings vary from 300 VA to 36 kVA (achievable by paralleling modules) [19]. The operation frequency scale is 45 Hz-440 Hz (400 Hz for aircraft applications). Working modes include constant current, constant impedance, constant voltage, constant power, unity power factor and nonlinear load. The crest factor for the emulation load could be controlled to be flexible between 1.4 and 5; power factor has the options between 0 and 1 (either leading or lagging). Commercial ac load emulators are mostly single-phase designed; for test of large power rating three-phase applications, multiple modular electronic loads are paralleled and connected according to the Y or delta connections desired [19].

Single-phase H bridge power converter is the major topology applied in the development of single-phase ac electronic load [96]-[100]. The focuses on the ac electronic load research are type of filter and current tracking algorithm. During these applications, repetitive controller for suppressing current error [96], PWM average current mode control with LCL filter [97], one cycle control [98], open loop control with LCL filter [100] are proposed.

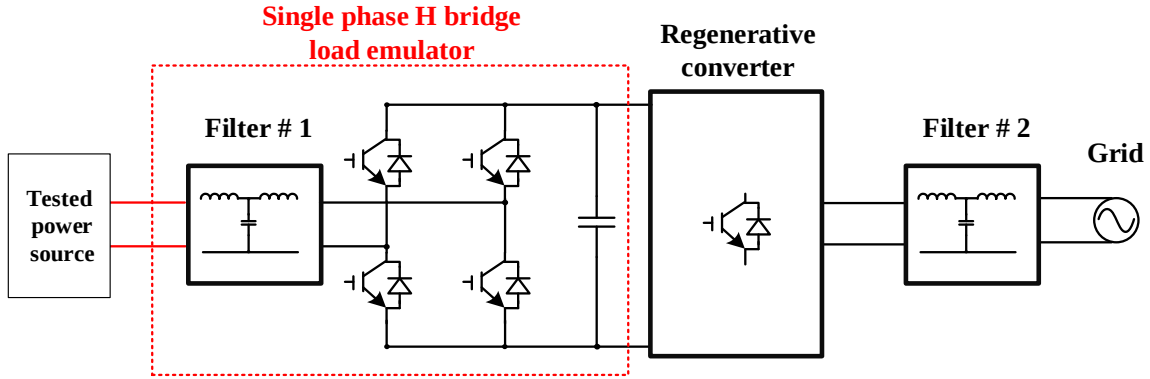


Figure 2-3 Single-phase H bridge load emulator configuration.

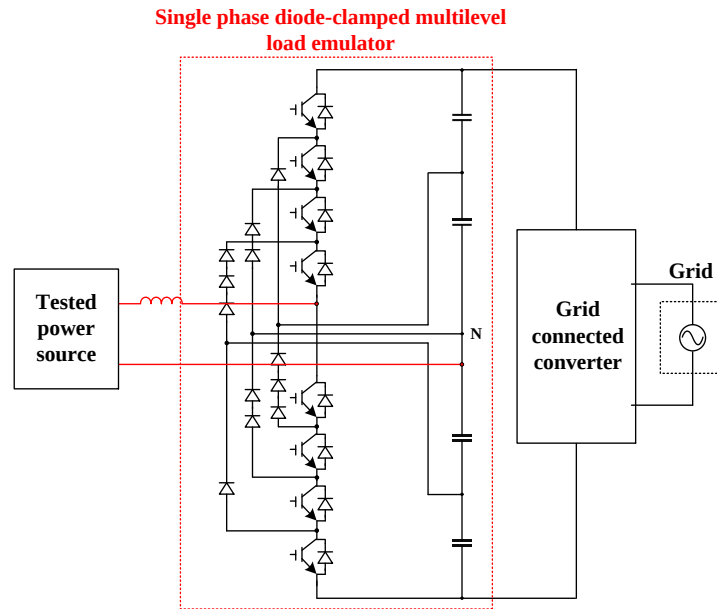


Figure 2-4 Single-phase five-level regenerative load emulator configuration [99].

Study in [99] demonstrates a multilevel converter structured electronic load required to handle medium voltage rated applications (2-22 kV). A diode-clamped multilevel converter (Figure 2-4) is proposed to deal with high voltage and power ratings

– it is controlled by one cycle control, emulating universal impedances and recycling testing energy back to the grid.

While most research on three-phase ac electronic loads were originally for uninterruptable power supply (UPS) burn-in test [93][94][95], they also have applications in the areas of power factor correction (PFC), electronic ballast, transformers, solid state transformers, alternators, aircraft applications, protection and switching devices, power inverters and other electronic components.

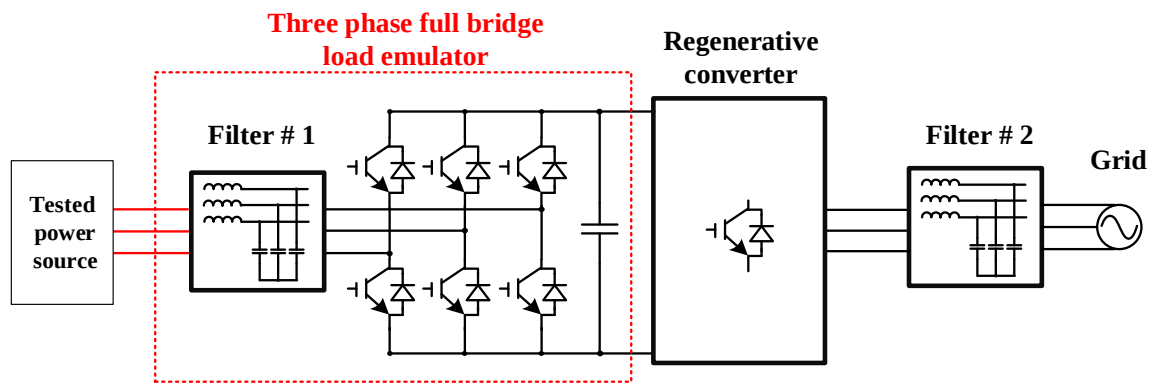


Figure 2-5 Three-phase full bridge load emulator configuration.

The back-to-back full bridge topology shown in Figure 2-5 is frequently used in power electronic load emulation [100]-[103][105]. Similar as single-phase ac electronic load, most of these three-phase ac electronic load applications use the full bridge topology, with L, LC or LCL as filter. Closed loop current control algorithms of three-phase power electronic static load could be divided into two categories: in abc domain [101][102][103] and in dq domain [104].

It is mentioned in [101] that the control process is achieved by comparing sampled *abc* current compared with the *abc* current references generated from V_{abc} and error signal going through a PI regulator. This scalar control is designed such that it could be made for general-purpose single-phase electronic load. Similarly, the current controller design in [103] has a similar concept, but with PI + pole compensator.

The current controller used in [102] is accommodated for its filter LCL and active damping control design. The controller has the characteristics of two integrators as well as two zeros, exclusively designed for reliable performance of the system.

In the design of [104], real and reactive power are controlled by controlling current in *dq* domain with proportional regulator. Duty cycles in *abc* domain are then converted as control signals for the load converter.

The alternative configuration shown in Figure 2-6 is another topology for three-phase load emulator, proposed in [104]. Each single-phase converter has its current regulated by its own control loop and three power electronic load (PEL) units are connected together as a three-phase load emulator.

However, not applied as much of an ac loading option for grid / micro-grid related analysis (most of them are using option 2.1.1), research in [54] describes the utilization of an ac electronic load as a loading option for comparing the impedance between grid and loads for stability analysis. The different modes applied in the research include 3 kW constant power, 12 A constant current as well as 20 Ω constant resistance.

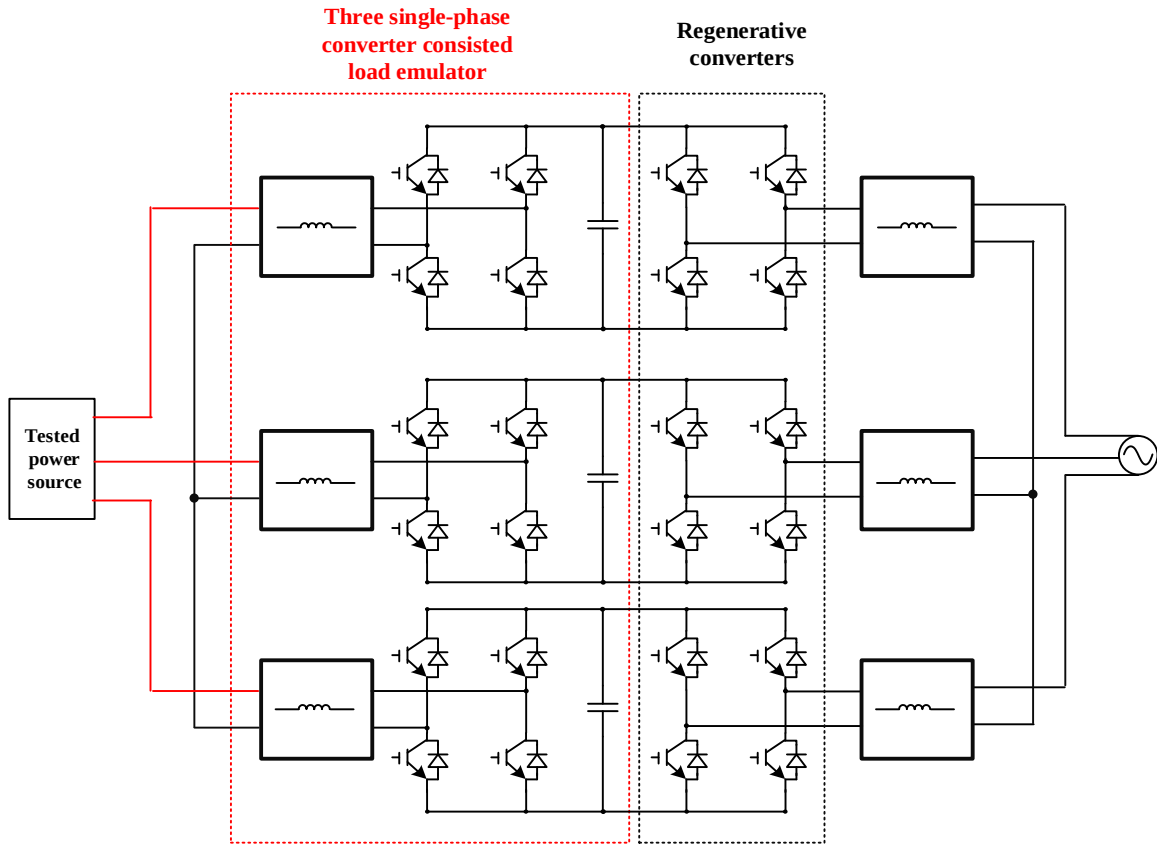


Figure 2-6 Three single-phase converter consisted load emulator.

There is no previous research using customized three-phase power electronic load emulator characterized as detailed power grid load profiles. However, as a flexible and accurate loading device, three-phase power electronics load emulator has its advantages in creating a detail profiled power PQ bus in the power distribution network.

2.1.3 Induction Motor Emulator

Induction motor emulator has its applications in the field of motor drive and generic power electronics converter testing [74]-[81].

Three-phase full bridge converter as picture in Figure 2-5 have been used in the previous development of motor emulator [74][76][79][81].

In the research shown in [76], the functions of emulating motor starting up as well as jump with load torque variation, three-phase with unbalanced current and harmonic references, nonlinear active load of diode rectifier have been demonstrated with the proposed emulator. During the implementation, hysteresis current control for each phase is used with notch filter optimized phase lock loop and LCL filter. However, the motor emulator's current output performance is not tracked well but with distorted waveform, and the calculated induction motor torque has unexpected oscillations.

Isolation transformer has been used in between motor drive and motor emulator in the research [79]. Calculation process of motor nonlinear model is implemented in RTDS and the controller platform is dspace. The motor model applied in the emulator is with input of current information and output control variables are voltage information.

Example of induction motor emulator system mimicking motor running in steady state of 30 Hz is presented in [81]. In the development, current control with PI controller in *abc* domain is applied with switching frequency of 13 kHz. The motor model is implemented under stator stationary reference frame, and involving mutual magnetic path saturation model as well.

During the development of motor emulator test-bed for motor drive, alternative topology shown in Figure 2-7 by paralleling switches to increase power and frequency capability has been applied in the research [80]. Sequential switching (modified interleaved

switching) as well as common-mode inductors are applied for utilizing paralleled device for dynamics with higher power and frequency. The induction motor model during calculation is with input of current information and output with voltage variables, so as to interface with motor drive with field-oriented current controller.

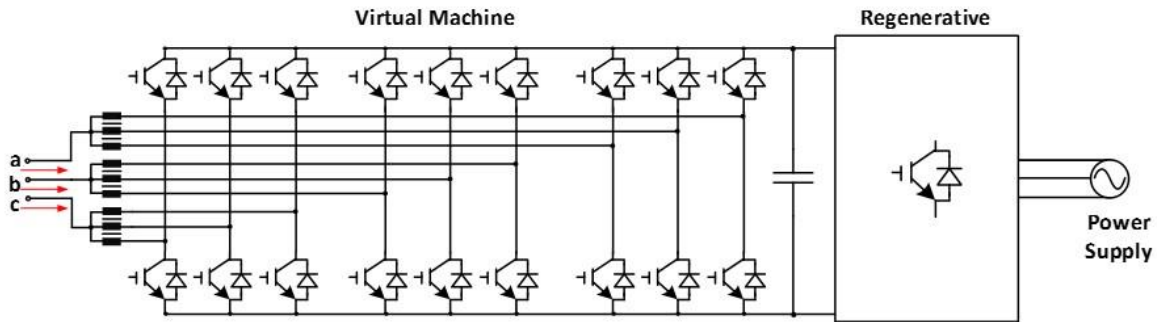


Figure 2-7 Virtual machine replacing motor using sequential switching converter [80].

Multilevel converter with four paralleled phase legs is also introduced in [76] as a prototype of motor emulator. With power stage structure similar to that of Figure 2-7, this application demonstrated its ability in interfacing with inverter under test for substituting the motor test platform.

Another topology using paralleling device is applied for solving the challenge of limited bandwidth of PHIL platform is discussed in [75]. The research proposes a motor drive test-bed with induction machine and load model controlled multilevel bridge based ‘LinVerter’. Figure 2-8 presents the virtual test-bed consisting of a motor test-bed emulator and regenerative converter regulating the dc voltage and feedback the power. In the figure,

the structure of converter within ‘LinVerter’ frame is a single-phase representation. Three-phase current control with voltage feedforward control is used in the system. This test-bed is demonstrated to draw the same currents from the motor drive performing field oriented control as motor-load combination during steady state and transients between states [75]. This development has the advantages of high bandwidth, low harmonics current content, however, disadvantages include the cost of structural complexity in three-phase LinVerter, large quantities of devices and common-mode chokes.

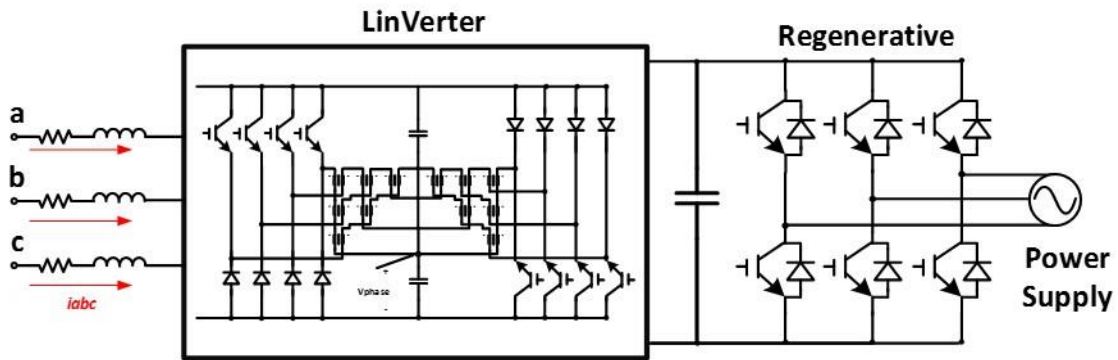


Figure 2-8 Motor PHIL simulation using LinVerter [75].

Motor emulator has the advantage of modular and flexible to control. Due to its performance and prospects, it has high application potential of representing motor elements in power system scenarios analysis. Development of the power converter stage and control algorithm, flexibility in emulation model as well as the accuracy and credibility of motor behavior represented, are the major concerns while developing motor emulator.

2.2 Real-time Transient Solutions

Previous PHIL research is mostly based on applications of power electronic converters amplifying digital models. During the development of modular, flexible and individual model-based PHIL emulator, the desired emulator's model is programmed within the digital controller together with the other power electronics system controller functions, such as sampling, closed loop control, PWM, communication and other I/Os, etc [75][76][81]. Most importantly, all the functions as well as model calculations are required to be completed within the time interval between switching instants.

As demanding as the PHIL power output performance, the selection of software integration methods for ensuring numerical accuracy and stability of represented model in stand-alone controller based PHIL unit in 'real-time' are rarely discussed.

Computer software simulation algorithms, such as the software solvers preprogrammed in Matlab [82], do not necessarily provide direct solution to this challenge – there is no time step constraints on the simulation, so the numerical methods can be as complicated as possible. Numerical ODE solvers for stiff or non-stiff model solutions in Matlab software, such as Runge-Kutta, Adams multistep, BDF, Trapezoidal rule with fixed or variable time steps, could be selected before simulation begins [82]. There is no limit on how complicated the system could be either – it just takes longer time. And 1 second calculation for dynamics in a complicated power electronics computer software simulation including switching stages and control algorithms, in computer software Matlab Simulink with a quad-core @2.83 GHz windows computer takes a whole ten minutes. What's more,

partitioning the fast and slow dynamics subsystems integrated by the same method, with different time steps is another important skill for mixed domain simulation in Matlab software.

With the development of micro-processor technology, visualized platforms with hardware interfaces, such as RTDS [38], OPAL-RT [39] as well as other similar commercial products, have been used to facilitate solving differential equations model in steady state and dynamic transient states under the ‘real-time’ constraints.

As an example of commercial real-time simulator, the software RSCAD designed for interfacing with RTDS hardware has its own integration algorithms, designed to perform electromagnetic transient simulation (EMTP) of AC and DC power systems with external hardware in the simulation loop [41]. Utilizing the advantages of parallel computation technology on mathematical model of large power systems, the real-time simulator still has its limitations on the size and rank of the power system it tries to solve – each PB5 (RTDS core of two dedicated processors at 1.7 GHz cycle frequency each) has the computation capability of 24 three-phase buses with minimum real-time simulation resolution of fixed 50 us time step [41]. However, for power electronics system, the real-time simulator has limitations on time step resolution and system scale.

Induction motor model has high order nonlinear differential equations, describing relationships among variables of voltage, current, flux, torque and rotor speed. Solving its transient model within digital controller switching interval imposes a big challenges on the

numerical integration algorithms applied, especially in the high power rated converters (due to lower switching frequency) [74].

Among the developments of induction motor emulators described in 2.1.3, motor model in dq domain has been applied. The 4th order Runge Kutta has been used to solve the equations at 12 kHz switching interval on the research [75], two step Adams-Bashforth integration method has been applied with time step of 20 us on the research [76] and the motor model equations are solved seven times within 13 kHz switching cycle in the research [81]. The other researchers are either using dspace platform [74], or RTDS system [79] with preprogrammed solver for these solutions.

A similar concern has been found on the topics of digital implementations of flux and rotor speed state estimators and observers during development of motor drive technologies. Due to the real-time constraint for these application, similar numerical unstable and inaccurate phenomena under low sampling frequency [38][123][126] are captured and discussed, which will be of major help during the development of full-dynamics real-time emulator applications.

Research in [123] proposes a predictor-corrector discrete model of induction motor based on stator current / rotor flux formulation for real-time control applications. In-depth discussions about motor model estimation accuracies and stabilities under steady states, with reference to different time steps (0-800 us) are involved.

Research in [126] talks about different integration methods, such as Forward Euler, Backward Euler and Adams Bashforth with reference to integration time steps (1-100 us)

and model dq reference frame rotation speed under steady state conditions. Conclusion of the minimum magnitude of numerical error occurs at model reference frame of synchronous speed has been reached.

As pointed out in [40], when solving real-time control models, if the model is a stiff one, adequate numerical methods, as well as reasonable time step are needed for a close enough-to-exact solution. Adams-Bashforth (AB), Adams-Moulton (AM), Backward Differentiation Formulae (BDF) are presented and compared, in terms of stability regions.

Although some numerical methods have been proposed for solving high order motor differential equation models, application of software solvers into hardware engineering with limited calculation resource and time constraint, aiming at solving full electrical as well as mechanical model, still remains a substantial challenge in developing real-time electro-mechanical emulation applications.

2.3 Research Challenges and Approaches

The commercial electronic load, scaled power loading prototypes, and previous researched load emulator types cannot sufficiently represent versatile power system load profiles nor could their concepts, and structures fit in the proposed configuration of real-time power system test-bed. The HTB loading emulator design should combine and improve the previous literature applications' advantages of the flexible modeling, real physical load characteristics, as well as the dynamic performance representations.

To fulfill the power system test-bed function of testing, and implementing higher level control algorithms, a comprehensive real-time responsive power load emulator is needed to provide loading scenarios in power system emulation. The research challenges are concentrated on the system design, and quantified evaluation of the composite load emulator in both hardware and software aspects.

As illustrated in Figure 2-9, for the power converter based emulator, hardware challenges are focused on how well the model references are reproduced by the emulator output. Also, software challenges are expressed as how well the programmed real-time model references represent the actual physical model.

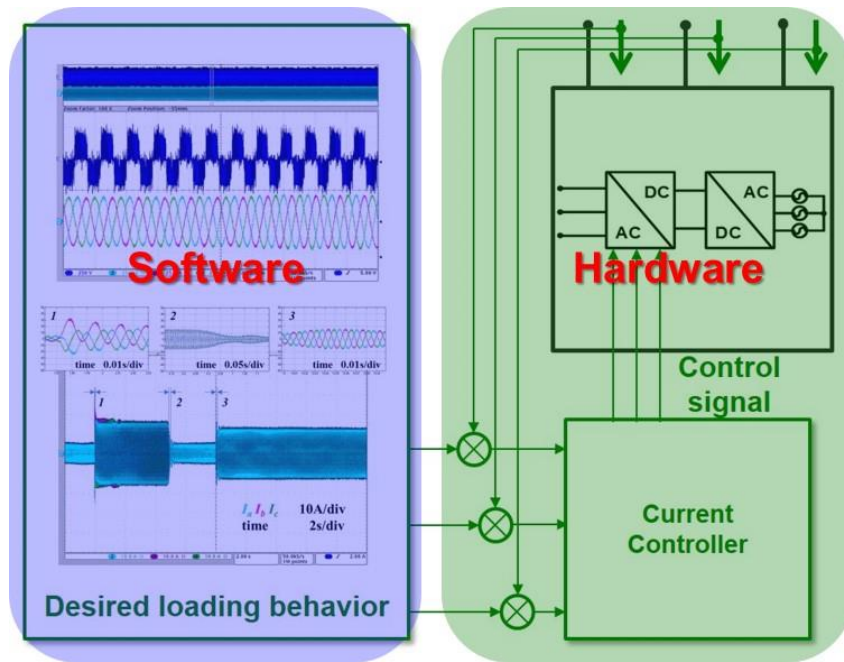


Figure 2-9 Power converter based real-time load emulator software and hardware division.

As for the hardware power topology, the chosen three-phase full bridge power converter with dq current tracking capability is designed, and evaluated for its signal tracking, and amplifying capability for representing real-time responsive load.

In regards to the hardware micro-controller, the modular DSP F28335 was selected, programmed, and evaluated for its real-time calculation capability with aggregated load model running in sequence with converter control functions.

For the software validation of the load model as the representation of induction motor power load, the dynamic power load model has its challenge in validating the model credibility. Comparison with a real motor is proposed as well as the corresponding improvement on the motor model with the magnetic saturation characteristics.

In terms of the software numerical implementation, real-time dynamic induction motor discrete models including electrical as well as mechanical performances, with different numerical methods, are proposed and designed with a stand-alone digital controller in the real-time emulator application. Stability regions for the numerical methods applied, as well as their performance on the motor model in the application, are compared, and evaluated.

CHAPTER 3

HTB POWER EMULATOR UNIT AND SYSTEM

3.1 Emulators Basic Units and Structure

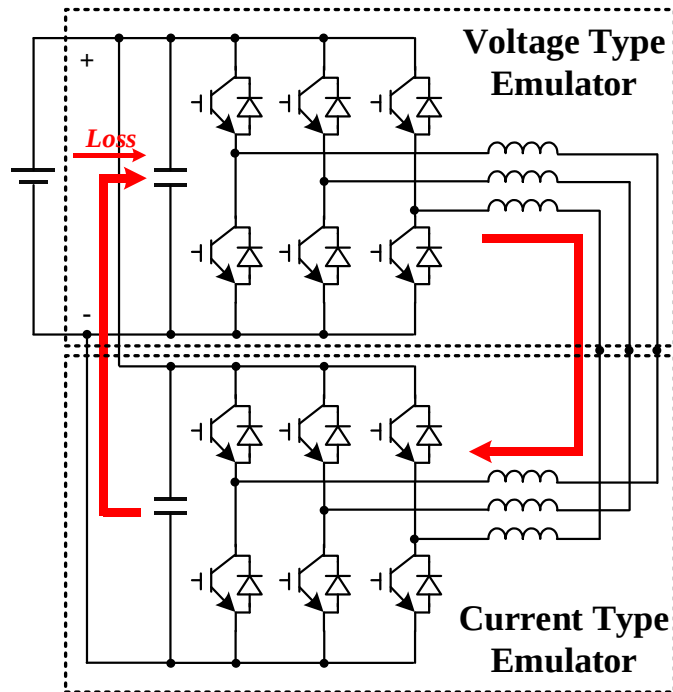


Figure 3-1 Regenerative structure of voltage and current type emulators.

For the development of the load emulator proposed, basic regenerative and filter structure applied are shown in Figure 3-1. The units in the testing loop are identical power electronic converters, sharing the same dc bus, creating the power loop for the tested power to be observed and studied on ac side while fed back to the source through dc side. The regenerative structure is highly efficient for high power applications, especially in that it

does not waste energy in the form of resistive load thus saving the cooling system and extra dc power supply as well. The shared dc voltage supply compensates for the loss, which consists of very small portion of the energy in this paralleled system.

3.2 HTB Two-area Network

Figure 3-2 (a) shows a typical two-area system with four conventional generators, two load centers, and an interconnecting long-distance transmission line between the two areas [61]. The corresponding emulation network structure consisting of real power electronic converter hardware in the unit of paralleled structure (shown in Figure 3-1), is shown in Figure 3-2 (b), with red highlighted three-phase interface as grid emulation dynamics analysis platform.

In Figure 3-2, G1 – 4 converters with filtering inductors represent four synchronous generators (or renewable generation centers such as PV or wind farm) while L7 and 9 with filtering inductors stand for load centers. Transmission line is substituted by the corresponding emulator with adjustable transmission length. The power flow is shown with a green arrow: from generator to load and also transmitted from Area 1 to Area 2 (bus 7 to bus 9). The whole structure is reconfigurable and could be changed to emulate a different power system structure.

Table 3-1 System parameters before and after scaling [109].

Parameter	Original	Rescaled	Actual Value	Parameter	Original	Rescaled	Actual Value
P_{TLbase}	100 M VA	15 kVA	15 kVA	L_{6-7}	0.01 p.u	0.7 mH	0.5 mH
V_{TLbase}	230 kV	208 V	208 V	L_{7-9}	0.11 p.u	7.6 mH	7.5 mH
f_{base}	60 Hz	60 Hz	60 Hz	L_{3-10}	0.0417 p.u	2.8 mH	2.5 mH
L_{1-6}	0.0417 p.u	2.8 mH	2.5 mH	L_{4-10}	0.0167 p.u	1.1 mH	0.7 mH
L_{2-6}	0.0167 p.u	1.1 mH	1 mH	L_{9-10}	0.01 p.u	0.7 mH	0.7 mH

3.3 Current Control Type Emulator Unit

According to converter topology, control requirements, loading conditions, and switching capabilities of semiconductor devices, closed-loop controlled behavior bandwidth of three-phase power electronic converters could be designed at several thousands of Hz [65]. Because of their fast, accurate, and flexible closed-loop behaviors and the enabling programmable computational technology of high-speed digital signal processor as controller, it is feasible to control power electronic converters to mimic dynamic electrical performance below emulator's bandwidth within acceptable performance accuracy.

