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Modeling, Stability and Accuracy of Power Hardware-in-the-loop Simulation of Power Electronic Systems

パワーエレクトロニクスシステムの PHILS (Power Hardware-in-the-loop Simulation)におけるモデリング，安定性および精度に関する研究

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Preface

This dissertation focuses on the development of power hardware-in-the-loop (PHIL) simulation of power electronics systems.

Due to the great progress of computer technology, hardware-in-the-loop (HIL) simulation is widely used in power system fields presently. HIL simulation provides advantages such as more flexibility, lower cost, design efficiency, etc. Presently, the concept of HIL simulation is extended to test power components other than controllers, such as generator, power converter, etc. In these cases, transferred signals are high power level and the hardware-under-tests (HUTs) generator/absorb power, which means that a real power must be exchanged between the simulation part of HIL system and the actual HUTs. Therefore, proper power interfaces are necessary in these cases. This is so called Power HIL (PHIL) simulation. PHIL simulation brings new challenge and extends the use of HIL simulation. However, there are two issues which severely limit its development: stability problem and acceptable calculation accuracy. Even the investigated system is of stable, the PHIL built for it may lose stability. Stability of the PHIL system must be analyzed before it is carried out, otherwise, the HUT may be severely damaged. Moreover, even a PHIL simulation is carried out successfully, it may be a futile effort if the simulation has low accuracy.

Factually, a PHIL simulation system consists of three parts: (1) HUT, (2) Simulation model of the rest of the investigated system other than HUT, (3) the power interface between HUT and simulation part. To achieve a high fidelity test of the HUT, models of the simulation part and the power interface must provide a circumstance to the HUT as if it were connected to a real system. Therefore, simulation models must have high fidelity and the power interface should works as a "transparent" part.

This research investigates the modeling, stability and accuracy of PHIL simulation through examples of PHIL which are built for a gas engine cogeneration system (GECS) and a chopper circuit. Before the real building of the GECS with a matrix converter(MC) which will increase efficiency, a PHIL simulation is carried out in which the HUT is the MC and the other part of the system is represented by simulation model. Stability study was carried out for the experimental system of GECS with the MC. Moreover accuracy analysis is also carried out for the boost chopper circuit, which is a simple circuit to evaluate accuracy.

The thesis is organized in five chapters as follows.

Chapter 1 gives the general introduction about PHIL simulation in power system. The obstacles of the development of the PHIL are presented and the past achievements are briefly reviewed.

Chapter 2 gives the numerical models of gas engine (GE) and permanent magnet synchronous generator (PMSG) of the investigated GECS which can be carried out in real time simulation. Models are verified through experiments of a commercial GECS with conventional ac/dc/ac. The good match of simulation results and experimental results shows that these numerical models can represent characteristics of GE and PMSG. Therefore, they can be used in PHIL to interface with MC and provides a "factual" environment to MC as if it were connected to a real GE and PMSG.

Chapter 3 analyzes the stability problem of the PHIL simulation and focuses on the inductor coupled system. Stability of a PHIL must be verified before it is implemented. Otherwise, it may bring severe damage to the HUT. The factors which affect the stability of PHIL simulation are pointed out in this chapter. It is found that, for the first time, the relationship between the simulation inductor and the real inductor plays an important role in the PHIL stability besides the time delay. A method to stabilize the PHIL simulation without decreasing the accuracy of it is also proposed and verified in this chapter.

Chapter 4 presents accuracy analysis of PHIL simulation. Usually, it is difficult to evaluate the accuracy of a PHIL simulation because in most case the should-be results, which means reference data obtained by the experiment of the real system, are unavailable. In this chapter, a PHIL of a boost chopper is constructed. Through the investigating of this PHIL, a method to calculate the error in PHIL is presented and verified by the experiment. Moreover, offline simulation of PHIL is also carried out. Through the comparison of the results of (1) PHIL simulation (2) offline simulation of PHIL and (3) experiment, the validity for the method to predict accuracy of a PHIL simulation is verified.

Finally, chapter 5 summarizes overall important results in this dissertation.

Dedicated to my daughter

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Contents

Preface

Chapter 1 Introduction

In this section, a general introduction about power hardware-in-the-loop (PHIL) simulation is given and the past achievements about PHIL simulation in power system are briefly reviewed. Finally, the main objectives of this dissertation are outlined.

1.1 Power Hardware-in-the-loop Simulation

1.1.1 Hardware-in-the-loop Simulation

Due to the great progress of computer technology, hardware-in-the-loop (HIL) simulation is widely used in power electronics and power system fields [1], [2]. As shown in Fig. 1.1, in a HIL simulation, part of the investigated system is simulated by a real time digital simulator. Signals obtained by this simulator are transferred to a real hardware-under-test (HUT) through an interface such as digital/analog converter(DAC), etc. On the other hand, the responses of the HUT are fed-back to the simulator through an analog/digital converter (ADC). Using this techonology, the HUT can be tested repeatly and thoroughly before the real building of the system or under the circumstances that the direct use of the simulation part is unavailable. Furthermore, HUT can be investigated even under boardline conditions which may destroy the

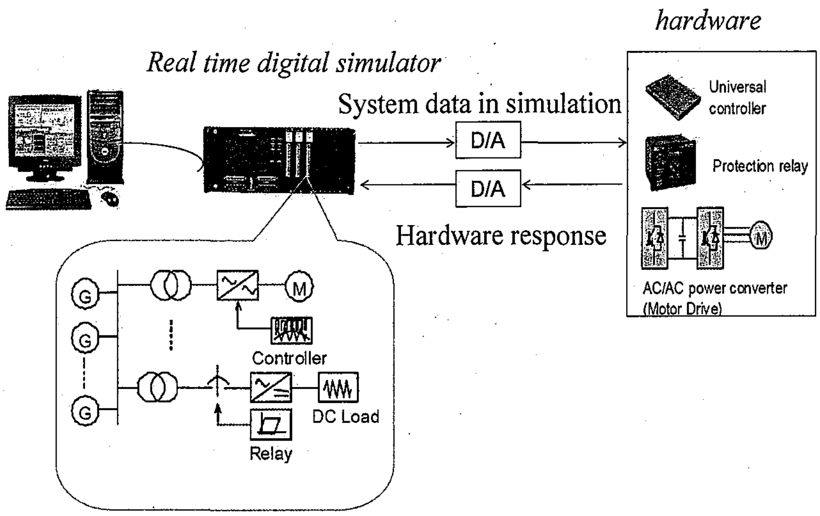


Fig.1.1 Configuration of a HIL simulation.

real products of the simulation part. The advantages of using HIL as a design step (as opposed to starting with actual hardware) include flexibility, reduced cost, design efficiency, etc.

1.1.2 Controller Hardware-in-the-loop Simulation

At present, HIL simulations are mainly used to the development of controllers, which are called controller HIL (CHIL) [3], [4]. For example, before using a motor controller with a real motor drive, the controller can be tested against a simulated motor model running in real time. The fidelity of this type HIL is mainly defined by the computational time for the model (including the I/O access times). The fast digital controller of the motor can have a very small sampling time below 10 µs, therefore, the computational time of the simulated motor should much lower than this value. Otherwise, the large computation time will add a large time delay in the closed-loop of HIL and the simulated motor may diverge from a real motor severely. Now, due to the advanced distributed calculation technology and fast I/O access time, the technology of CHIL gets great progress and is widely used in the power system and power electronics. The application of CHIL includes:

- Automated on-line tuning of control parameters of a universal controller used for power electronic building blocks
- Investigation of a commercial thyristor firing board
- Real-time controller concept demonstration for interconnection of DG sources to an electric distribution grid.

In CHIL simulation, signals which are exchanged between the simulator and HUT are low power level (+/-10V, mA) and can be transferred easily by A/D and D/A converters.

1.1.3 Power Hardware-in-the-loop Simulation

Presently, the concept of HIL simulation is extended to test power devices other than controllers, for example, generator, power converter, etc. In these cases, the transferred signals are high power level (kV, kA) and HUTs absorb/sink power, which demands that a real power be exchanged between the simulator and HUTs. Therefore, proper power interfaces are necessary to sinks/absorbs a real power. This is so called power HIL (PHIL) simulation. Fig. 1.2 illustrates the different configurations of CHIL and PHIL simulation. Obviously, PHIL simulation brings new challenges and significantly extends the application of HIL technology. However, unavoidable problems introduced by the power interface such as noise injection, non-ideal

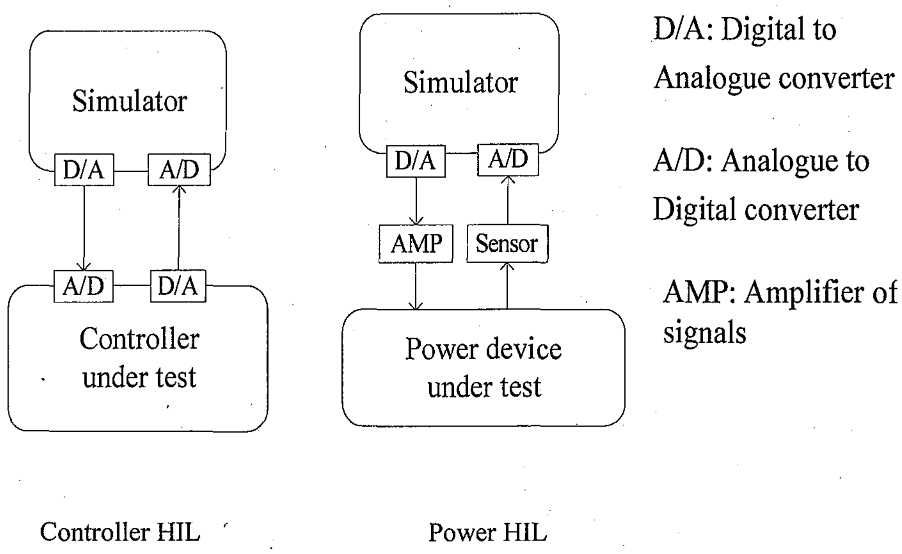


Fig. 1.2 Configuration of controller HIL and power HIL.

transfer function, limited bandwidth, etc, all bring critical obstacles for the development of PHIL.

1.2 Obstacles to the Development of Power Hardware-in-the-loop Simulation

From Fig. 1.2, it can be concluded that a PHIL factually consists of three parts: (1) simulation of the part of the investigated system, (2) hardware to be test and (3) power interface between the simulation and real hardware. To achieve a high fidelity of a PHIL and a valid test of the HUT, the simulation part, together with the power interface, should provide environment to the HUT as if it were connected to the real system. Therefore, the first step of a PHIL is that the simulation of the system should have high fidelity and can be carried out in a real time situation. Otherwise, the test environment for the HUT will severely deviate from a real one and the test of the HUT will lose meaning.

It is obvious that the introduced power interface brings two obstacles which severely limit the development of PHIL simulation: stability issue and calculation accuracy.

1.2.1 Stability Problem of PHIL Simulation

It should be pointed out that even the real system is stable, the PHIL built for it may lose stability due to the introduced power interface. In comparison to CHIL, PHIL has more critical problem on stability problem due to the non-idealities of the introduced power interface.

Therefore, a PHIL simulation may suffer from artificial instabilities, which are artifacts of the test setup and are not present in a real system involving the test device and hardware implementation of the simulated system. Before a PHIL is carried out, the stability of it must be verified, otherwise, it may cause severe damage to the HUT.

1.2.2 Accuracy Problem of PHIL Simulation

The most important claim of a simulation is that it should have high accuracy, if not, the simulation will lose meaning. Unfortunately, it is difficult to analyze the accuracy of a PHIL. Even if simulation models of the HUT exist, they will never match the hardware characteristics exactly. Moreover, even the simulated part of a PHIL has a good match with the real system it represents, it can not always insure a high accuracy of the PHIL simulation due to the introduced power interface, which factually does not exist in a real investigated system.

In most cases, the reference of should-be results is unavailable, otherwise there is no need to carry out a PHIL. Therefore, to evaluate the accuracy of a PHIL simulation, a valid method to predict the accuracy of it must be presented. As a result, the accuracy of a PHIL simulation can be predicted even without the reference data.

1.3 Review on the Achievments of Power Hardware-in-the-loop Simulation

In comparison to CHIL simulation, literature about PHIL is fairly rare. In ref. [5], an implementation of a PHIL simulation is described. This PHIL is built to investigate a DC electric drive system. The authors point out that the PHIL achieves stable operation even with nonlinear load. In this PHIL, a monitoring system based on a multi-agent platform is added to the PHIL to verify the effectiveness of the proposed system. However, it has no mention of the stability and accuracy problem of the PHIL.

Papers [6] and [7] both mention that the instability of PHIL simulation is caused by the sampling frequency of the power interface. It is a common sense and the conclusion only addresses the interface performances while neglects the fact that PHIL simulation is a closed-loop system. The stability problem of a PHIL should be analyzed basing on the whole closed-loop system instead of just basing on the power interface.

In ref. [8], a method to evaluate the accuracy, which is based on the concept of "electric power matching capability", is proposed, nevertheless, even for the simplest cases, it involves laborious work and is very difficult for the practical implementation.

Ref. [9] verifies that even the power interface has high precision, the accuracy of the PHIL may be poor. It provides a method to evaluate the accuracy of PHIL using the system transfer function. However, these results are still based on very simple model, in which the simulation part only consists of a power source and a resistor and real load consists of a resistor and an inductor. Furthermore, the analysis about how to predict accuracy of PHIL of non-linear load is inadequent. Therefore, the utilization of the conclusions is limited.

In ref. [10], different interface algorithms for PHIL simulation are proposed and compared. It indicates that the interface algorithm has serious influence on the accuracy and stability. Nevertheless, the authors simply mention that the stability of PHIL simulation has relationship with the magnitude of the open loop transfer function and provides no detail analysis. Furthermore, the model used in this paper is still very simple which restricts the application of the results.

Ref. [11] discusses the idea of using "transparency performance index" to evaluate the fidelity of a HIL simulation. This approach compares the difference between the actual HUT impedance and the equivalent HUT impedance seen from the other side of the interface. However, this method also focuses on the performance of the interface only. A counterexample of it is discussed in ref [9], which shows that high transparency may also lead to large simulation error.

1.4 Objectives of this Research

This research focuses on developing high fidelity PHILs of power electronics systems.

First, a PHIL for developing a power converter (a matrix converter) of a gas engine cogeneration system (GECS), shown as Fig. 1.3, is investigated. Detail description about the GECS can be found in ref. [12]. In the PHIL simulation, a piece of real matrix converter (MC) is hardware-under-test (HUT). Gas engine (GE) and permanent magnet synchronous generator (PMSG) are simulated by numerical model. With this PHIL simulation, the MC can be investigated repeatedly and thoroughly, even under extreme conditions which may damage real GE and PMSG. Since both simulation part and real part have an inductor, this type PHIL simulation is an inductor coupled system. Despite the fact that the inductor coupled system is the most common system in power system. for example, (1) an AC electric drive system

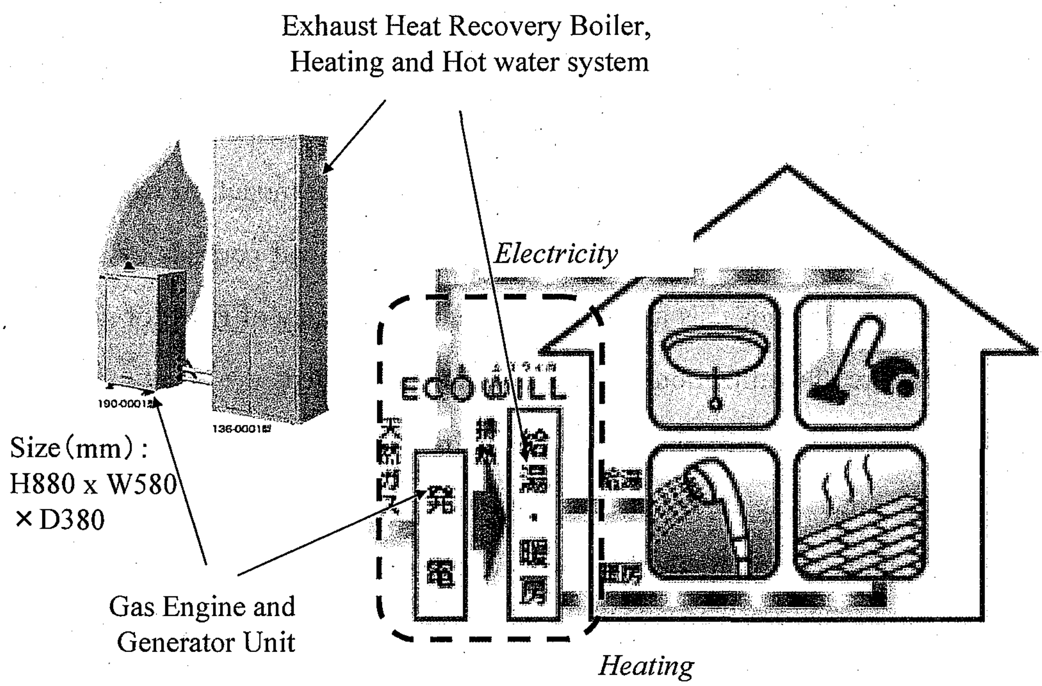


Fig. 1.3 the gas engine cogeneration system (GECS)

consisting of AC motor, an inverter, transformer and (2) a distribution system consisting of power converter, transformer and transmission line, etc., the report about the stability and accuracy analysis of this type PHIL is very few. In this research, the analysis of modeling, stability and accuarcy of the PHIL is carried out based on this type systems.

The works that serve the objective are listed as below:

(1)Numerical models of GE and PMSG are built based on MATLAB/Simulink/SimPowerSystem and verified by experiment. Moreover, to provide "real time" circumstance to test MC, the models are modified by using advanced real time solver- ARTEMIS.

(2) Before the implementation of the PHIL, stability problems about inductor coupled PHIL are analyzed. Factors which will affect the PHIL stability are summarized.

(3) A method to stabilize PHIL simulation without decreasing its accuracy is proposed and verified by both analytical and simulation results.

(4) A method to predict the accuracy of PHIL simulation is also presented. To verify this method, a PHIL of a boost chopper is investigated. Three results are compared: (a)

experimental results, (b) PHIL simulation results, (c) results of offline simulation of PHIL simulation. By the comparison of these results, the proposed method to predict accuracy of PHIL is verified.

Based on all above works, how to develop a high fidelity PHIL of power electronic system is demonstrated. Moreover, through this research, some problems for the practical use of MC in a GECS are found and improved. The achievements of this research not only benefit to the development of the MC in other variable speed systems, such as gas turbine and wind turbine system, but also can broaden the application of PHIL simulation in power system.

References

[1] P. Forsyth, T. Maguire, R. Kuffel: "Real time digital simulation of control and protection system design",35th annual IEEE Power electronics specialist conference (PESC) 2004, Vol. 1, pp. 329-335 (2004).

[2] S. Abourida, J. Belanger, C. Dufour: "High Fidelity Hardware-in-the-loop Simulation of Motor Drives with RT-LAB and JMAG",2006 IEEE International Symposium on Industrial Electronics, Vol. 3, Issue, 9-13, pp. 2462-2466 (July, 2006).

[3] S. Vamsidhar, B. G.Femandes, "Hardware-in-the-loop Simulation Based Design and Experimental Evaluation of DTC Strategies", 35th IEEE Power Electronics Specialists Conference(PESC), Vol. 5, 20-25 June, pp. 3615-3621 (June, 2004).