Instead of having to control three individual single-phase converters and overcome the difficulties of phase synchronization and shifting as well as circulating current between phases, an individual three-phase hardware converter could undertake the duty of providing

flexible electrical profiles for algorithm test platform and system behavior estimation [73]-[87].

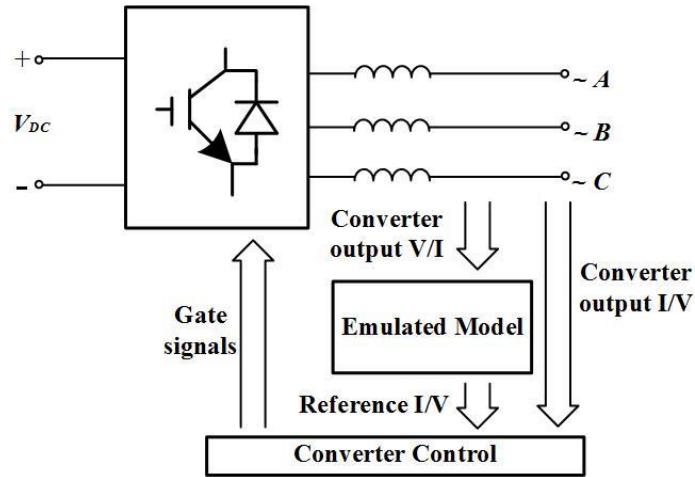


Figure 3-3 Three-phase power electronic converter based emulator unit (PHIL).

As illustrated from a three-phase emulator unit example shown in Figure 3-3, the converter is designed to react within its control bandwidth capability to track current/voltage references from the emulated model. The three-phase ac side of the converter is the electrical behavior interface with the rest of the electrical system. Voltage/current inputs are sampled in real time for updating the emulated model calculation. The references from the model will be given to the converter closed-loop digital controller, so that the electrical behavior from the three-phase interface will represent that of the model.

Different from conventional RLC loads, a power electronic load offers the option of circulating the energy, which is especially beneficial for high power applications. However, compared with other general-purpose current controlled power converters, there are several technical challenges for the load emulator developments within HTB, including the concerns on stability, accuracy and implementation of the load emulator.

3.3.1 Emulator Tracking Bandwidth

Circuit schematic and control structure of current controlled load emulator in abc is presented in Figure 3-4 (a), while the circuit modeling and current controller in dq is in Figure 3-4 (b).

The load emulator functions as a controlled active rectifier mode. Three-phase currents are sampled in real time for closed-loop control; three-phase voltages are sampled and phase locked of frequency and phase angle for power invariant dq transformation [61]; and real-time input updates for the emulated model are provided.

For the determination of each emulator unit current controller parameters, classical three-phase dq averaging circuit is analyzed for small signal stability around a steady state operating point [65]. The current control system is a classical PI controller designed in dq frame with decoupled d and q axes. The calculation for each switching interval current reference and actual duty cycle are done within the DSP. In the emulator implementation, the three-phase currents are controlled to track the references calculated in real-time from the power system load model. While modeling in dq domain, the influence of PLL and abc - dq transformation are not considered in the closed loop functions of dq variables.

The tracking capability of the current controlled load emulator is represented in the form of current controlled closed-loop transfer function i_d / i_{dref} and i_q / i_{qref} . The frequency range covering 0 db and 0 degree in the closed loop transfer function bode figures, represents the frequency range for the emulator to track theoretically without distortion in amplitude or time delay.

As introduced in section 3.1, current controlled emulator control structure in HTB has generator emulator controlling ac side voltage (constant V_d and V_q in Figure 3-4 (b)) and rectifier regulating dc side (constant V_{dc} in Figure 3-4 (b)).

The emulator's current controller was designed and modeled individually without any consideration of disturbances on the paralleled dq and dc voltage source side. However, while combining with the voltage controlled emulator (which is also independently and individually designed), the PI parameters are adjusted (to be slower) for the stability of the whole paralleled system.

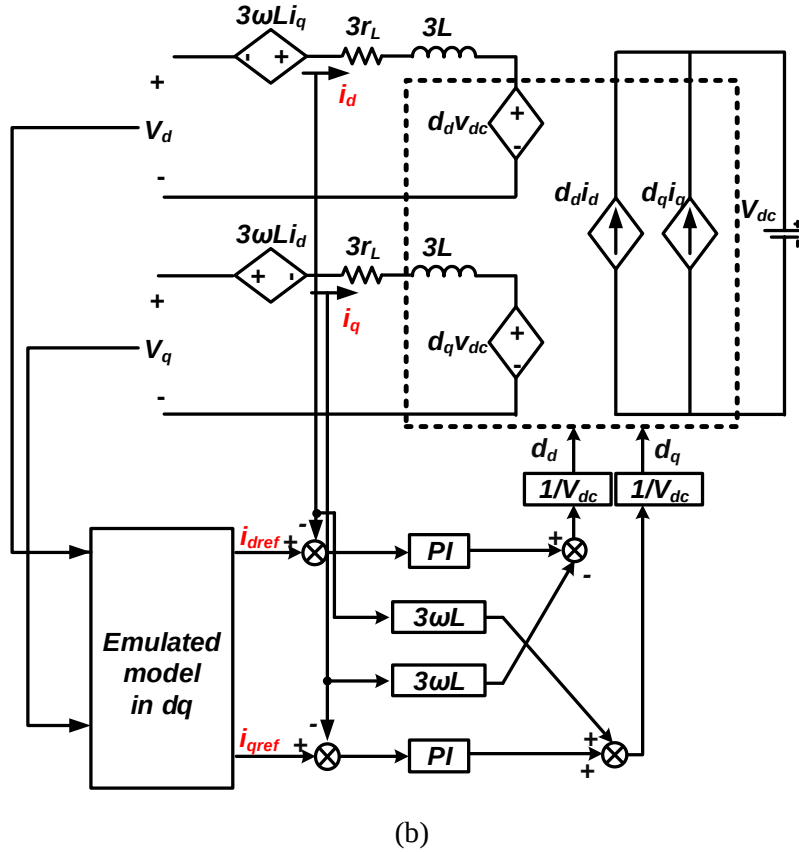
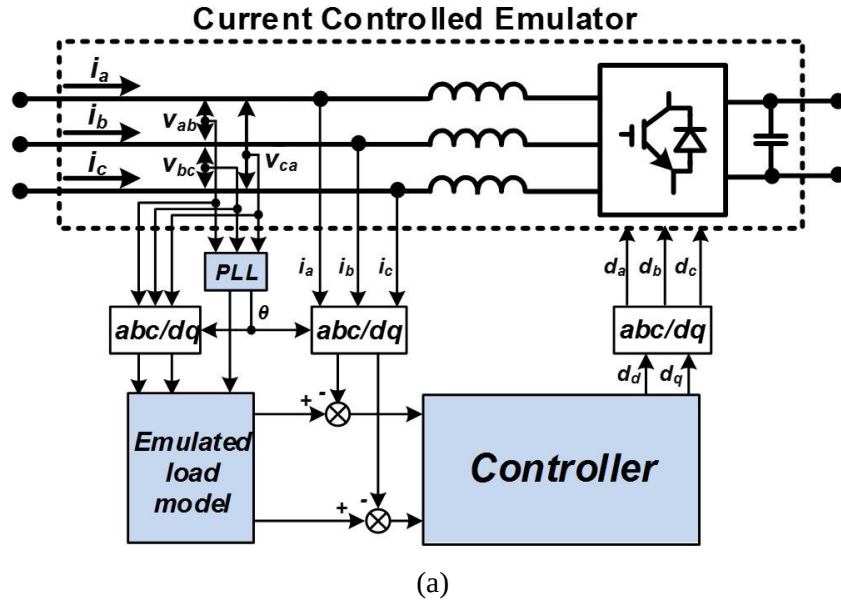


Figure 3-4 Equivalent averaging circuit in (a) *abc* (b) *dq* for load emulator.

From Figure 3-5, the left side bode plot curves show the open loop transfer functions for the load emulator power converter on d axis without compensator and with adjusted compensator, while the right side bode plot curves show the closed loop transfer function on d axis with adjusted compensator. The designed controller decouples d and q axis, and transfer function on q axis has identical result as that of d axis.

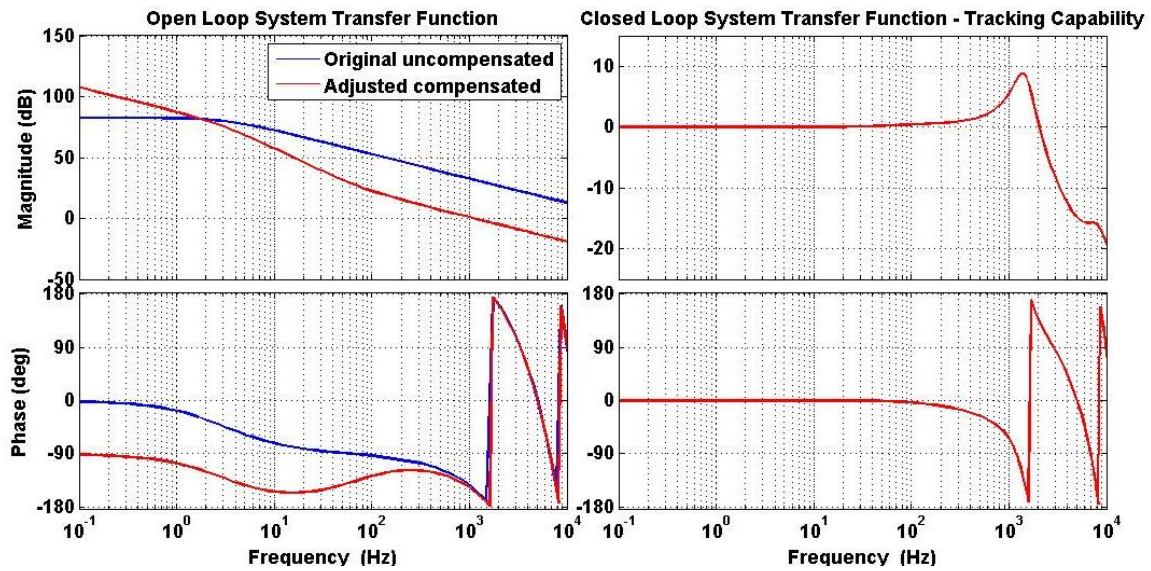


Figure 3-5 Controller design and tracking capability of the load emulator.

With consideration of the digital implementation delay and filtering inductor value for the converter, the current controller bandwidth is designed to 1.2 k Hz. As measured from Figure 3-5, the modified emulator could track dq reference signals with up to 100 Hz variation within 0.35db distortion in amplitude, 4 degrees in phase delay.

Figure 3-6 illustrates the startup transient stator current references for the induction motor model in electric machine synchronous dq coordinates ([57], in section 3.3.4.2) applied in the load emulator: after spectrum analysis, the magnitude of stator current references in dq corresponding to frequencies higher than 100 Hz is negligible. The overall and detailed curves in Figure 3-7 further confirm the experimental tracking performance of the induction motor emulator.

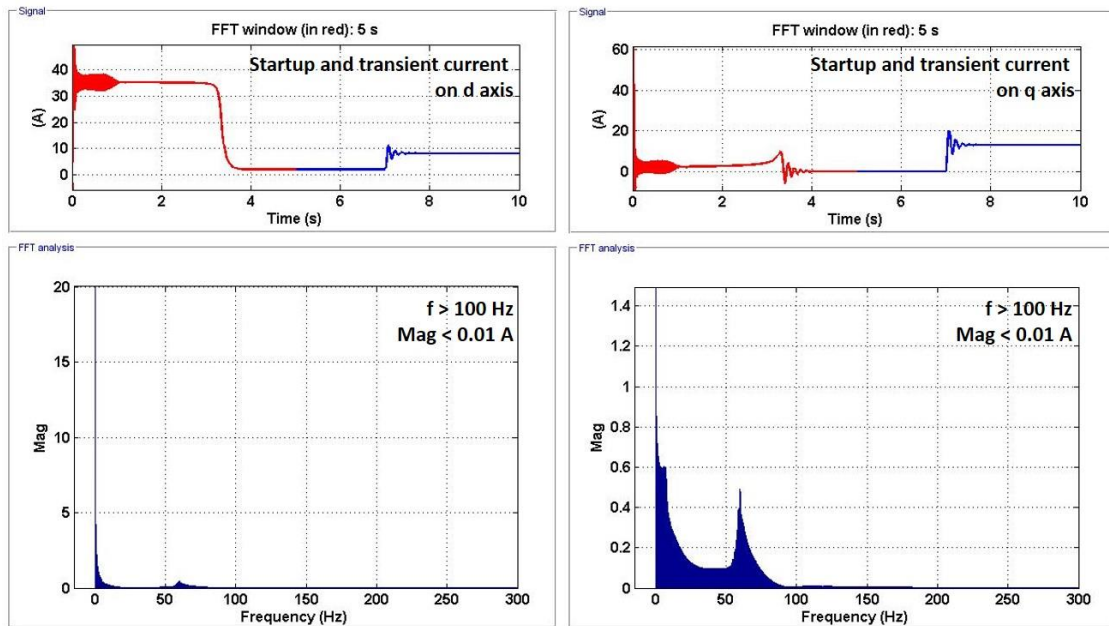


Figure 3-6 Spectrum analysis of induction motor startup current dynamics in dq .

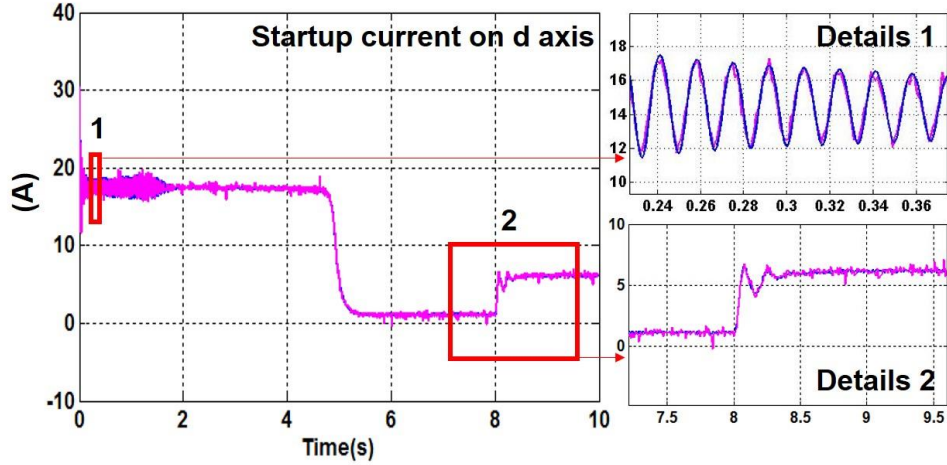


Figure 3-7 Detailed example of recorded experimental results comparing induction motor emulator current references and outputs in dq domain.

3.3.2 Converter Interface Issues

Although multiple converters are connected in paralleled structure in the HTB, only three-phase ac interface contains the current and voltage variables that are dynamically closed-loop controlled. Due to the regenerative structure, the dc interface for the system has high equivalent load impedance for the dc voltage regulating rectifier, which is connected to the utility grid and compensates for the whole HTB structure's power loss.

Previous research has studied stability problems involving multiple regulated power converters, by reducing them to a simpler structure unit consisting of a voltage-controlled converter interfacing a current-controlled converter [66][67]. The stability evaluations are done through source output impedance and load input impedance in dq domain and Generalized Nyquist Criterion (GNC) for characteristics loci of the impedance return-ratio matrix [67][68]. Moreover, considerations about implementation related

factors, such as phase-lock-loop (PLL) [70], digital processor time delay, dead-time compensation, voltage feed-forward in the current control loop [71], as well as the structure related factors, such as number of load emulators paralleled, passive inductor (or even LCL) filter [69], inductors representing transmission impedance, would provide better accuracy for the stability evaluations.

In the PHIL case, not only the power converter's characteristics should be included in the stability evaluation, but also the impedance between ac terminals of individual emulators, large-signal stability challenges, as well as the emulated model reference influence on the load impedance should be considered as well (though in the grid emulation scenario, the emulated model will mostly affect the low frequency domain impedance).

With the paralleled structure, power is circulated among converters. Various measures have been taken to attenuate the circulating current caused by this parallel structure and switching transients in the HTB [108]: (1) synchronization of Pulse Width Modulations (PWM) for different converters has been adopted to reduce the switching frequency circulating current, (2) common mode choke, (3) zero-sequence current controller and (4) dead-time compensation have been developed for optimizing the performance of paralleled converters.

3.3.3 Numerical Performance of Real-time Model

As a prototype of the load emulator, static [61] and dynamic model types are established with classical mathematical equations. Within limited computation resource, the current references are calculated in real time. Numerical issues, especially due to high

order of numerical model and strong dynamics, insufficient time step, and improper numerical methods, may result in discrete-time approximation inaccuracies, steady state errors, or distortion of the calculation results [123][126].

As discussed in section 2.2, computer simulation tools, such as Matlab/Simulink, offer higher discrete approximation and bounded numerical error capability with longer calculation time. Thus, in the later chapters, simulation results are used as references to verify load emulator experimental results under the same input conditions.

The real-time implementation platform in this emulation prototype is the digital microprocessor DSP Texas Instruments TMS320F28335 with clock frequency of 150 MHz (6.67 ns cycle time) and 32-bit floating type single precision. All required firmware and software functions are programmed in DSP and running in real time. Figure 3-8 illustrates the algorithms within switching cycle of 100 μ s time frame inside the digital controller. They include Analog to Digital Conversion (ADC) and signal sampling, PLL and dq transformations, real-time emulated model calculation, and closed-loop control functions.

In order to operate the emulator in real time, implementation of all DSP algorithms is required to be finished within the time frame of each time step. Under this application, each function block inside the DSP is optimized, sequenced, and timed as shown in Figure 3-9. The emulated model illustrated in the example is a combination of ZIP and two motor models (will be elaborated in section 5.3). In addition, the implementation of the motor models depends on the discretization of the numerical methods applied (one example is using 4th order Runge Kutta). The CAN communication function is not routinely

implemented in each time step – it irregularly interrupts in the DSP when a message is received and regularly sends message once every eight PWM cycles.

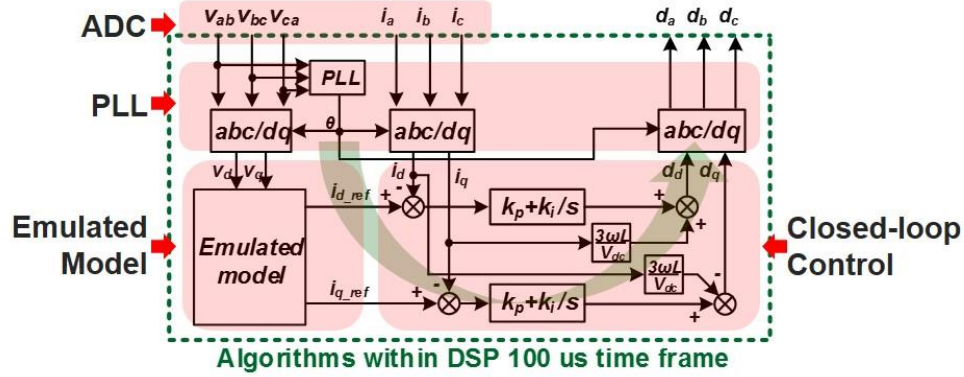


Figure 3-8 Real-time algorithms in DSP and implementation timing sequence.

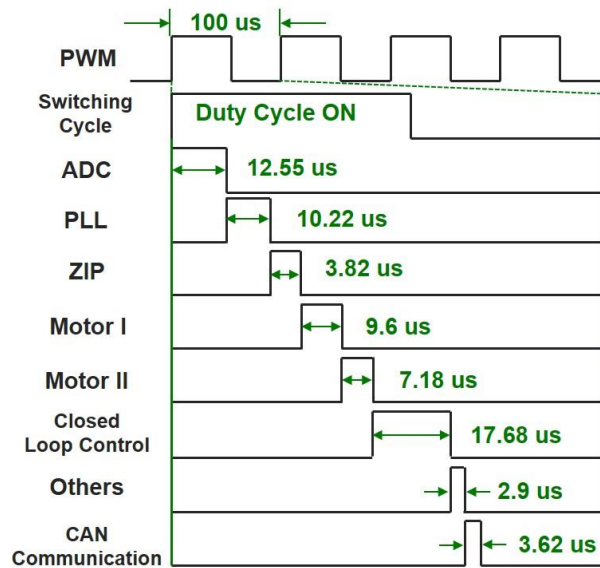


Figure 3-9 Function blocks timing sequence in DSP and their implementation duration within real-time constraint.

It is clearly demonstrated that the real-time load emulator including model implementation and converter control functions is well-within the calculation capacity of the DSP chosen for this emulation platform.

However, with the composite load model (which includes ZIP and Motor I and Motor II models) with more dynamic or static sub-models, the implementation timing sequence within the DSP could be optimized by the following three methods.

3.3.3.1 Equivalent Smaller Time Step

In order to achieve an equivalent smaller time step (to achieve higher accuracy calculations), each ordinary differential equation (ODE) model can be computed multiple times within a switching cycle, and then real-time input variables will be updated after several calculation cycles (at the beginning of each switching cycle).

Similar equivalent smaller time step strategy is used in [81], where the induction motor's full model was calculated 7 times within a switching cycle using Euler's method.

The timing sequence for load emulator application example is indicated in Figure 3-10. Figure 3-10 (a) shows the timetable of composite load model including ZIP (without numerical method) and motor I & II (both with 4th order Runge Kutta (RK4), implemented 3 times per 100 us switching cycle which makes it equivalent to a time step of 33.33 us). Total DSP numerical model calculation implementation time is 54.16 us. Figure 3-10 (b) shows the real-time models calculated once per switching interval, and the total implementation time for the numerical model is 20.6 us. The benefit for this type of

equivalent smaller time step numerical implementation is higher numerical calculation accuracy, however with the cost of longer implementation time in DSP. The sensitivity of numerical accuracy with reference to time step is evaluated in section 7.4.1 of this dissertation.

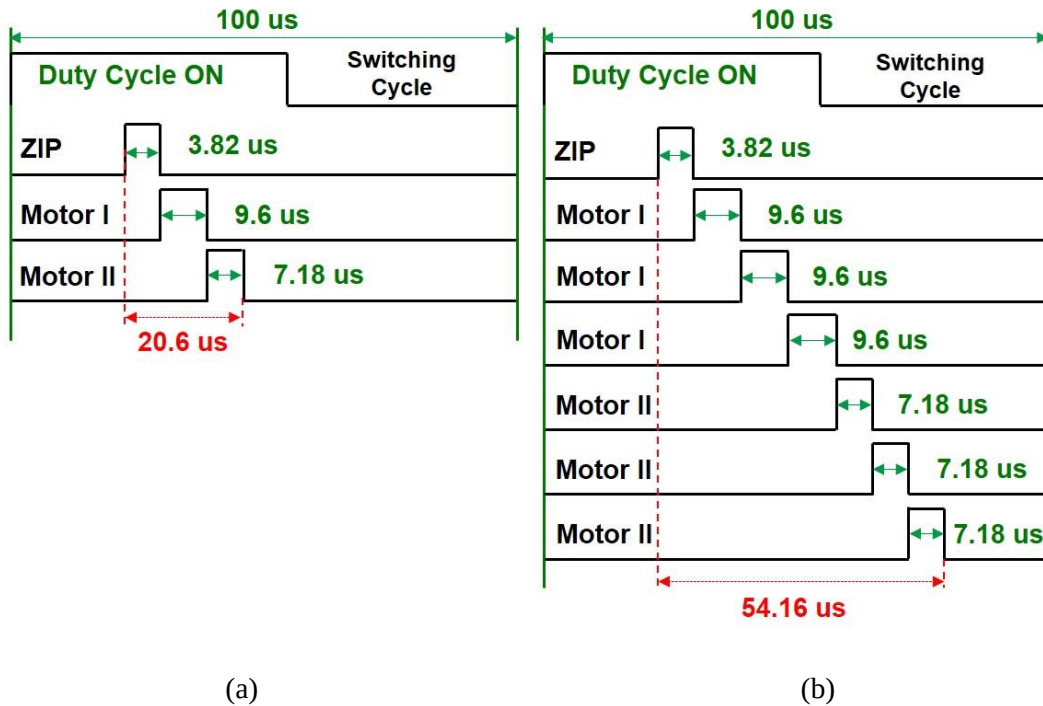


Figure 3-10 Timing sequence of motor I & II models implementations with (a) 100 us time step and (b) equivalent 33.33 us time steps in DSP.

3.3.3.2 Different Numerical Solvers

Besides the time step, solvers will impact the numerical performance of the real-time model as well, in terms of its digital implementation as well as the accuracy.

However, according to the complexity of the operations involved in the numerical implementation, the time cost on each method is different. Usually, higher order approximated numerical solver means longer implementation time.

As demonstrated below in Figure 3-11 about the timing sequence, example of motor model I and II implemented in explicit Runge Kutta 4th order (Figure 3-11(b)) with accuracy of T_s^4 is compared with the same model implemented in Trapezoidal based Predictor Corrector method (PECECE in Figure 3-11(a)) with accuracy of T_s^3 . In RK4, there are 227 multiplication operations and 156 addition operations within calculation of a motor model. In PECECE, there are 155 multiplication operations and 88 addition operations within calculation of a motor model. Total implementation time in this DSP platform for the composite load model using PECECE is 18.61 us, while the calculation time with RK4 is 20.6 us.

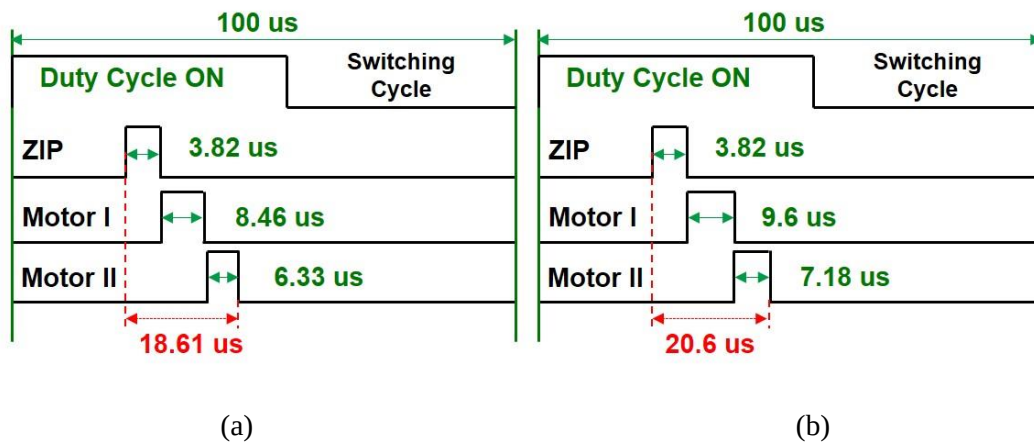


Figure 3-11 Timing sequence of motor I & II models implementations with (a) PECECE and (b) RK4 and 100 us time step in DSP.

Details about the sensitivity of numerical accuracy for different numerical solvers on the same model is elaborated in section 7.4.2.

3.3.3.3 Microprocessor and Switching Frequency

The clock frequency of the digital microprocessor DSP on the platform determines how much time each calculation cycle will take, and the total time of implementation equals the multiplication of DSP cycle period and cycle quantities within numerical calculation. Higher DSP clock frequency means that under the same number of calculation cycles (same model calculation task) the real-time implementation takes less processing time.

More advanced DSP series could be found with less processing time. One example is the dual-core DSP TMS320F28377 with 200 MHz clock frequency [130], which means just a single core from DSP 28377 will boost the performance by decreasing the implementation time by 25%.

Besides clock frequency, multiple CPUs in parallel during the calculation could effectively reduce the calculation burden imposed, compared with a single core CPU. Such computation will reduce the operation time and enable a more complicated real-time model to be calculated on a single emulator.

As indicated in Figure 3-8, the emulator processor has to function as power electronics closed loop digital controller, real-time model simulator, and data recorder

(optional). If each portion of the functions could be divided into different cores and run in parallel, the time could be drastically reduced.

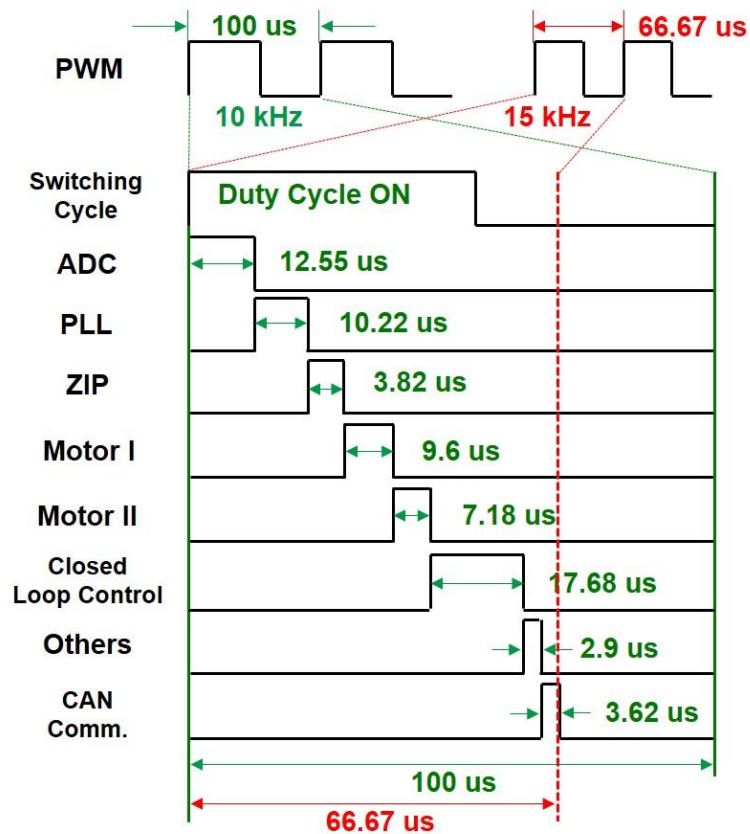


Figure 3-12 Timing sequence in DSP and model implementation durations with different real-time constraints.

The concept of 'real-time' implies that the model and signal calculations are accomplished with a microprocessor within a switching cycle and updated in real time for the emulator to track. The timeframe for all these implementations is needed to be done between real-time PWM updates for converter. As shown in Figure 3-12, for the designed

composite load model, the real-time implementations are well within 10 kHz switching frequency constraints. However, if the emulator's switching frequency is increased to 15 kHz, existing microprocessor DSP will not be able to finish the calculation task of the design composite load model within the switching interval.

Power electronics switching frequency is directly related with hardware design, including semiconductor device, system cooling structure, as well as software program, including enabling the interrupts, sampling frequency and functions' structure. The higher switching frequency means less processing time within real-time operation timeframe constraint. The tradeoffs between advantages of higher accuracy implied with smaller time step and disadvantages of shorter implementation time are the major concerns in choosing the appropriate real-time power electronics emulator application switching frequency.

3.3.4 *Abc-dq* transformation

The commonly accepted *dq* transformations, which are differentiated by *dq* axis positions and coefficients of transformation matrixes, if not defined and transformed well, could be major sources of error during calculation.

Usually, for the converter design, classic design procedure follows q axis leading d axis by $\frac{1}{2}\pi$ (which is Parks transformation). While as for the machinery study, the *dq* system is usually the other way around. Figure 3-13 illustrated that under the same *abc* system, relative positions of d and q axes with transformation matrixes of T_{conv} and T_{mach} .

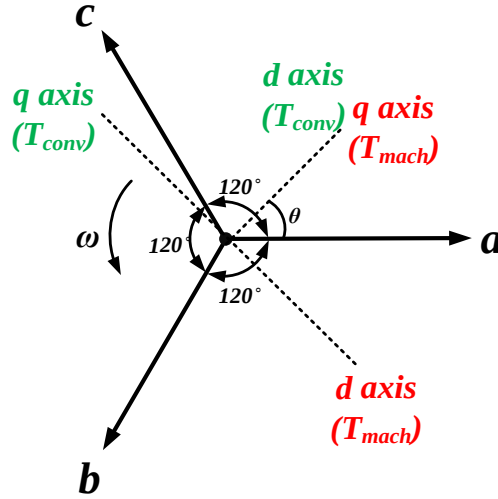


Figure 3-13 Dq transformation applied in converter and machinery modeling.

Also the coefficient $\frac{2}{3}$ or $\sqrt{\frac{2}{3}}$ for the transformation matrix varies depending on whether it's based on amplitude-equivalence or power-equivalence.

However, for the control system to work, conversions between different dq systems are made during programming in DSP. As illustrated in Figure 3-14, conversions are done at the interfaces of converter and machine dq transformations.

3.3.4.1 Converter abc - dq transformation

In the design of the converter controller, including converter model and averaging circuit design, as well as the modeling of emulated target (excludes machinery modeling), the transformation follows the above (1) [61].

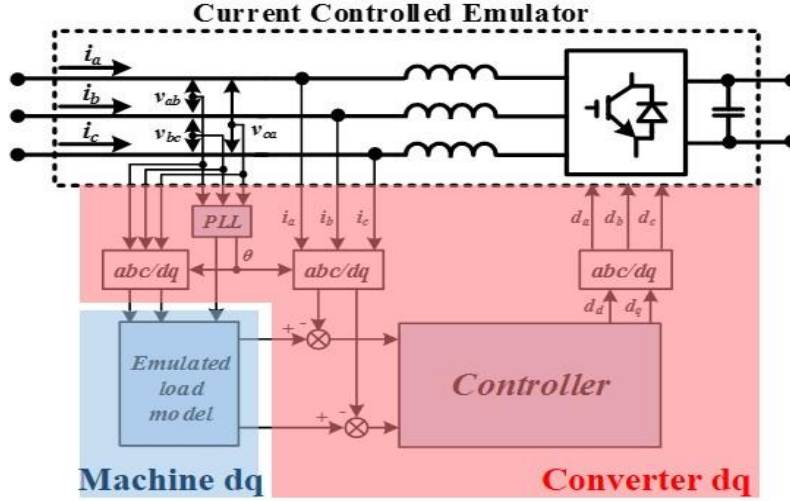


Figure 3-14 Dq transformations applied in load emulator controller.

The $abc \rightarrow dq0$ matrix above is denoted as T_{conv} and it has the properties as (2). This transformation follows power equivalence rules. The instantaneous real and reactive power calculation are calculated as (3) and (4).

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta + \frac{2}{3}\pi) \\ -\sin \theta & -\sin(\theta - \frac{2}{3}\pi) & -\sin(\theta + \frac{2}{3}\pi) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \quad (1)$$

$$T_{conv} = T_{conv}^{-1} = T_{conv}^T \quad (2)$$

$$P = v_d i_d + v_q i_q \quad (3)$$

$$Q = v_q i_d - v_d i_q \quad (4)$$

3.3.4.2 Machine model abc - dq transformation

In the induction machine modeling, the transformation process equations (5) - (8) are adopted as conversion between three-phase abc and dq domain variables [57].

The abc - dq matrix is denoted as T_{mach} , and the inverse of the T_{mach} is shown in the following equation of (6). This transformation follows amplitude equivalence rules. The instantaneous real and reactive power calculation are calculated as (7) and (8).

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\theta & \sin(\theta - \frac{2}{3}\pi) & \sin(\theta + \frac{2}{3}\pi) \\ \cos\theta & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta + \frac{2}{3}\pi) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \quad (5)$$

$$T_{mach}^{-1} = \begin{bmatrix} \sin\theta & \cos\theta & 1 \\ \sin(\theta - \frac{2}{3}\pi) & \cos(\theta - \frac{2}{3}\pi) & 1 \\ \sin(\theta + \frac{2}{3}\pi) & \cos(\theta + \frac{2}{3}\pi) & 1 \end{bmatrix} \quad (6)$$

$$P = 1.5 * (v_d i_d + v_q i_q) \quad (7)$$

$$Q = 1.5 * (v_q i_d - v_d i_q) \quad (8)$$

3.4 Hardware Design and Structure

3.4.1 Overall Structure (Teamwork)

The hardware test-bed has the ambition of combining multiple clusters of power converter groups, paralleled on ac and dc, forming the network of power system large distribution centers in the whole United States.

Communication structure is based on CAN between digital controllers (one DSP from Texas Instruments for each emulator), Ethernet between cluster hubs (one CompactRIO from National Instruments for each cluster) and Labview visualized operation center, shown in Figure 3-15 (c).

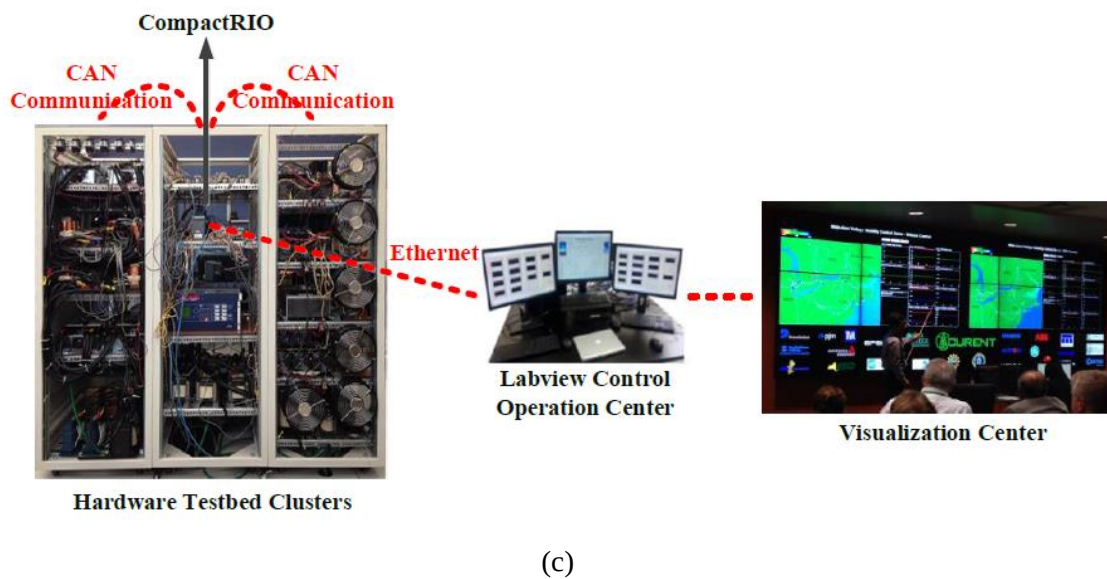
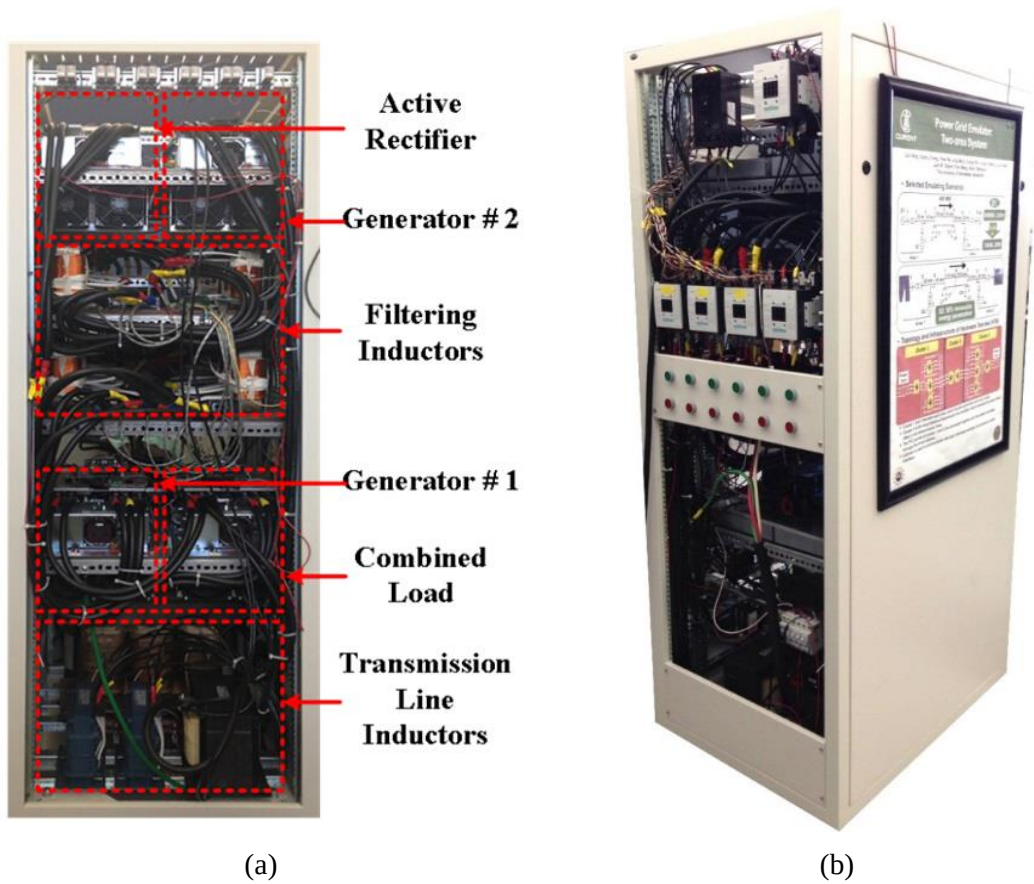


Figure 3-15 Experimental hardware of HTB: (a) (b) back and front views of a whole cluster representing a single area, (c) HTB communication and control structure.

CompactRIO is used to collect information from converter sensing signals by DSP CAN bus [108] as well as real-time measurement instruments of Potential Transformer (PT) and Current Transformer (CT) on HTB. Then, the signals from individual CompactRIO (one for each cluster) and Phasor Measurement Unit (PMU) are fed through ethernet to Labview for status estimation and higher control function implementation, while corresponding command signals are delivered through the same network frame backwards. Control center computer screens are shown on a video wall for real-time update and visualization.

As shown in Figure 3-15 (a) and (b), each single cluster includes: active rectifier for establishing and stabilizing dc bus voltage, generators 1 and 2 in each area, combined static and dynamic load, and local transmission line inductors.

3.4.2 Emulator Unit Configuration

As shown in Figure 3-17, each single emulator unit contains a three-phase DC/AC converter. The power converter for the emulator is sponsored from Vacon company with modified version from model number of X4C41000C [57]. The rated electrical duty is 75 kW (100 hp). The devices used in the power stage are three-phase-leg IGBT modules, controlled at the switching frequency of 10 kHz.

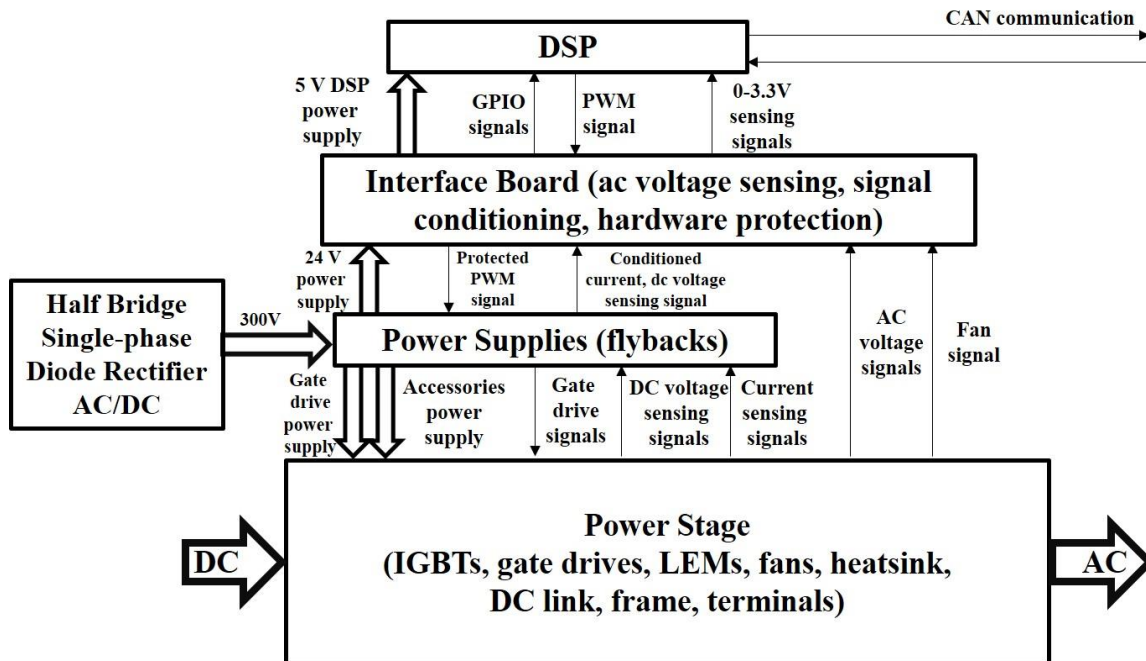


Figure 3-16 Power converter based emulator unit structure.

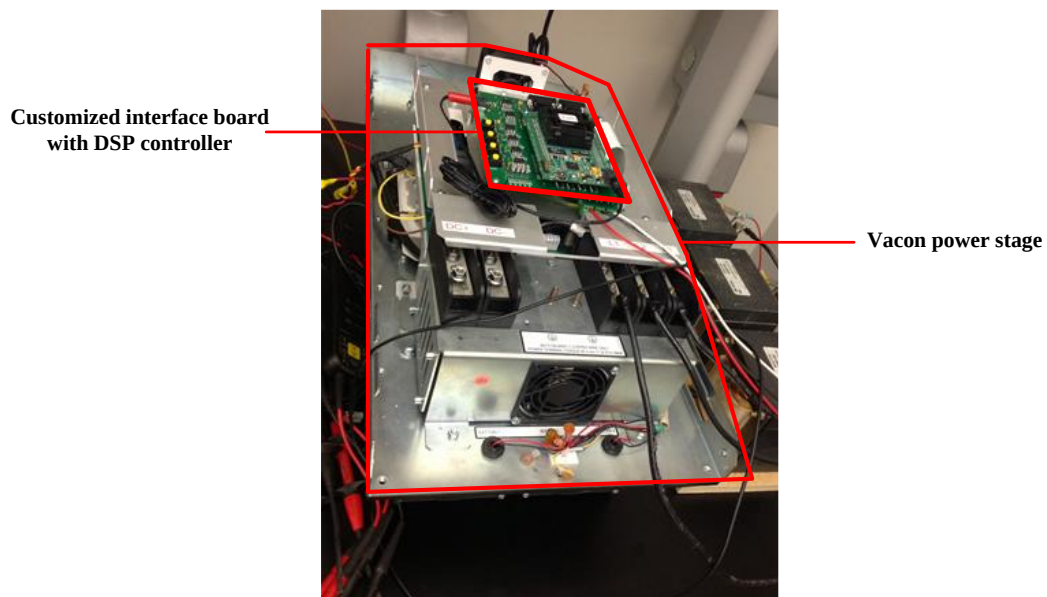


Figure 3-17 Photograph of single emulator hardware.

According to the current ripple filtering requirement, the three-phase inductor filter is designed to be 0.5mH. Instead of using the original controller from the Vacon commercial motor drive, TMS320F28332 from Texas Instruments integrated by Spectrum Digital eZdsp peripherals has been used as the digital controller for the emulator. Interface between controller and power stage has been customized for the power signal sampling and level differences adjustments.

Detailed power converter emulator unit structure is shown in Figure 3-16. The signal flow as well as power supplies among DSP, interface board, and power stage are shown as indicated.

Sensing signals including ac, dc voltage and ac currents are collected, conditioned for DSP ADC inputs within 0-3.3V, and used as hardware protection signals for determining whether PWM should be delivered to gate drive or not. Current sensing signals are using conditioned signal outputs from LEM current sensor on the power stage while ac and dc voltage sensing signals are obtained using differential amplifier based circuit. The upper and lower threshold voltage levels for hardware protection is changeable on the interface board through adjustable resistors.

GPIOs on DSP EVM are used as manual indicators of operations desired. Their functions are also integrated in the interface board by means of touch buttons. Anytime when there is fault protection signals triggered, it will be delivered through GPIO to DSP to be processed as well. CAN communication is also used in the system as exchanging the input and output variables with Labview.

The original power supply circuit input for flyback is using half bridge single-phase diode rectifier ac/dc converting 120 Vac to 300 Vdc under 500 W operating state. Details are introduced in section 3.4.3 .

3.4.3 Auxiliary Power Supply

Due to the modification of the Vacon power stage design, the previous back-to-back motor drive design has been changed to a single dc fed three-phase converter for the application in HTB. However, in the previous design, the control power including gate drive, sensor, fan as well as the interface board was supplied by the flyback converter groups powered by V_{dc} self-excited when it reaches higher than 300 V (rectified by diode rectifier from 208 V_{llrms}).

The design requirement for the power supply is: from input of 60 Hz 120 Vac, output higher than 300 V for loaded conditions of 500 W and simple structure.

Figure 3-18 half bridge rectifier is proposed under these requirements, with output voltage to be 340 Vdc. Negative Temperature Coefficient (NTC) thermistor is used in the circuit which limits the inrush current to be below 15 A as illustrated in Figure 3-20 (a).

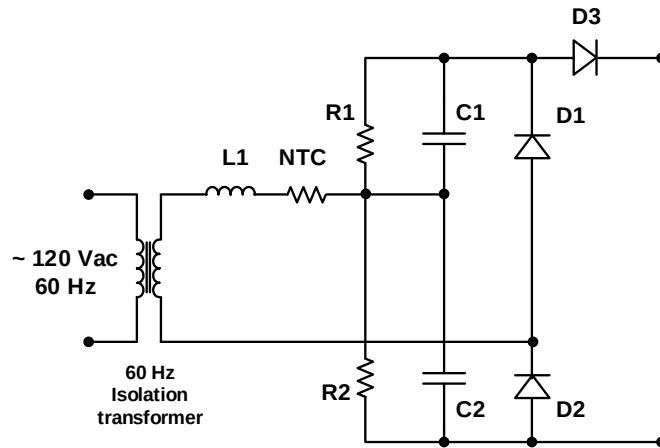
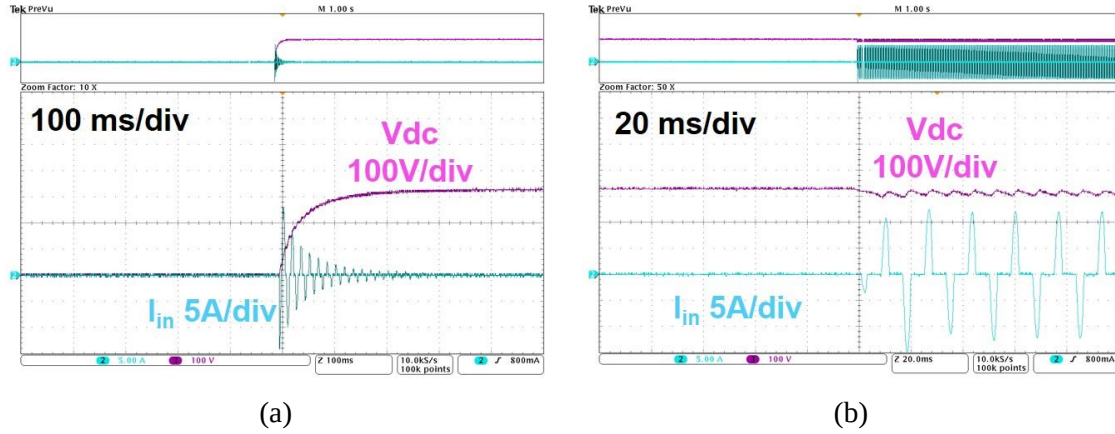


Figure 3-18 Circuit schematic of auxiliary power supply AC/DC.



Figure 3-19 Photograph of half-bridge auxiliary power supply.

Figure 3-20 has the startup waveform for the half bridge rectifier without load and transient of sudden connection with load. Due to there is no power factor correction circuit in the front stage, the current waveform looks distorted with typical diode rectifier current waveform characteristics. However, since the power level is low around 300 – 500 W, the harmonics to the building power distribution system is trivial and not within consideration.



3.5 Summary

Hardware test-bed of universal reconfigurable grid emulator is introduced in this chapter. Two types of emulators are included in the system: voltage type emulator representing generator and current type emulator representing load.

The concerns with emulator tracking bandwidth, numerical reference, paralleled converter interface stability and dq transformations are discussed. Hardware design for individual and whole system is introduced as well.

CHAPTER 4

STATIC LOAD EMULATOR

In order to provide power grid emulator with desired and flexible loading conditions in steady state analysis, constant impedance, current and power load emulator with reference to terminal voltage and frequency variations has been developed in this chapter, with the control and structure of current controlled three-phase converter.

4.1 Static Load Model

According to standard power system load models defined by IEEE task force [25], in large-scale transient stability simulations, loads are typically modeled as static functions of voltage and frequency, as the features of ZIP or exponential forms. They are continuous representation of steady state power flow, except for when model converts to impedances at voltages below 0.3 – 0.7 pu [25]. Usually, one static model is required per bus.

4.1.1 ZIP Representations

In system steady state power flow analysis, conventional static load model is represented by a series of equations (shown below), which are called ZIP load. They stand for the combination of constant impedance (Z), constant current (I), and constant power (P) loads in both real and reactive power.

Commonly adopted in calculations, the ZIP model represents the combination of the static characteristics of power system load. The mathematical polynomials are written

as (9) and (10) under presumption of minor fluctuations around nominal grid voltage. Also, frequency dependency effect on the load behavior is considered with the coefficients on real and reactive power.

$$P_{ZIP} = P_0 * (p_1 \left(\frac{V}{V_0}\right)^2 + p_2 \left(\frac{V}{V_0}\right) + p_3) (1 + k_{pf} \Delta f) \quad (9)$$

$$Q_{ZIP} = Q_0 * (q_1 \left(\frac{V}{V_0}\right)^2 + q_2 \left(\frac{V}{V_0}\right) + q_3) (1 + k_{qf} \Delta f) \quad (10)$$

In the equations, P_0 and Q_0 stand for real and reactive power base value. p_1 and q_1 are coefficients for constant impedance portions for real and reactive power, while p_2 and q_2 are for constant current portions, and p_3 and q_3 are for constant power portions. k_{pf} and k_{qf} are coefficients for the load frequency dependency characteristics.

ZIP model could be used to fit the power consumption curves for most kinds of power system loads: higher order polynomials are neglected for simplifying the model. In the meantime, the percentage of Z, I and P for the system load is determined by aggregating different load types and their usage within the grid. By determining the values for p_1 , p_2 , p_3 and q_1 , q_2 , q_3 , the static load operating state could be specified. It is always set such that the sum of p_1 , p_2 , p_3 is unity and the sum of q_1 , q_2 , q_3 , is unity, the typical value range for k_{pf} is 0 ~ 3 and that for k_{qf} is -2 ~ 0 [61], corresponding to different loading situations.

As presented in Figure 4-1, the emulated model uses voltages in dq domain and emulated grid frequency as inputs for the ZIP model. External base real and reactive power commands are given to the model for specifying the actual power desired by customers, through Labview manual operations. Output currents are calculated using (3) and (4) based

on power equivalence relationship in dq domain. The load emulator current behavior is controlled accurately according to the references so as to ensure the power consumptions at the load bus to be the ones described in (11) and (12). The voltage V_q is controlled by Phase Lock Loop (PLL) to be 0 while V_d is calculated based on sampled voltage and the angle extracted from PLL.