[4] O. A. Mohammed, Z. Liu and S. Liu, "Equivalent Hardware representation of PM Synchronous Machine Realized by a Physics Based Machine Model for Hardware-in-the-loop Simulation Applications", IECON, 2008, 34th annual conference of IEEE on Industry Electronics, pp. 1185-1188 (Nov,2008).

[5] X. Wu, S. Lentijo, A. Deshmuk, A. Monti, F. Ponci, "Design and implementation of a power-hardware-in-the–loop interface: a nonlinear load case study," Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, 2005, Vol. 2, (March, 2006).

[6] W. Zhu, S. Pekarek, J. Jastkevich, O. Wasynczuk and D. Delisle. "A Model-in-the-loop

interface to Emulate Source dynamics in a Zonal DC Distribution System," on Power Electronics, IEEE Trans. Vol.20, issue.2, pp.438-445 (March, 2005).

[7] S. Ayasun, R. Fischl, S. Vallieu, J. Braun and D. Cadirh. "Modeling and stability analysis of a simulation-stimulation interface for hardware-in-the-loop application," Simulation Modelling Practice and Theory, 15, pp. 734-746, (2007).

[8] S. Ayasun, R. Fischl, T. Chmielewski, S. Vallieu, K. Miu and C. Nwankpa: "Evaluation of the Static Performance of a Simulation-Stimulation Interface for Power Hardware in the Loop", IEEE Power Tech Conference Proceedings, 2003 Bologna, Vol.3, issue.23-26, pp.1-8 (March, 2003).

[9] W. Ren, M. Steurer, T. L. Baldwin, "An Effective Method for Evaluating the Accuracy of power Hardware-in-the Loop Simulations" IEEE Transactions on Industry Applications, Vol.45, Issue.4 July/Aug 2009. pp: 1484-1490 (July/August, 2009).

[10] W. Ren, M. Steurer, T. L. Baldwin , "Improve the Stability and the Accuracy of power Hardware-in-the Loop Simulation by selecting Appropriate Interface Algorithms" IEEE Transactions on Industry Applications, Vol.44, No.4 July/Aug 2008. pp: 1286-1294 (July/August, 2008)

[11] M. Bacic, "On hardware-in-the-loop simulation," proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference 2005, Seville, Spain, December 12-15,2005 (Dec., 2005)

[12] Y. Miura, S. Kokubo, D. Maekawa, and T. Ise: "Efficiency Improvement of a Gas Engine Cogeneration System by Power Factor Control with an IGBT Rectifier". Proceedings of the power conversion conference (PCC) Nagoya, 2007, pp.534-541, (April, 2007).

Chapter 2 Power Hardware-in-the-loop Simulation of a Gas Engine Cogeneration System for Developing a Power Converter System

2.1. Introduction

Cogeneration systems realize simultaneous generation of both heat and power in a single process from one energy source, which is also known as CHP (Combined Heat and Power). Through the utilization of exhaust heat, CHP can achieve the total efficiency of 70-80%, while the efficiency of conventional power system is around 35% [1]. A gas engine cogeneration system (GECS) which employs a gas engine as a prime mover is one of the promising CHPs. At present, GECS is well introduced into households as well as factories and office buildings. However, since the size of the household type GECS is small, it has a problem of relatively low efficiency of the system. To solve this problem, we focus on the improvement of the electric output, which is around 20% of the input energy. The circuit configuration of a conventionally commercial 1 kW household GECS is shown in Fig. 2. 1. This household type GECS consists of a gas engine (GE), a permanent magnet synchronous generator (PMSG) and an ac/dc/ac converter which transfers generator output electricity (3 phase, 307.5 Hz) to the utility (single phase, 60 Hz). In this GECS, the PMSG couples with the GE directly. The elimination of

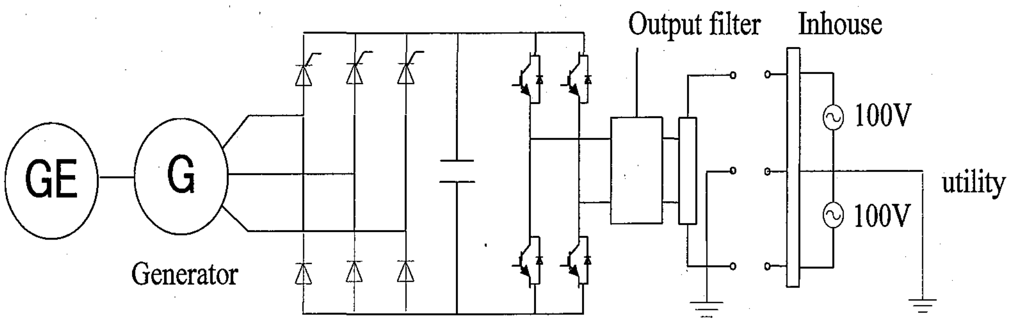


Fig. 2.1 Configuration of a commercial 1 kW household GECS.

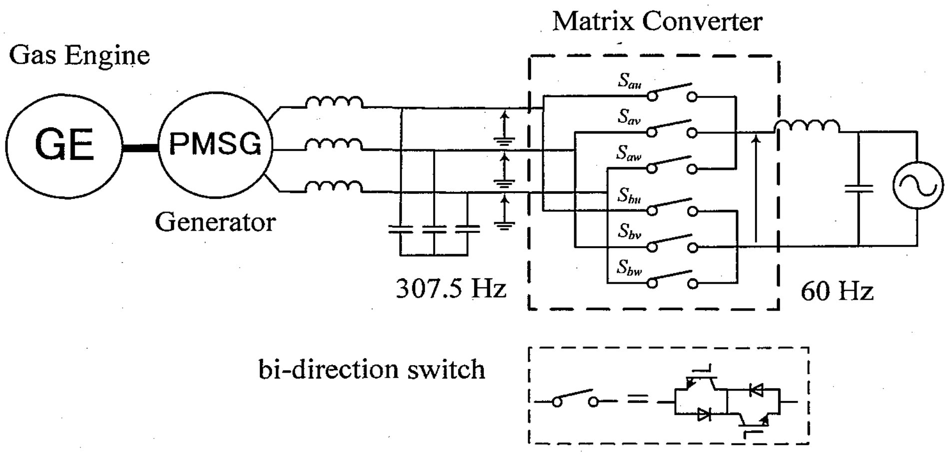


Fig. 2.2 Configuration of the proposed GECS with a matrix converter.

gearbox, which is used to reduce a high shaft speed to generator, provides the GECS unit with compact structure and reduces cost.

As shown in Fig. 2.1, the ac/dc/ac converter consists of a half-controlled rectifier with thyristors and diodes, a dc link capacitor and a single phase IGBT inverter. The thyristors are simply turned on when the voltage of dc link is lower than the threshold value. Therefore, the waveform of the current is similar to that of a full-bridge diode rectifier and the power factor of the generator is relatively poor. In this research, a direct ac/ac matrix converter (MC) is proposed to substitute the ac/dc/ac converter, which is shown in Fig. 2.2. The MC realizes reduction of reactive current and harmonics components, therefore, the electric efficiency of the GECS can be improved. Moreover, the employment of Reverse-Blocking (RB) devices reduces the number of the switching devices on the current path and as a result it can reduce the losses of the converter. Since our proposed MC configuration have no energy storage component, the power pulsation that has twice the frequency of the single phase utility appears directly on the three phase side [2].Therefore, a novel method was proposed to treat this power pulsation in ref. [2]. This method realizes that the instantaneous three phase power is modulated with the MC and the power pulsation is absorbed by the rotor inertia of the PMSG and GE. This power treatment method and the proposed power factor modulation were verified by experiment in ref. [3]. Because prime movers such as gas turbines and gas engines are not easily available for experiment, the experiment carried out in ref [3], using an induction motor (IM) to simulate the GE in a GECS. In comparison to the IM, the GE has more pulsation in torque and results obtained in [3] may not demonstrates MC characteristics thoroughly. Therefore, a power hardware-in-the-loop (PHIL) simulation is proposed to investigate the interaction between the GE-PMSG and the MC. In the PHIL simulation, a piece of real matrix converter is hardware-under-test (HUT) and GE-PMSG are simulated by numerical model. With this PHIL simulation, the MC can be investigated repeatedly and thoroughly, even under extreme conditions which may damage real GE and PMSG.

Presently, technology of hardware-in-the-loop (HIL) simulation is used extensively in power system for system prototyping. Nevertheless, the application of HILs is mainly limited to test controller (so-called CHIL). In a CHIL, signals exchanged between the simulated part and the real contrller are low power and voltage level (+/− 15V, mA). In this case, the transfer of signal can be implemented by A/D and D/A converter conveniently. However, in PHIL simulation, the HUT is a power device (such as generator or power converter) which needs to absorb/sink a real power. Therefore, a power interface, including power amplifier and sensor, is necessary to realize real power exchange. Unavoidable problems (such as time delay, limited bandwidth) induced by power interface bring the PHIL simulation more challenges on stability and accuracy. Although there are some trials on PHIL, successful implementation of PHIL is still rare. [4],[5]

It is obviously that to execute the proposed PHIL simulation of GECS successfully, the first step is to bulid valid models of GE and PMSG which can be carried out in real time condition. Models of GE and PMSG are presented in section 2.2, an experiment to verify these models is presented in section 2.3, the configuration and results of PHIL simulation are presented in section 2.4 and conclusions are described in the final section.

2.2. Models of Gas Engine and Permanent Magnet Synchronous Generator

The models for GE and PMSG, which will be implemented in PHIL simulation, should be: (1) stable (2) accurate enough with respect to the test plan and (3) the algorithms need to be execute in real time.

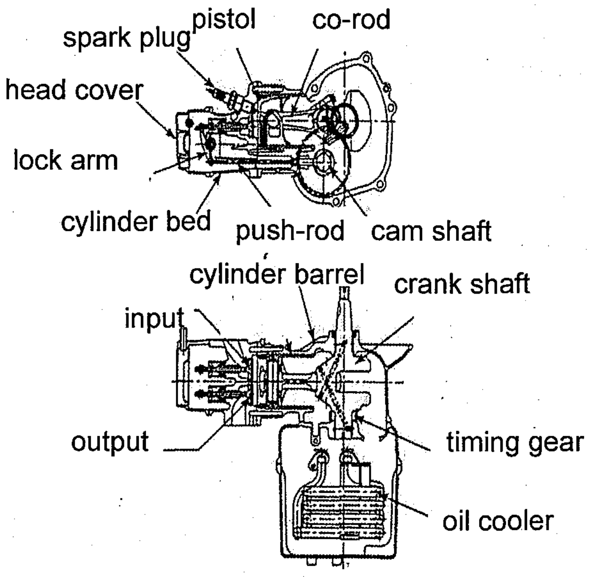


Fig. 2.3. Structure of the gas engine.

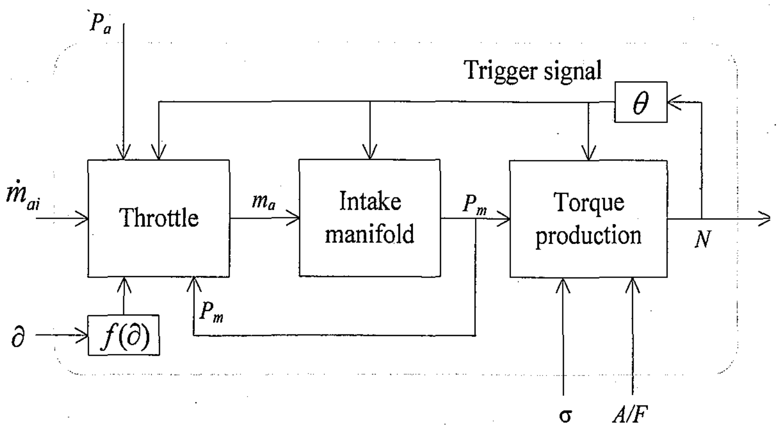


Fig. 2.4. Simulation model of the gas engine.

2.2.1 Gas Engine model

The GE employed in this household GECS is shown as Fig. 2.3. It has only one cylinder, which makes the GECS unit compact and then it is suitable for household. The GE works with four stroke cycles, which means its operation includes four events. The first operation step is the ingestion of gas through an inlet (intake), following by compression of the gas, power generation and exhaust air output [6]. Therefore, the model includes following parts: events of throttle and intake manifold, compression and torque generation.

The math model built for the GE is presented by the equations (2.1) to (2.6).

$$\dot{m}_{ai} = f(\partial)g(P_m) \quad (2.1)$$

$$g(P_m) = 2\sqrt{P_m P_a - P_m^2}\, sign(P_a - P_m)/P_a \quad (2.2)$$

$$f(\partial) = 2.281 - 0.05231\partial + 0.10299\partial^2 - 0.00063\partial^3 \quad (2.3)$$

$$\dot{P}_m = \frac{RT}{V}(\dot{m}_{ai} - \dot{m}_{a0}) \quad (2.4)$$

$$\dot{m}_{ao} = -0.366 + 0.08979NP_m - 0.0337NP_m^2 + 0.0001N^2P_m \quad (2.5)$$

$$T_{eng} = -181.3 + 379.36m_a + 21.91(A/F) - 0.85(A/F)^2 + 0.26\sigma - 0.0028\sigma^2 + 0.0027N - 0.000107N^2 + 0.00048N\sigma + 2.55\sigma m_a - 0.05\sigma^2 m_a \quad (2.6)$$

where	∂	:	Throttle angle (degree)
	$\dot{m}_{ai}$	:	Mass flow rate into manifold (g/s)
	P_m	:	Manifold pressure (bar)
	P_a	:	Atmospheric pressure (bar)
	R	:	Special gas constant
	V	:	Manifold volume (m^3)
	A/F	:	Ratio of air and fuel
	T_{eng}	:	Torque generated by gas engine (N·m)
	N	:	Engine speed (rad/s)
	σ	:	Spark advanced angle (degree)
	m_a	:	Mass of air in cylinder for combustion (g/s)

The mass flow rate into manifold is calculated by Eq. (2.1) as the function of the throttle angle and manifold pressure. The throttle angle and manifold pressure are obtained by Eq. (2.2) and Eq.(2.3), respectively. Eqs. (2.4) and (2.5) calculate cylinder air mass for combustion. Eq. (2.6) describes the torque generated by the engine. It should be noted that coefficients in equations were obtained through experiments in ref. [6]. Differing from GE in ref. [6], this GE has only one cylinder, so every stoke happens only once during two cycles of GE-PMSG rotation. It means that this GE generates only one output torque in every two rotations, that is power generation event. During orther three events, GE rotates by inertia. The simulation model built for it is shown in Fig. 2.4. A trigger signal, which is calculated from the rotation angle, controls the occurrences of every stroke cycle.

2.2.2 Permanent Magnet Synchronous Generator Model

The structure of the permanent magnet synchronous generator (PMSG) with an outer rotor is shown in Fig. 2.5 and major parameters about it are shown in table 2.1.

This PMSG works as a starter motor to drive engine during the starting period of the GECS and then works as a generator after system reaches rated speed. In comparison to a micro-turbine-generator cogeneration system, which generally has the rated speed of tens of thousands rpm, this GECS unit operates at relative low speed (the rated speed of the GECS is 2050 rpm). The PMSG in this GECS has 18 poles. To install so large number of poles in a relatively compact structure, the PMSG adopts an outer rotor design. This design not only contributes spacious space for the permanent magnets installation but also large inertia for smoothing the torque pulsation caused by the gas engine.

Table 2. 1. Major parameters and dimension of the PMSG

Pole pairs	9
Rated power	1.3 kW
Output phase voltage (generator mode)	189-231 V
Output frequency	307.5
Number of phase	3
Air gap length	5 mm
Inertia	0.0195 kg·m^2
Axial length of stator core	47cm
Stator out diameter	156mm
Rotor out diameter	178mm
Permanent magnets	ferrite
Rated speed	2050 rpm
Number of slots of stator	27

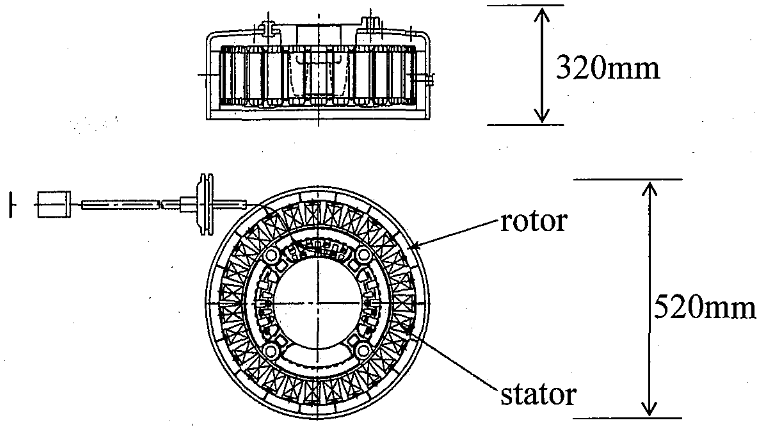


Fig. 2.5. Structure of the permanent magnet synchronous generator.

It is assumed that outer rotor PMSG has the same electromagnetic characteristics as traditional surface mounted permanent machine. The three phase model for the outer rotor PMSG is presented as (2.7)-(2.12).

$$\begin{bmatrix} d\psi_{s1}(t)/dt \\ d\psi_{s2}(t)/dt \\ d\psi_{s3}(t)/dt \end{bmatrix} = \begin{bmatrix} u_{s1}(t) \\ u_{s2}(t) \\ u_{s3}(t) \end{bmatrix} - R_s \begin{bmatrix} i_{s1}(t) \\ i_{s2}(t) \\ i_{s3}(t) \end{bmatrix} \tag{2.7}$$

$$\begin{bmatrix} \psi_{s1}(t) \\ \psi_{s2}(t) \\ \psi_{s3}(t) \end{bmatrix} = \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{bmatrix} \begin{bmatrix} i_{s1}(t) \\ i_{s2}(t) \\ i_{s3}(t) \end{bmatrix} + \sqrt{2/3}K_m \begin{bmatrix} \cos\theta_R \\ \cos(\theta_R - 2/3\pi) \\ \cos(\theta_R + 2/3\pi) \end{bmatrix} \tag{2.8}$$

$$L_s = \frac{3}{2}\frac{\pi\mu_0 l_1 l_2 N_s^2}{8g} \tag{2.9}$$

$$K_m = \sqrt{\frac{2}{3}}\frac{\kappa\pi l_1 l_1 B_m N_s}{4} \tag{2.10}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - 2/3\pi) & \cos(\theta + 2/3\pi) \\ -\sin(\theta) & -\sin(\theta - 2/3\pi) & -\sin(\theta + 2/3\pi) \end{bmatrix} \begin{bmatrix} u_{s1} \\ u_{s2} \\ u_{s3} \end{bmatrix} \tag{2.11}$$

$$V_d = l_{dd}\frac{di_d}{dt} + l_{dq}\frac{di_q}{dt} - \omega_e\psi_q - i_d R_s \tag{2.12}$$

$$V_q = l_{qq}\frac{di_q}{dt} + l_{qd}\frac{di_d}{dt} + \omega_e\psi_d - i_q R_s \tag{2.13}$$

where, g is the air gap length, l_1 and l_2 are axial length and diameter of the rotor, ψ_s is the flux linkage in stator phase, N_s is number of turns per phase winding, κ means coupling factor, θ_R denotes the angular position of the rotor defined as the normal stator loop. l_{dd} and l_{qq} are self inductance of d and q axis, l_{dq} and l_{qd} are mutual inductance. R_s is stator resistor. ω_e is synchronous speed.

Eq. (2.8) shows that the stator flux linkage is caused by the combination of stator armature current and magnets. The linkage performance is related to shapes dimensions of the magnets, paths of the flux, the distribution of the stator winding and armature current. All these factors contribute to the space harmonics.

To simplify the simulation of PMSG, three phase model can be transferred to dq model by Eq. (2.11) when the three phase voltages are balanced. Eq. (2.12), (2.13) describe dq model of PMSG.

The accurate value of inductance in Eq.(2.12) and (2.13) can be obtained through finite-element analysis, analytical method, etc. However, because one critical challenge of real time simulation is calculation speed, which has significant influence on both accuracy and numerical stability of real time (RT) simulation [4], space harmonics are ignored to save calculation time. Therefore, in this research, factually values of d and q axis inductances which contain harmonics are replaced by their average value to achieve high fidelity PHIL simulation.

2.3. Experimental and Simulation Results

The numerical simulation model of the GECS shown in Fig. 2.1 was made based on MATLAB/Simulink/SimPowerSystem. In order to verify the fidelity of these built models, the actual measurement of rotor speed, output line-to-line voltage and line current of the generator by using the experimental setup shown in Fig. 2.6 was also carried out using the commercial product which employed the same GE and PMSG as the numerical MATLAB/simulink models. Tables 2.2 and 2.3 summarize the parameters of the GE and PMSG in the commercial GECS, which are used in simulation.

Table 2.2 Simulation parameters of gas engine

Form	Four stoke cycle, one cylinder
Displacement	163 cm^3
Compression ratio	11
Rated speed	2050 rpm
Spark angle	BTDC 22°
Fuel	City gas 13A

Table 2. 3. Simulation parameters of the permanent magnet synchronous generator.

Pole pairs	9
Rated power	1.3 kW
Output phase voltage (generator mode)	189-231 V
Output frequency	307.5 Hz
Inductance	6 mH
Resistor	3.7 Ω
Inertia	0.0195 kg·m^2
Flux induced by magnet	0.13 Wb

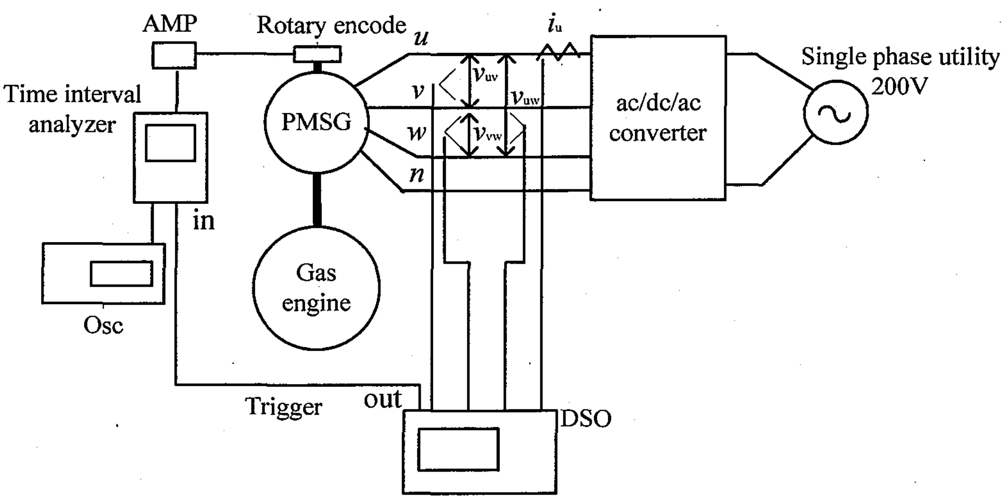


Fig. 2.6 Experimental setup.

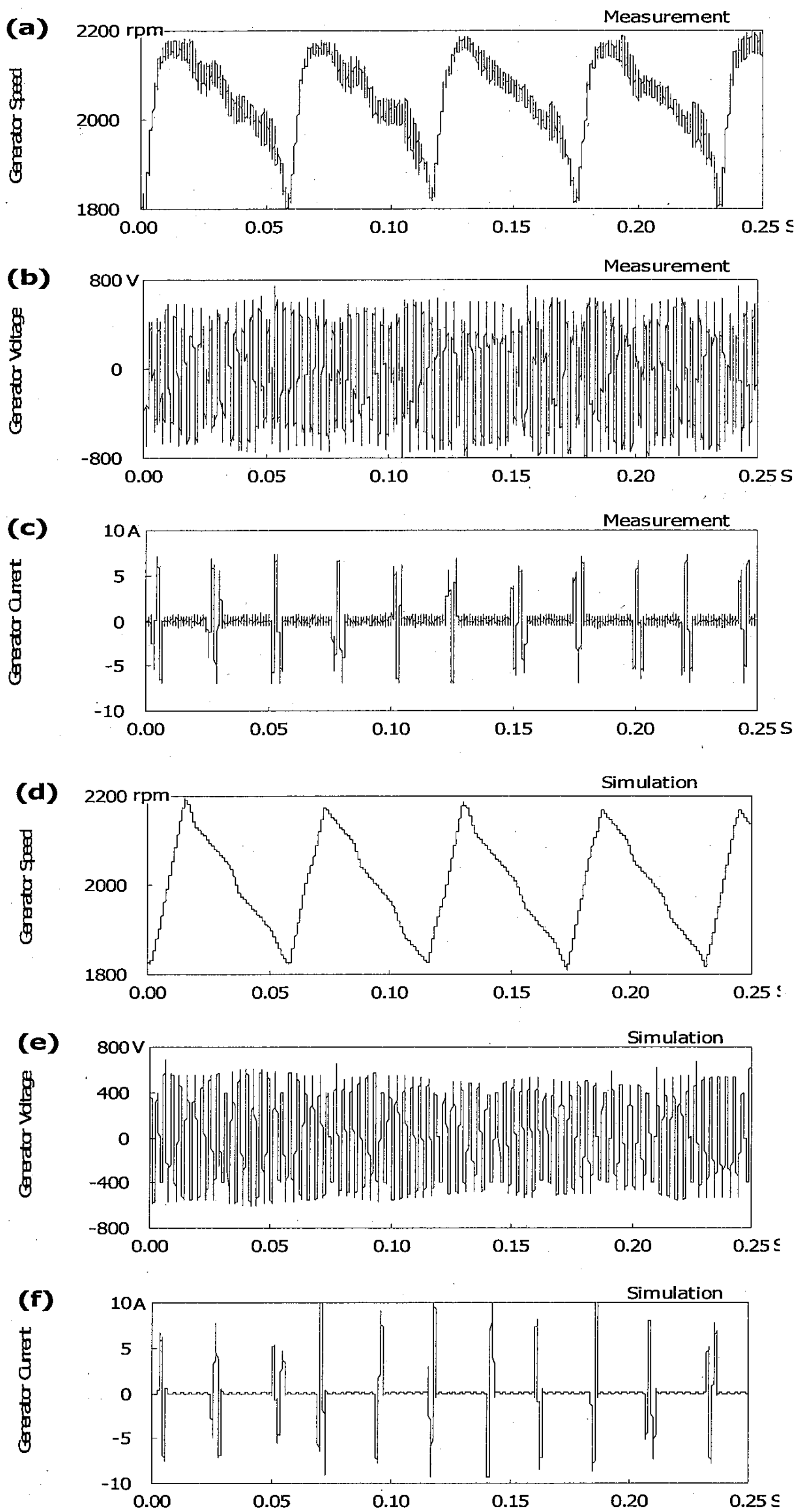


Fig. 2.7 Comparison of measurement and simulation results. (a) GECS speed (measurement) (b) generator output line to line voltage (measurement) (c) generator phase current (measurement) (d) GECS speed (simulation) (e) generator output line to line voltage (simulation) (f) generator phase current (simulation)

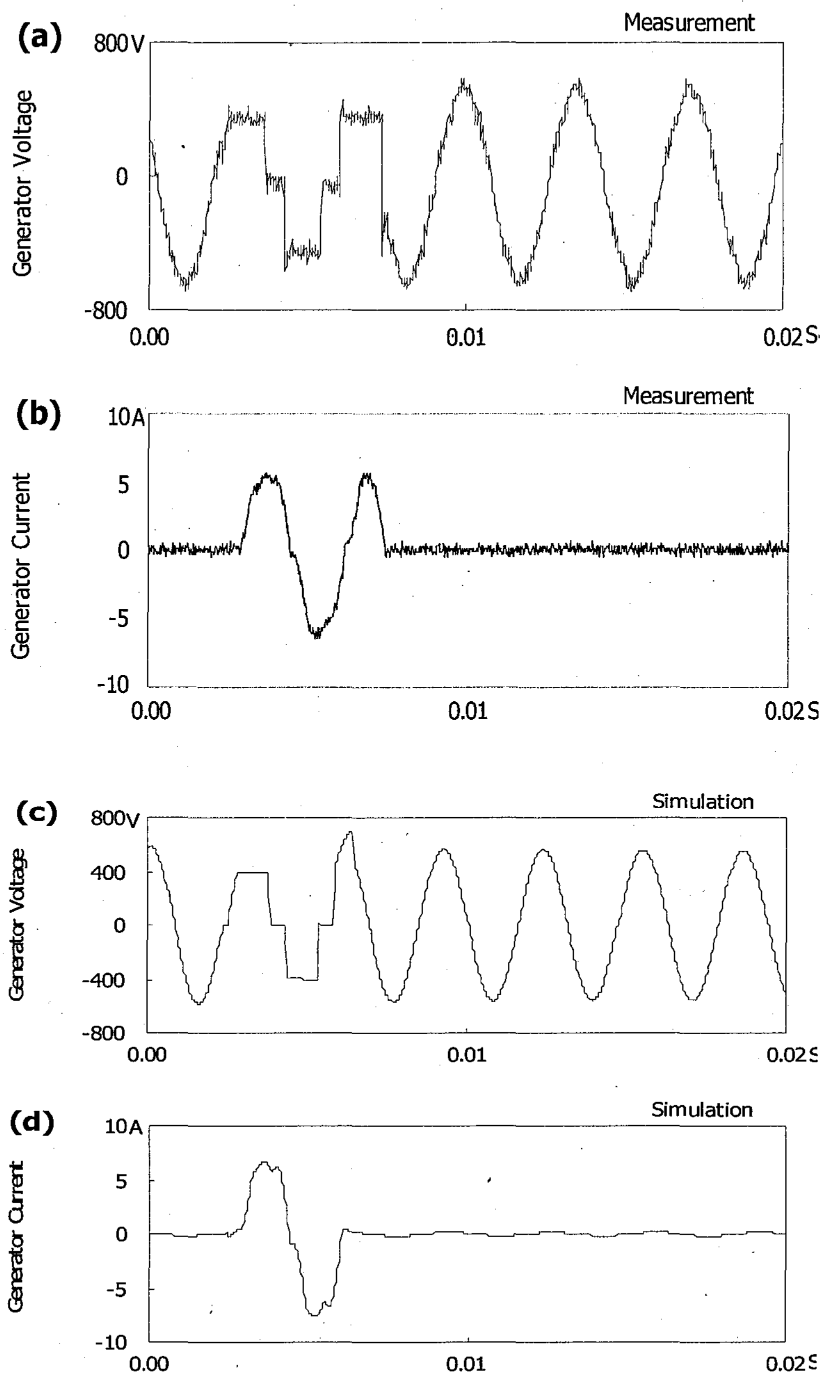


Fig. 2.8 Expansion of generator voltage and current waveforms. (a) generator output line to line voltage (measurement) (b) generator phase current (measurement) (c) generator output line to line voltage (simulation) (d) generator phase current (simulation).

Simulation and experimental results are shown in Fig.2.7 and Fig.2.8. Fig 2.7(a) is the measured rotational speed of the GECS. Figs 2.7(b) and (c) are generator line to line voltages and line current by measurement. Figs 2.7(d), (e) and (f) are simulation results of the rotational speed, generator voltage and current respectively. Fig. 2.8 shows extended figures of generator voltage and current.

As the GE has only one cylinder, output torque is generated for each two rotation cycles, which means the torque is generated around every 58.5 ms. Torque pulsation causes the speed pulsation in the GECS. Therefore, GECS speed also has pulsation around every 58.5 ms as shown in Figs 2.7(a) and (d).The speed pulsation also causes the variation of voltage value as Figs 2.7(b) and (e). Since the rectifier in the ac/dc/ac converter is a half controlled type configuration, when the dc-link voltage is higher than a threshold value, thyristors are turned off and there is no current flowing during this period. In this period the generator output voltage has a perfect sinusoidal waveform. When the dc-link voltage is lower than the threshold value, thyristors are turned on and power flows from the generator during this period. During this period, the generator output voltage is limited by the threshold voltage. Figs 2.7 (c) and (f) show the measurement waveform and simulation waveform of generator output current respectively. It can be seen that the sinusoidal current flowed intermittently.

Detail waveforms of generator voltage and current can be found in Fig.2.8. Fig.2.8 clearly shows that when there is no current, the generator voltage has sinusoidal waveform. When there is current, which means thyristors are turned on, the maximum value of generator voltage equals to the threshold value of dc-link.

From Fig. 2.7 and Fig. 2.8, it can be concluded that experimental and simulation results have good match in their characteristics. Therefore, the numerical models built for GE and PMSG can well demonstrate their real characteristics. Thus, they can be applied in PHIL simulation and interfaced with a real MC to behalf a real GE and PMSG.

2.4. PHIL Simulation for Gas Engine Cogeneration System with Matrix Converter

2.4.1 Power Hardware-in-the-loop Simulation

In this research, to test a real MC proposed for the GECS, a power hardware-in-the-loop (PHIL) simulation is carried out. In this PHIL simulation, the GE and PMSG are represented by their numerical models and the real MC, together with its controller, is interfaced with the simulation of GE and PMSG.. It is obviously that numerical models must represent characteristics of real GE and PMSG in a real time (RT) condition, otherwise, the test of MC will lose meaning. In comparison to conventional non real time simulation, RT simulation poses strict demand on calculation speed. Generally, a combined set of advanced hardware and comprehensive software is necessary to achieve a RT simulation. PHIL simulation does provide salient advantages such as: (1) the MC can be tested thoroughly and repeatedly even real GE and PMSG is unavailable. (2) the MC can be tested with borderline conditions such as that GE-PMSG are broken. Nevertheless, there are three main challenges for this PHIL simulation:

(1) A power amplifier is adopted to realize real power exchange between the MC and simulated GE and PMSG. The unavoidable problems, such as time delay, limited frequency band, noise injection, etc, may cause the PHIL simulation instability even the real system shown in Fig. 2.2 is stable.

(2) Since the sampling time of the test MC controller is 100 μs, the computational time of the simulated part should much lower than this value. This requirement is posed by the reason that the computational time add a delay in the closed loop of PHIL simulation and if it is too large, the PHIL simulation may diverge from real GECS with a MC (shown as Fig. 2.2) or may even lose its stability due to the delay. At the time when this paper is writing, there is still no report about successful implementation of PHIL in power system simulation with the time delay less than 50 μs.

(3) Almost all analysis of PHIL simulation presented previously used simple model, in which the simulation part was represented by a resistor and the real hardware consisted of a resistor and an inductor.[5],[7],[8] However, the simulation part of this PHIL is GE and PMSG and the real part is MC including a controller and a filter, which means that the PHIL presented in this paper is an inductor coupled system. Although most power system are inductor coupled system, such as 1) an AC electric drive system consisting of AC motor, an inverter, transformer and 2) a distribution system consisting of power converter, transformer and transmission line, etc., the reports about stability and accuracy of PHIL simulation of inductor coupled system are still very limited. Therefore, the experience obtained by this PHILs can be applied to many of power system.

2.4.2 Software Preparation for the Hardware-in-the-loop Simulation

The GE and PMSG models were made in Simulink/SimPowerSystem, which is a powerful, graphical interfaced, modeling and simulation tool contained in MATLAB. Although having well performance for off-line simulation, it does have limitation to achieve real-time performance of the simulated components. For example, the traditional approach for Simulink to resolve high frequency components in power electric circuits is to use a variable step solver. However, the fundamental constraint of real-time simulation is that the model must use fixed-step integration solvers. When changing the variable time step to fixed time step in simulink, errors will be introduced unavoidably. In this research, to achieve the RT simulation of GECS, a real-time toolbox ARTEMIS was adopted. ARTEMIS integrates fully with simulink/SimPowerSystem. It introduces innovative fixed-step solvers and efficient computational techniques which improve both computational speed and calculation accuracy. It differs from simulink in the point that it pre-computes all the system matrix of switching conduction states before the beginning of the real time loop. [9]

In this research, an ARTEMIS guide block was added to the Simulink/SimPowerSystem, the model of GECS, which implements the discretization method and algorithms of the ARTEMIS add-on in simulink. The use of ARTEMIS helps to develop this RT-simulation with improved calculation speed and accuracy. The modified model which is implemented in teal time simulation is shown as Fig. 2.9.

2.4.3 Simulation Platform

In this PHIL simulation system, an integrated RT simulation platform, RT-LAB, is adopted to carry out calculation. RT-LAB simulator works with MATLAB/simulink, using ultra-fast processors, the best available inter communication technology and FPGA-based I/Os. This simulator achieves real-time performance by distributing models to across multi-processor targets.

Table 2.4 shows the main structure of RT-LAB simulator. CPUs and FPGA can provide parallel calculation of the GE and PMSG models, which can provide fast calculation speed. The Opal-RT OP5110 family of I/O cards is used. Opal-RT OP5110 FPGA based I/O cards feature 100 nanosecond digital in and digital out, 2 microsecond A/D converter and 1 microsecond D/A converter. Both the fast FPGA based I/O access and A/D, D/A converter contribute to make calculation speed fast , hence short time step size in the simulation.