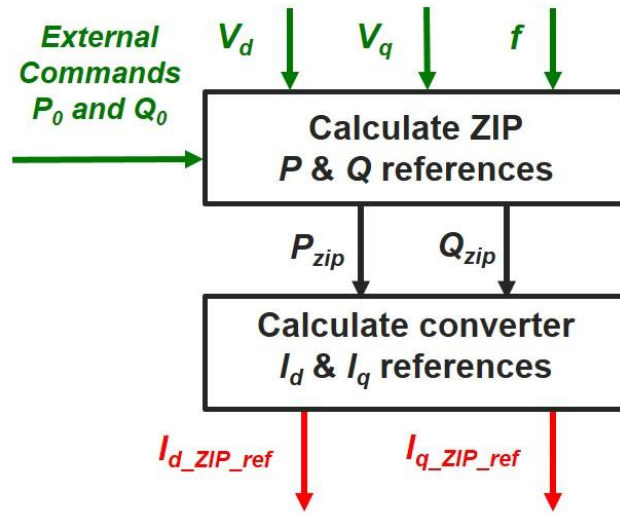


Figure 4-1 Emulated ZIP model inputs and outputs relationship.

$$I_{d_ZIP_ref} = \frac{V_q \cdot P_{ZIP} + V_d \cdot Q_{ZIP}}{V_q^2 + V_d^2} \quad (11)$$

$$I_{q_ZIP_ref} = \frac{V_d \cdot P_{ZIP} - V_q \cdot Q_{ZIP}}{V_q^2 + V_d^2} \quad (12)$$

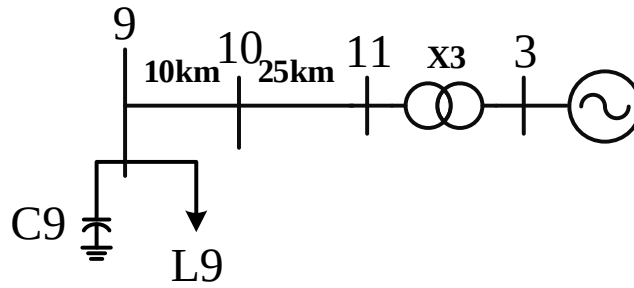
When the grid voltage falls below a specified value during a fault-caused sag, the polynomials described above no longer represent the real power flow condition, because of the relay protection and stall effect of motors in the grid. Switching static load models

to constant impedance expressions becomes necessary under that circumstance. p_2, q_2 and p_3, q_3 will be set to zero and p_1, q_1 will be adjusted in order to accommodate the change [61].

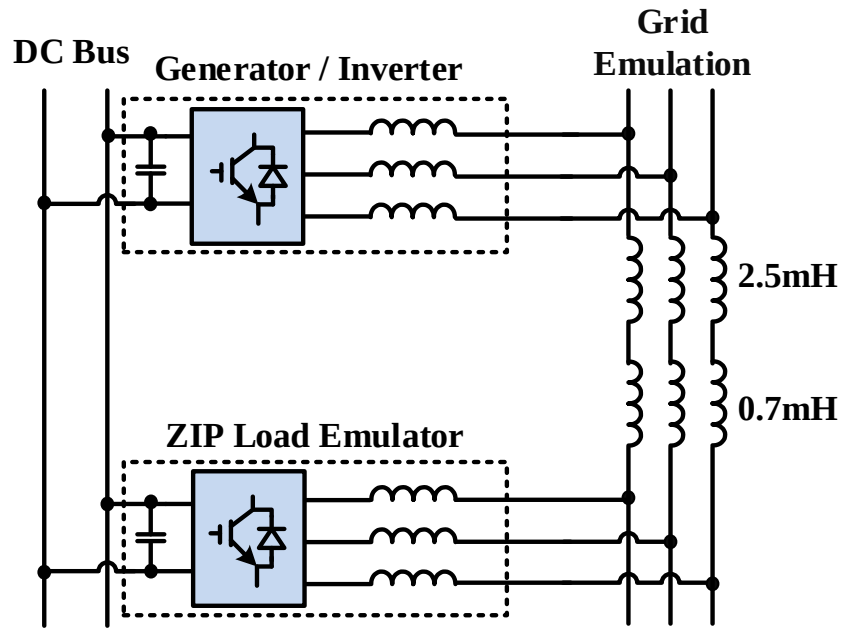
As concluded in [122], the approximate time scale for power flow (static load) is seconds, sometimes minutes or even longer, which is well within the capable tracking frequency of the emulator.

4.2 Power Static Load Characteristics

In order to present the load characteristics on their different percentages about constant impedance, constant current and constant power as well as their dependence on frequency variations, test-bed structure of Figure 4-2 is applied to evaluate the load emulator's performances. Generator / inverter unit in the structure is used to create the testing scenarios needed voltage and frequency variations for demonstration of ZIP power load characteristics.



(a)



(b)

Figure 4-2 G3L9 ZIP emulator test: (a) grid scenario, (b) HTB energized structure.

4.2.1 Voltage Dependence Characteristics

The real and reactive power of ZIP load are determined not only by the P and Q commands, but also by how much the load bus voltage deviates from 1 pu due to the power consumption, i.e. responsive load.

Table 4-1 ZIP load parameters and test conditions case 1.

ZIP Load Model		Test Conditions	
Parameters	Values	Parameters	Values
p_1	0.2	V_{llrms}	208 V
p_2	0.2	V_{dc}	400 V
p_3	0.6	P_{base}	15 kVA
k_{pf}	1	f_{base}	60 Hz
q_1	0.2	P_0	0 – 0.8 pu
q_2	0.2	Q_0	-0.4 – 0 pu
q_3	0.6		
k_{qf}	-1		

In order to test the ZIP load consumption according to terminal voltage variations, scenario is designed with conditions shown in Table 4-1 and system configuration in Figure 4-2. The voltage controlled emulator is controlling the G3 terminal voltage as infinite bus and L9 controlled as ZIP load emulator. By manually inputting the real and reactive commands, the loading conditions on L9 will change accordingly.

Figure 4-3 illustrates the data recorded by Labview during the scenario variations. The differences between P command and L9P as well as Q command and L9Q, are due to the bus 9 terminal voltage variations. The larger differences between load bus terminal voltages, the more differences are there between power command and actual power consumption.

Figure 4-3 illustrates the data recorded by Labview during the scenario variations. The differences between P command and L9P as well as Q command and L9Q, are due to the bus 9 terminal voltage variations. The larger differences between load bus terminal voltages, the more differences are there between power command and actual power consumption.

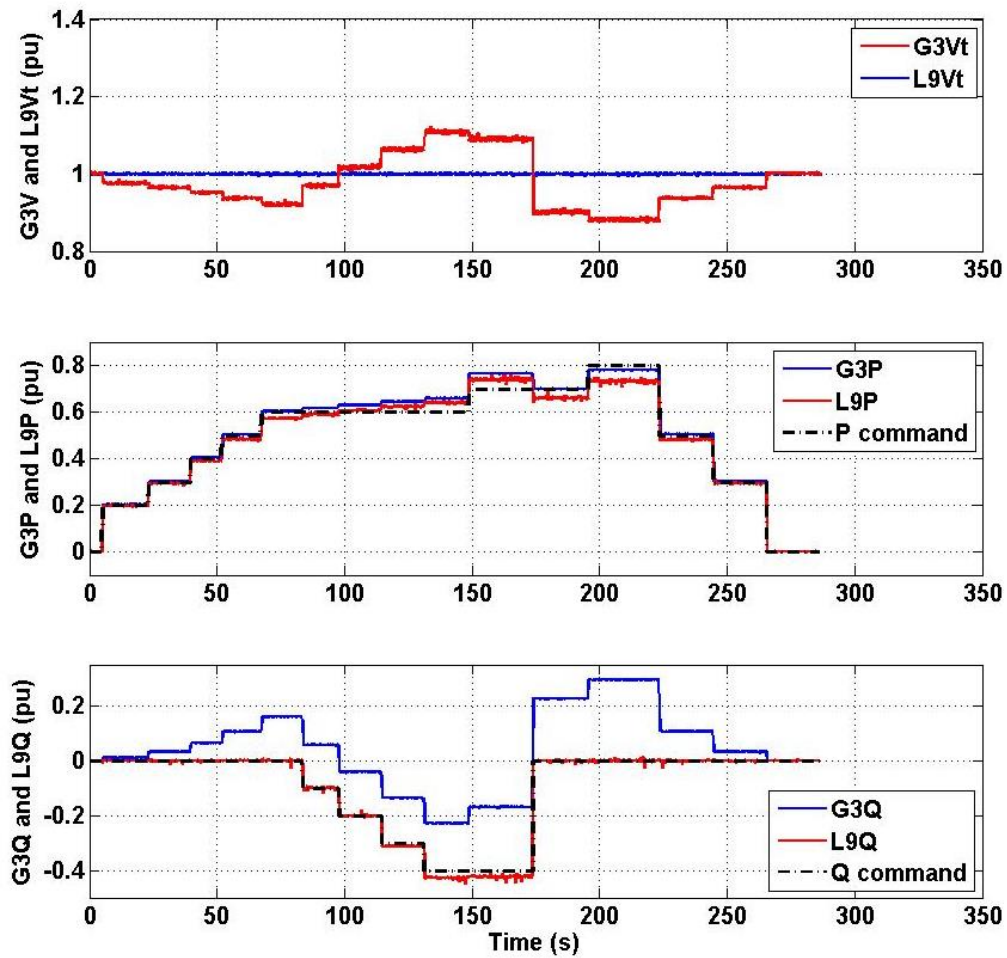


Figure 4-3 Real and reactive power loading conditions variations case 1 record with Labview.

The differences between power of generation and load, are due to the physical inductor represented short transmission line between G3 and L9. The resistance on the inductor component is causing the real power differences, and the inductance value is causing the reactive powers differences.

During the scenario, the reactive power required on L9 is negative – this could be considered physically as scenario of reactive power compensation. Accordingly, the terminal voltage through time range of $t = 83.5 - 174$ s is higher than the conditions without reactive power support.

4.2.2 Frequency Variation Characteristics

Another factor causing differences in power consumption of ZIP load emulator, is the frequency in the ac system.

In order to test the ZIP load consumption according to system frequency variations, scenario is designed with conditions shown in Table 4-2 and system configuration in Figure 4-2. The voltage controlled emulator is controlled as a synchronous generator with power system stabilizer PSS (terminal voltage has transient with frequency fluctuations) and L9 controlled as ZIP load emulator. By manually inputting the mechanical power input for G3, the ac line frequency and voltage amplitude will change correspondingly. In the same time, ZIP load real and reactive power input commands are not changed.

Table 4-2 ZIP load parameters and test conditions case 2.

ZIP Load Model		Test Conditions	
Parameters	Values	Parameters	Values
p_1	0.2	V_{llrms}	208 V
p_2	0.2	V_{dc}	400 V
p_3	0.6	P_{base}	15 kVA
k_{pf}	1	f_{base}	60 Hz
q_1	0.2	P_0	0.6 pu
q_2	0.2	Q_0	-0.2 pu
q_3	0.6		
k_{qf}	-1		

As observed from Figure 4-4, the multi-time scale observations of the ZIP dynamics could be illustrated in the results. At $t = 2$ s, the mechanical power input for G3 is increased while at $t = 8.5$ s and 14 s, the mechanical power input for G3 is reduced separately. These changes induce transients in the L9 terminal voltage amplitude and frequency.

Figure 4-4 (a) shows the seconds-scale results obtained from the central visualized operation Labview data recorder, illustrating the power system dynamics slow-changing trend and overall power flow amplitude variations. The accurate correspondence between simulation and experimental results (bottom left and right) proves the successful emulation of the ZIP load. Figure 4-4 (b) presents the transients of load increase and decrease in micro-seconds time scale. Line to line voltage is in PWM shape due to no capacitor filtering

in the power circuit. Obvious changes in the current amplitude could be observed, corresponding to the power fluctuations shown in Figure 4-4 (a).

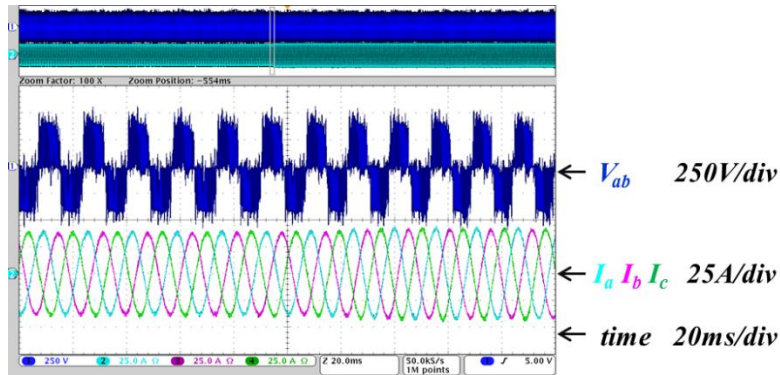
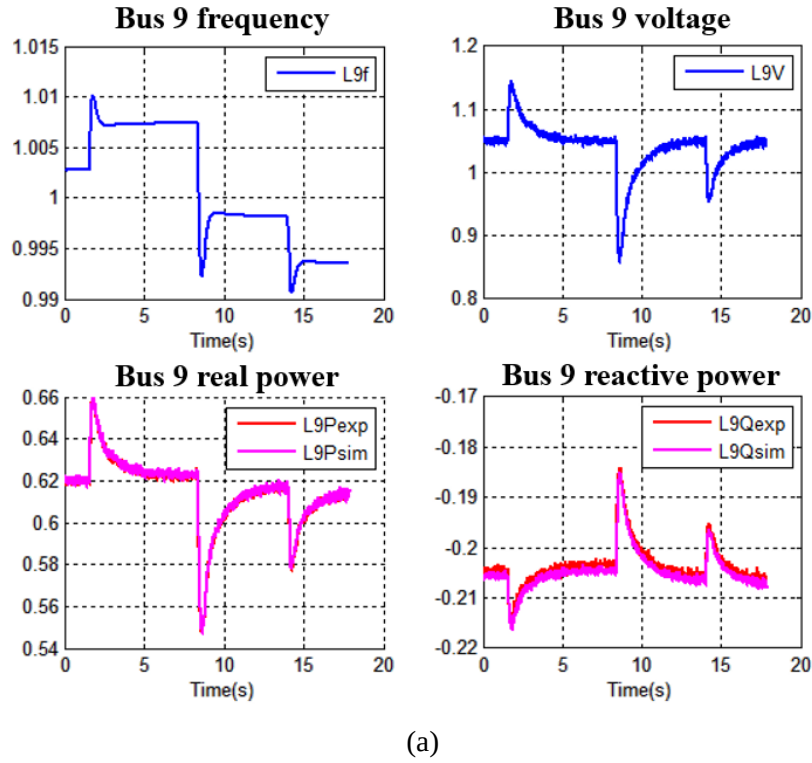


Figure 4-4 (a) Real and reactive power loading conditions variations case 2 record with Labview, (b) three-phase currents and line-line voltage experimental transients with oscilloscope.

4.3 Summary

Modeled with constant impedance, current and power model with voltage and frequency variation relationships, the static ZIP load emulator has been verified by comparing the actual power consumption with real and reactive power command.

The ZIP load emulator development in the power system emulation of hardware test-bed could enable reproducing various scenarios, providing static power flow testing environment for real-power based devices and algorithms.

CHAPTER 5

DYNAMIC LOAD EMULATOR

In order to provide power grid emulator with dynamic loading conditions in transient analysis, full stator dynamics detailed induction motor emulator has been developed in this chapter, with the control and structure of current controlled three-phase converter.

5.1 Dynamic Load Model

Induction motor was represented in power system load modeling with static models. However, more than 70% of industrial loads are powered by induction motors, and as such it is the major element contributing to the dynamics and transients for load variations [25].

With computer capabilities and numerical techniques nowadays, more accurate induction motor models including stator, rotor dynamics with inertias should be substituting the static ones to increase the credibility of power system simulation programs.

The high-current start-up process could induce visible grid voltage and frequency fluctuations, while on the other hand, rich dynamic behavior details could be observed under grid variations. An accurate load emulator representing its dynamic behavior is crucial to the system overall loading behavior estimation, especially during transient analysis.

5.1.1 Induction Motor Equations

The dynamic model for induction motor is used to obtain transient responses, small-signal equations, and a multitude of transfer functions, all of which are useful in the study of converter-fed induction motor drives [1].

The assumptions made in the derivation of the equations are that the core losses (eddy currents, hysteresis and saturation) are negligible. To simplify the simulation, parameters are assumed to have constant values for all conditions. Since only 3 wire balanced voltage system without a neutral return are considered, the zero axis quantities V_{0s} V_{0r} i_{0s} and i_{0r} could be omitted [112].

The induction motor voltage equations are often written in expanded form as (13)-(16). Combined with the flux linkages expressed as (17)-(20), the dynamic equivalent circuit for an induction machine is expressed in Figure 5-1.

$$v_{qs} = r_s i_{qs} + \omega \lambda_{ds} + p \lambda_{qs} \quad (13)$$

$$v_{ds} = r_s i_{ds} - \omega \lambda_{qs} + p \lambda_{ds} \quad (14)$$

$$v_{qr} = r_r i_{qr} + (\omega - \omega_r) \lambda_{dr} + p \lambda_{qr} \quad (15)$$

$$v_{dr} = r_r i_{dr} - (\omega - \omega_r) \lambda_{qr} + p \lambda_{dr} \quad (16)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_M (i_{qs} + i_{qr}) \quad (17)$$

$$\lambda_{ds} = L_{ls}i_{ds} + L_M (i_{ds} + i_{dr}) \quad (18)$$

$$\lambda_{qr} = L_{lr}i_{qr} + L_M (i_{qs} + i_{qr}) \quad (19)$$

$$\lambda_{dr} = L_{lr}i_{dr} + L_M (i_{ds} + i_{dr}) \quad (20)$$

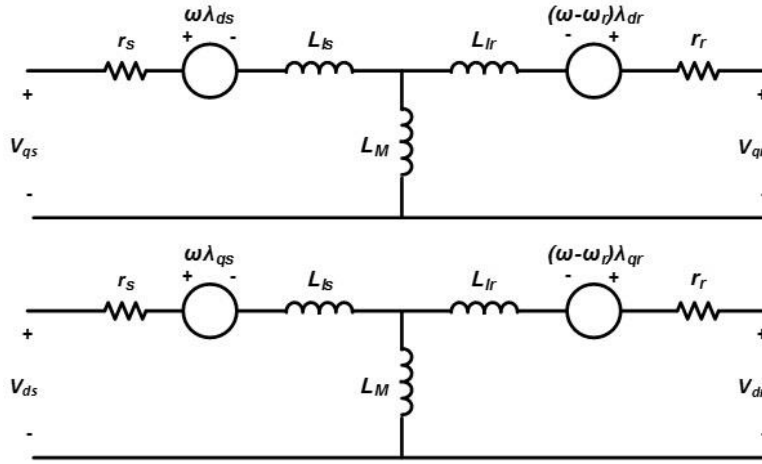


Figure 5-1 Dynamic dq equivalent circuit for induction motor (0 axis omitted) [58].

In the equations, v_{qs} and v_{ds} are the variables for stator terminal voltage in q and d axis; v_{qr} and v_{dr} are the variables for rotor terminal voltage in q and d axis (for squirrel cage induction motor, they are both 0); i_{qs} and i_{ds} are variables for stator current in q and d axis; i_{qr} and i_{dr} are variables for rotor current in q and d axis; λ_{qs} and λ_{ds} are variables for stator flux linkages in q and d axis; λ_{qr} and λ_{dr} are variables for rotor flux linkages in q and d axis; r_s and r_r are variables of stator and rotor resistance; ω is stator electrical angular frequency; ω_r is rotor rotation angular frequency; L_{lr} and L_{ls} are rotor and stator

leakage inductances; L_M is mutual inductance, p is the derivative symbol. For all rotor variables, they are already converted to stator side.

There are three ways of modeling induction motor in dq domain, depending on the reference frame rotation speed: stationary, rotor speed or synchronous speed [57].

In the vector controlled motor drive applications, variables of flux and torque are desired to be estimated and controlled during real-time calculation. By locating the d axis on rotor flux vector, the stator current vector could be directly decoupled as torque generating current portion on q axis, and flux generating current portion on d axis [57]. By controlling the stator current on q and d axis, the torque and flux could be controlled correspondingly with linear relationship during ordinary operating conditions.

However, in the application of motor emulator, instead of locating the dq axis on rotor flux vector, the modeling in the motor emulator directly uses the voltage electrical frequency and voltage angle from phase lock loop as the synchronous reference frame frequency.

The induction motor load emulator is modelled inside the digital controller in the current controlled power converter. The desired modeling relationship for the output is stator current references in dq domain.

Equations (13)-(20) could not provide a straightforward relationship between input stator voltage, electrical frequency and output stator current – flux and torque are the variables in the calculation process, they do not need to be visible for input or output

terminals. Desired relationships between input voltage, angles as well as the output current could be expressed by Figure 5-2.

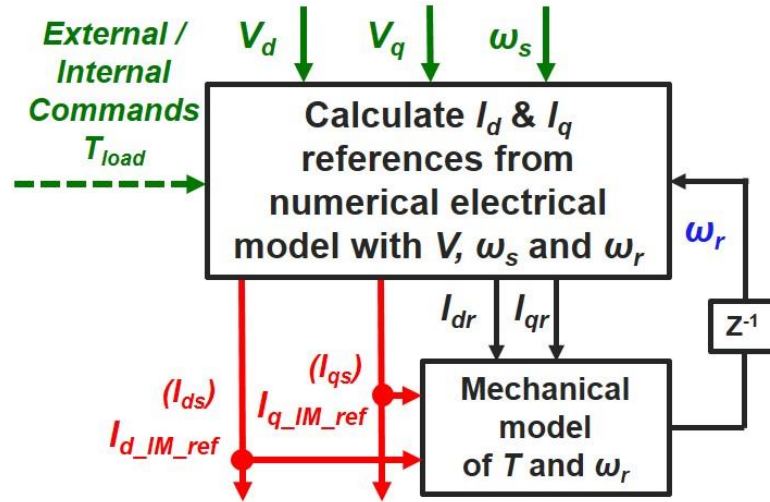


Figure 5-2 Emulated induction motor model inputs and outputs relationship in dq .

The induction motor per unit model established in dq domain as shown in (21)-(23), provides direct state space equation relationship between input voltage and electrical frequency and output current vector. The mathematical matrix equations for the model are described with relationships among voltage, current, torque, inertia and rotating speed. The real-time update of electromagnetic torque and rotor speed in the mechanical model are the mechanical part of the model, necessary in calculating accurate current references. In a nutshell, both electrical and mechanical variables are working together to determine the system's behavior.

$$\begin{bmatrix} v_{qs}^{pu} \\ v_{ds}^{pu} \\ v_{qr}^{pu} \\ v_{dr}^{pu} \end{bmatrix} = \begin{bmatrix} r_s^{pu} & \omega^{pu} \cdot X_{ss}^{pu} & 0 & \omega^{pu} \cdot X_M^{pu} \\ -\omega^{pu} \cdot X_{ss}^{pu} & r_s^{pu} & -\omega^{pu} \cdot X_M^{pu} & 0 \\ 0 & (\omega^{pu} - \omega_r^{pu}) \cdot X_M^{pu} & r_r^{pu} & (\omega - \omega_r) \cdot X_{rr} \\ -(\omega^{pu} - \omega_r^{pu}) \cdot X_M^{pu} & 0 & -(\omega - \omega_r) \cdot X_{rr} & r_r^{pu} \end{bmatrix} \cdot \begin{bmatrix} i_{qs}^{pu} \\ i_{ds}^{pu} \\ i_{qr}^{pu} \\ i_{dr}^{pu} \end{bmatrix} \quad (21)$$

$$+ \begin{bmatrix} X_{ss}^{pu} & 0 & X_M^{pu} & 0 \\ 0 & X_{ss}^{pu} & 0 & X_M^{pu} \\ X_M^{pu} & 0 & X_{rr}^{pu} & 0 \\ 0 & X_M^{pu} & 0 & X_{rr}^{pu} \end{bmatrix} \cdot \frac{1}{\omega_b} \cdot \frac{d}{dt} \begin{bmatrix} i_{qs}^{pu} \\ i_{ds}^{pu} \\ i_{qr}^{pu} \\ i_{dr}^{pu} \end{bmatrix}$$

$$T_{em}^{pu} = X_M^{pu} (i_{qs}^{pu} i_{dr}^{pu} - i_{ds}^{pu} i_{qr}^{pu}) \quad (22)$$

$$\omega_r^{pu} = \int_0^t \frac{T_{em}^{pu} - T_{Load}^{pu}}{2H} d\tau \quad (23)$$

In the model, the parameters with superscript of pu indicate that they are converted to per unit values, under base values equal to their ratings. In the equations, v_{qs}^{pu} and v_{ds}^{pu} are the variables for stator terminal voltage in q and d axis; v_{qr}^{pu} and v_{dr}^{pu} are the variables for rotor terminal voltage in q and d axis (for squirrel cage induction motor, they are both 0); i_{qs}^{pu} and i_{ds}^{pu} are variables for stator current in q and d axis; i_{qr}^{pu} and i_{dr}^{pu} are variables for rotor current in q and d axis; the r_s^{pu} and r_r^{pu} are variables of stator and rotor leakage resistance; ω^{pu} is stator electrical angular frequency; ω_r^{pu} is rotor rotation angular frequency; ω_b is base angular frequency; X_M is the mutual inductance, X_{ss}^{pu} and X_{rr}^{pu} are stator and rotor inductances, representing the sum of mutual and leakage inductances for stator and rotor; T_{em} is the electromagnetic torque generated by the induction motor; T_{load} is the load torque on the rotor; H is the inertia constant converted from rotor inertia J , which is determined by the rotor mass, shape, motor rated power and pole pair numbers. For all rotor variables, they are already converted to stator side.

5.1.2 Dynamic Model Simulation

The simulation results based on the motor model with parameters in Table 5-1 are shown in Figure 5-3. The motor model is started up with ideal voltage ($V_q = 1$, $V_d = 0$) and frequency ($\omega = 1$) input conditions, no motor drive adjustment and free acceleration without load ($T_{load} = 0$). The top left waveform shows the startup torque, while the top right one represents the rotor speed. The bottom pictures illustrate the d and q axis stator currents. The whole startup process takes around 4 s, which is determined by both the induction motor electrical parameters and also the mechanical inertia time constant.

Table 5-1 Induction motor model parameters under test.

Parameters	Values	Parameters	Values
X_m^{pu}	10.32 p.u.	ω_b	377
X_{ss}^{pu}	10.64 p.u.	H	0.13 s
X_{rr}^{pu}	10.60 p.u.	V_{qr}^{pu}	0
r_s^{pu}	0.02 p.u.	V_{dr}^{pu}	0
r_r^{pu}	0.018 p.u.	V_{ds}^{pu}	0
		V_{qs}^{pu}	1

As could be observed from the simulation results, the motor behavior from 0 – 1.5 s has the oscillation dynamics around 60 Hz. This period corresponds to the stator

dynamics. After the stator transients, the rotor starts to accelerate until eventually stabilized in steady state.

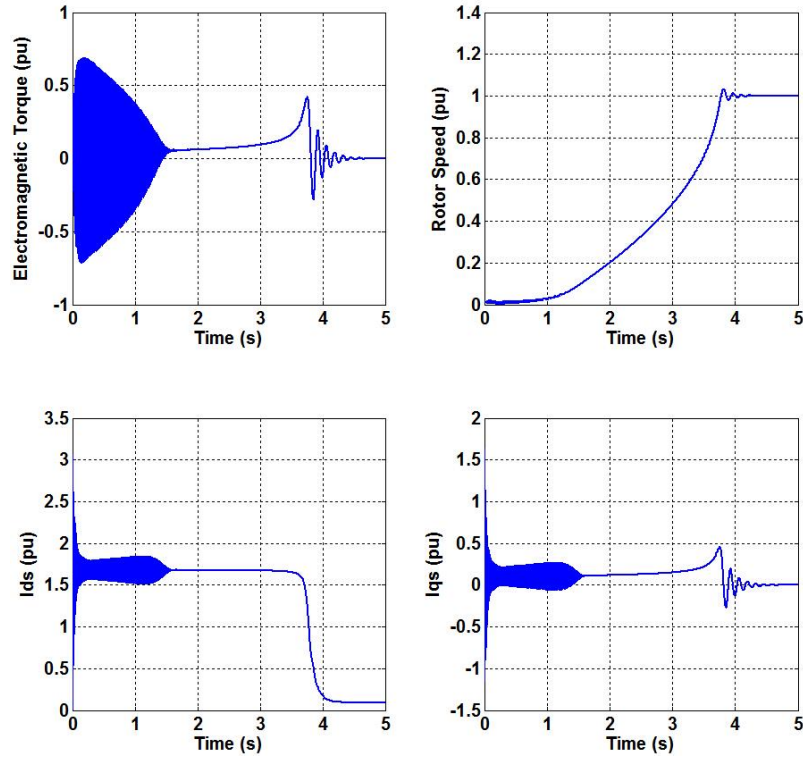


Figure 5-3 Induction motor model online free acceleration startup simulation results (in pu).