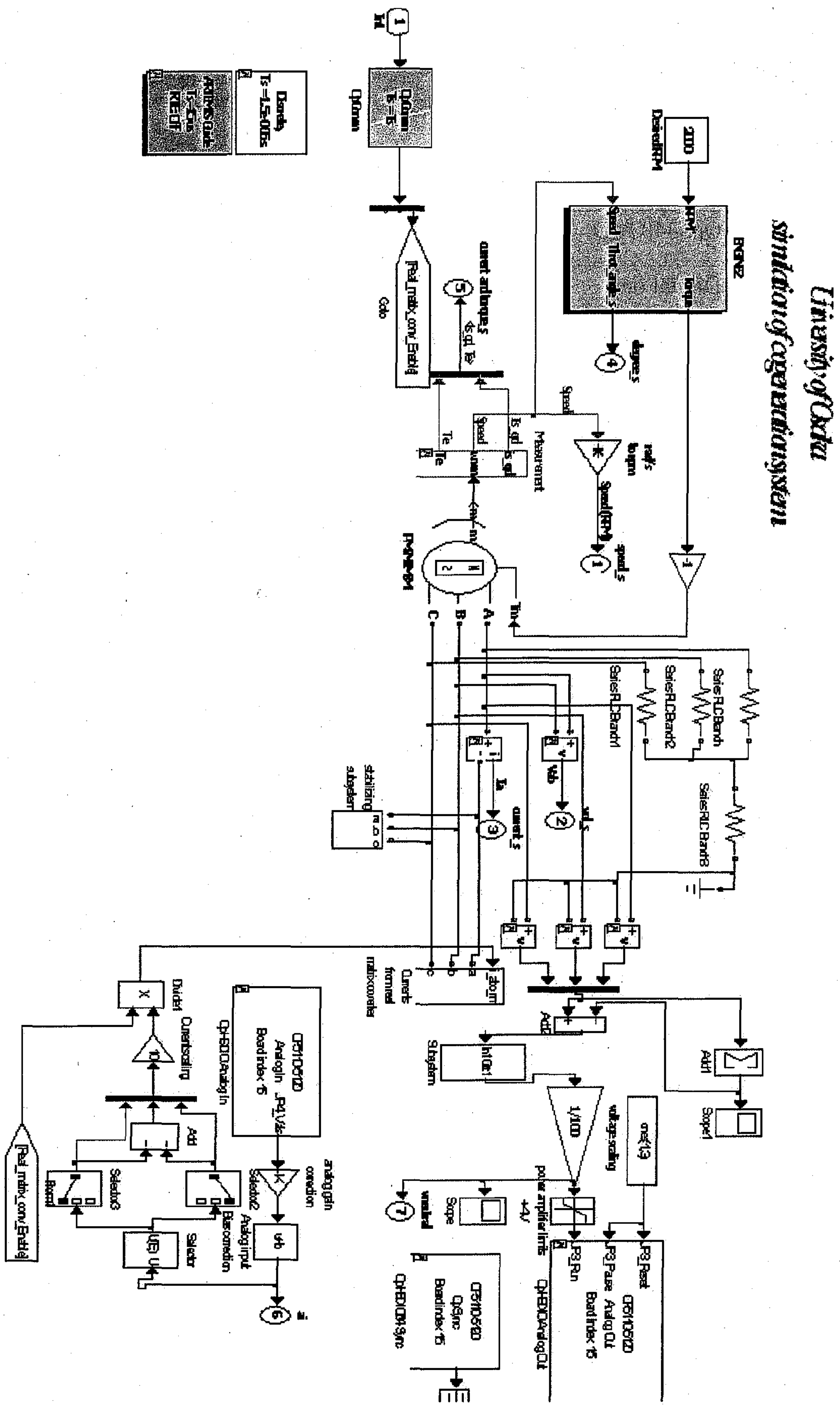


Fig. 2.9 Modified model of GE and PMSG implemented in real time simulation

Table 2.4. Structure of OPAL-RT Simulator

CPU	three , Intel Core 2 Quad, 2.66GHz
FPGA	one, VirtexIIpro
Op5330 D/A	16 channels, 16bits,1 μs
Op5340 A/D	16 channels, 16bits,2 μs
Digital out	32 channels, 100 ns
Digital in	32 channels, 100 ns

2.4.4 Configuration of the PHIL Simulation

PHIL simulation is able to be carried out in different ways according to the type of the exchanged signal and the selected power interface between simulated part and real part of the investigated system. In this PHIL simulation, the modified models of GE and PMSG using ARTEMIS were built and compiled by host computer and then downloaded to RT-LAB target processors. The signals of the PMSG output voltage were transferred to a power amplifier via the D/A converter. The power amplifier, working as a voltage gain, received the voltage signals, amplified the voltage signals and then reproduced them as a physical voltage to drive the real MC, which was the hardware under test (HUT) in this PHIL simulation. The currents of the MC in the three phase side were measured and fed back to the simulator via the A/D converter. This type interface method between simulated part and real part of the PHIL simulation is called voltage type ideal transformer model (ITM). According to ref [5], ITM interface method was chosen for its high simulation accuracy. The concept of this PHIL built for the GECS is shown as Fig. 2.10 and the configuration of it is shown in Fig.2.11. Fig. 2.11 clearly indicates that this system is a closed loop system.

Parameters of the power amplifier used in this research are shown in Table 2.5. It is a class-A amplifier. The capacity of the power amplifier is 6 kVA and the maximum response frequency at rated power is 1.1 kHz. Therefore, it is applicable for this research because the rated power of the GECS is 1 kW and the frequency of the PMSG output is 307.5 Hz. Moreover, the phase delay of the power amplifier can be neglected in the bandwidth of 5-1.1kHz according to the maker.

Table 2.5. Rated value of the power amplifier

Rated power	6 kVA
Rated output voltage	100Vrms, 200Vrms
Output voltage range	0-144Vrms, 0-288Vrms
Maximum output current	20Arms, 10Arms
Output frequency	5Hz-1100Hz

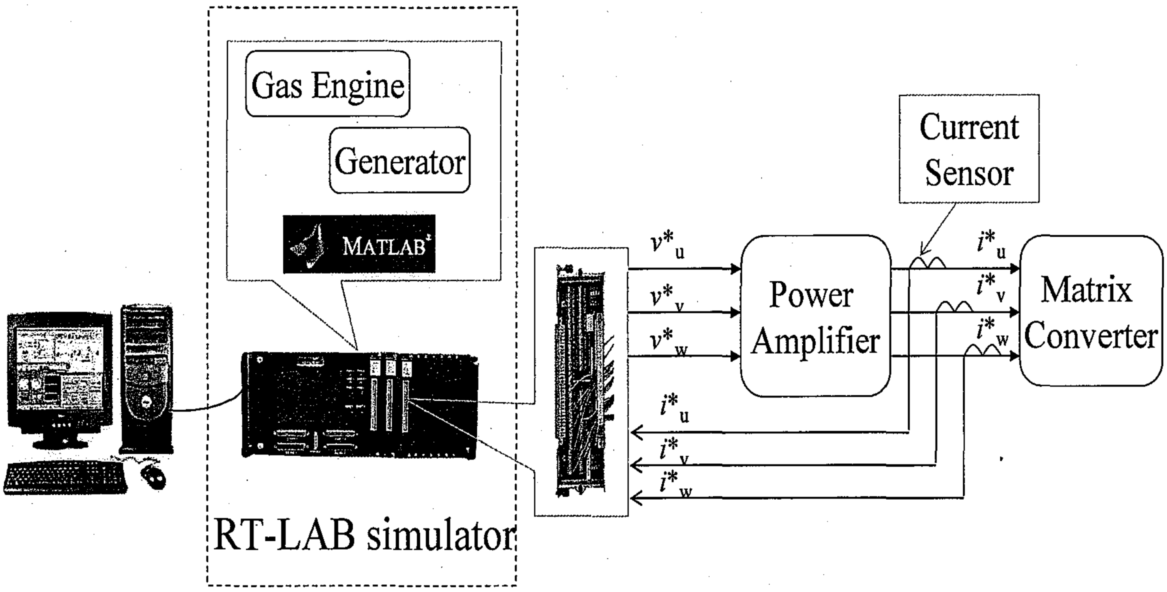


Fig.2.10 Concept of the PHIL built for GECS

Fig.2.12 is about the control block diagram of the MC. Detail description of it can be found in ref [3]. Because the sampling time for control of the MC is 100 μs, the time step size of the PHIL simulation should be less than it. As mentioned before, the PHIL may become unstable even the original system shown in Fig.2.2 is stable due to the introduced power amplifier and current sensor. Therefore, in the configuration of the PHIL simulation, there was a gain in the feedback current circuit to control the value of the measured current as shown in Fig. 2.11. This gain was added to test and analyze the stability problem of this PHIL simulation system. It is

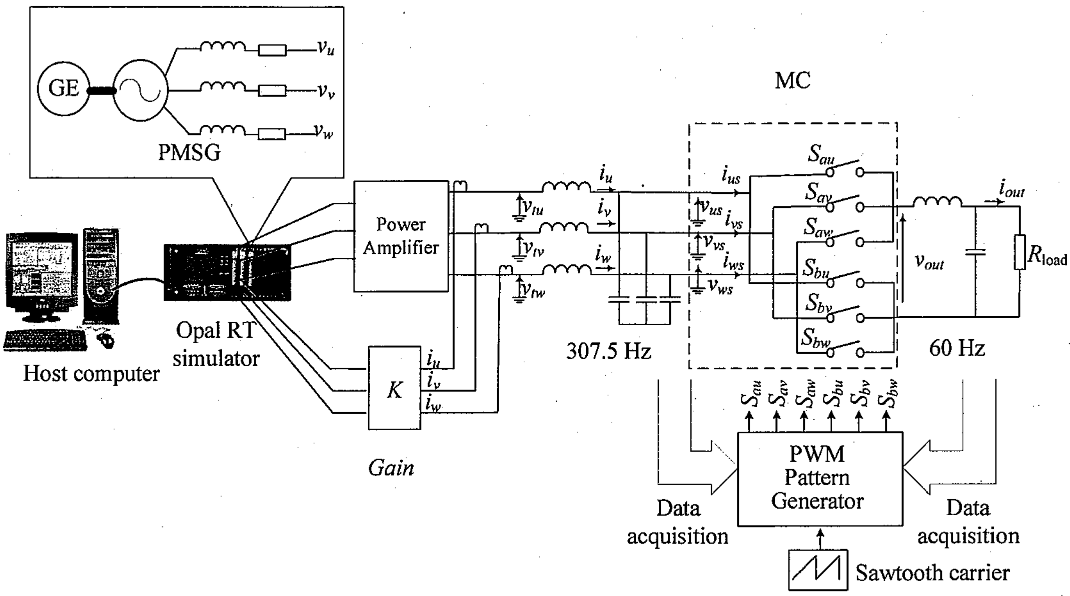


Fig. 2.11 Configuration of the PHIL simulation.

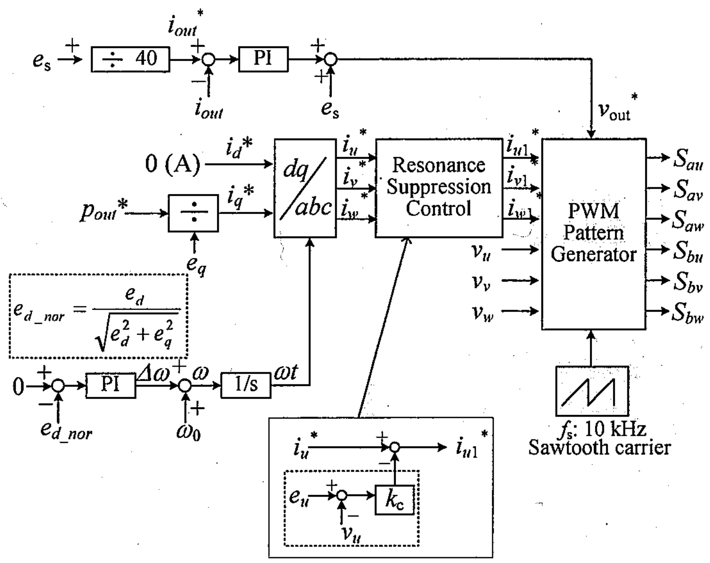


Fig. 2.12 Control block diagram of the matrix converter.

clear that only when the gain equals to 1 means an expected PHIL simulation is realized. When the PHIL simulation is carried out, the gain should be increased carefully to avoid the occurrence of PHIL instability which may destroy the hardware under test.

This PHIL is an inductor coupled system. In comparison to the PHIL in which simulation part is only consists of a resistor, this type PHIL has more critical stability problem. The stability of PHIL not only is determined by time delay in the closed-loop but also by the relationship of inductance values in the simulation and real part respectively. Detailed stability analysis of this PHIL is discussed in the next chapter 3. [10].

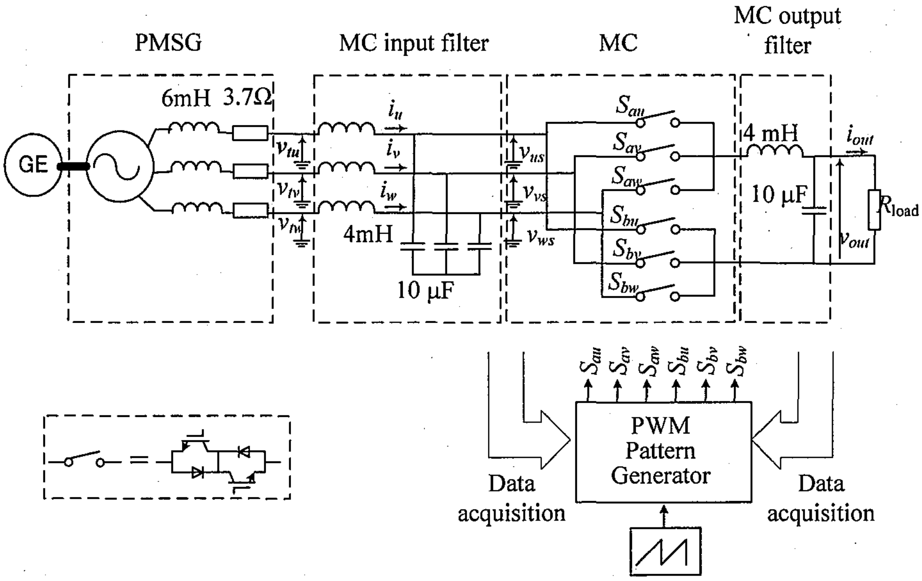


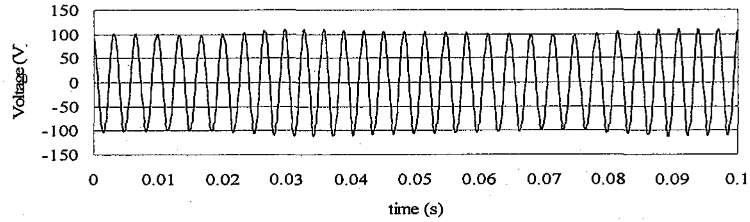
Fig.2.13 Configuration on the GECS with matrix converter

Table 2.6. Parameters used in PHIL

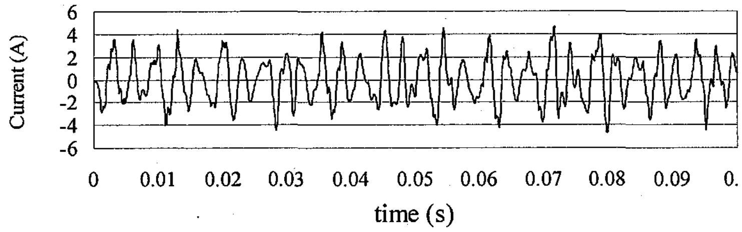
Input filter	L_{in}=4 mH,C_{in}=10 μF
Output filter	L_{out}=4 mH, C_{out}=10 μF
Load resistor	18 Ω
Carrier frequency	10 kHz
Gain of the resonance suppression control	0.01
Input voltage of the MC	66-78 V
Output voltage of the MC	60 V
Output power of the MC	230 W

2.4.5 Results of PHIL Simulation

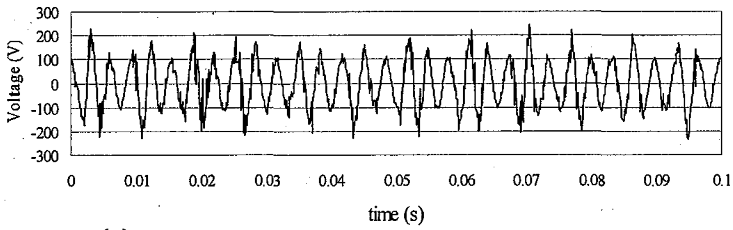
PHIL simulation of the system shown in Fig.2.13 was carried out. Due to the combined advanced software and simulator, the achieved time step size without calculation overrun of this PHIL was 15 μs, which can satisfy the demand of MC controller. Furthermore, results from refs. [7] and [10] show that this short time step size also benefits high accuracy and stability of PHIL simulation. Conditions of the PHIL simulation are summarized in Table 2.6 and results of PHIL are shown in Fig.2.14. The gain in the feedback current circuit of Fig. 2.11 equals to 0 means open loop control of the PHIL simulation. The results of this case are shown in Figs 2.14 (a) and



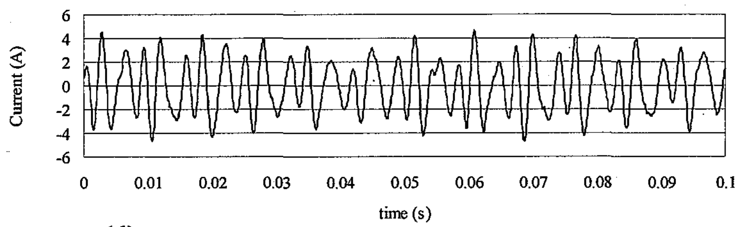
(a) output voltage of power amplifier v_{tu} (K=0)



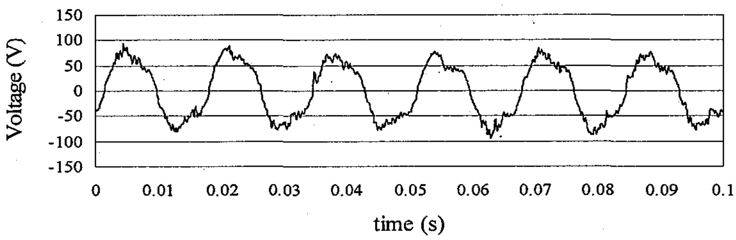
(b) output current of power amplifier i_u (K=0)



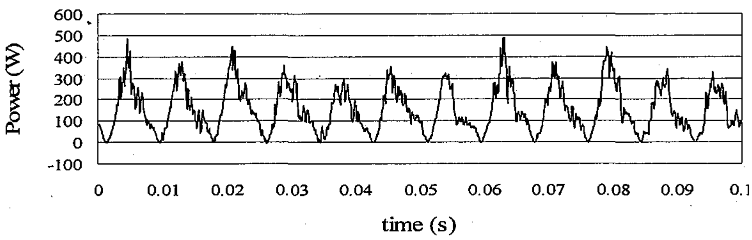
(c) output voltage of power amplifier v_{tu} (K=1)



(d) output current of power amplifier i_u (K=1)



(e) matrix converter output voltage v_{out} (K=1)



(f) matrix converter output power (K=1)

Fig.2.14 PHIL Simulation results. (a) output voltage of power amplifier (K=0) (b) output current of power amplifier (K=0) (c) output voltage of power amplifier (K=1) (d) output current of power amplifier (K=1) (e) output voltage of MC (K=1) (f) MC output power (K=1) (b), which are the voltage waveform and current waveform measured on the output side of the power amplifier, respectively. It can be concluded that without feedback current, the voltage has a perfect sinusoidal waveform and the value changes slightly due to speed pulsation caused by the engine torque pulsation.

Fig.2.14 (c) is the voltage waveform of the output of the power amplifier when the gain equals to 1, which means that the measured current value is fed back to the simulation part of the PHIL. Fig.2.14 (b) shows that the output current of the power amplifier, which is also the MC input current, was modulated synchronously with single phase power pulsation by the MC. Comparing Figs.2.14 (a) and (c), it is clear that modulation of MC input current has substantial feedback influence on output voltage of the power amplifier, which in an ideal condition is also the voltage of the generator output voltage. This influence was caused by the voltage drop when the current flowed through the internal impendence of the generator. Comparing Figs. 2.14 (b) and 2.14(d), it can be concluded the MC input current has little relationship with the value of feedback current and merely affected by the MC modulation.

Figs.2.14 (e) and (f) are the voltage and power waveforms measured on the MC single phase side. The frequency of the single phase side was 60 Hz. The waveform of the voltage was sinusoidal with distortions. Because the load of the MC output was a pure resistor, the current had similar waveform to voltage. Therefore, the waveform of output power of the MC also had obvious distortions. This distortion is caused by the commutation of switches and will be improved by modulation technology and commutation control in the following research. However, even under adverse conditions that GE torque had pulsation and input voltage was fluctuated, the stable operation of MC was demonstrated. As a result, the proposed application of MC in GECS was verified.

2.5. Summary

Advanced RT simulation as a power HIL simulation was carried out in this research to verify the application of the MC to the GECS, which was proposed to substitute a conventional ac/dc/ac converter to improve the efficiency.

The following achievements were made in this chapter:

1) Numerical models of GE and PMSG were constructed based on

MATLAB/Simulink/SimPowerSystem and verified through the comparison of simulation and actual measurement results.

2) The models were modified to meet the needs of real time simulation by using software as ARTEMIS. Then, the configuration of a PHIL simulation, in which MC was the device under test, was constructed. The PHIL simulation was successfully carried out and the minimum time step size achieved without overruns of calculation was 15 μs.

3) Through the RT simulation, stable operation of MC with proposed power factor control was demonstrated. As a result, the possibility of applying the proposed MC in a household type GECS, which was aiming to improve GECS efficiency, was verified.

References

[1] K. Furusawa, K. Yanase, H. Sugihara, K. Tsuji: "A cooperation with customer-side cogeneration systems for power flow congestion relief and its environment impact", IEEE, Power Engineering Society General Meeting, pp. 8 –15, (June, 2006).

[2] Y. Miura, S. Kokubo, D. Maekawa, and T. Ise: "Efficiency Improvement of a Gas Engine Cogeneration System by Power Factor Control with an IGBT Rectifier". Proceedings of the Power Conversion Conference (PCC), Nagoya, 2007, pp. 534-541, (April, 2007).

[3] Y. Miura, S. Kokubo, D. Maekawa, S. Horie, T. Ise, T. Momose and Y. Sato: "Power Modulation control of a Three Phase to Single Phase Matrix Converter for a Gas Engine Cogeneration System". 39th IEEE Annual Power Electronics Specialist Conference (PESC), Greece, 2008, pp: 2704-2710, (June, 2008).

[4] S. Abourida, J. Belanger, C. Dufour: "High Fidelity Hardware-in-the-loop Simulation of Motor Drives with RT-LAB and JMAG",2006 IEEE International Symposium on Industrial Electronics, Vol. 3, Issue, 9-13, pp. 2462-2466 (July, 2006).

[5] W. Ren, M. Steurer, T. L. Baldwin, "Improve the Stability and the Accuracy of Power Hardware-in-the Loop Simulation by selecting Appropriate Interface Algorithms" IEEE/IAS, Industry & Commercial Power Systems Technical Conference (ICPS), 2007,

pp.1-7(May 2007).

[6] P. R. Crossley, J. A. Cook, "A nonlinear engine model for drive train system development", International conference of control 1991 (Control apos, 91), Vol.2, pp.921-925, (March, 1991).

[7] W. Ren, M. Steurer, S. Woodruff: "Accuracy Evaluation in Power Hard-ware-in-the-Loop (PHIL) simulation" Proceedings of the 2007 summer computer simulation conference, pp.489-493 (2007).

[8] X. Wu, S. Lntijo, A. Deshmuk; A. Monti, F. Ponci, "Design and implementation of a power-hardware-in-the–loop interface: a nonlinear load case study," IEEE Twentieth Annual Applied Power Electronics Conference and Exposition (APEC), 2005, Vol. 2, pp.1332-1338 (March, 2005).

[9] Reference for RT-LAB "www.opal-RT.com".

[10] M. Hong, S. Horie, Y. Miura, T. Ise, C. Dufour, " A Method to Stabilize a Power Hardware-in-the-loop Simulation of Inductor Coupled System" International Conferrence on Power System Transients (IPST 2009), issue.239, (June, 2009).

Chapter 3 Stability and Accuracy Analysis of Power Hardware-in-the-loop Simulation of Inductor Coupled System

3.1. Introduction

As mentioned previously, hardware-in-the-loop (HIL) simulation is widely used in power system fields due to the great progress of computer technology [1], [2]. In comparison to conventional off-line simulation, HIL simulation provides advantages such as more reliability, lower cost, design efficiency, etc. Nevertheless, most HIL simulations in power system are controller hardware-in-the-loop (CHIL) simulation. Presently, the concept of HIL simulation is extended to test power components other than controllers, for example, generator, power converter, etc. In these cases, transferred signals are high power level (kV, kA) and HUTs absorb/generate power, which demands that real power be exchanged between the simulation part of HIL system and actual HUTs. Therefore, proper power interfaces are necessary. This is so called power HIL (PHIL) simulation. Different configurations of CHIL and PHIL simulation are shown in Fig. 1.2. Obviously, PHIL simulation brings new challenges and extends the application of HIL simulation. However, there are two obstacles which severely limit its development: calculation accuracy and stability issue.

Calculation accuracy is the primary consideration for all HIL simulation, otherwise, the simulation results may lose meaning. According to ref. [3], the accuracy of PHIL simulation is severely affected by the time delay which mainly arises from the computation time of the simulation and the time caused by A/D, D/A converters. However, practical time step size achieved in PHIL simulation rarely goes beneath 50 μs even with GHz-speed processor because of reasons such as I/O delay, communication latencies and solving methods [2]. The large time step size does not only cause inaccuracy of results but also may cause the PHIL simulation failure. For example, if the power devices under test have a sampling frequency of 20 kHz, any step size longer than 50 μs will make the PHIL simulation a futile effort.

The other obstacle which constricts the development of PHIL simulation is the problem of closed-loop instability. Even the investigated real system is stable, the PHIL simulation for it may lose stability due to the inevitable issues such as time delay, harmonic injection, limited bandwidth, etc. The instability problem must be treated seriously; otherwise, it may cause critical damage to the HUT.

There are some trials and analyses on the PHIL simulation [4], [5], [6]. In ref. [4], an implementation of a PHIL simulation is described. However, there is no analysis about the stability. Papers [5] and [6] both mention that the instability of PHIL simulation is caused by the sampling frequency of the power interface. The conclusion only addresses the interface performances while neglects the fact that PHIL simulation is a closed-loop system. In ref. [7], different interface algorithms for PHIL simulation are proposed and compared. It indicates that the interface algorithm has serious influence on the accuracy and stability. Nevertheless, authors simply mention that the stability of PHIL simulation depends on the magnitude of the open loop transfer function and provides no detail analysis. Furthermore, the analysis uses very simple model, in which the simulation part is represented by a resistor and the real hardware consisted of a resistor and an inductor. The model is relatively simple and results may be insufficient for PHIL simulation which has more complicate construction.

This chapter focuses on the stability issue of the PHIL simulation of inductor coupled systems and a method to improve stability without deteriorating simulation accuracy is proposed and verified.

3.2 Stability Analysis of the Power Hardware-in-the-loop Simulation

3.2.1 Configuration of the Power Hardware-in-the-loop Simulation

To investigate the stability problem of the PHIL of inductor coupled system, a simple PHIL simulation shown in Fig. 3.1 is considered as an example. In Fig.1, since both the simulated part and the real hardware consist of an inductor, the results obtained by it can represent the inductor coupled systems in power system. In this PHIL, a voltage source V_s and the source resistor R_1, inductor L_1 are simulated by a real time digital simulator, while the HUT is a linear load consisting of a resistor R_2, an inductor L_2 and a capacitor C_2. Signal of output voltage V_1 is transferred to a power amplifier through a D/A converter. The power amplifier receives the

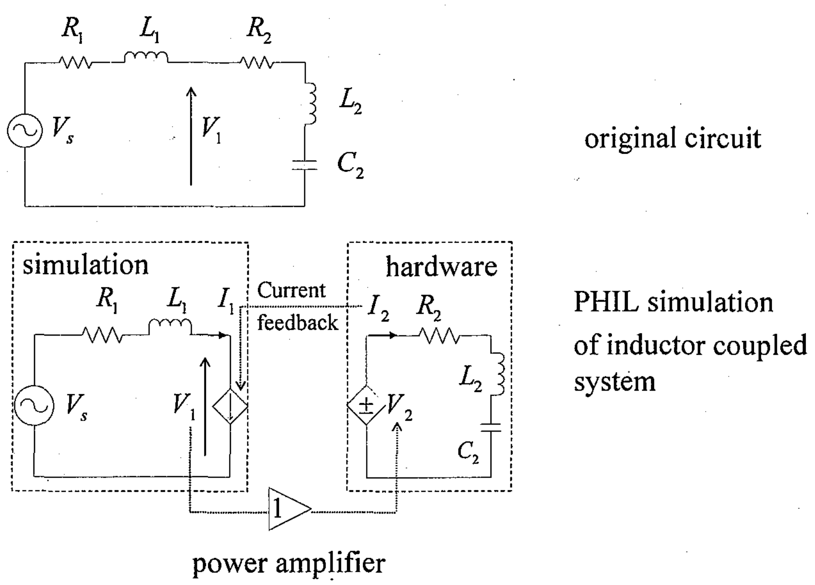


Fig. 3.1 Simple example of a PHIL simulation of inductor coupled system.

voltage signal and reproduces it as a physical voltage, V_2. Then, the voltage V_2, working as a controlled voltage source, is supplied to the real load as power source. On the other hand, the actual current I_2 of the real impedance is measured and fed back to the simulation part as a controlled current source (I_1) through an A/D converter. This type interface algorithm is called ideal transformer model (ITM) which is widely used in PHIL simulation due to its high accuracy. [7]

It is obvious that under an ideal situation, voltage V_2 should equal to V_1 and I_1 should equal to I_2. However, this ideal situation can not be realized due to the non-ideal of interface. Assuming that all signals are transferred ideally except the introduced time delay in the PHIL simulation, following equations can be obtained:

$$V_2 = V_1 e^{-T_{d1}s} \tag{3.1}$$

$$I_1 = I_2 e^{-T_{d2}s} \tag{3.2}$$

T_{d1} is the delay time of the forward loop which mainly introduced by numerical calculation time of simulation in a PHIL, D/A converter, time delay of power amplifier. T_{d2} is the time delay

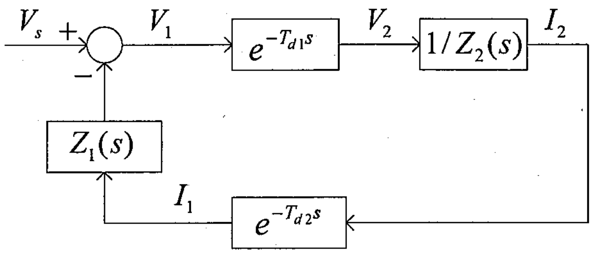


Fig. 3.2 Block diagram of PHIL simulation.

of feedback loops and is mainly introduced by an A/D converter. Then, the block diagram of the PHIL can be drawn as Fig. 3.2, where $Z_1(s)$ and $Z_2(s)$ are transfer function of simulation part and real part and can be expressed by following Eqs. (3.3) and (3.4).

$$Z_1(s) = R_1 + sL_1 \tag{3.3}$$

$$Z_2(s) = R_2 + sL_2 + \frac{1}{sC_2} \tag{3.4}$$

The open loop transfer function $G_0(s)$ of the PHIL simulation can be presented by (3.5):

$$G_0(s) = \frac{Z_1(s)}{Z_2(s)} e^{-T_d s} \tag{3.5}$$

where $T_d = T_{d1} + T_{d2}$ and it is the whole time delay in the PHIL simulation. Typically, if there were no time delay, Eq. (3.5) can be presented by Eq. (3.6).

$$G_0(s) = \frac{Z_1(s)}{Z_2(s)} \tag{3.6}$$

3.2.2 Stability Analysis of the PHIL Simulation

Characteristic equation of the system in Fig. 3.2 can be described as Eq. (3.7).

$$1 + \frac{Z_1(s)}{Z_2(s)} e^{-T_d s} = 0 \tag{3.7}$$

To simplify the analysis, $e^{-T_d s}$ is represented by first order Pade approximation:

$$e^{-T_d s} = \frac{1 - T_d s/2}{1 + T_d s/2} = \frac{-s + a}{s + a} \quad a>0 \tag{3.8}$$

where, a is a constant defined by the time delay T_d. (a=2/T_d) It should be noted that a larger T_d corresponds to a smaller value of a and vice versa. Substituting Eqs. (3.3), (3.4) and (3.8) to (3.7), Eq. (3.9) can be obtained:

$$(L_2-L_1)C_2s^3+(R_2-R_1+aL_1+aL_2)C_2s^2+(1+a(R_1+R_2)C_2)s+a=0 \quad (3.9)$$

Applying Routh rule to Eq. (3.9), Eqs. (3.10), (3.11) and (3.12) must be satisfied to keep the system stable:

$$L_2 > L_1 \quad (3.10)$$

$$a > \frac{R_1 - R_2}{L_1 + L_2} \quad (3.11)$$

$$a^2(R_1+R_2)(L_1+L_2)C_2+a(2L_1+R_2^2C_2-R_1^2C_2)+(R_2-R_1)>0 \quad (3.12)$$

It should be noted that the pade approximation of the time delay is carried out around operation point of the system and the following results are also valid for the operation points. From Eqs. (3.10), (3.11) and (3.12), following statements can be concluded:

(1) To keep the stability of the inductor coupled PHIL simulation, the real inductor must be larger than the simulated inductor.

(2) The constant a, which is determined by the time delay T_d, also has effect on the simulation stability. According to Eqs. (3.11) and (3.12), a smaller time delay, which means a larger value of a, benefits to the PHIL stability. On the contrary, a larger time delay will imposes more critical request on the impedance value. Detail relationship of the time delay and the value of impedance which can maintain PHIL simulation stability can be calculated from Eqs. (3.11) and (3.12).

3.2.3 PHIL Simulation to Verify the Analysis of the Stability

3.2.3.1 An inductor coupled PHIL simulation system

To verify conclusions in the previous section, a PHIL simulation illustrated in Fig. 3.3 is carried out. As shown in Fig. 3.3, the PHIL simulation is a closed-loop system. In order to apply root locus method to analyze the stability of this PHIL simulation system and to analyze the stability of a PHIL simulation by using a quantitative method, a gain, K, is introduced

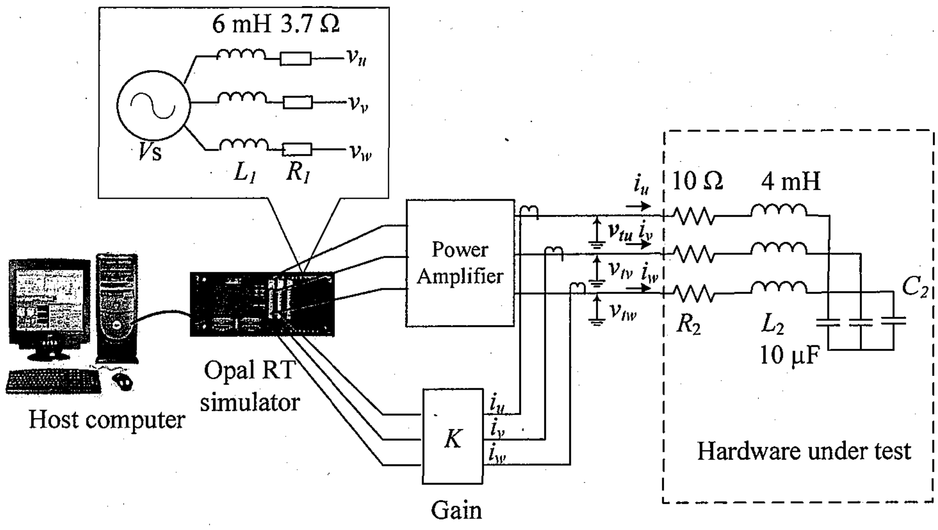


Fig. 3.3 a PHIL simulation of inductor coupled system.

intentionally in the feedback current loop for the following reasons. (1)By introducing the K, it is possible to evaluate the stable margin for the stable PHIL simulation. The value K_{smax} is also introduced to indicate the maximum value of K by which stability can be achieved in a PHIL. The K_{smax} should be greater than "1" for successful PHIL simulation, because the results with K=1 is meaningful as a PHIL simulation. Moreover, the difference between K_{smax} and 1 (K_{smax}-1) gives stable margin. The larger stable margin provides higher stable ability and more reliable simulation results. (2) When a PHIL simulation is carried out, the K must not be set as "1" from the beginning. It should be increased from "0" to "1" step by step with cautious to avoid unanticipated instability which may destroy the hardware of the system.

In this PHIL simulation system, an integrated real time (RT) simulation platform, RT-LAB, is adopted to carry out calculation. RT-LAB simulator works with MATLAB/simulink, using ultra-fast processors, the best available inter communication technology and FPGA-based I/Os. This simulator achieves real-time performance by distributing models to across multi-processor targets.

The main structure of RT-LAB simulator is as table 2.4 and detail description of it can also be referred to the chapter 2.

Parameters of the circuit in the PHIL are summarized in table 3.1.

Table 3.1. Circuit constant

R_1	3.7 Ω
L_1	6 mH
R_2	10 Ω
L_2	4 mH
C_2	10 μF

In this PHIL simulation, since the time delay is as short as 15 μs, the constant a is as high as about 1.33×10^5. Therefore, Eqs. (3.11) and (3.12) are both satisfied. However, because the simulated inductor is 6 mH and the real inductor

is 4 mH, which means Eq. (3.10) is not satisfied, the system is unstable. In fact, this PHIL simulation loses stability when the value of the gain K is larger than 0.67.

3.2.3.2 Fundamental cause for instability

If there were no time delay in the PHIL simulation, the open loop transfer function of the PHIL simulation of Fig. 3.3 can be presented as:

$$G_0(s)=\frac{Z_1(s)}{Z_2(s)}=\frac{6s^2+3700s}{4s^2+10000s+10^8} \tag{3.13}$$

Considering the time delay, which is mainly caused by computation time and A/D, D/A converter, the open loop transfer function can be written as Eq. (3.14):

$$G_0(s)=\frac{Z_1(s)}{Z_2(s)}e^{-T_d s}=\frac{6s^2+3700s}{4s^2+10000s+10^8}e^{-T_d s} \tag{3.14}$$

where, T_d = T_{d1} +T_{d2}=15 μs, which mainly includes time step of the calculation of the simulator(12 μs), A/D and D/A converter shown in table. 2.4.

The block diagram of PHIL simulation in Fig. 3.3 is drawn as Fig 3.4, where K is the value of gain in the current feedback loop. Fig. 3.5 is the root locus figure for this closed-loop system if the system has no time delay (T_d=0). Fig. 3.6 is the root locus figure when the time delay of this system is 15 μs. Fig. 3.5 shows that the closed loop system should always be stable if there were

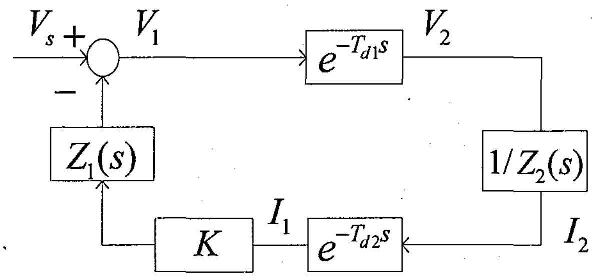


Fig. 3.4 Block diagram of the closed-loop PHIL simulation.