5.2 Experimental Behavior of Induction Motor Emulator

The tests in this section is done on the platform of load emulator paralleled with three-phase voltage controlled inverter (G3 without generator model) with 3.2 mH transmission line impedance in between, as illustrated in Figure 5-4. All the motor model calculation results are real-time recorded in DSP memory of L9 controller, and read after

tests. Besides the induction motor's parameters indicated in Table 5-1, Table 5-2 also includes the rest of parameters associated with the testing conditions.

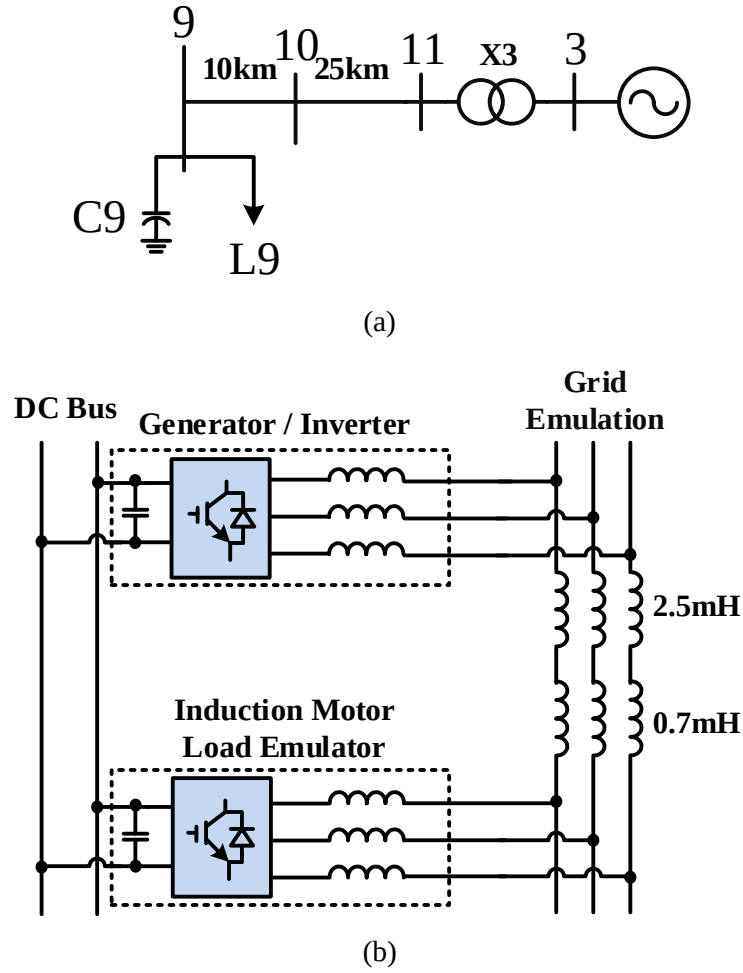


Figure 5-4 G3L9 induction motor emulator test: (a) grid scenario, (b) HTB energized structure.

Table 5-2 Three-phase induction motor load parameters and test conditions

Induction Motor Load Condition		Test Conditions	
Parameters	Values	Parameters	Values
T_{load}	0 @ 0-8 s 0.6 p.u. @ 8-10 s	V_{llrms}	208 V
		V_{dc}	400 V
		P_{IMbase}	2.55 kVA
		f_{base}	60 Hz

Due to the numerical performance requirements of solving the dynamic 4x4 differential equations in real time, higher order numerical method has been applied to guarantee the accuracy as well as the stability of the calculation results. Details about the numerical methods are discussed in CHAPTER 7, so it is not elaborated here. The numerical method applied for the induction motor model is Trapezoidal based predictor-corrector method with twice correction-PECECE. As stated in section 3.3.3, Matlab results are used as references to validate the performance of the emulator output. In the case of comparing with experimental data, the input for the real-time model during the experiment was recorded and given to the simulation in Matlab, the results obtained are used as simulation references.

As shown in Figure 5-5 (a), the top left part shows the comparison between dq currents calculated from simulation and experimental outputs while the top right one shows the comparison between simulation results and calculated electromagnetic torque and rotor speed (in per unit) recorded in the DSP memory. The bottom left and right waveforms

present the voltage and frequency inputs (in real value) for the induction motor model during the experiment. The load for the induction motor is a constant torque load: $T_{load} = 0$ for $t < 8$ s, and a transient happens at $t = 8$ s, where the T_{load} has a step change to 0.6 pu. Details about tracking accuracy about the current waveforms during dynamics could be referred to by Figure 3-7.

Induction motor emulator startup current waveforms in abc domain are observed from Figure 5-5 (b), with the transients zoom-in pictures on the top of the oscilloscope watch window showing multiple time-scale observations of the emulator behavior: for $t < 2$ s, the emulator reaches steady state, behaving as constant current load of 5 A, while $t > 2$ s, the induction motor model starts acceleration and changes loading conditions.

The real-time calculated results exhibit high accuracy and robustness after repetitive tests of the whole startup process and the sudden jump of constant torque load. The stable and robust model references calculation and tracking performances in dq and abc domain of the load emulator are illustrated in Figure 5-5 with the smooth transients and close alignment between the references and the experimental outputs.

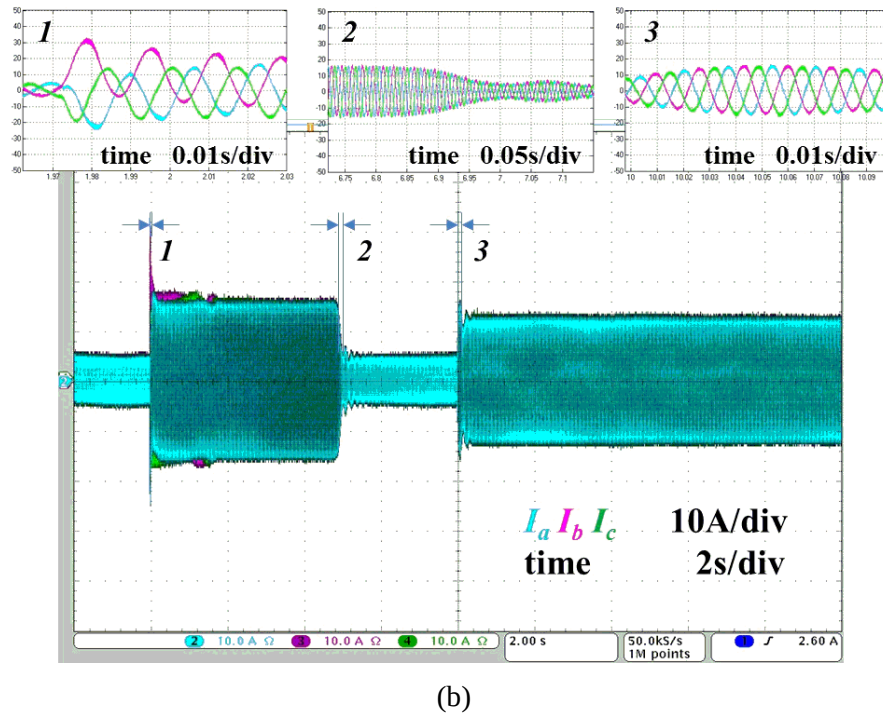
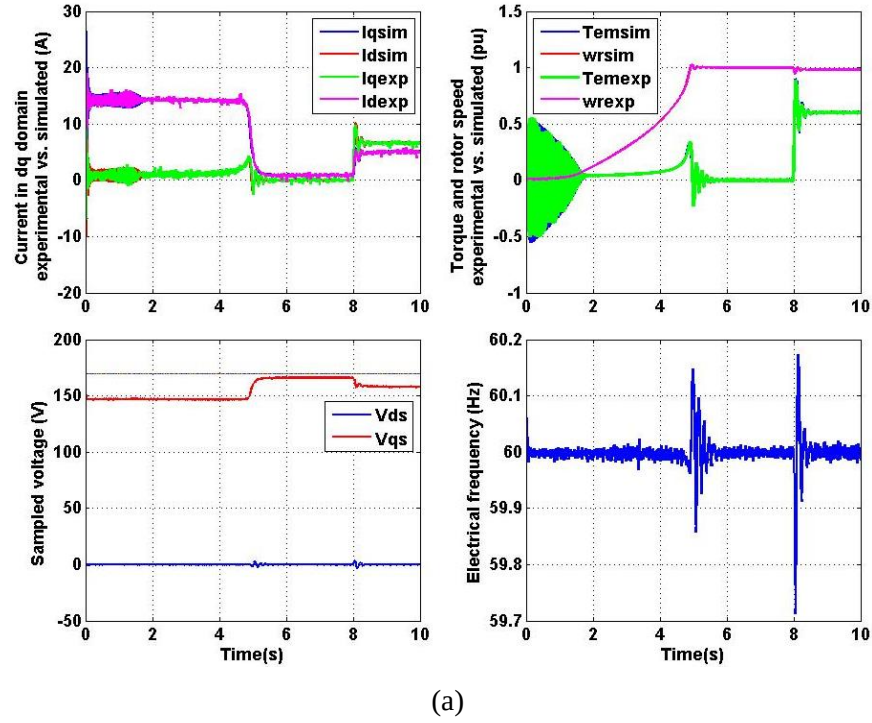


Figure 5-5 Induction motor startup process experimental results with PECECE:
(a) DSP recorded experimental results in dq with simulation, (b) oscilloscope results.
(with constant current reference of 5 A before motor emulator starts).

5.3 Composite Load Represented PQ Bus

The design aim for the load emulator in HTB is to represent the composite load in a power system area, including the static as well as the dynamic types. The load bus is usually referred to as PQ bus in power system studies.

According to Western Electricity Coordinating Council (WECC) power system load modeling approach, static and dynamic models are major components mapping to different end-use load consumptions [110]. The system composite load model could reflect the seasonal change and area substation load class (agricultural, commercial, industrial or residential) by adjusting the percentages between and within static and dynamic load models [110].

5.3.1 Emulator Implementation in HTB

The application design aim is to implement multiple induction motor models as well as static model in real-time inside one composite load emulator.

A composite load model has been designed, consisting of a ZIP static load model, a three-phase large motor, and a three-phase small motor with structure shown in Figure 5-6, to represent the dynamic and static load performance using a single load emulator converter. Similarly, in order to test the load bus power flow, test circuit structure shown in Figure 5-4 is used. The implementation of real-time composite load model is illustrated as Figure 5-7. ZIP and motor models are implementation with same input information and in sequence.

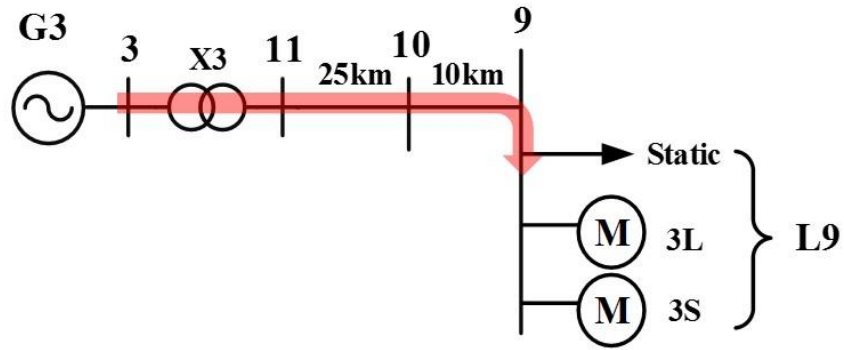


Figure 5-6 Composite load model structure.

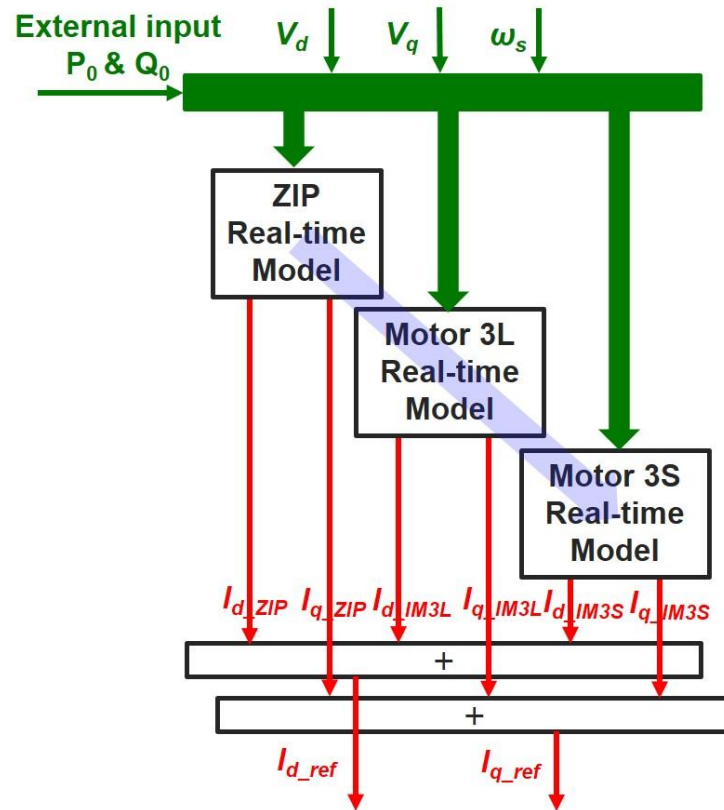


Figure 5-7 Real-time composite load model implementation.

The composition of each portion of the load model is indicated in Table 5-3. The ZIP load model is modeled to behave as constant power and constant current load, while the motor 3L is assumed to be loaded with 0.9 pu speed-square-related torque in Table 5-4 and Table 5-5, steady state and motor 3S with 0.5 pu speed-square-related torque in steady state (fan or pump type of load). The load expressions for torque for 3L and 3S are expressed as shown in, as well as the other parameters for large induction motor 3L and small induction motor 3S. The data of motor 3S and 3L, and ZIP model is based on PSS/E simulation profile dynamic composite load P-Q bus.

Table 5-3 Percentage of composite load components in real and reactive power (in pu).

	ZIP		Three-phase large motor 3L			Three-phase large motor 3S		
	Constant Power	Constant Current	Power	Capacity	Loading factor	Power	Capacity	Loading factor
P	33.8%	23.9%	15.7%	15.7%/0.9	0.9	26.6%	26.6%/0.5	0.5
Q	33.8%	23.9%	Q3L			Q3S		

Table 5-4 Three-phase large induction motor model 3L parameters (in pu).

p	2	X_{m3L}^{pu}	3
r_{s3L}^{pu}	0.014	X_{ls3L}^{pu}	0.083
r_{r3L}^{pu}	0.01165	X_{lr3L}^{pu}	0.1077
H_{3L}	1	X_{ss3L}^{pu}	3.083
T_{L-3L}^{pu}	$0.9*(\omega_r^{pu})^2$	X_{rr3L}^{pu}	3.1077

Table 5-5 Three-phase small induction motor model 3S parameters (in pu).

p	2	X_{m3S}^{pu}	2.4
r_{s3S}^{pu}	0.037	X_{ls3S}^{pu}	0.3626
r_{r3S}^{pu}	0.0488	X_{lr3S}^{pu}	0.132
H_{3S}	0.6	X_{ss3S}^{pu}	2.7626
T_{L-3S}^{pu}	$0.5*(\omega_r^{pu})^2$	X_{rr3S}^{pu}	2.532

All three components are started at the same time. The real-time experimental electromagnetic torque and rotor speed calculation transients in DSP record are shown in Figure 5-8.

The induction motors were starting with the fan/pump type load until reaching steady state. As could be told from Figure 5-9, the L9 terminal voltage has a period from 0 – 11 s of voltage sag, down to 0.8 p.u., due to motors starting up. While during the same time, the real and reactive power on L9 bus are having transients due to the induction motor 3L and 3S starting up process. Real power consumption on L9 are increasing due to acceleration of the rotor with mechanical load. Reactive power on L9 are returning back to ZIP steady state value after the motor establishing the magnetic field in the starting up transient.

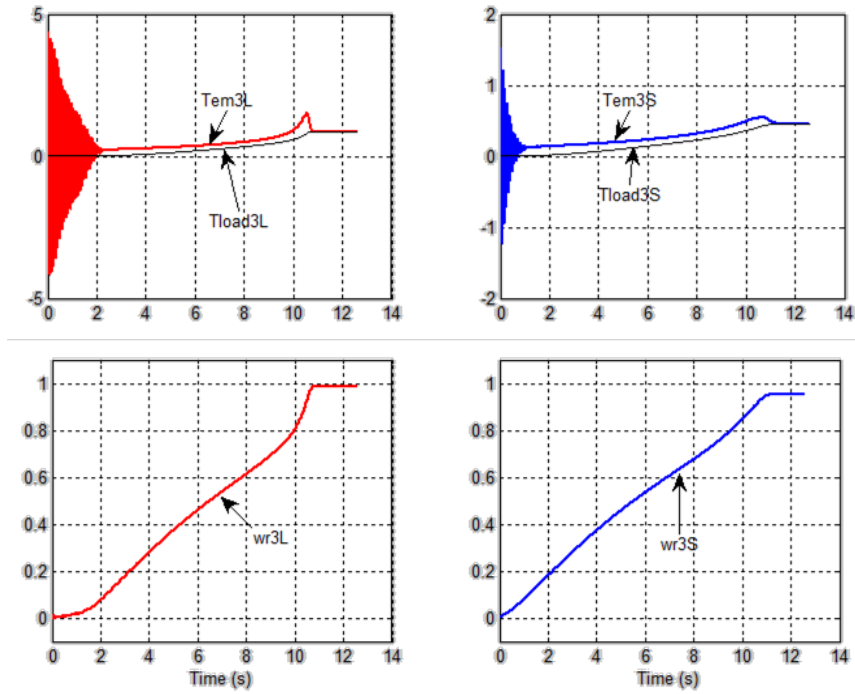


Figure 5-8 Experimental DSP record of three-phase induction motor 3L and 3S startup transients loaded with torque load of 0.9 pu and 0.5 p.u in steady state.

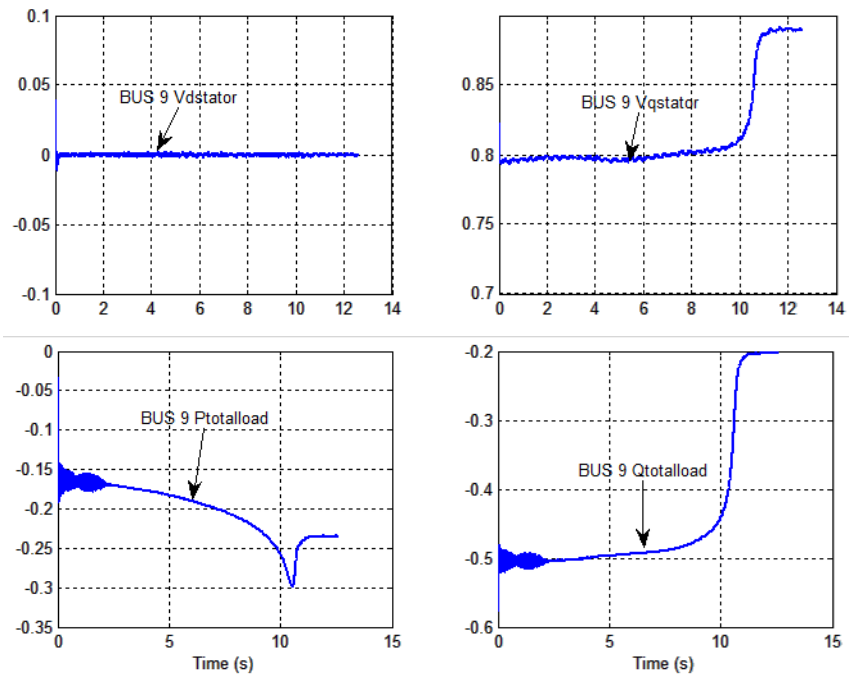


Figure 5-9 Experimental Bus L9 terminal voltage & real power P and reactive power Q recorded in DSP.

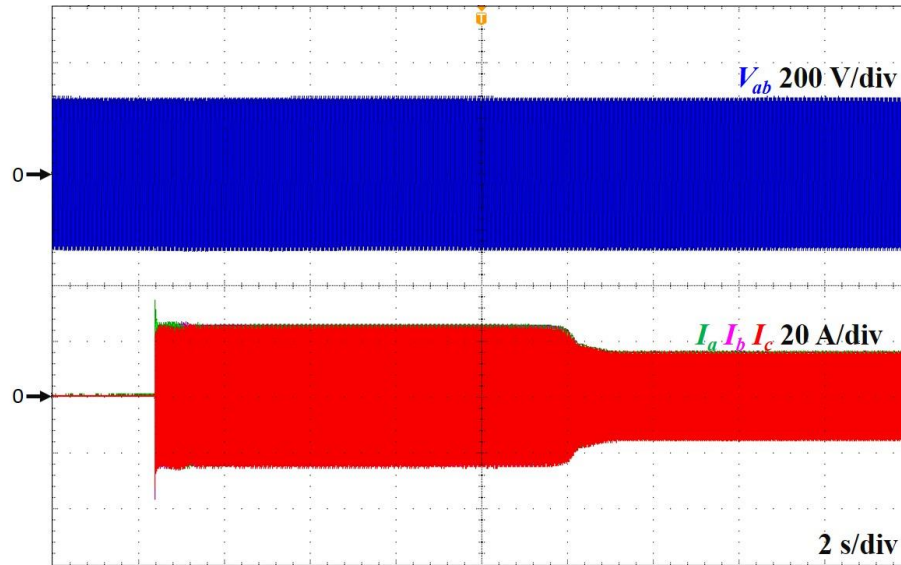


Figure 5-10 L9 bus voltage and current waveform for composite power load in abc domain.

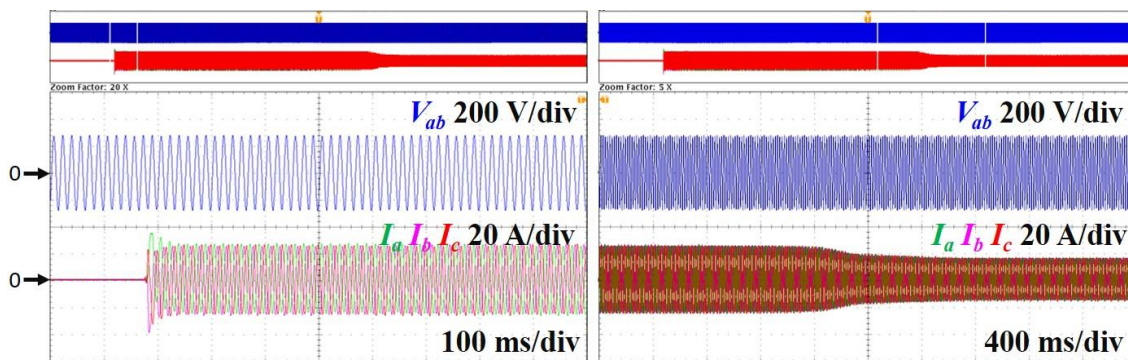


Figure 5-11 Details of L9 bus voltage and current waveform for composite power load in abc domain.

5.3.2 Other Factors in Power System Load Performance

Heavily loaded transmission lines during low voltage conditions may trigger protective relays (depending on individual threshold settings and load compositions). After fault clearing with transmission outages, transient of motors loads starting up

simultaneously will draw very high current. This phenomenon will slow down the voltage recovery process [22].

The scenario shown in the above section 5.3.1, demonstrates the substantial voltage sag for the duration of motor starting transients. As could be observed from Figure 5-9 and Figure 5-10, bus voltage amplitude has a temporary sag for 11 seconds during the two major induction motor loads starting up synchronously.

A typical post-fault transient voltage recovery phenomenon was introduced in [23], demonstrating typical Fault Induced Delayed Voltage Recovery (FIDVR) during which the system voltage remains at significantly reduced levels for several seconds after a transmission, sub-transmission, or distribution fault has been cleared [23]. The phenomenon is illustrated in Figure 5-12. Different from the scenario demonstrated from above section 5.3.1, the cause of the post-fault voltage recovery scenario from the system point of view, has taken into account the different layers of protections and reactive compensator control.

The transients in Figure 5-12 could be divided into: ① fault and clearing fault, ② stalled AC motors due to low-voltage, then tripped by thermal overload protection, ③ voltage overshoot during enabling load tap changer (LTC) or reactive power compensation, ④ voltage dropping during disabling LTC or reactive power compensation, ⑤ voltage falling into standard range, load getting connected back.

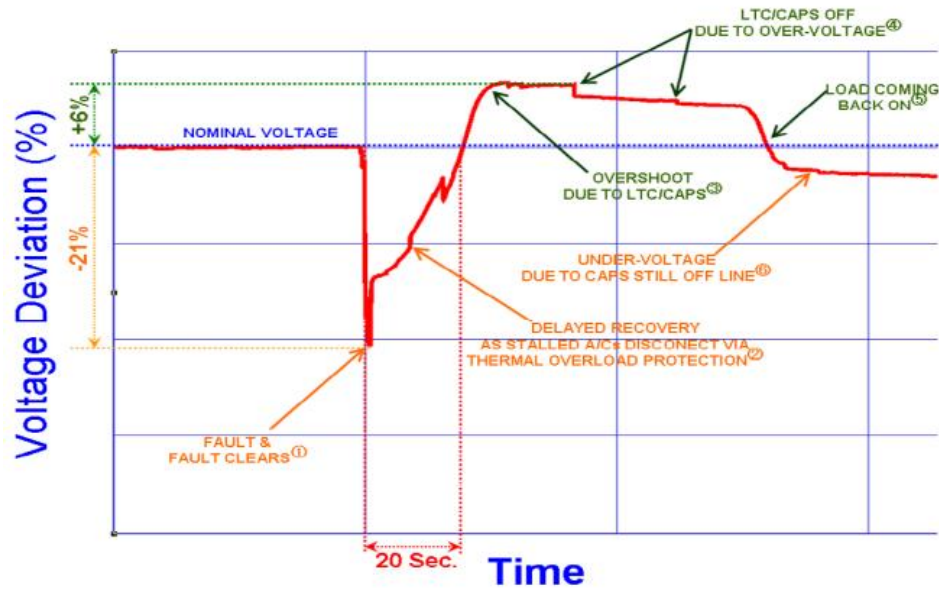


Figure 5-12 Post-fault transient voltage characteristics [23].

5.4 Summary

Modeled with static and rotor dynamics, the induction motor emulator has been developed and implemented as the dynamic loading condition in the HTB.

By combining multiple induction motor models and ZIP model, composite load emulator has been developed, representing the PQ bus with static and dynamic characteristics.

During the actual power system voltage transients, the voltage recovery scenario is not only dominated by the load composition and models, but also the relay protection settings and distribution/transmission load control algorithms.

CHAPTER 6

INDUCTION MOTOR EMULATOR VALIDATION

The work in this chapter is optimizing and validating the proposed induction motor emulator with saturation models intending for more accurate behavior estimation of grid interaction with strong system load startup dynamics.

6.1 Electrical Behavior Validation

In order to validate how well the power output from the emulator is actually representing the modeled induction motor, output from real physical motor is used as experiment reference in this chapter.

The motor object under test is a three-phase 3 hp induction motor, with the photo as shown in Figure 6-1. The details about the power rating, type as well as the voltage and current ratings, are shown in Table 6-1.



Figure 6-1 Photograph of three-phase 3 hp induction motor under test.

Table 6-1 Startup tested 3 hp induction motor nameplate parameters.

Power	3 hp	Synchronous Speed	1800 rpm
Model No.	B0034FLF2AM Toshiba	Full Load Speed	1730 rpm
Voltage	230/460 V	NEMA Design	NEMA B
Frequency	60 Hz	Full Load Current	8.4/4.2 A
Pole Pairs	2	Service Factor	1.15

6.1.1 Motor Characterization

In order to compare the electric performance of the induction motor and the emulator with reasonable data, equivalent magnetizing, leakage inductances as well as the leakage resistances for stator and rotor are needed for the emulation. All these parameters are obtained through standard three-phase motor characterization procedure [133].

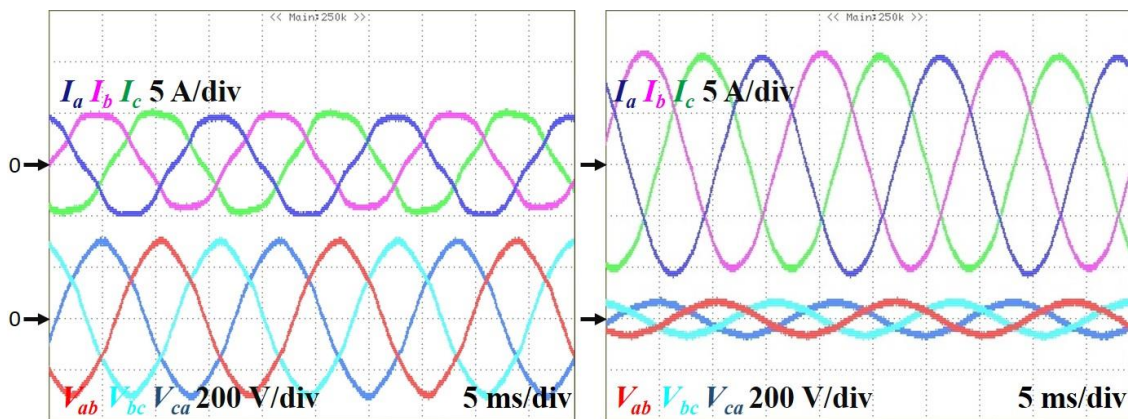


Figure 6-2 Three-phase induction motor characterization open and short circuit waveforms.

During the open circuit test, the motor terminal voltage is kept at rated voltage and the current is no-load current, representing the magnetizing current for the motor. In the short circuit test, the motor terminal voltage is gradually adjusted higher until the three-phase current reaching rated current, representing the leakage branch in the induction motor. The whole process is completed fast, to keep the temperature of the motor windings from increasing too much which will lead to the variations on the leakage resistances. The calculated parameters for the motor, including the base values and testing condition are shown in the Table 6-2.

Table 6-2 Motor under test characterized parameters around rated conditions.

Induction Motor Characterization Parameters			
Parameters	Values	Parameters	Values
V_{grid}	208 V	r_s	0.8466 Ω
V_b	187.8 V	r_r	0.75 Ω
I_b	11.88 A	X_m	31.96 Ω
ω_b	377 rad/s	X_{ls}	1.205 Ω
Z_{base}	15.81 Ω	X_{lr}	1.81 Ω
p	2	H	0.09 s

6.1.2 Test Results Comparison

As presented in the previous chapter, induction motor emulator was implemented with ideal model and current controlled three-phase emulator. The constant parameter based induction motor model is highly representative in current performance under rated frequency and around rated steady state operating conditions. But comparison between current outputs from the ideal model vs. the physical motor reveal non-ideal characteristics of the inductances while predicting motor's behavior during overcurrent conditions with strong transient dynamics, such as online startups.

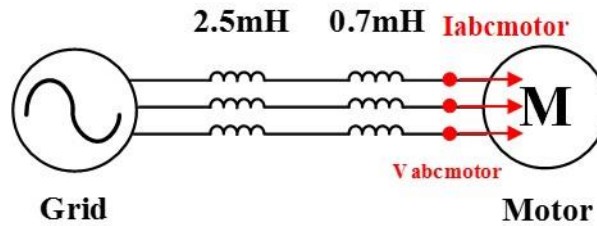


Figure 6-3 Test structure of motor online startup with long impedance connected with grid.

As shown in Figure 6-3, the testing conditions are setup the same for a 3 hp three-phase induction motor is connecting with grid through long transmission line represented by 3.2mH inductances. The setup of motor online startup is to match the HTB experiment scenario mentioned in section. During the startup process, $V_{abcmotor}$ and $I_{abcmotor}$ (as indicated in Figure 6-3) were recorded as input and output references for the induction motor model to compare with.

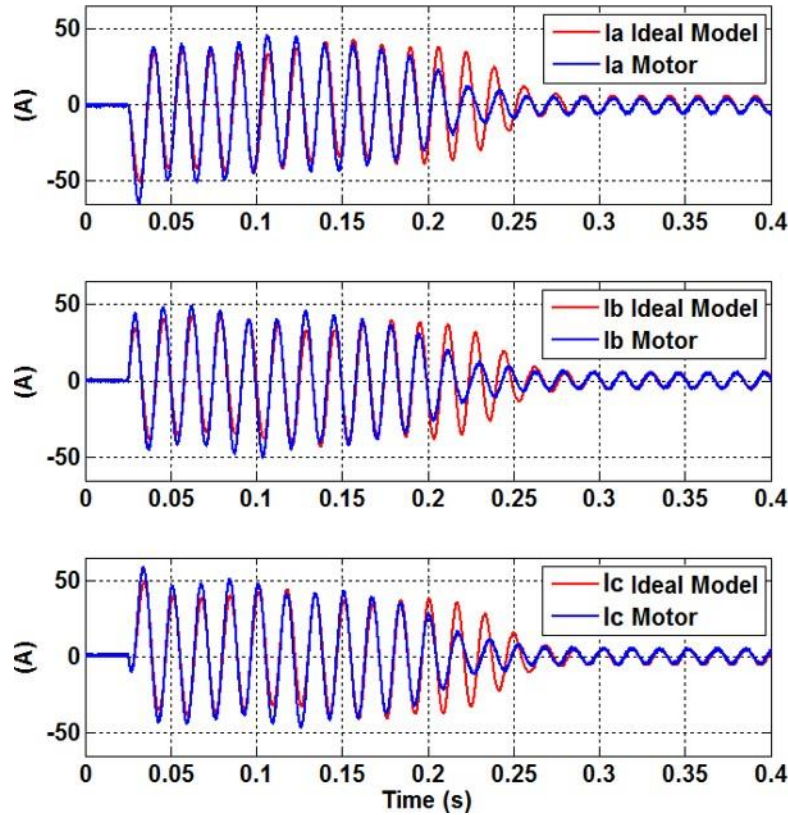


Figure 6-4 Comparison between online startup results with constant parameter based motor model and 3 hp motor.

However, the comparison result between motor and ideal-model based simulation as shown in Figure 6-4, presents that although with the same voltage inputs, neither the current amplitudes nor the startup dynamics time duration match. Nevertheless, the steady state *abc* currents after startup transient match very well in terms of fundamental frequency amplitude and phase angle, which indicates the steady state parameters for the motor is accurate.

6.2 Saturation Characteristics of Induction Motor Model

During normal steady state rated operations, the magnetic paths in stator, air and rotor work under rated conditions, of which the stator, rotor leakage and magnetizing inductances could be considered constant.

However, during strong electrical (magnetic) transients such as direct line start or fault conditions, flux saturations (iron as well as air related) as important factors cause unexpected behaviors other than the ones predicted by the ideal model [134]. The analysis for scenarios of intense induction motor online startup disturbance impact on the grid, will be under doubt if the emulator is modeled without the saturation.

The electrical-magnetic parameters of an induction machine can vary widely during starting. The high inrush currents that flow through the stator and induced in the rotor during this strong transient could result in the iron material dependent portion to saturate [134]. As a result, the parameters of the induction machine model that are generally obtained through routine open and short circuit tests as constants, should be modeled as functionally dependent on the currents.

The inaccuracies of the classic induction motor model in dq domain have been noted first during simulation of induction motor model. Specifically aiming at solving starting up problems, leakage saturation modeling was investigated from aspects of spatial structure and iron/air dependent parameters of induction motor, and leakage fluxes are represented as functions of saturation factor [134].

However, later with the development of motor drive technologies, the optimization focus of motor model shifted to compensating dq model's shortcoming of not representable for current and torque ripples near switching frequency. Solutions for modeling magnetizing, leakage saturation and distributed circuit in the rotor are addressed by representing inductances with polynomials as functions of flux [136], or finite element analyzed motor represented model for including the effects of spatial and winding configurations [137].

In the implementation of HTB induction motor emulator, fundamental frequency current performance is the criterion of validating the electrical behavior. However, in the absence of detailed design information of the motor, the saturation functions related with current and reactance are hard to quantify with too much details – different motors have their own parameters or even design 'tricks' in terms of structure and operating conditions. The most direct and straightforward way is by means of open circuit and locked rotor tests with voltage variations and record current values [133].

The assumptions for adding saturation effects in the emulator motor model could be summarized as:

1. Magnetizing reactance X_m as well as the leakage reactance on the stator X_{ls} and rotor X_{lr} are represented as functions of magnetizing I_m , stator I_s and rotor I_r currents.
2. Following the NEMA B design criterion [133], the stator leakage inductance X_{ls} is assumed to be 2/3 that of rotor leakage inductance X_{lr} in the equivalent circuit

modeling. And it is assumed in this saturation model to be the same under saturated conditions.

3. Resistances r_s and r_r of the motor windings are considered constant – the motor is considered ventilated and under constant temperature.
4. The three-phase input voltage is symmetrical and balanced. Only the fundamental frequency 60 Hz contents are considered. Higher frequency impacts on the reactance are not modeled.

6.2.1 Saturation of X_m

The magnetizing inductance saturation test is performed by running the machine as a motor at rated voltage and rated frequency 60 Hz with no connection to load. Open circuit voltage ranges from 150% of rated voltage down to when further voltage reduction increases the current [133].

The whole test has been done fast. During the test, the rotor speed is running at nearly synchronous speed. While analyzing the open-circuit test data, since the leakage reactance and resistors of stator and rotor circuit are less than 1/10 that of magnetizing reactance, it is not considered in the magnetizing reactance calculation.

The test circuit schematic is in Figure 6-5, Motor three-phase terminals are connected with auto-transformer for higher voltage variation range. The open circuit test voltage has the variation range from 316 V (152%) till 37 V (18%). The recorded data as well as the curve fitted characteristics of magnetizing reactance X_M vs. magnetizing current I_m are shown in Figure 6-6.

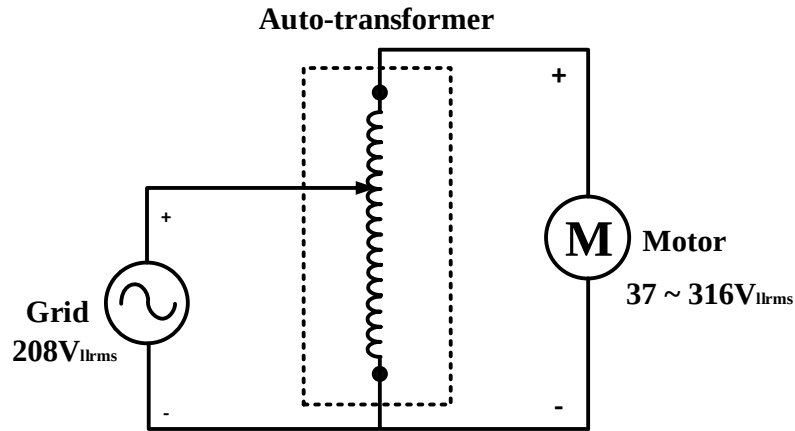


Figure 6-5 Circuit schematic of motor open circuit magnetizing saturation test.

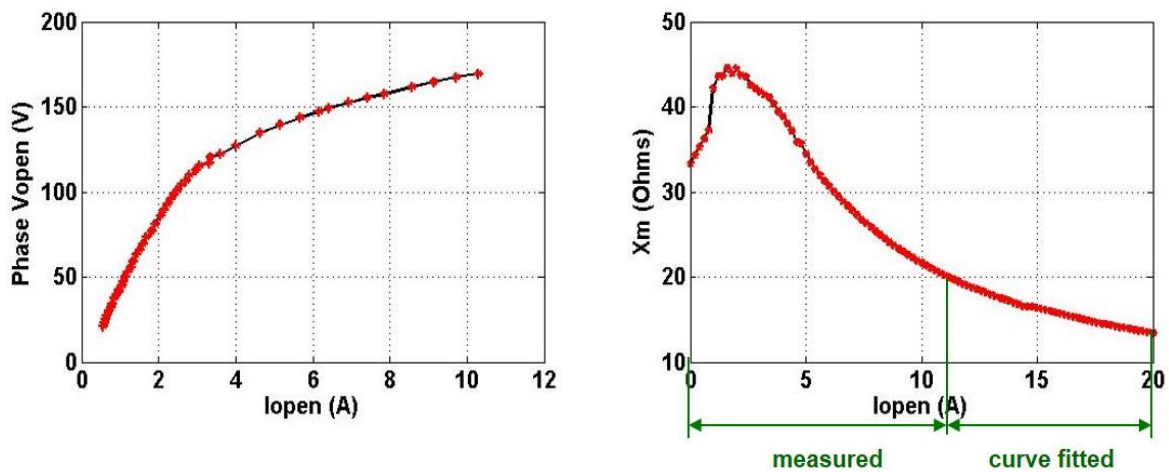


Figure 6-6 Motor magnetizing inductance measurement and curve fitted values.

6.2.2 Saturation of Xls and Xlr

At the moment when motor terminals are connecting to the constant voltage source, the equivalent model for induction motor could be viewed as blocked-rotor case. The high current inrush (5-7 times rated currents) into the stator will induce the stator and rotor

leakage inductance to fully saturate. Under this condition, the values for stator and rotor leakage reactance play very important role in terms of modeling of motor's behavior.

The 3 hp motor under test is squirrel cage induction motor, which has symmetrical bar windings – impedance of the motor is the same for any rotor positions relative to the stator [133]. During the blocked rotor test, the rotor is completely blocked without any movement. The terminal voltage is decreased from 75 V until 10 V to keep the temperature during test stabilized. Stator current reading is recorded.

The highest current value in the blocked rotor test is 13.5 A (150% rated current) in configuration of Figure 6-7. Test results are shown in Figure 6-8, with curve fitting estimated values for higher current corresponded impedances.

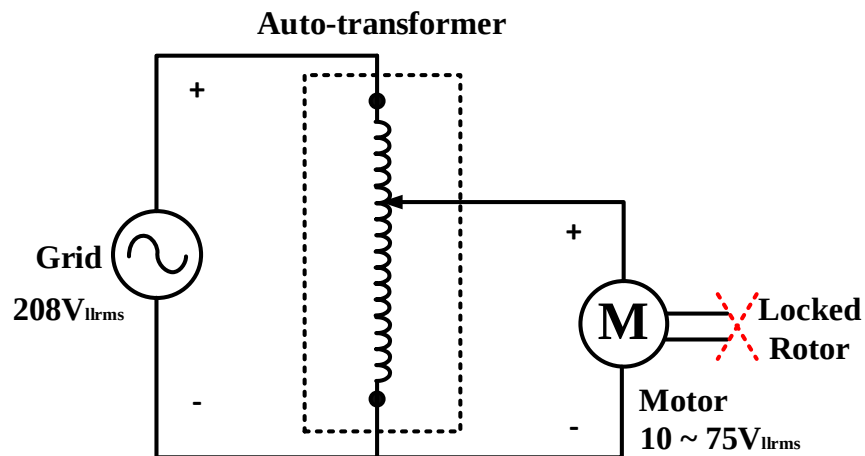


Figure 6-7 Circuit schematic of motor locked rotor leakage saturation test.

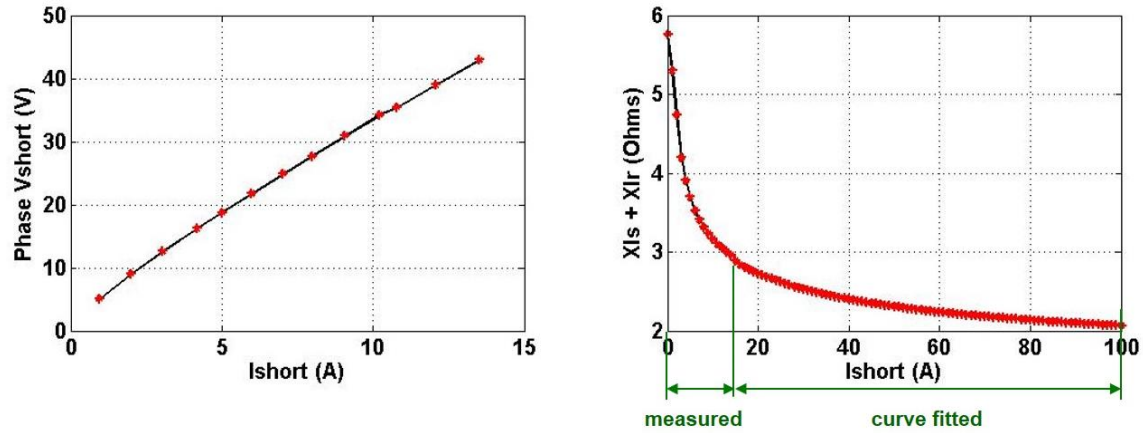


Figure 6-8 Motor leakage inductance measurement and curve fitted values.

6.3 Motor Behavior vs. Simulation

While implementing the saturation model in the induction motor model, it is assumed uniformly distributed stator and rotor windings as well as no higher frequency responses other than fundamental frequency.

The magnetizing reactance X_m is programmed to be function of magnetizing current I_m , while stator leakage reactance X_{ls} being function of stator current amplitude I_s and rotor leakage reactance X_{lr} being function of rotor current amplitude I_r . They are updated during each calculation iteration adapting to new current level calculated.

$$I_s = \sqrt{I_{ds}^2 + I_{qs}^2} \quad (24)$$

$$I_r = \sqrt{I_{dr}^2 + I_{qr}^2} \quad (25)$$

$$I_m = \sqrt{(I_{ds} + I_{dr})^2 + (I_{qs} + I_{qr})^2} \quad (26)$$

In order to verify the induction motor model, motor online startup test results were compared with the motor model-based simulation results with the motor three-phase terminal voltage $V_{abcmotor}$ record. Figure 6-10 shows the detailed startup currents in different time intervals, as zoomed in detailed transients from Figure 6-9.

Figure 6-11 shows the saturated leakage and magnetizing reactance with the ‘tested’ constant values for rated conditions, during strong dynamics of stator, rotor and magnetizing current inrush in startup. As can be seen from the comparison, when the rotor and stator current are higher than rated conditions, the leakage inductances are saturated and much less than the constant steady state values, while the magnetizing branch is gradually catching the current flow and magnetizing inductance varies and eventually goes to constant steady state values.

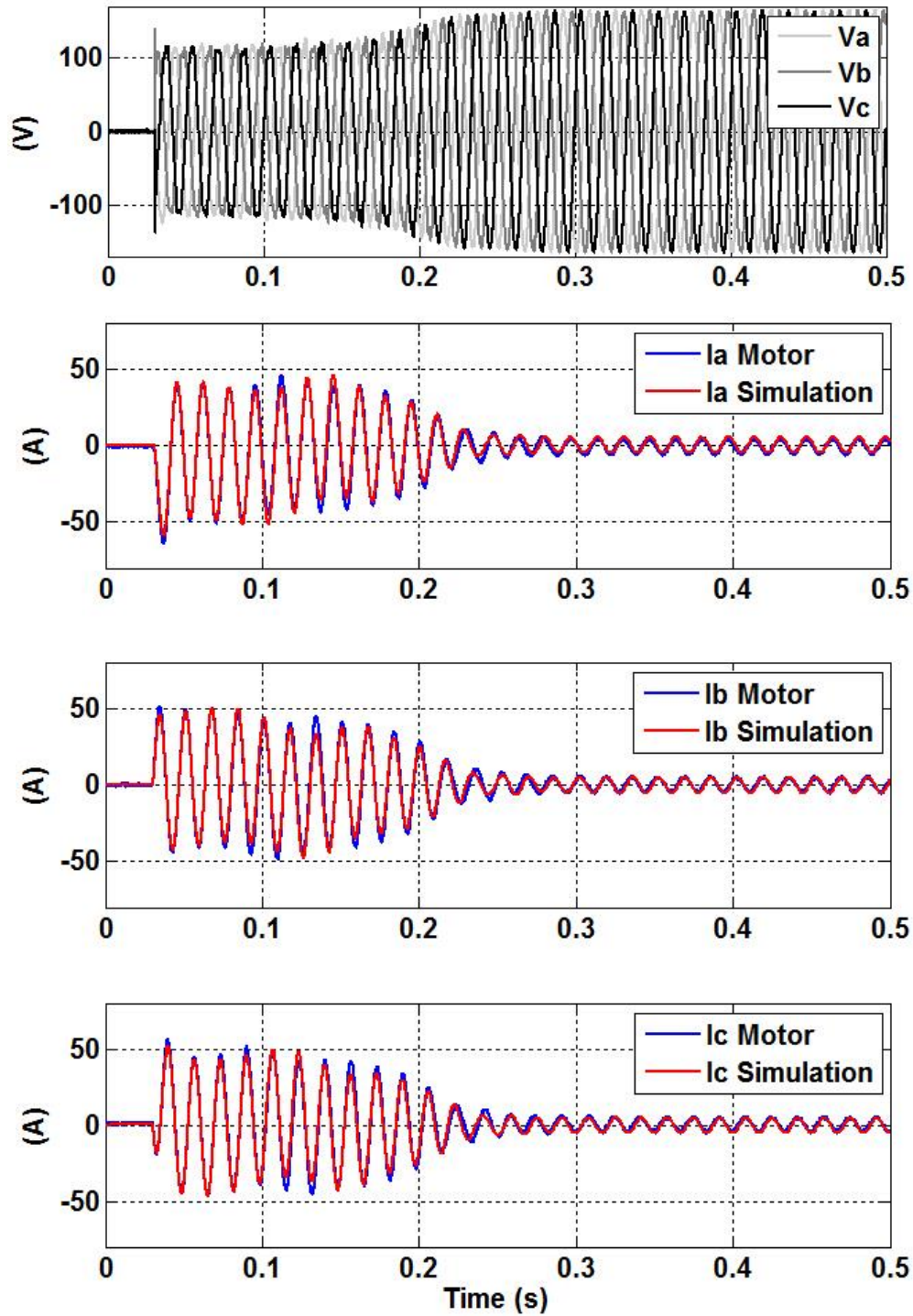


Figure 6-9 Startup voltage V_{abc} and current I_{abc} comparison between motor and simulation with saturation model.

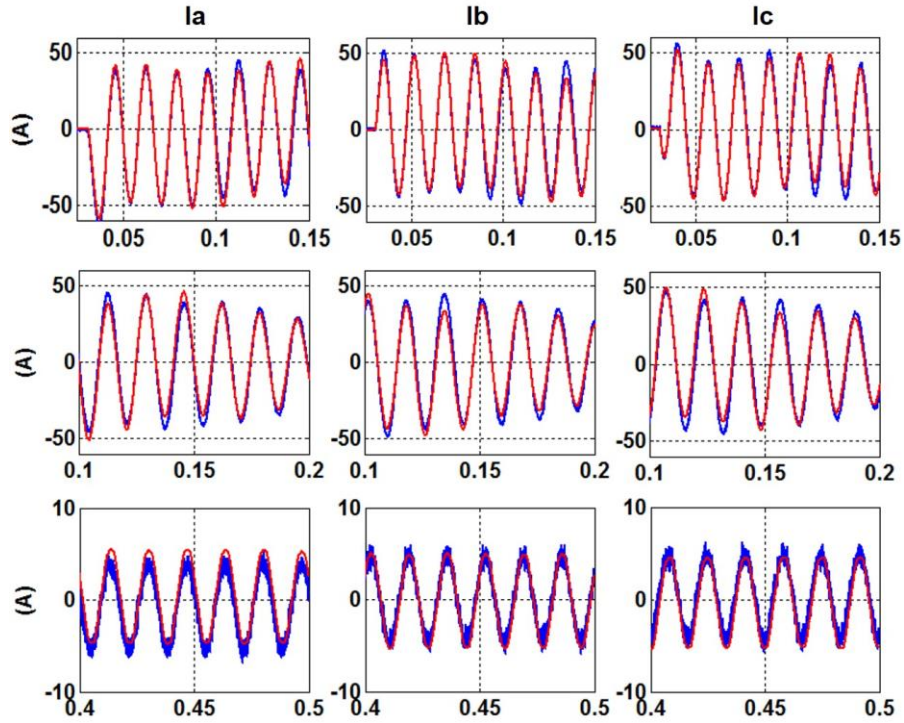


Figure 6-10 Detailed current I_{abc} comparison from transients from Figure 6-9.

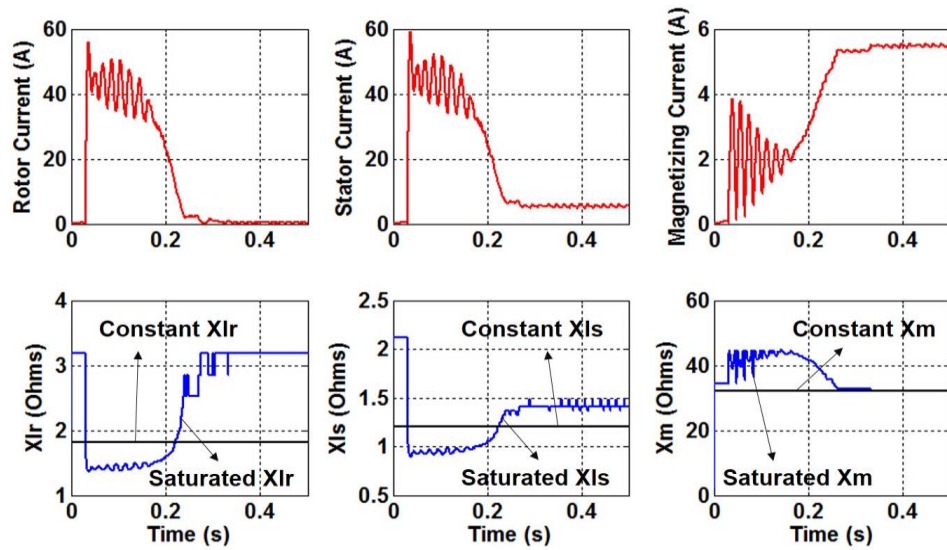


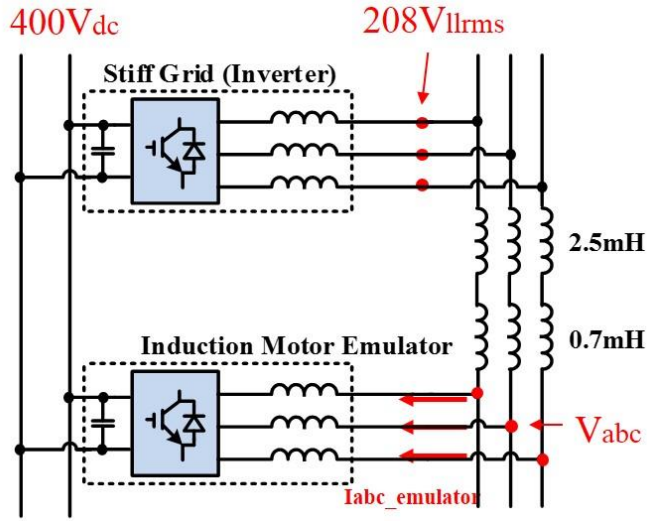
Figure 6-11 Stator, rotor and magnetizing current amplitudes and corresponding leakage & magnetizing reactance during online startup transient.

The differences between steady state and saturated values of the motor reactance could reach as high as 80%. They are the major source for unmatched behavior between the load emulator and motor waveform. Especially, variations of the leakage inductance values are dominating the over-current phenomenon during startup, because the equivalent motor start-up circuit is almost short-circuited with the leakage reactance – any small differences between physical motor and the model will cause obvious difference between the current behaviors.

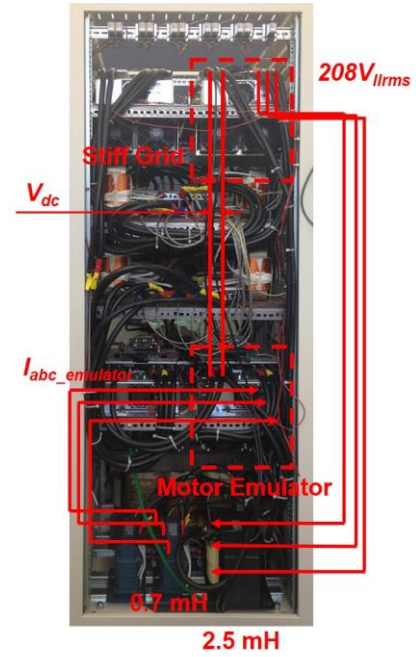
6.4 Experimental Validation of Motor Emulator

After validating the induction motor model, the emulator is implemented with induction motor saturation model. The motor and corresponding induction motor emulator test schematics are shown as Figure 6-12. The generator emulator three-phase terminals are controlled as inverter (208 V line to line rms, 60 Hz) to represent stiff grid, whose frequency and voltage amplitude does not change with load.