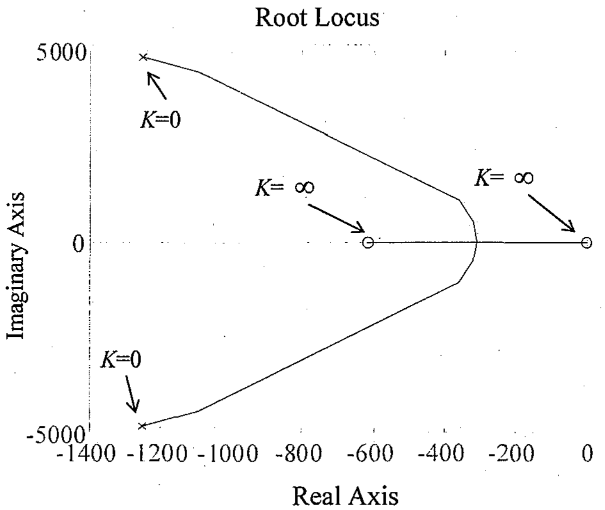


Fig. 3.5 Root locus figure of the closed-loop PHIL simulation without time delay.

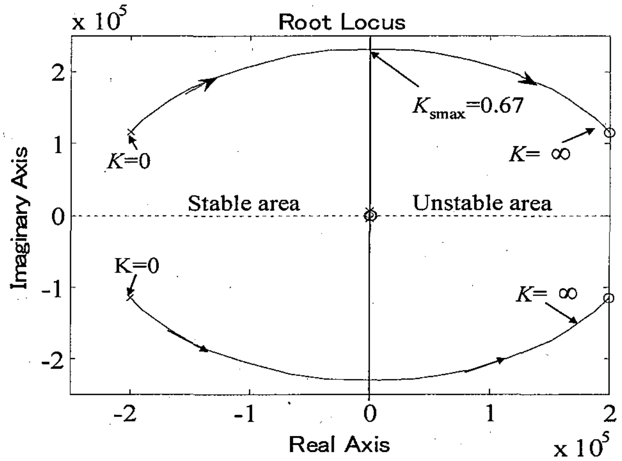


Fig. 3.6 Root locus figure of the closed-loop PHIL simulation with time delay.

no time delay, no matter what the value of the K is. However, Fig. 3.6 clearly indicates that, when time delay is considered, the system changes from stable state to unstable state with the increasing value of K. Fig. 3.6 also shows the maximum value of K which can keep the system stable, named as K_{smax}, is 0.67. Because only when K equals to1 means the measured current is fully fed back to the simulation part and a complete PHIL simulation is realized, the system of Fig. 3.3 is unstable. Obviously, the fundamental cause for the instability is the time delay, even it is as short as 15 μs.

3.2.3.3 Analysis of stable area

The characteristic equation of the system in Fig. 3.4 is:

$$1+K\frac{Z_1(s)}{Z_2(s)}e^{-T_d s}=0 \tag{3.15}$$

$$(L_2-KL_1)C_2s^3+(R_2-kR_1+aKL_1+aL_2)C_2s^2+(1+a(KR_1+R_2)C_2)s+a=0 \tag{3.16}$$

Considering the high value of a (1.33×10^5), together with values of R, C in table 3.2, the PHIL system in Fig. 3.3 can maintain stability under the following condition:

$$L_2 > KL_1 \tag{3.17}$$

Eq. (3.17) also means that the maximum value of the feedback gain (K_{smax}) which can maintain the stability of the PHIL simulation in Fig. 3.4 is determined by the following equation:

$$K_{s\max} = L_2 / L_1 \tag{3.18}$$

To verify Eqs. (3.17) and (3.18), experiments which had same configuration as Fig. 3.3 were carried out. Values of impedances used in the experiment are summarized in table 3.2 and results of experiments are shown in Fig. 3.7 and Fig. 3.8.

Table 3.2 Parameters for stability experiments

experiment	Case 1	Case 2	Case 3
R_1	3.7 Ω	3.7 Ω	3.7 Ω
L_1	3,4,5,6,7 mH	3,4,5,6,7,8 mH	3,4,5,6,7,8,9 mH
R_2	10 Ω	10 Ω	10 Ω
L_2	4 mH	6 mH	8 mH
C_2	10 μF	10 μF	10 μF

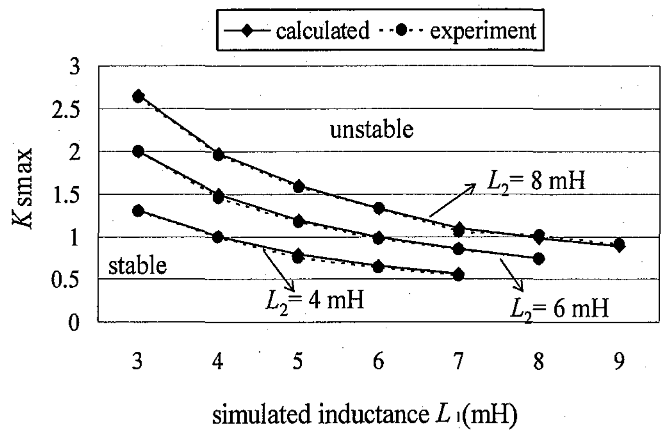


Fig. 3.7. Comparison of values of the K_{smax} calculated from Eq. (18) and obtained by experiment.

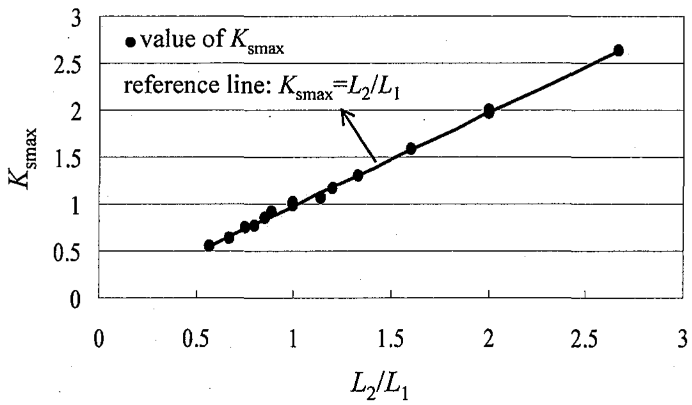


Fig. 3.8. Relationship of L_2/L_1 and the value of K_{smax} obtained by experiment.

Fig. 3.7 shows the comparison of K_{smax} calculated from Eq. (3.18) and K_{smax} obtained by experiment. The dashed line is obtained by the experiments and the solid line shows results of the calculation by Eq. (3.18). The below area of the line means a stable area for the PHIL simulation and the upper area means an unstable area. Fig. 3.8 shows the relationship of the measured K_{smax} and the ratio of L_2/L_1 in that experiment. The black point means the value of K_{smax} obtained by experiments and the solid line is the reference of L_2/L_1. From Fig. 3.7 and Fig. 3.8, three main conclusions can be achieved:

(1) Under the condition of a constant simulated inductor, a larger real inductor means a larger stable area for the PHIL simulation.

(2) In the PHIL simulation of Fig. 3.3, the maximum feedback gain in the current loop which can maintain the PHIL stability approximates to the ratio of L_2/L_1, as shown in Fig (3.8).

(3) The good match of the analysis results and the experimental results also verify that the application of 1st order Pade approximation in Eq. (3.8) is enough for the stability analysis.

3.3. Proposed Solution to PHIL Simulation Instability

3.3.1 Modification of the PHIL Simulation

According to conclusions in the previous section, the PHIL simulation in Fig. 3.3 is intrinsically instable because of $L_1>L_2$. Ref. [7] also points out the interface algorithm used in this PHIL simulation, ITM, exhibits high accuracy but low stability. In order to improve stability, the PHIL simulation system of Fig. 3.3 has to be modified. One proposed method is to change the interface algorithm. However, other interface algorithms, such as transmission line model (TLM), partial circuit duplication (PCD) method and damping impedance method (DIM), only theoretically provide high stability while are difficult to be implemented. Furthermore, these interfacing algorithms exhibit lower accuracy than ITM [7].

To improve the stability without deteriorating the accuracy of the PHIL simulation, we proposed a method which can be implemented easily in practice: the inductor in the simulated part decreased from 6 mH to 4 mH and the real inductor increased from 4 mH to 6 mH. The total inductor of the PHIL simulation is still 10 mH while the ratio of L_2/L_1 increases to 1.5, therefore, stable operation with K=1 can be expected. The modified PHIL simulation is shown in Fig. 3.9. Other parameters of the system are same as that in Fig. 3.3.

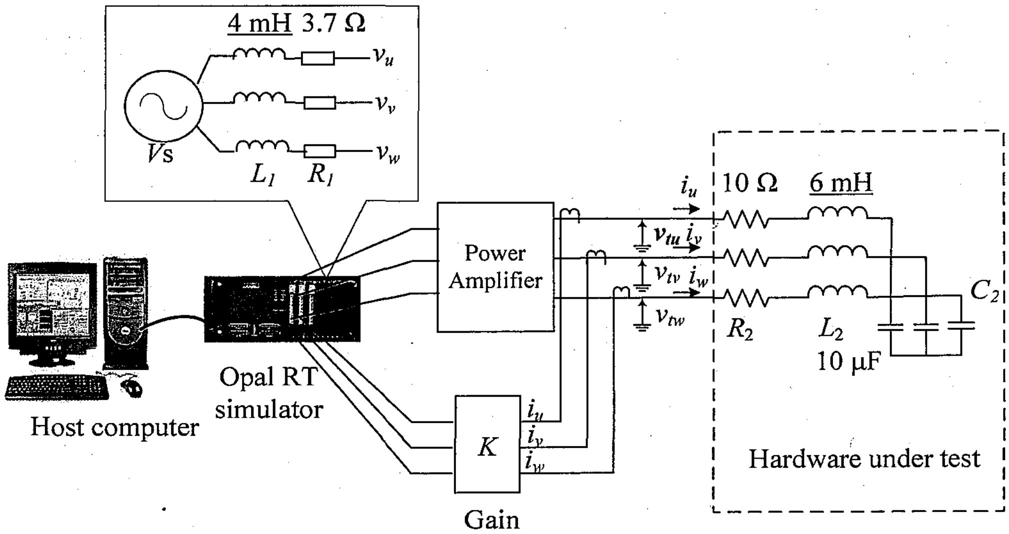


Fig. 3.9 Modified PHIL simulation.

3.3.2 Verification of the Modification

Obviously, the modified PHIL simulation should have same behaviors as the original one. Otherwise, the proposed method is unacceptable.

According to Thevenin's theory, all the part of the PHIL simulation system before real R_2, L_2 and C_2 can be represented by an equivalent voltage source V_{es} and an equivalent internal impedance Z_{es}. Therefore, Fig. 3.3 can be simplified as Fig. 3.10. The voltage source V_{es} and the internal impedance Z_{es} are expressed by following Eqs. (3.19) and (3.20). Eq. (3.21) presents the total impedance of whole PHIL simulation.

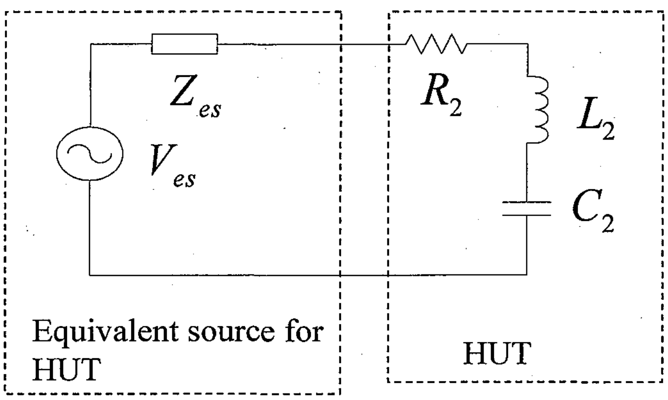


Fig. 3.10 Equivalent circuit of PHIL simulation.

$$V_{es} = V_s e^{-T_{d1}s} \tag{3.19}$$

$$Z_{es} = Z_1 e^{-T_d s} \tag{3.20}$$

$$Z_s = Z_1 e^{-T_d s} + Z_2 \tag{3.21}$$

where, V_s is the simulated voltage source; $Z_1 = R_1 + sL_1$. It should be noted that V_{es} and Z_{es} behalf integrated characteristics of V_s, Z_1, A/D, D/A converter and power amplifier. Eq. (3.19) indicates that the proposed method has no effect on V_{es}. However, Eq (3.21) shows that total impedance of the whole PHIL simulation, Z_s, may be affected by the proposed method.

Bode diagrams of Z_s of the original and modified systems are both shown in Fig. 3.11. Assuming the interested frequency region is 0 to 1000Hz, Fig. 3.11 shows that performance of Z_s of original and modified PHIL simulation are same in this bandwidth region. Therefore, the PHIL simulation of Fig. 3.9 has same performance as the one shown in Fig. 3.3.

It should be noticed that if the time delay increases, characteristics of Z_s may change greatly due to the proposed stability method according to Eq. (3.21). Fig. 3.12 shows the bode diagram of original and modified Z_s when the time delay is 100 μs.

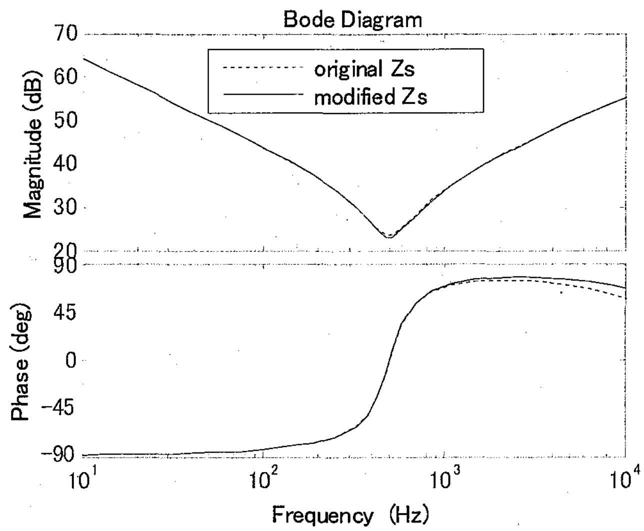


Fig. 3.11 Bode diagram of Z_s of the original and modified PHIL simulation. (the time delay is 15 μs)

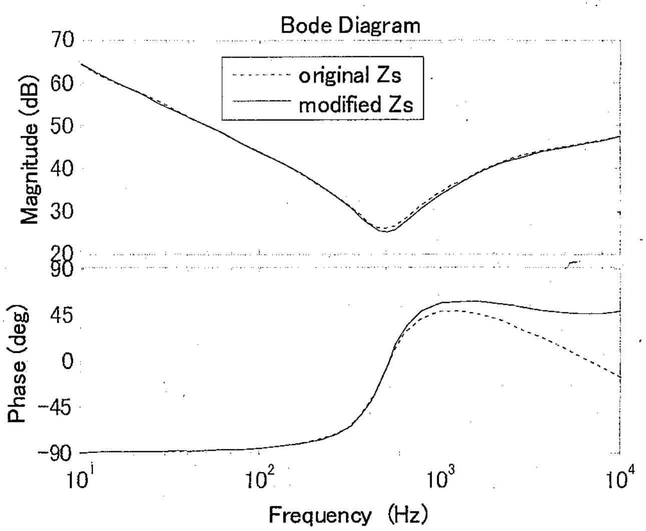


Fig. 3.12 Bode diagram of Z_s of the original and modified PHIL simulation. (the time delay is 100 μs)

It also should be pointed out that according to previous conclusions of section 3.2, modifications of the PHIL simulation of Fig. 3.3 which decrease L_1 less than 4 mH and increase L_2 lager than 6 mH also can improve the stability. Nevertheless, these modifications have more serious effects on Z_s according to Eq.(3.21) and then performances of original PHIL simulation may be seriously changed.

3.3.3 Accuracy Analysis of the Proposed Solution to Instability Problem

The other issue which should be concerned about is how the modification affects the accuracy of the PHIL simulation. Error of PHIL simulation is mainly caused by the non-ideal PHIL interface, which is called interface transfer function perturbation (TFP) and noise introduced in the real system, which is called noise perturbation (NP) [3].

3.3.3.1 Interface transfer function perturbation (TFP)

Assuming that all the signals are transferred ideally and the error of the PHIL simulation is only caused by the time delay, Fig. 3.2 can be drawn as Fig. 3.13, in which the dashed line means introduced errors by TFP.

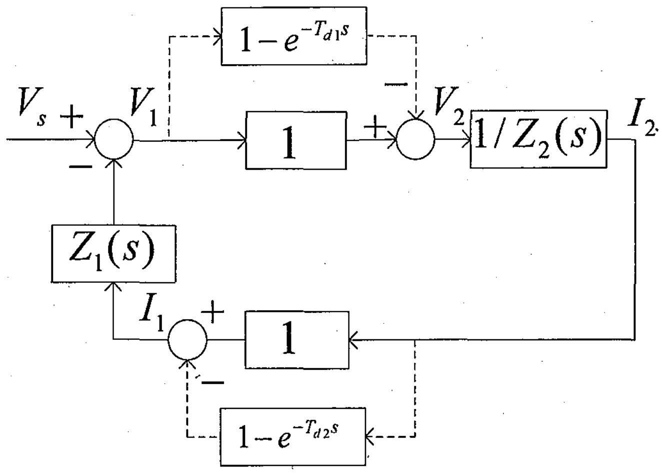


Fig. 3.13 Block diagram of PHIL simulation including TFP.

It is assumed that V_1 is interested signal. Definiting V_1 as original value and $V_{1\text{-TFP}}$ as the value with TFP, a reasonable approach to evaluating the accuracy can be defined by following equation:

$$E_{v1-TFP} = \left| \frac{V_{1-TFP} - V_1}{V_1} \right| \quad (3.22)$$

Subsituting impedance parameters of PHIL simulation to Eq. (3.22), $E_{v1\text{-}TFP}$ can be presented as follwing:

$$E_{v1-TFP} = \left| \frac{Z_1(s)/Z_2(s)(1-e^{-T_d s})}{1+Z_1(s)/Z_2(s)e^{-T_d s}} \right| \quad (3.23)$$

Therefore, TFP errors of original PHIL simulation of Fig. 3.3 and modified PHIL simulation of Fig.3.9 can be calculated respectively by Eq. (3.23). It is obvious that the value of $E_{v1\text{-}TFP}$ varies against both the frequency and the time delay T_d. Without loss of generality, it is assumed interested frequency is 300 Hz and Fig. 3.14 shows relationship of the TFP error versuses the time delay. On the other hand, assuming time delay of the PHIL simulation is 15 μs, the TFP error versuses frequency is shown Fig. 3.15. It is clear that $E_{v1\text{-}TFP}$ increases dramatically with the increasing of time delay for a certain frequency. At the same time, TFP error also increases with the increasing of frequency when the time delay is a constant.