In order for a fair comparison for current behavior performance between motor and emulator, the starting phase angle of emulator is controlled and monitored by PLL to match that of the motor terminals. The voltage comparison of input for physical motor and motor emulator in *abc* domain is shown as Figure 6-13.



(a)



(b)

Figure 6-12 (a) Induction motor emulator test circuit,
(b) induction motor emulator test schematic in HTB picture.

Starting up current comparison from the emulator with the 3 hp motor is presented in Figure 6-14 with overall, detailed dynamics and steady state three-phase current. The fundamental frequency contents of 3 hp motor and emulator currents are matched in terms of amplitude and phase angles. Compared with the results obtained in Figure 6-4, the induction motor saturation model is accounted for the major differences in fundamental frequency current amplitude as well as the startup transient time duration.

During test, the dq domain readings including stator and rotor dq current as well as dq voltage and electrical frequency, electromagnetic torque and rotor speed are recorded

in the physical memory of DSP. Validation of whether the induction motor model with variable saturated reactance is numerically calculated with accuracy within digital controller is done by comparing DSP records with Matlab references (Figure 6-15). The startup stator and rotor currents in dq domain is calculated with simulation software Matlab platform with higher order solver and better calculation capability, under the same input conditions as emulator experiment. As could be visually observed from Figure 6-15, I_{dqs} from dsp are matching those from Matlab simulations, in terms of amplitude and time duration.

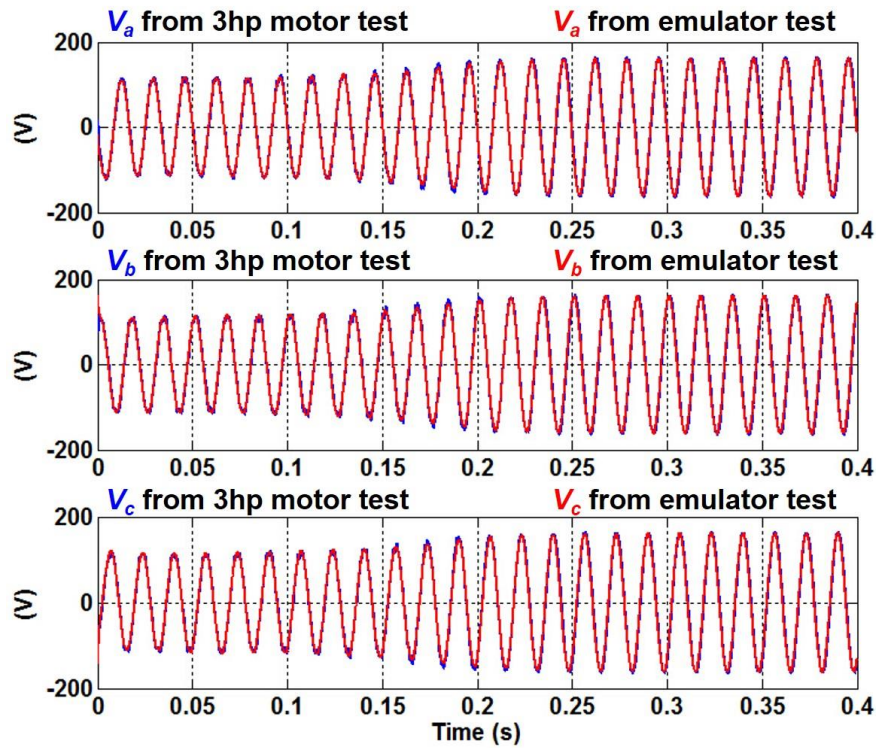


Figure 6-13 V_{abc} testing object terminal voltage of motor vs. emulator (DSP record, low pass filtered) during startup transient.

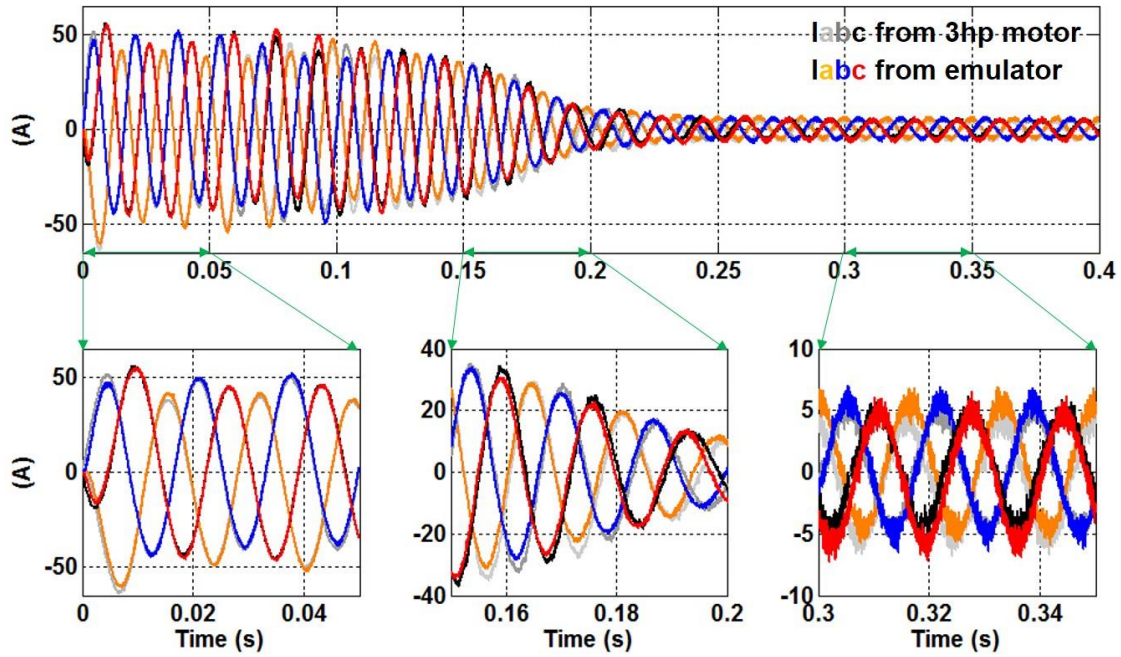


Figure 6-14 Motor emulator I_{abc} vs. motor three-phase current during startup transient (I_{abc} filtered by 2000 Hz low pass filter).

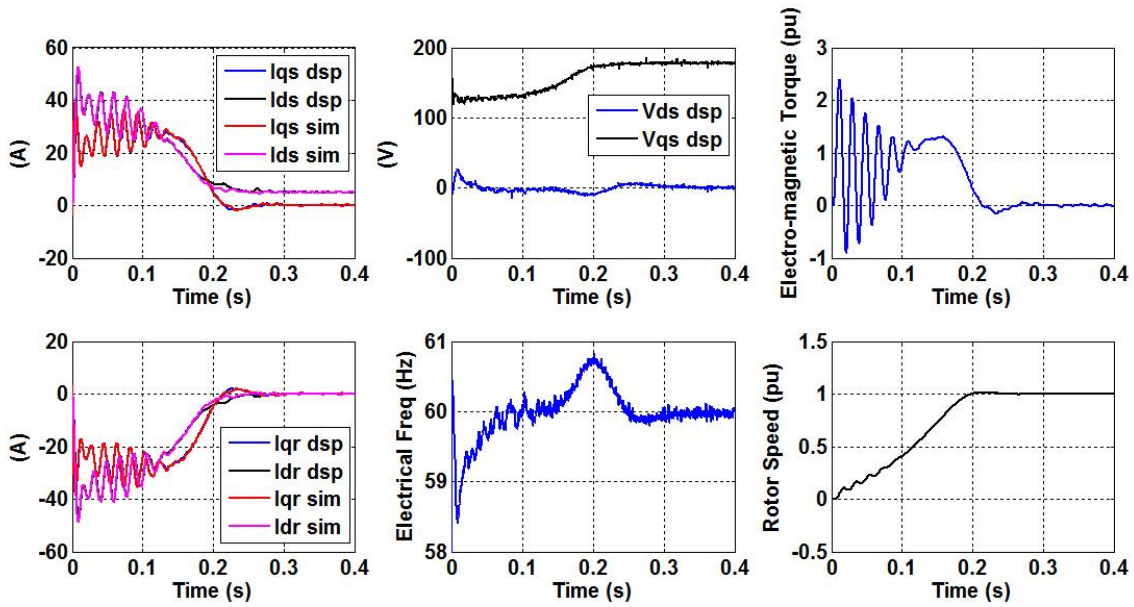


Figure 6-15 Corresponding DSP record vs. simulation (calculation reference) in dq domain under same input conditions.

6.5 Summary

Differences in current amplitude and startup time between physical motor and motor emulator require saturation model to be added to the motor model in order to optimize the its electrical behavior.

The motor's model is upgraded with saturation details (tested on example 3 hp induction motor) representing variable leakage and magnetizing reactance with reference to stator current, rotor current and magnetizing current contents during deep saturated startup process.

CHAPTER 7

REAL-TIME NUMERICAL MOTOR MODEL

Induction motor continuous model in the application is a set of high order ordinary differential equations. In order to solve it in real time and with limited DSP resource, numerical algorithms must be considered in order to provide stable and accurate reference results for emulator. In this chapter, numerical issues, stability and accuracy as well as cases comparison between different numerical methods with discrete motor model implementation in the emulator are discussed.

7.1 Issues with Real-time Model Numerical Performance

In the digitalized computations, higher order mathematical equations will cost more resource, which results in the limitations for computation model complexity, as well as results with less accuracy, which might eventually lead to calculation instabilities.

The numerical methods are designed with corresponding hardware processor and time step, aiming at solving complex dynamic system problems. The issues are not related with HIL system design stability or emulator tracking capability. Similar as reasons for higher order simulation solver and smaller time step needed for more complicated network or limited nodal calculation capacity for real-time digital HIL, the challenges with implementing numerical model within digital signal controller for converter are finding the best tradeoff between calculation resource and the numerical solver.

Numerical issues have been noticed during implementation. ZIP model doesn't include differential equation – static load references are calculated based on basic multiplication or division operations. However, unstable and inaccurate performances of three-phase induction motor model real-time calculation are observed due to inappropriate numerical method in solving strong dynamics differential equations.

While solving the motor state space model represented by time-variant coefficient ordinary differential equations (ODE) containing vectors of 4x1 variables, hardware limitations and real-time sampling signals of the HTB platform should be included within considerations.

As introduced in section 2.2, numerical methods have been applied in solving the transient calculation problems areas of computer software and real-time software / hardware. However, as individually modeled and programmed load emulator compared with other types of numerical solutions, the limitations from both hardware and software are posing numerical challenges.

In order to choose the right numerical method satisfying (solving) the above application requirements, popular numerical methods such as single-step method, and multistep method have been considered as candidates. However, due to the non-self-starting nature of some multistep methods [113], in this application, only the method needing the previous immediate variable vector is considered, to avoid numerical failure due to unreasonable initial guesses.

7.2 Induction Motor Discrete Modeling

As mentioned in section 5.1.1, the ideal state space modeling of induction motor includes electrical and mechanical portions. Equation (21) is describing the electrical and magnetic relationships between current and voltage in dq domain, containing the variable of rotor speed. Equations (22)(23) describe the mechanical characteristics and calculate the rotor speed status.

For the input for motor numerical model, the voltage vector $\vec{v} = [v_{qs}^{pu} \ v_{ds}^{pu} \ v_{qr}^{pu} \ v_{dr}^{pu}]^T$ is set as ideal input $[1 \ 0 \ 0 \ 0]$ while the electrical frequency input ω^{pu} is constant 1. The motor model is started free acceleration with no load.

Direct line start for induction motor is a transition interval between two big status: from zero to steady state. Unlike the transitions between different operating points (one steady state to another), the direct line start will induce strong dynamics, which is mathematically a big challenge for the convergence of the numerical model.

The model of induction machine combines all voltage v_{qdsr}^{pu} , current i_{qdsr}^{pu} , leakage and magnetizing reactance X_{srm}^{pu} , resistance r_{sr}^{pu} , dq reference frame rotation speed ω^{pu} and the rotor speed ω_r^{pu} . Equation (21) could be represented in the differential equation with matrix coefficient as (27), where $\vec{i}(t)$ is the output current vector, $\vec{v}(t)$ is the input voltage vector.

Under rated operating conditions, $A(t)$ contains variable matrix coefficients, including input variable of $\omega^{pu}(t)$ and updated variable $\omega_r^{pu}(t)$ and B is a constant matrix.

Under strong dynamics especially saturated conditions, the matrix $A(t)$ and B contain variable reactance X_{srm}^{pu} which is representing the induction motor magnetic saturation phenomenon. However, in order to linearize and simply the analysis, the saturation parameter changes are not included in the stability and accuracy of numerical analysis.

Equation (27) is a non-homogeneous matrix differential equation standard form. Different from the constant A matrix non-homogenous differential equations, the A in (27) contains $\omega_r^{pu}(t)$. Due to the nonlinear nature of the torque calculation, this speed-current relationship adds to the complexity in analysis of the accuracy and stability issues in induction machine numerical solutions.

$$\frac{d}{dt} \vec{i}(t) = A(\omega(t), \omega_r^{pu}(t)) \cdot \vec{i}(t) + B \cdot \vec{v}(t) = f(t, \vec{i}) \quad (27)$$

$$\frac{d}{dt} \omega_r^{pu}(t) = g(\vec{i}) \quad (28)$$

At time t_k , the snapshot for and (28) are be expressed as (29) and (30).

$$\frac{d}{dt} \vec{i}(t_k) = A(\omega(t_k), \omega_r^{pu}(t_k)) \cdot \vec{i}(t_k) + B \cdot \vec{v}(t_k) = f(t_k, \vec{i}(t_k)) \quad (29)$$

$$\frac{d}{dt} \omega_r^{pu}(t_k) = g(\vec{i}(t_k)) \quad (30)$$

The discrete representation for (29) and (30) could be denoted as (31) and (32).

$$\frac{d}{dt} \vec{i}_k = A_k \cdot \vec{i}_k + B \cdot \vec{v}_k \quad (31)$$

$$\frac{d}{dt} \omega_{rk}^{pu} = g(\vec{i}_k) \quad (32)$$

In order to estimate $\vec{i}_{k+1}$ from $\vec{i}_k$, the analytical solution for discretized (31) by time step of T_s could be denoted as (33). However, the coefficient $e^{A_k T_s}$ (which is referred to as “transition matrix”) makes it impossible for digital processor to calculate: it is expanded as Taylor series polynomials, shown in (34). Due to the simple integration equation (32), the solution for ω_r^{pu} is expressed as (35).

$$\vec{i}_{k+1} = e^{A_k T_s} \cdot \vec{i}_k + A_k^{-1} (e^{A_k T_s} - I) B \cdot \vec{v}_k \quad (33)$$

$$\vec{i}_{k+1} = \sum_{n=0}^{\infty} \frac{1}{n!} (A_k T_s)^n \cdot \vec{i}_k + A_k^{-1} \left(\sum_{n=0}^{\infty} \frac{1}{n!} (A_k T_s)^n - I \right) B \cdot \vec{v}_k \quad (34)$$

$$\omega_{r(k+1)}^{pu} = \omega_{rk}^{pu} + g(\vec{i}_k) \cdot T_s \quad (35)$$

In order to accommodate application accuracy, time-urgent requirements and hardware capabilities, different numbers (orders) of approximations polynomials in (34) are proposed by different numerical methods to get as close to (33) as possible and stable in the same time.

7.3 Numerical Discretization Methods

As shown in Figure 7-1, the real-time induction motor model is calculated in the digital controller with numerical methods applied to electrical model. Due to the constant

integration nature of mechanical model (32), it is not using higher order numerical integration.

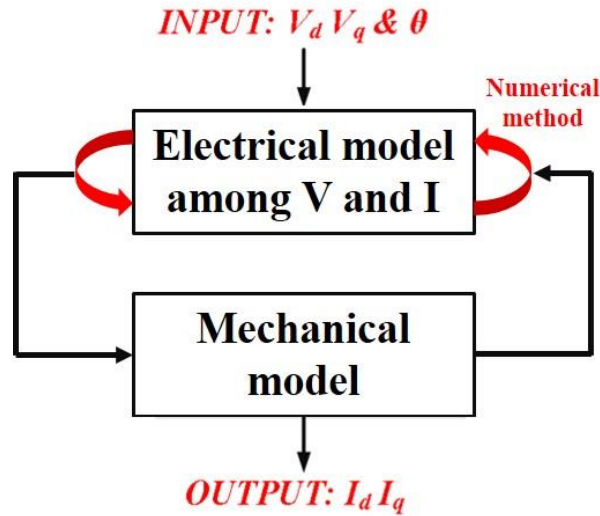


Figure 7-1 Proposed numerical calculation scheme for real-time induction motor model.

In the following sections, simple integration over time step (7.3.1), Runge Kutta 4th order from single-step family (7.3.2) and Trapezoidal based Predictor-Corrector PECECE from multi-step family (7.3.3) are selected as numerical examples to compare and analyze different types of numerical methods' impact on the numerical accuracy of the model strong dynamic transient calculation inside an industrial digital controller. In the evaluation process, two motor models are used: motor model I with parameters from Table 6-2, and motor model II with parameters from Table 5-1.

7.3.1 Explicit Euler Method

The first reaction about solving differential equations model in DSP, is to program through simple integration over each time step for the derivatives. By approximating the left side of (29) as (36), the simplest 1st order explicit Euler method is using one step discretize the equation (29) at time t_k as:

$$\frac{\vec{i}_{k+1} - \vec{i}_k}{T_s} \approx \frac{d\vec{i}_k}{dt} = f(t_k, \vec{i}_k) = A_k \cdot \vec{i}_k + B \cdot \vec{v}_k \quad (36)$$

$$\begin{aligned} \vec{i}_{k+1} &= [I + T_s \cdot A_k] \cdot \vec{i}_k + T_s \cdot B \cdot \vec{v}_k \\ &= \vec{i}_k + T_s (A_k \cdot \vec{i}_k + B \cdot \vec{v}_k) \end{aligned} \quad (37)$$

The solution shown in (37) explains the explicit Euler simple integration over the time step. Compared with the full polynomial solution in (34), the explicit Euler method provides simple solution but only with first order approximation ($\sim T_s$).

7.3.2 Runge Kutta Method

Achieving the accuracy of a Taylor series approach without higher derivatives calculation, the Runge Kutta method is using one-step multiple-stages approximations to discretize the equation (29) at time t_k [113]. The Runge Kutta method, according to different step numbers, could be 2nd, 3rd, 4th or higher order [76].

The most commonly used 4th order Runge Kutta (RK4) method is shown as below (38)- (42) [113]. The intermediate coefficients k_1 k_2 k_3 and k_4 are individually calculated

within one step: by combining these coefficients and making corresponding percentages on the solution estimation, the next step current status $\vec{i}_{k+1}$ could be concluded in (38).

$$\vec{i}_{k+1} = \vec{i}_k + \frac{1}{6}T_s \cdot (k_1 + 2k_2 + 2k_3 + k_4) \quad (38)$$

$$k_1 = f(t_k, \vec{i}_k) \quad (39)$$

$$k_2 = f(t_k + \frac{T_s}{2}, \vec{i}_k + \frac{T_s}{2}k_1) \quad (40)$$

$$k_3 = f(t_k + \frac{T_s}{2}, \vec{i}_k + \frac{T_s}{2}k_2) \quad (41)$$

$$k_4 = f(t_k + T_s, \vec{i}_k + T_s k_3) \quad (42)$$

$$\vec{i}_{k+1} = \sum_{n=0}^4 \frac{1}{n!} (A_k T_s)^n \cdot \vec{i}_k + A_k^{-1} \left(\sum_{n=0}^4 \frac{1}{n!} (A_k T_s)^n - I \right) B \cdot \vec{v}_k \quad (43)$$

After combining (31) and (38) - (42), the polynomial approximation result for $\vec{i}_{k+1}$ is concluded in (43). The solution shown in (43) explains the RK4 integration over the time step.

Compared with the full polynomial solution in (34), the RK4 method requires much more calculations including four coefficients and sum of their right proportions as integration over time step. RK4 concludes the solution with approximation polynomials up to 4th order ($\sim T_s^4$).

7.3.3 Predictor-Corrector Method

As multistep numerical method, the Predictor Corrector (PC) method is using an explicit method for the predictor step and an implicit method for the corrector step. All PC procedures are done within a time step.

Predictor-corrector similar methods are mentioned in previous research, examples are: computer simulation tool for power system transients [120], digital computer simulation for induction motor dynamics [119] as well as motor behavior prediction in sensorless motor drive application [123].

In this implementation, 1st order Euler is used as the explicit prediction and 2nd order trapezoidal is used as the implicit correction. The PC procedures are repeated twice, which is generally referred to as Euler-Trapezoidal method twice corrections PECECE.

As shown in (44) (45) (46), the predictor is with superscript of p while the corrector 1 and corrector 2 are noted as c1 and c2. Similarly, by concluding the polynomials, (47) could be obtained as approximation of Taylor series.

$$\vec{i}_{k+1}^p = \vec{i}_k + T_s \cdot f(t_k, \vec{i}_k) \quad \text{-- Explicit Euler Predictor} \quad (44)$$

$$\vec{i}_{k+1}^{c1} = \vec{i}_k + T_s \cdot \frac{f(t_k, \vec{i}_k) + f(t_{k+1}, \vec{i}_{k+1}^p)}{2} \quad \text{-- 1st Trapezoidal Corrector} \quad (45)$$

$$\vec{i}_{k+1}^{c2} = \vec{i}_k + T_s \cdot \frac{f(t_k, \vec{i}_k) + f(t_{k+1}, \vec{i}_{k+1}^{c1})}{2} \quad \text{-- 2nd Trapezoidal Corrector} \quad (46)$$

$$\begin{aligned}
\vec{i}_{k+1} &= \vec{i}_{k+1}^{c2} = [I + T_s \cdot A_k + \frac{1}{2}(T_s \cdot A_k)^2 + \frac{1}{4}(T_s \cdot A_k)^3] \cdot \vec{i}_k \\
&\quad + A_k^{-1} \cdot (T_s \cdot A_k + \frac{1}{2}(T_s \cdot A_k)^2 + \frac{1}{4}(T_s \cdot A_k)^3) \cdot B \cdot \vec{v}_k \\
&= \sum_{n=0}^3 \frac{1}{n!} (A_k T_s)^n \cdot \vec{i}_k + A_k^{-1} \left(\sum_{n=0}^3 \frac{1}{n!} (A_k T_s)^n - I \right) B \cdot \vec{v}_k - \frac{1}{12} (T_s \cdot A_k)^3 \cdot \vec{i}_k - \frac{1}{12} T_s^3 A_k^2 B \cdot \vec{v}_k
\end{aligned} \tag{47}$$

Compared with the full polynomial solution in (34), the PECECE method expands up to 3rd order of the polynomials (T_s^3) with errors $\sim 1/12 T_s^3$.

7.4 Numerical Performance

A stiff system is a system involving rapidly changing dynamics together with slowly changing ones [114]. And in many real-world cases, the fast dynamics will die away quickly until dominated by slow dynamics. The induction motor continuous model has the mixed characteristics of fast and slow dynamics. The motor model under analysis is motor model I, without considerations of saturation.

As indicated in Figure 7-2, four traces of eigenvalues $\lambda_1 - \lambda_4$ represent the frequencies of corresponding time constants, of motor model I under rotor speed from 0 to 1. These are solved by calculating the eigenvalues of the A_k matrix (show in (31)) with different rotor speed values from 0 to 1. Due to the nature of stiff system, the furthest eigenvalues, as indicated as λ_1 and λ_2 in the figure during initial startup transient, has the imaginary part of $\pm j377$, which corresponds to the oscillation frequency of 60 Hz in dq stator current. And the negative real parts of the eigenvalues represent how fast the dynamics are decaying.

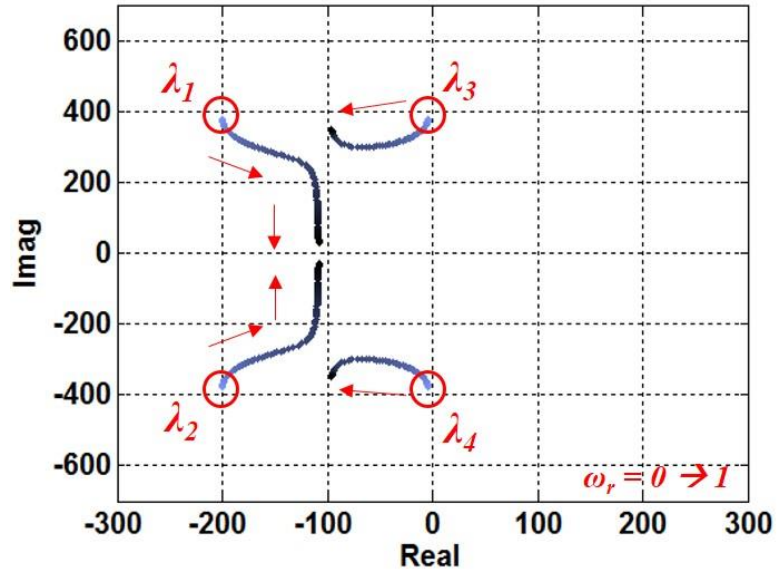


Figure 7-2 A_k eigenvalues traces of motor model I with rotor speed from 0 to 1.

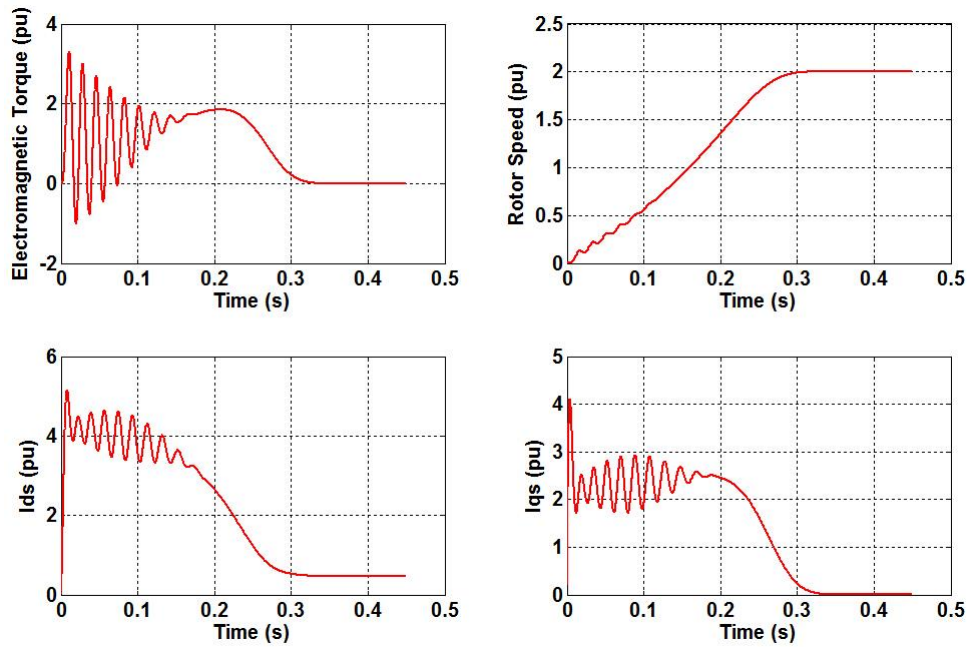


Figure 7-3 Starting up transients of motor model I.

Figure 7-4 shows the examples of chosen time steps for induction motor model based on $\frac{1}{3}, \frac{1}{4}, \frac{1}{5}, \frac{1}{6}$ of $\frac{1}{60}$ s (fast oscillation time constant). It is common knowledge that the smaller time step will bring more details to characterize the dynamics. Larger the time step, the more delay for the dynamics characterized will be observed: examples as those of Figure 7-4.