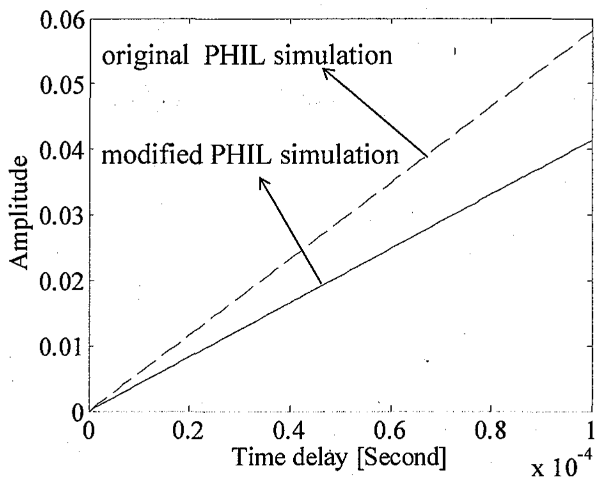


Fig. 3.14 $E_{v1\text{-}TFP}$ versus time delay for original and modified PHIL simulation.

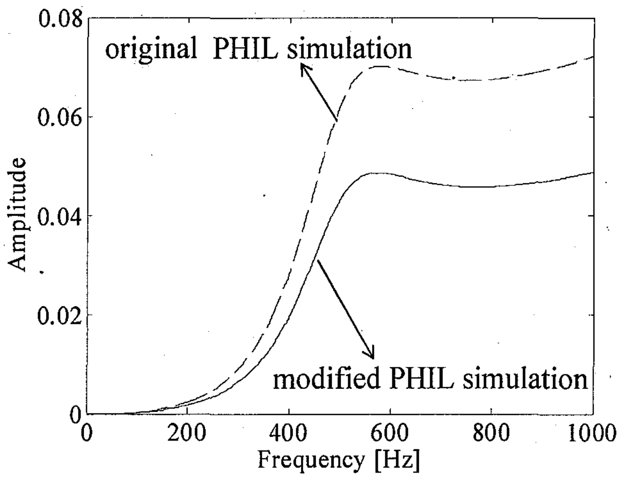


Fig. 3.15 .TFP errors versus frequency for original and modified PHIL simulation.

It can be concluded from Fig. 3.14 and Fig. 3.15 that the proposed modification to stabilize the PHIL simulation can also decrease the simulation error caused by TFP.

3.3.3.2 Noise perturbation (NP)

Supposing that all signals in the PHIL simulation of Fig. 3.1 transferr ideally except that there is a sensor noise when the real current I_2 is measured, the block diagram of Fig. 3.2 can be drawn as Fig. 3.16. Treating the sensor noise as white noise ε, which means that it is a random siganal with a flat power spectral density, and assuming V_1 is interested siganl, PHIL simulation

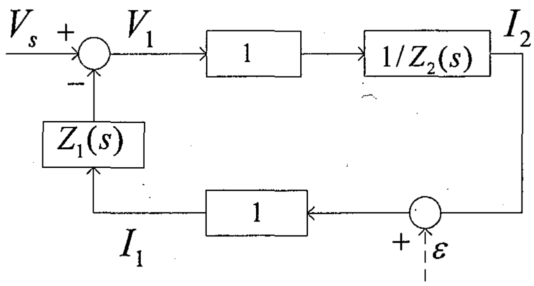


Fig. 3.16 Block diagram of PHIL simulation including NP.

error can be evaluated by the following eqution:

$$E_{v1-NP} = \left| \frac{V_{1-NP} - V_1}{V_1} \right| \tag{3.24}$$

V_1 is the value without NP and $V_{1\text{-NP}}$ is the value with NP. Then, E_{v1} can be written as:

$$E_{v1-NP} = |\varepsilon| \left| \frac{Z_1(s)}{1 + Z_1(s)/Z_2(s)} \right| \tag{3.25}$$

Fig. 3.17 shows the value of $|Z_1(s)/(1+Z_1(s)/Z_2(s))|$ against frequency. Dashed line means original system of Fig. 3.3 and solid line means modified system of Fig. 3.9.

Fig. 3.17 shows that the proposed modification of PHIL simulation can decrease the simulation error caused by NP in the frequecy region of 0-800 Hz, while slightly deterioate

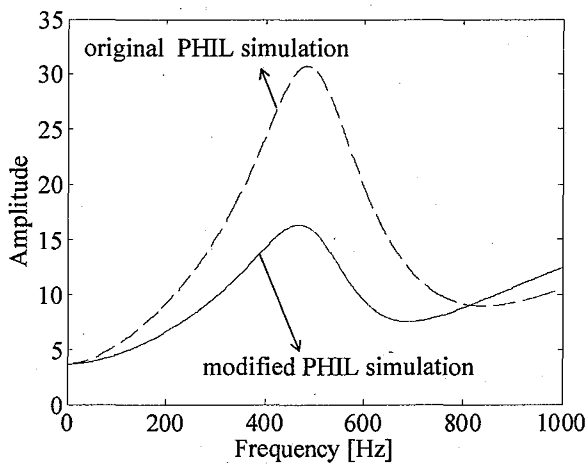


Fig. 3.17 Value of $\left| \frac{Z_1(s)}{1+Z_1(s)/Z_2(s)} \right|$ versus frequency.

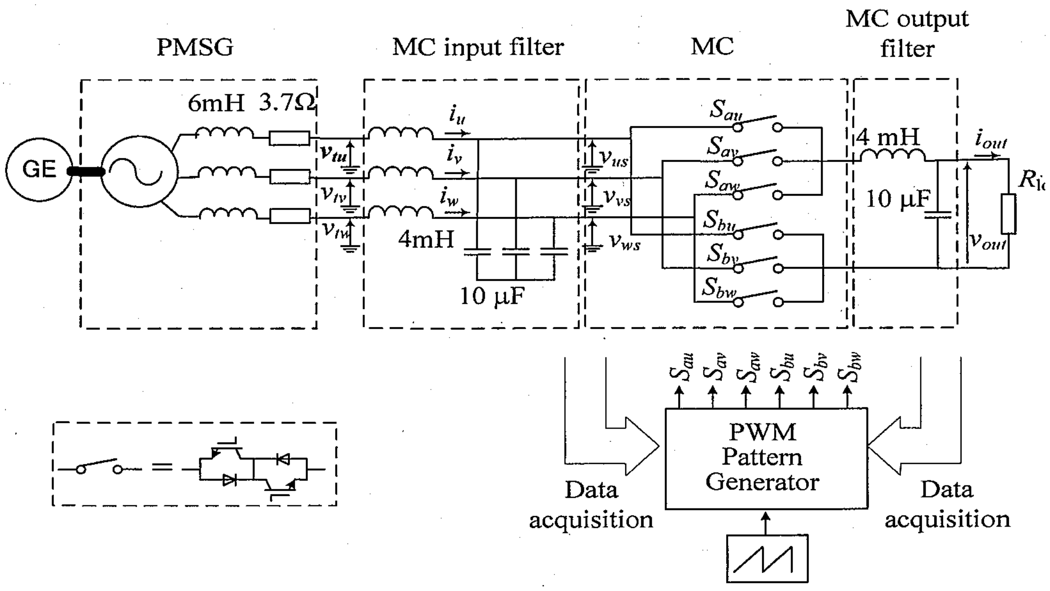


Fig. 3.18 Configuration of the proposed GECS with a matrix converter.

accuracy when frequency is larger than 800 Hz. Considering the small magnitude of ε, this deterioation can be neglected.

From above analysis, it can be concluded that the proposed modification to improve stability of PHIL simulation can also improve its accuracy.

3.4. a PHIL Simulation of a Gas Engine Cogeneration System with a Matrix Converter

3.4.1 Configuration of the PHIL Simulation of GECS

This PHIL is developed to investigate a gas engine cogeneration systenm (GECS) with a matrix converter (MC) as shown in Fig. 3.18 [8]. In order to investigate how the torque pulsation of gas engine (GE) affects the operation of MC and how the proposed modulation [9] of the MC affects the operation of the GE and the permanent magnet synchronous generator (PMSG), a PHIL simulation is carried out in which the HUT is the MC, including its controller and filter. Fig. 3.19 is the original configuration of the PHIL simulation.

In this PHIL, time-domain numerical models of GE and the PMSG are simulated based on MATLAB/simulink/ SimPowerSystem, compiled by the host computer and then downloaded to the Opal-RT simulator.

The signal of the PMSG output voltage is transferred to a power amplifier via a D/A converter which is installed on the RT simulator. The power amplifier receives the voltage signal and regenerates it as physical voltage which is used as the power source of the proposed MC. Currents of the MC on the three phase side are measured and fed back to the simulator via an A/D converter.

Parameters of the GE, PMSG and power amplifier used in this research are shown in tables 2.2, 2.3 and 2.5.

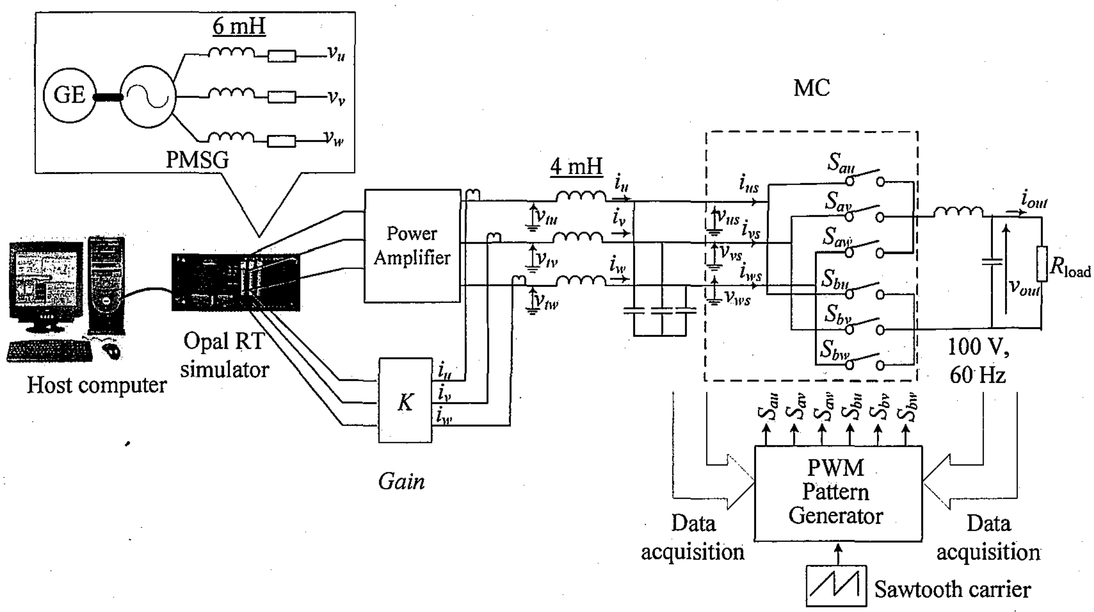


Fig. 3.19 Original PHIL simulation of a GECS with a MC

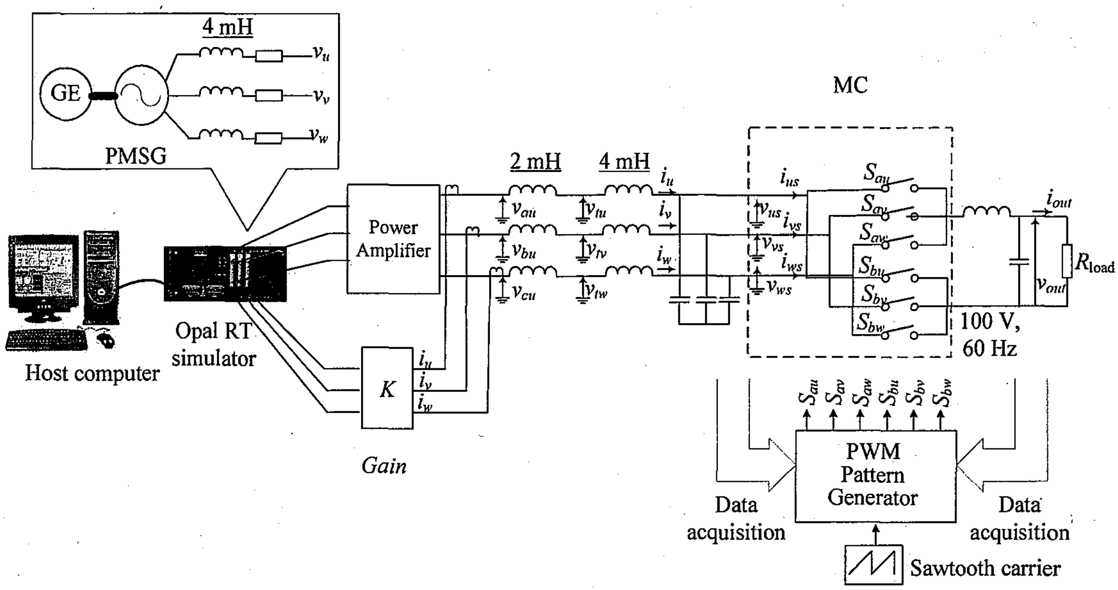


Fig. 3.20 Modified PHIL simulation of a GECS with a MC

Detail parameters of the MC are shown in Table 2.6. Because the sampling time for control of the MC is 100 μs, the time step size of the PHIL simulation should be less than it.

The MC is a non-linear HUT in this PHIL simulation. However, in this GECS, the MC adopts a power factor modulation on the three phase side [8] and the power factor on the three phase side of MC is kept constant 1, which means that input voltages (v_{us}, v_{vs}, v_{ws}) and input currents (i_{us}, i_{vs}, i_{ws}) of MC has same phase angle. Then, the MC,including its output filter and R_{load}, can be ideally treated as an equivelent resistor at the standpoint on the MC three phase side. As a result, the whole HUT, which includes MC, its input filter, output filter and R_{load}, can be ideally treated as a linear impedence load. Therefore, previous conclusions in section 3.2 and section 3.3 can be applied to this PHIL simulation.

Because the internal inductor of PMSG is 6 mH while the inductor of MC input filter is 4 mH. Since the inducor of simulation is larger than the real inductor, the PHIL simulation is unstable. In fact, the value of K_{smax} can be achieved is only 0.67, which equals to L_2/L_1.

To achieve stable operation of the PHIL simulation, a modification, that the simulated inductor decreases to 4 mH and the filter inductor increases to 6 mH, is made. The modified PHIL simulation is shown in Fig. 3.20. With this modification, a stable PHIL simulation under the condition that K=1, is achieved and the total time delay is 15 μs.

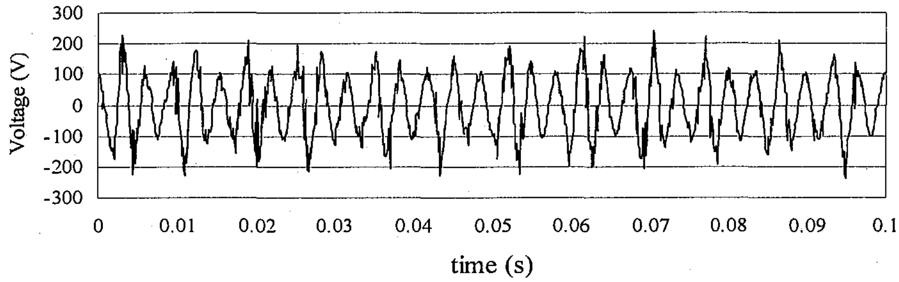
3.4.2 Results of the Modified PHIL Simulation and Verification of the Results

In order to verify results of the modified PHIL simulation, off-line simulation of the original system, shown in Fig. 3.18, is also carried out based on MATLAB/simulink and SimPowerSystems. It should be noted that in the off-line simulation, the inductor of the generator is still 6 mH while the inductor of the input filter of the MC is still 4 mH.

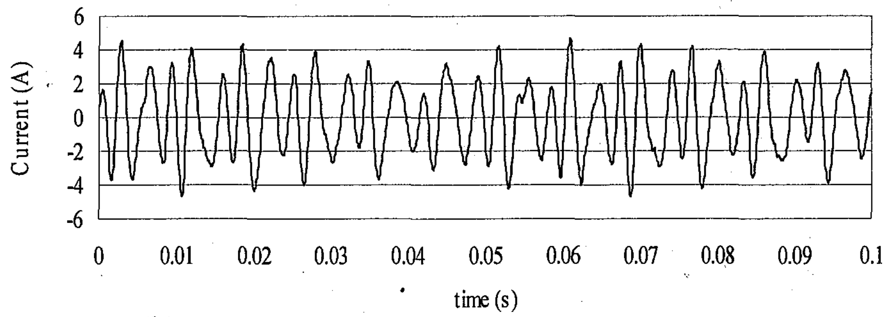
Results of modified PHIL simulation of Fig. 3.20 and off-line simulation of Fig. 3.18 are shown in Figs. 3.21, 3.22, respectively.

Figs. 3.21 (a), (b), (c) and (d) are results obtained by modified PHIL simulation when K equals to 1. Waveforms from top are output voltage of the power amplifier (v_{au}), output current of the power amplifier (i_u), output voltage of the single phase of the MC (v_{out}) and output power of the MC on the single phase, respectively.

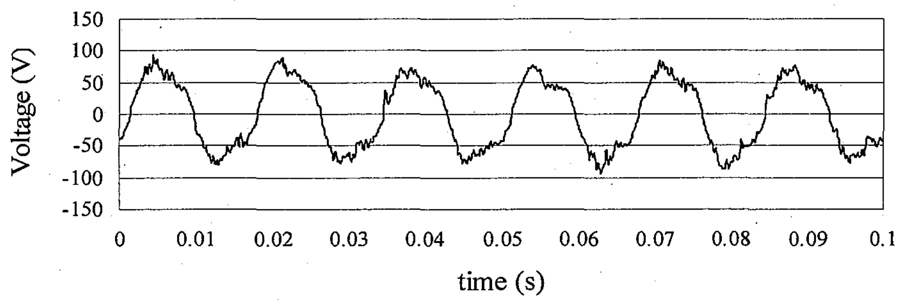
Fig. 3.21 (a) shows that when the feed back gain K equals "1", the output voltage of the power amplifier which is almost equivalent to the generator output voltage except the voltage drop of



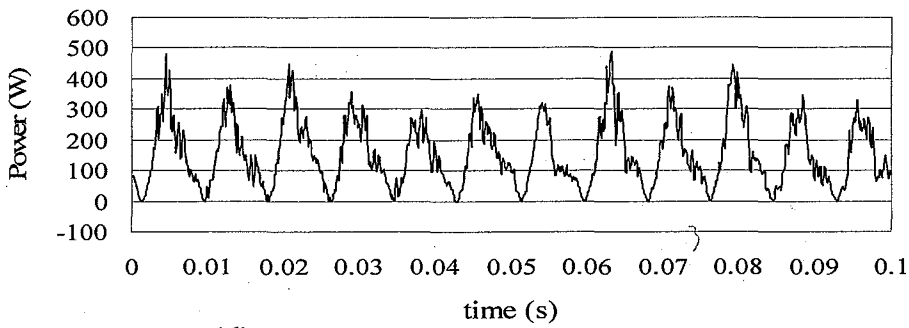
(a) output voltage of power amplifier (v_{au})



(b) output current of power amplifier i_u



(c) matrix converter output voltage (v_{out})



(d) matrix converter output power

Fig. 3.21 Results of the modified PHIL simulation of GECS (K=1).