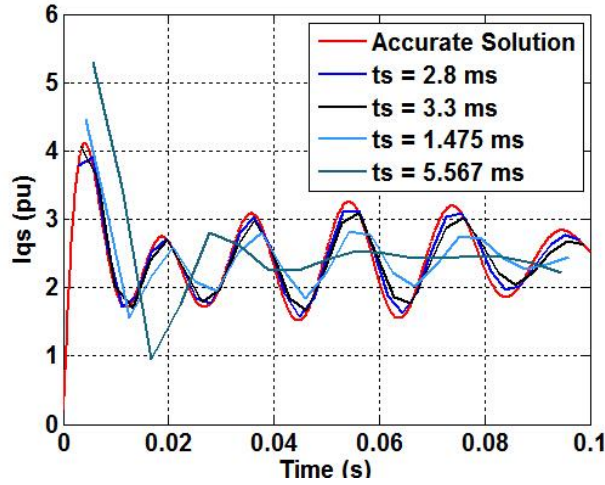


Figure 7-4 Numerical results for I_{qs} of model I, during startup transient with different time steps.

Different numerical methods are expressed in different orders of solution approximations to the full polynomial solution. The model under test is inherently stable – all the eigenvalues of the characteristics matrix has negative real time constant. The dynamics are evolving towards stabilizing point.

However, as numerical solutions to a stable system model represented in equation (27), different approximations by numerical methods could yield unstable numerical results. In order to consider numerical stability for different methods over a single dynamic system with analytical solutions, stability function R corresponding to the model

characteristics matrix & time step $T_s\lambda$ and numerical method are usually used to evaluate for their eigenvalues spectrum [113] – in the analysis of analytical form integration, R should be within unit circle to guarantee the stability of numerical discretization solution.

An example is presented based on 1st order explicit Euler. The equation for stability function R under this case is expressed in (48), according to the derivation in section 7.3.1.

$$R(T_s\lambda) = I + T_s \cdot A_k \quad (48)$$

The corresponding contours for stability region of Euler is expressed in Figure 7-5. The range of stable $T_s\lambda$ is the area of shifted unit circle with an origin of -1 on the real axis.

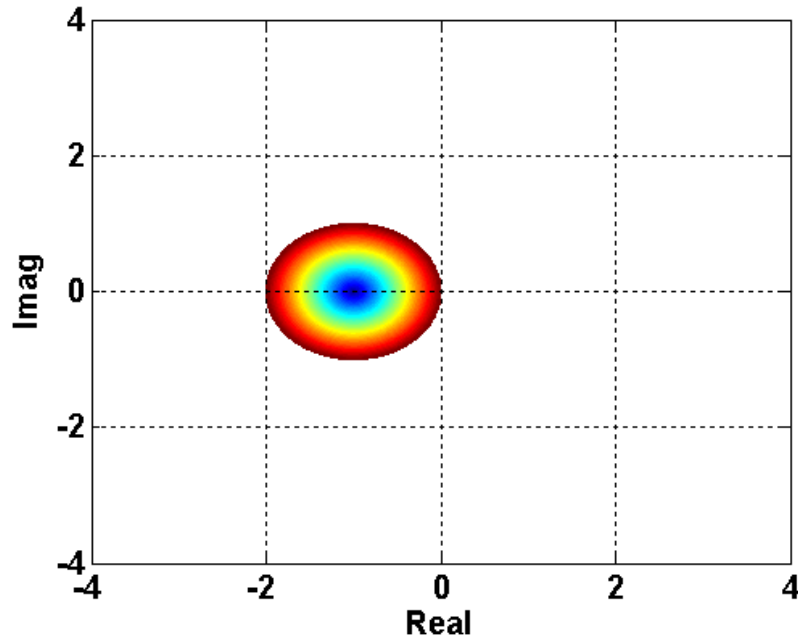


Figure 7-5 Numerical stability range for $T_s\lambda$ of Euler.

Similarly, the stability function R for RK4 and PECECE could be expressed as (49) and (50), according to sections 7.3.2 and 7.3.3.

$$R(T_s \lambda) = \sum_{n=0}^4 \frac{1}{n!} (A_k T_s)^n = I + T_s \cdot A_k + \frac{1}{2} T_s^2 \cdot A_k^2 + \frac{1}{6} T_s^3 \cdot A_k^3 + \frac{1}{24} T_s^4 \cdot A_k^4 \quad (49)$$

$$R(T_s \lambda) = I + T_s \cdot A_k + \frac{1}{2} T_s^2 \cdot A_k^2 + \frac{1}{4} T_s^3 \cdot A_k^3 \quad (50)$$

Their corresponding contours for stability regions are expressed in Figure 7-6 and Figure 7-7. As can be seen from these figures for the numerical calculation of constant λ based characteristics matrix A_k , RK4 has wider stability range than that of PECECE, and they both have better stability performances than that of Euler.

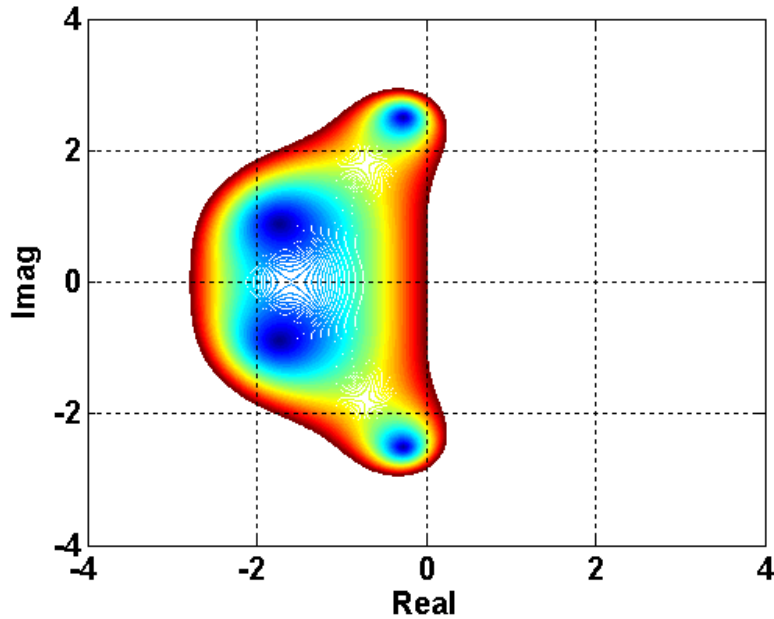


Figure 7-6 Numerical stability range for $T_s \lambda$ of RK4.

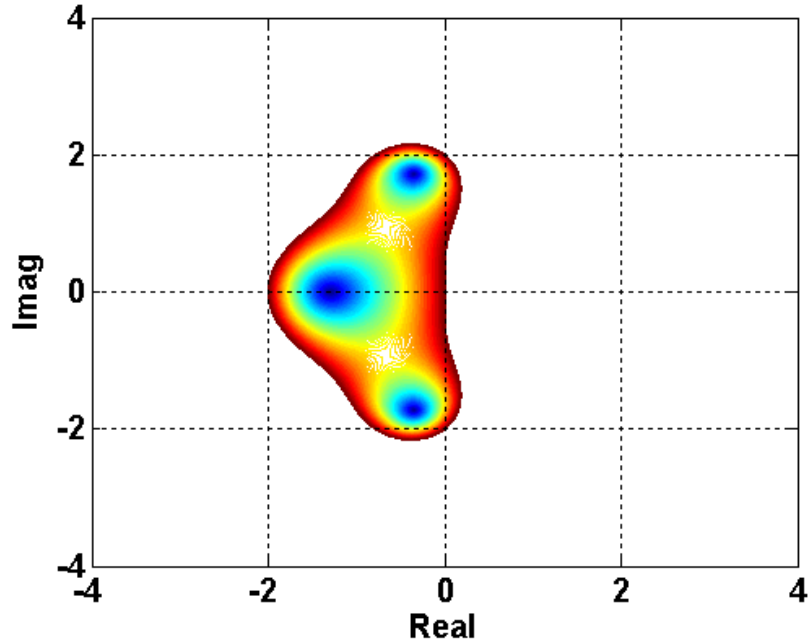


Figure 7-7 Numerical stability range for $T_s\lambda$ of PECECE.

The method of stability function R has its application on the analysis of motor drive under steady state operating condition [123] with stable ω_r^{pu} (constant characteristics matrix A_k), with which the whole system could be linearized to linear system.

7.4.1 Accuracy with Various Time Steps

Explicit Euler method doesn't generate satisfactory result for the motor numerical method with the time step implemented in the application. Example of the motor model II, even under ideal voltage, and frequency input conditions, the maximum time step for the numerical results to converge is 5 μs , which is beyond emulator controller hardware handling capability.

With the same motor parameters as above example in Euler, RK4, and PECECE numerical performance of the dynamical system with time step varying from 8 ms to 1 us are shown individually in Figure 7-8, and Figure 7-9.

The performances for stable numerical methods have different accuracies, and trend towards exact solution. Curves in the same color in Figure 7-8 and Figure 7-9 are illustrating the results from the same time step. Although the methods are approaching the solution marked in black, the ways of approaching the answer differ dramatically.

In order to have close look at the two numerical methods calculation results, Figure 7-10 shows two short time frame starting up transients. The results are the zoomed-in details from the red-framed time intervals in Figure 7-8, and Figure 7-9.

With the same time step difference applied to numerical models in RK4, and PECECE, the torque calculation results show dramatic differences in the accuracy, and variation trend. Compared with Figure 7-10, due to the approximation orders towards exact solution, the results of RK4 calculation yield highly nonlinear trend towards convergence with different time steps. However, under the same time step condition, PECECE calculation results yield much higher linear trend in terms of accuracy. The comparison of accuracy trend proves that RK4 is very sensitive to change of time step – small differences in time steps might yield dramatic difference in the model solutions.

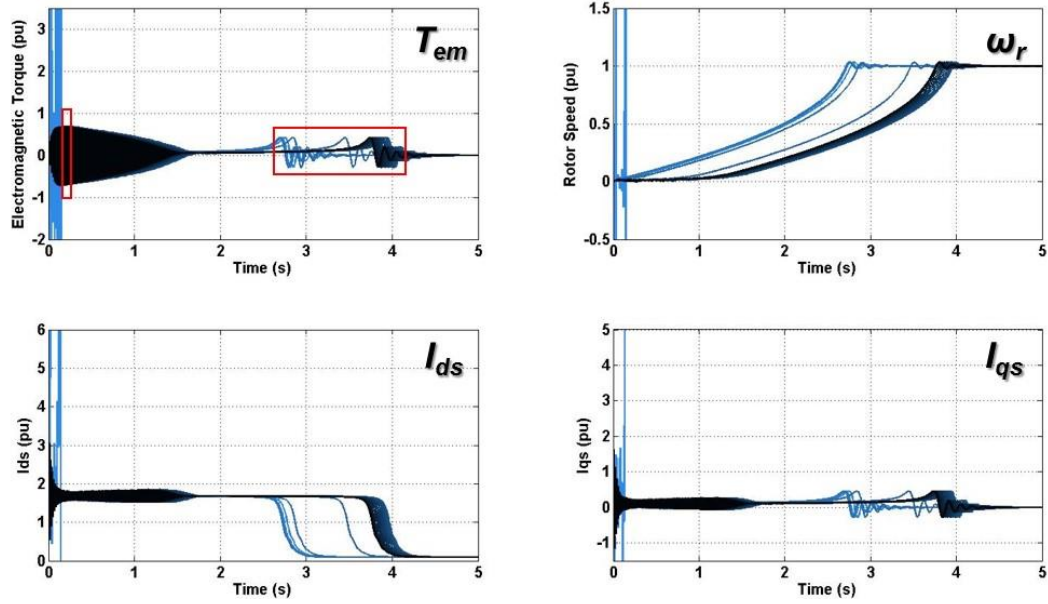


Figure 7-8 Ideal performance of motor model II direct free startup with 4th Runge Kutta method and time steps from 8 ms (blue) to 1 us (black).

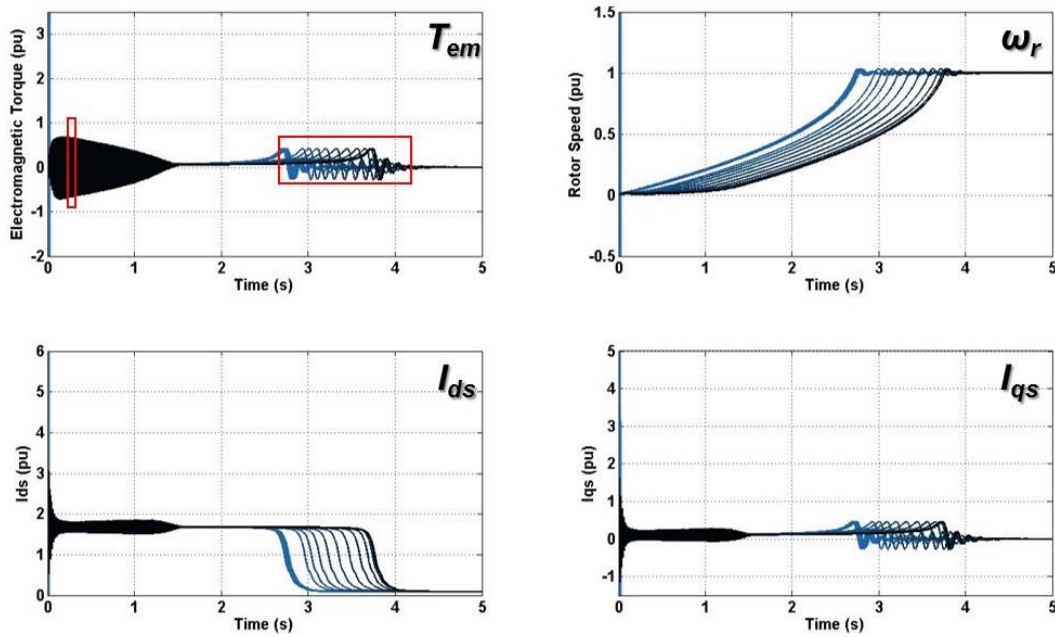


Figure 7-9 Ideal performance of motor model II direct free startup with Trapezoidal based PECECE method and time steps from 8 ms (blue) to 1 us (black).

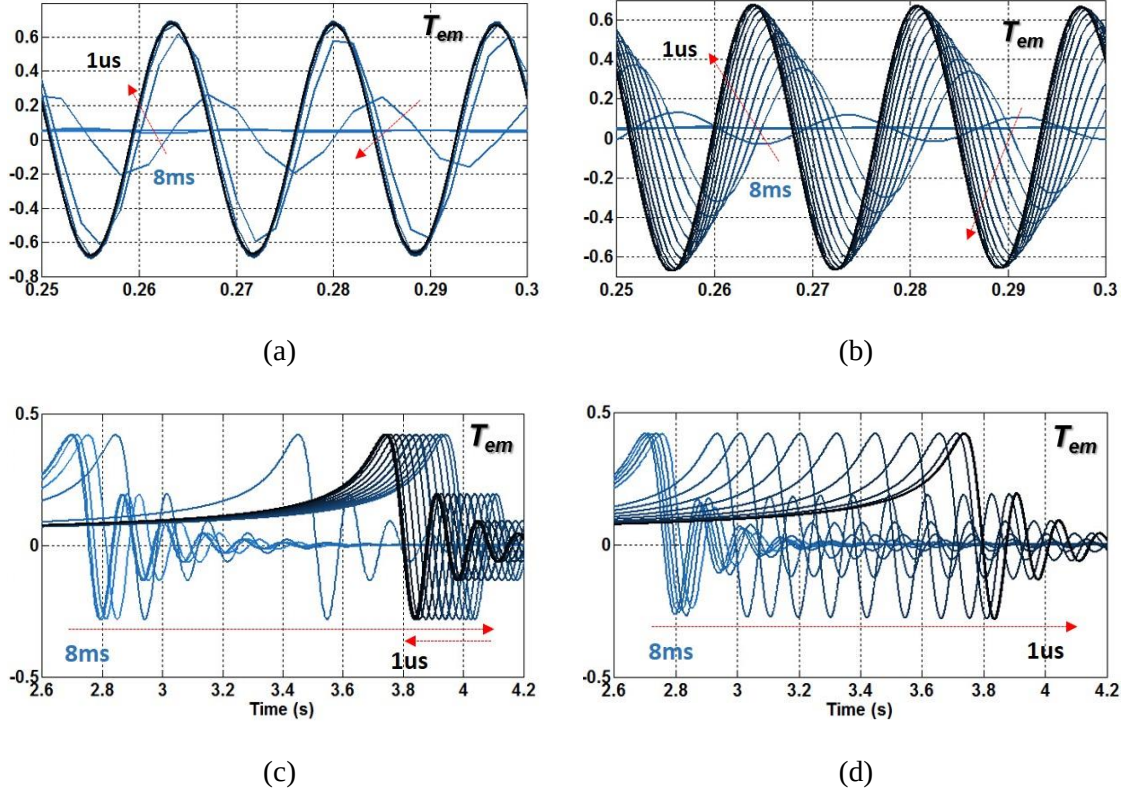


Figure 7-10 Detailed performance comparison by the methods of (a)(c) RK4 and (b)(d) PECECE, red framed areas on Figure 7-8 and Figure 7-9.

7.4.2 Accuracy with Fixed Time Step

Under actual real-time applications, it is not practical to vary the time step conditions. Feasible time step within accuracy requirement will be the optimum solution. The rule of thumb value for choosing maximum time step for explicit numerical methods is believed to be $\frac{1}{5}$ of corresponding dynamics time constant [115]. In the real-time load emulation application, the time step is determined by the switching time interval of the power amplifier, which is a fixed 100 μ s. Compared with 60 Hz (16.7 ms) dq dynamic

oscillations, the time step is well within the range of maximum $\frac{1}{5}$ of dynamic time constant (3.34 ms). The numerical performances for the motor model II under the numerical methods introduced in 7.3 are illustrated in Figure 7-11.

By looking at the overall shape, there is no major visible difference between the results of RK4, PECECE with exact solution (reference obtained from matlab simulation with 1 us time step to guarantee the solution accuracy) – the overall shape and time duration seem aligned very close.

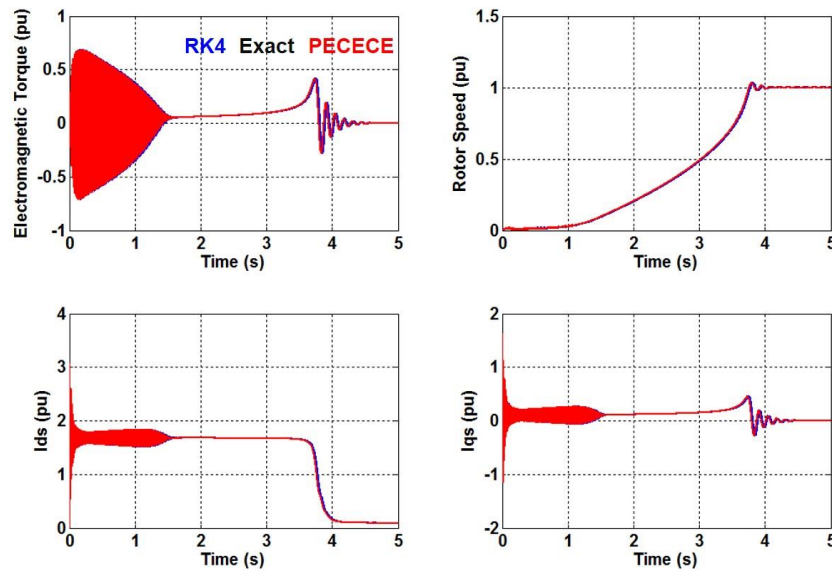


Figure 7-11 Performance comparison of RK4, PECECE and exact solutions for motor model II with 100 us (black) time step.

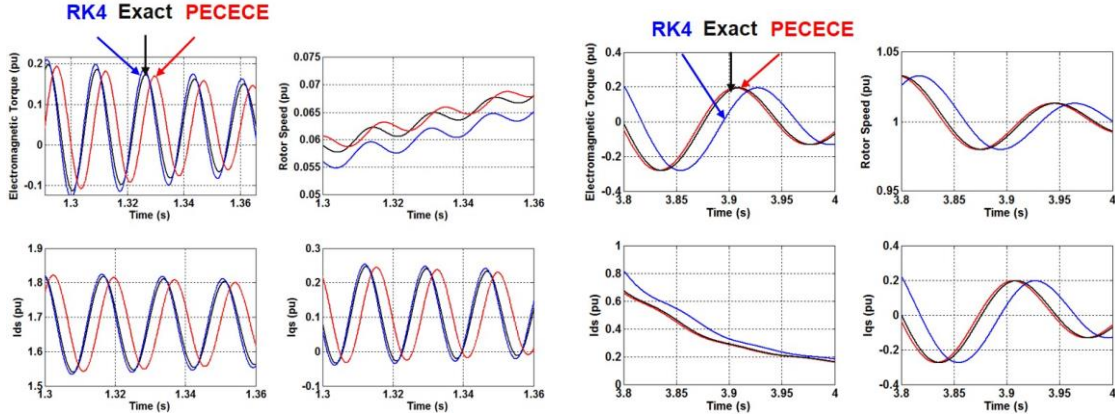


Figure 7-12 Transient details I and II of Figure 7-11.

However when taking a close look at the waveforms, as shown in Figure 7-12, the two numerical methods are exhibiting different characteristics. In the period of motor model higher frequency oscillations, the RK4 has advantage of high accuracy while PECECE is showing delay in the waveform. However, in the lower frequency oscillations, the PECECE has the advantage of high alignment with the exact solution.

In the actual implementation, the input conditions are not as ideal as the ones provided in the computer numerical calculation, the voltage input vector $\vec{v} = [v_{qs}^{pu} \ v_{ds}^{pu} \ v_{qr}^{pu} \ v_{dr}^{pu}]^T$ fluctuates around $[1 \ 0 \ 0 \ 0]$ due to the line impedance between voltage source and emulator terminals. On the other hand, the frequency input ω^{pu} for the model will fluctuate around constant 1 due to PLL dynamic bandwidth.

What's more, in the digital control system, quantization errors are categorizing the inaccuracies of computation results caused by analog-to-digital (AD) process of sensing

signals and numerical calculations [127]. Data formats of AD channels as well as digital processors, including number of bits and fixed or floating type are sources of errors as well.

In the HTB platform, the 32-bit floating digital signal processor TMS320F28335 from Texas Instruments [130] 12-bit AD channel is applied to collect analog sensing signals of current, and voltage [132]. Due to floating data format, variable truncation error will also be imposed on calculation during each iteration.

7.5 Summary

In this chapter, real-time numerical discrete motor models using explicit Euler, 4th order Runge Kutta, and Trapezoidal Prediction-twice-correction PECECE methods are proposed and evaluated with their numerical performances including linear stability regions, and accuracy sensitivities with various time steps.

During comparison with discrete model using RK4, and PECECE, it is found that both methods show advantages as well as disadvantages during real-time implementation in the emulator application.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

This dissertation focuses on development of power system static, dynamic load emulator based on current controlled three-phase full bridge converter, aiming at providing flexible loading conditions for universal reconfigurable grid emulator HTB.

In CHAPTER 3, under the HTB application environment, current based emulator has been validated for its tracking capability of current references in dq . Development concerns such as emulated model dynamics bandwidth, numerical convergence, and accuracy, interface stability, circulating current issues, and feasibility of numerical implementations to improve accuracy are discussed and evaluated.

During the development of load emulator, steady state power system simulation load models have been adopted in CHAPTER 4 – by adjusting the percentage among constant impedance, constant current, and constant current, different area load could be represented with flexibility. The models of voltage, and frequency dependency are added in order to describe load behaviors representing PQ bus in power system analysis.

In order to represent the power system dynamic load characteristics, induction motor model with transient modeling on both stator, and rotor is implemented within current controlled load converter. Straight relationships between input voltage, and frequency vs. output current are expressed in state space equations. The motor emulator

prototype with ideal induction motor is fulfilled in CHAPTER 5. Then the composite load emulator representing PSS/E simulation profiled power system load P-Q bus is demonstrated with its real-time emulation performances in HTB, and differences due to the relay protections and load control algorithms are illustrated as well.

However, challenged by the same reason of computer simulation, real-time emulation of induction machine behavior is validated by comparing its online startup process with that of a 3 hp induction motor, as described in CHAPTER 6. Significant current amplitude differences, and time duration indicate the need for the saturation model to be added to induction motor modeling in the emulator. Induction machine emulator with saturation model is proposed, and then validated to properly represent the strong dynamics of the real induction motor, in the application of HTB.

In the CHAPTER 7, due to the numerical challenges posed by strong electromagnetic transient of the induction motor model during startup, Euler, RK4, and PECECE are analyzed with two motor models, representing large industrial, and small horsepower types. By analyzing the eigenvalues corresponding to electrical model characteristics matrix, time constants of the motor model dynamics are revealed, and the followed by the evaluation of the right time step for characterizing the dynamics. Stability regions of numerical methods are compared with the three numerical methods. First order Euler discretized model is not capable of providing the right dynamics in the application. While model with RK4 has high accuracy and better stability, but it is very sensitive on change of the time step. Model with PECECE has comparative linear trend with reference to change in the time step, however, comes with smaller stability region. Comparison on

models with RK4, and PECECE are compared under the application time step as well, showing their numerical capabilities in solving faster and slower time transient dynamics.

8.2 Future Work

Induction motor emulator is an interesting, and promising research topic. Although in this dissertation, induction motor emulator for HTB is designed as dynamic power system load, this application concept has high potential of other applications, such as substitution of the motor drive test bed.

If designed properly, motor load for motor drive under test could be substituted by a motor emulator sharing dc bus, and ac interface. However, due to the different natures of motor and converter, limitations as well as design challenges could be summarized as:

1. Power amplifier interface bandwidth.

As discussed in section 3.3.1, the emulator converter for HTB could track dq signal up to 100 Hz with 4% amplitude distortion, and 4 degree phase delay. However, for the tracking performance compatible with motor drive, and capability of emulating higher frequency motors, a power electronics converter has its limitations. The dynamic tracking bandwidth of the emulator hardware could be improved by applications of higher frequency semiconductor devices such as SiC, and GaN, paralleled phase leg converter topology, higher switching frequency, and higher bandwidth control algorithm.

2. PLL performance under dynamic, steady state, and fault conditions.

PLL for motor emulator in HTB has limitations on tracking performance when there is dynamic voltage input fluctuations. Different from stiff grid voltage, motor drive is often designed to be ramping up voltage and frequency from zero, while controlling the motor starting up current dynamics. When the voltage, and frequency are both zero during motor drive enabling transient, PLL has its control response time, and behavior for tracking the accurate frequency, and angle information. In addition, real-time calculation of motor model current reference amplitude and phase is highly sensitive towards the initial startup electrical information due to the short-circuit phenomenon.

During transitions between steady state operating points, motor drive terminal voltage variations imposed by control algorithms will introduce research challenge on the PLL dynamic bandwidth as well. Also, the PLL's performance under fault condition needs to be verified.

3. Induction motor model in *abc* or *dq* domain.

Emulator control algorithm, and model under *dq* domain has the advantage of constant control reference under steady state, and no steady state error. However, motor's model in *dq* has many shortcomings in terms of accuracy, particularly in the case of switching frequency effects such as current, and torque ripple [136]. The motor dynamic model under *abc* domain has the trouble of calculating sinusoidal waveform, and the quantitative errors correspondingly. However, the model under *abc* domain has the benefit

of being able to contain higher frequency content, and capability of non-symmetrical fault calculation.

4. Voltage/current interface type, and stability.

General motor drives have control algorithms based on open-loop control, and closed-loop control. The control variables, correspondingly, are interface voltage (duty cycle), and currents. The interface stability issues between motor drive, and emulator are based on control variables conflict. The emulator should be designed to react to motor drive signals as ‘passive’ as possible – if the interface voltage is controlled by motor drive, emulator should be regulating the current, and vice versa.

5. Switching frequency current waveform.

Due to interface PWM nature for both motor drive, and emulator, the current ripples around switching frequency will clearly show the differences between motor drive PWM, and emulator PWM. The issue is similar in emulator in HTB. Synchronization is one way to attenuate the differences [108].

6. Torque ripples, and high frequency impedance.

Emulator test-bed’s performance on higher order harmonics / distorted waveform will be compromised due to the hardware’s bandwidth (unless further improved). Also due to structural difference between converter, and motor test bed, the parasitic coupling EMI impedance will not be the same. This high frequency impedance is one of the limitations that the emulator would not be representing compared with that of a real motor.

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