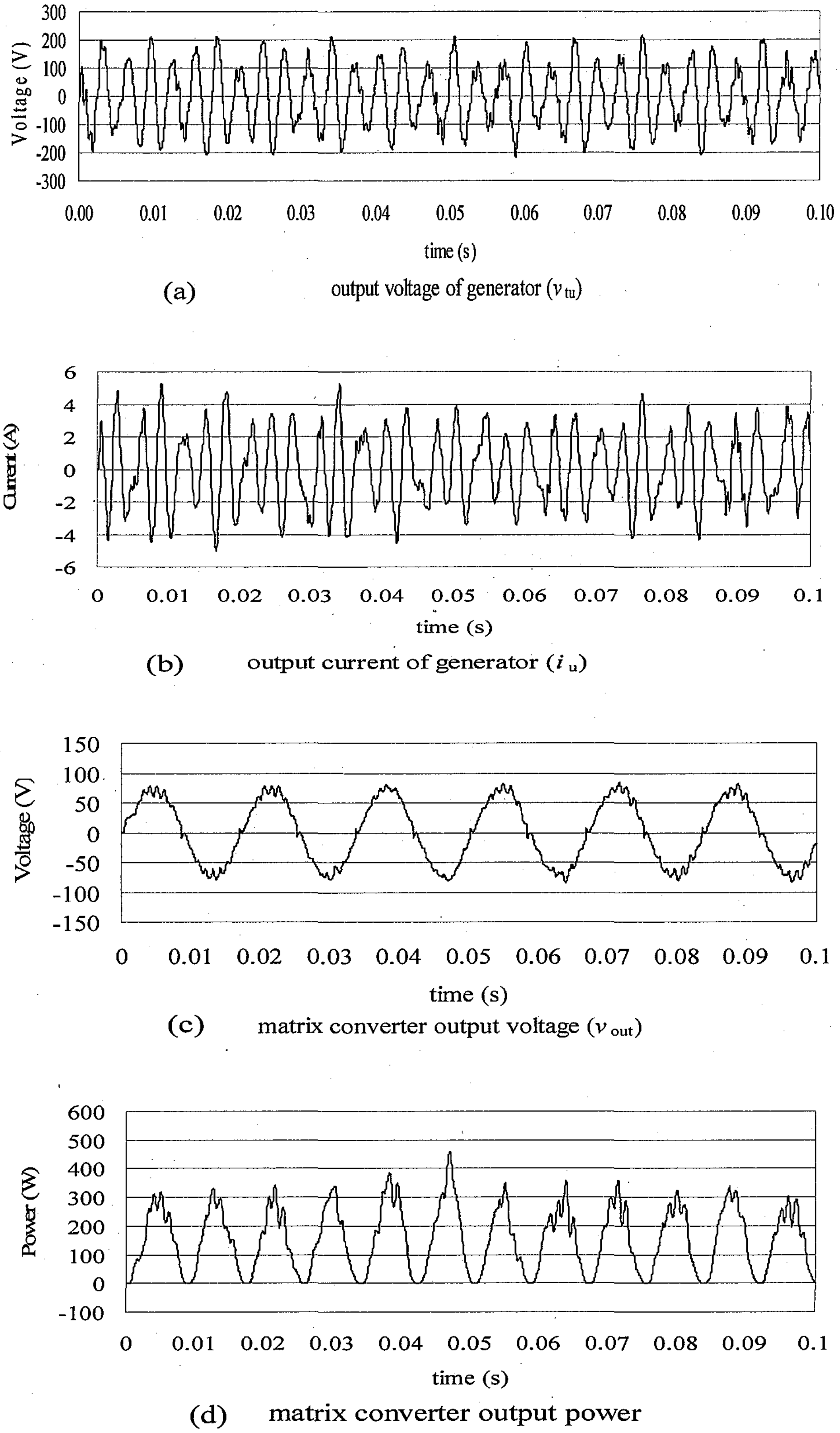


Fig. 3.22 Results of the off-line numerical simulation of the original GECS.

the 2 mH inductor moved to the hardware part in Fig. 3.20 is distorted, which means that modulation of MC three phase power has substantial feedback influence on the output voltage of generator. This influence is caused by the voltage drop when the current flows through the internal impendence of the generator. Because the load of the MC is a pure resistor s influence is caused by the voltage drop when the current flows through the internal impendence of the generator. Figs.3.21(c) indicates that waveforms of the voltage on the single phase of MC (60 Hz) are sinusoidal with distortions. Because the load of the MC output is a pure resistor R_{load}, the current has similar waveform to voltage. Therefore, waveforms of output power of the MC, shown in Fig. 3.21(d) also has obvious distortions.

However, even under adverse conditions that GE torque has pulsation and input voltage is fluctuated, the stable operation of MC is achieved. As a result, the proposed application of MC in GECS is demonstrated through the proposed PHIL.

Fig. 3.22 show results obtained by the offline simultion of the GECS as shown in Fig. 3.18. The waveforms from the top are generator output voltage, generator output current, output vlotage of the MC and output power of the MC.

Comparing Fig. 3.21 to Fig. 3.22, results are similar and both can well indicate characteristics of the application of MC in GECS. The difference between Figs. 3.21(a) and 22(a) is due to the inductor voltage across the 2 mH inductor moved to the hardware part in Fig. 3.20. The difference between Figs. 3.21 (c) and 3.22 (c) is due to the controller of matrix converter which needs some improvement to compensate voltage drop of semiconductor devices and etc.

The good match of modified PHIL simulation (shown in Fig. 3.20) and results by the off-line simulation of original system (shown in Fig. 3.18) indicates that the proposed method to stabilize the PHIL simulation is acceptable. Therefore the results obtained by the modified PHIL simulation can well demonstrate characteristics of the MC when it is applied to the GECS.

3.5. Summary

This chapter focuses on the stability issue of PHIL simulation of inductor coupled systems. Following conclusions are achieved:

(1) Time delay introduced by numerical calculation of simulation, A/D and D/A conversion, etc, is the fundamental cause for the instability happened in the closed-loop system of PHIL

simulation. Even the originally investigated system is in stable, the PHIL simulation developed for it may lose stability due to the time delay.

(2) In a PHIL simulation of inductor coupled system, the stable area is defined by the ratio of the real inductor and simulated inductor (L_2/L_1). It only can achieve stability under the condition that L_2/L_1 is greater than 1. Moreover, combined relationship of values of impedance and the time delay also affects the stability.

(3) A method to improve stability, which can be implemented easily in practice, is proposed. Furthermore, this modification can also improve the accuracy of the PHIL simulation.

(4) A high fidelity PHIL simulation with a non linear HUT, which is a MC of a GECS, is described in this chapter. Through this PHIL simulation, the proposed method to stabilize the PHIL simulation of inductor coupled system is demonstrated and results are verified by off-line simulation results.

Since inductor coupled systems are the most common systems in power system, these conclusions can be widely applied and then are benefit to the development of PHIL simulation of power systems.

References

[1] P. Forsyth, T. Maguire, R. Kuffel: "Real time digital simulation of control and protection system design", 35th annual IEEE Power electronics specialist conference (PESC) 2004, Vol. 1, pp. 329-335 (2004).

[2] S. Abourida, J. Belanger, C. Dufour: "High Fidelity Hardware-in-the-loop Simulation of Motor Drives with RT-LAB and JMAG",2006 IEEE International Symposium on Industrial Electronics, Vol. 3, Issue, 9-13, pp. 2462-2466 (July, 2006).

[3] W.Ren, M. Steurer, T. L. Baldwin, "An Effective Method for Evaluating the Accuracy of power Hardware-in-the Loop Simulations" IEEE Transactions on Industry Applications, Vol.45, Issue.4 July/Aug 2009. pp: 1484-1490 (July/August, 2009).

[4] X. Wu, S. Lentijo, A. Deshmuk, A. Monti, F. Ponci, "Design and implementation of a power-hardware-in-the–loop interface: a nonlinear load case study," Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, 2005, Vol. 2, (March, 2006).

[5] W. Zhu, S. Pekarek, J. Jastkevich, O.Wasynczuk and D. Delisle. "A Model-in-the-loop

interface to Emulate Source dynamics in a Zonal DC Distribution System," on Power Electronics, IEEE Trans. Vol.20, issue.2, pp.438-445 (March, 2005).

[6] S. Ayasun, R. Fischl, S. Vallieu, J. Braun and D. Cadirh. "Modeling and stability analysis of a simulation-stimulation interface for hardware-in-the-loop application," Simulation Modelling Practice and Theory, 15, pp. 734-746, (2007).

[7] W. Ren, M. Steurer, T. L. Baldwin , "Improve the Stability and the Accuracy of power Hardware-in-the Loop Simulation by selecting Appropriate Interface Algorithms" IEEE Transactions on Industry Applications, Vol.44, No.4 July/Aug 2008. pp: 1286-1294 (July/August, 2008).

[8]Y. Miura, S. Kokubo, D. Maekawa, and T. Ise: "Efficiency Improvement of a Gas Engine Cogeneration System by Power Factor Control with an IGBT Rectifier". Proceedings of the power conversion conference (PCC) Nagoya, 2007, pp.534-541, (April, 2007).

[9] Y. Miura, S. Kokubo, D. Maekawa, S. Horie, T. Ise, T. Momose and Y. Sato: "Power Modulation control of a Three Phase to Single Phase Matrix Converter for a Gas Engine Cogeneration System". IEEE 39th Annual Power Electronics Specialist Conference (PESC),Greece, 2008, pp.2704-2710, (June, 2008).

[10] Reference for RT-LAB www.opal-RT.com.

Chapter 4 Accuracy Evaluation of Power Hardware-in-the-loop Simulation of a Boost Chopper

4.1. Introduction

To carry out a power hardware-in-the-loop simulation with high fidelity, an important claim is its accuracy. However, it is difficult to evaluate the accuracy of a PHIL because in most case, reference of should-be results are unavailable. Otherwise, there is no need to develop a PHIL.

In ref. [1], a method to evaluate the accuracy, which is based on the concept of "electric power matching capability," is proposed, nevertheless, it is very difficult for the practical implementation. Ref. [2] mentions that appropriate interface algorithms can improve the accuracy and stability of PHIL simulation without providing detail method to analyze stability and to predict accuracy. A method to evaluate PHIL accuracy is proposed in ref. [3], however, these results are still based on a very simple model, in which the simulation part only consists of a power source and a resistor and real load consists of a resistor and an inductor. Furthermore, the analysis about how to predict accuracy of PHIL of non-linear load is inadequent.

As mentioned before, inductor coupled system is the most common system in power system and almost all systems include nonlinear component (as the PHIL of a GECS with a MC in chapter 3). However, the accuarcy analysis of it is generally difficult because of the lack of reference data. In this chapter, through investigating a PHIL simulation of a boost chopper, the accuracy of PHIL is analyzed.

4.2. PHIL Simulation of Boost Chopper

4.2.1 Cnfiguration of PHIL of Boost Chopper

An investigated chopper is shown in Fig. 4.1. The switch in the chopper is an IGBT. This boost chopper adopts a constant output voltage control, which is described in Fig. 4.2. Fig. 4.3 is the PHIL simulation configuration built for it. Parameters of the power amplifier are summarized in table 4.1.

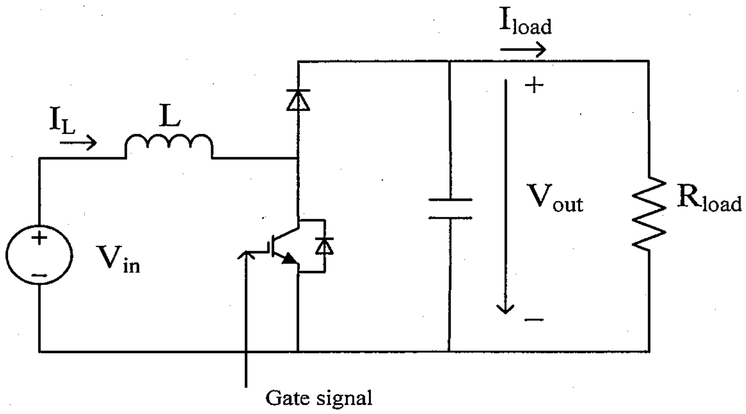


Fig. 4.1. Boost chopper.

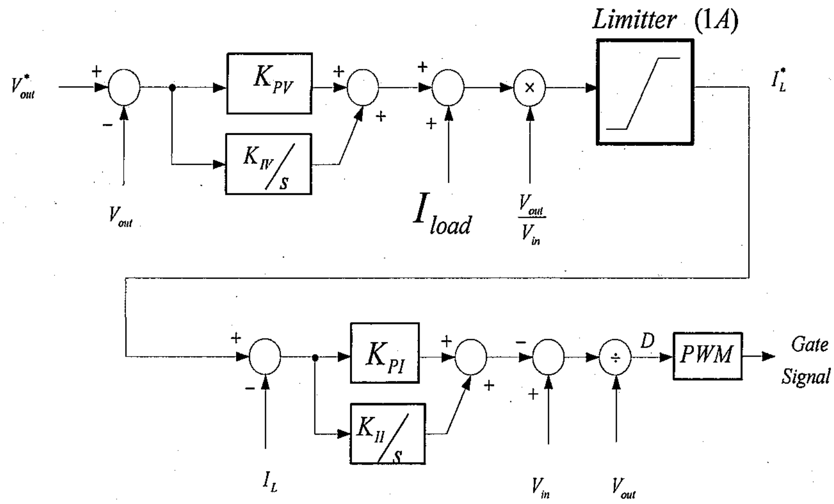
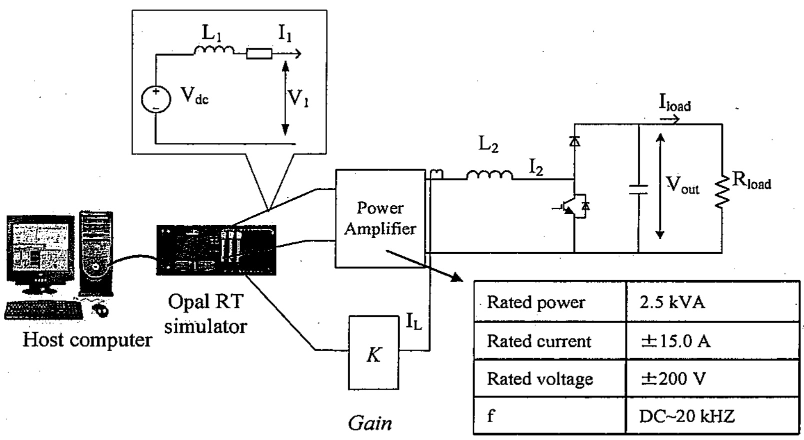


Fig. 4.2 Control block of the boost chopper.



Rated power	2.5 kVA
Rated current	±15.0 A
Rated voltage	±200 V
f	DC~20 kHZ

Fig. 4.3 PHIL for chopper.

Table 4.1 parameters of the power amplifier

Rated power	2.5 kVA	Rated current	DC	± 15.0A
			AC	16.7 Arms
Rated Voltage	±200V	Bandwidth		DC~20 kHz

In the PHIL, the inductor (L) in the real chopper is divided to two parts: a simulation inductor (L_1) and a real inductor (L_2). The total of inductor equals to L (L=L_1+L_2). After this division, both simulation part and real part of PHIL have inductor. Therefore, This is an inductor coupled system and how the inductor affect stability and accuracy of PHIL can be investigated.

4.2.2 Equivalent Circuit of the PHIL Simulation

In this PHIL, voltage source and part of the inductor are simulated by digital simulator coming from OPAL-RT LAB. The output voltage signal V_1 is transferred to a power amplifier via a D/A (digital/analog) converter and then regenerated as a physical voltage V_2 to the rest of the system. On the other hand, the current I_2 is measured and feedback to the simulator through an A/D (analog/digital) converter. Assuming that all signals transfer ideally except time delays in the feedback and feedforward loop, equivalent circuit of the PHIL can be drawn as Fig. 4.4.

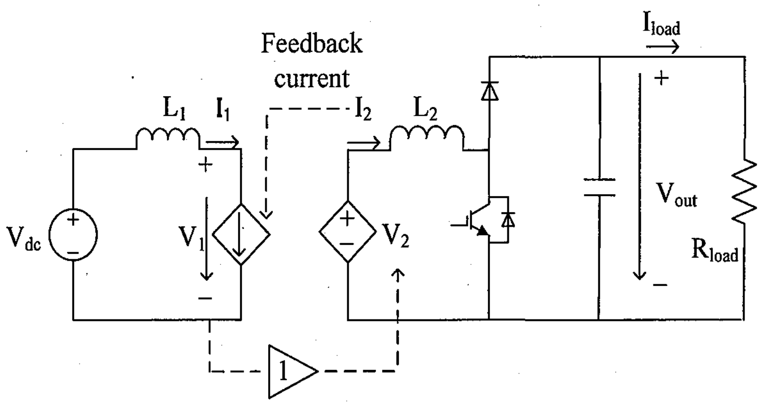


Fig. 4.4 Equivalent circuit of the PHIL.

4.2.3 Stability Analysis of the PHIL Simulation [4]

Before the implementation of a PHIL, closed-loop stability must be verified firstly, otherwise, the system may be severely damaged.

Average model of the boost in Fig. 4.1 can be written as following:

$$V_{in} = L\frac{di_L}{dt} + (1-D)V_{out} \tag{4.1}$$

$$(1-D)i_L = C\frac{dV_{out}}{dt} + i_{load} \tag{4.2}$$

$$V_{out} = R_{load} i_{out} \tag{4.3}$$

Then, the transfer function between input V_{in} and current flowing the inductor I_L is:

$$I_L = \frac{sC + 1/R_{load}}{s^2LC + sL/R_{load} + (1-D)^2} V_{in} \tag{4.4}$$

where V_{in} and V_{out} are input and output voltage of the chopper; I_{load} is output current, D is the duty ratio and equals to T_{on}/T. Therefore, the block diagram of Fig. 4.4 can be drawn as Fig. 4.5, where T_{d1} and T_{d2} are time delays of the feedforward and feedback loops of PHIL, respectively.

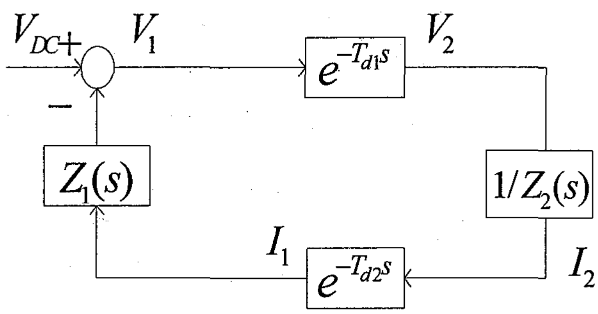


Fig. 4.5 Block diagram of PHIL

The characteristic equation of this closed-loop system is:

$$1 + \frac{Z_1(s)}{Z_2(s)} e^{-T_d s} = 0 \tag{4.5}$$

where, $T_d = T_{d1} + T_{d2}$, and

$$Z_1(s) = sL_1 \tag{4.6}$$

$$1/Z_2(s) = \frac{sC + 1/R_{load}}{s^2 L_2 C + sL_2/R_{load} + (1-D)^2} \tag{4.7}$$

L_1 is the inductor in the simulation part, L_2 is the inductor of the real HUT, C is the capacitance of HUT. According to Pade approximation,

$$e^{-T_d s} = \frac{-s+a}{s+a} \tag{4.8}$$

It should be noted that a is a constant which is always greater than 0 and is defined by T_d (a=2/T_d). A shorter time delay T_d corresponds to a larger value of a and vice versa.

Substituting Eqs. (4.6)-(4.8) to Eq. (4.5), characteristic equation of the closed-loop of PHIL simulation can be presented by Eq. (4.9).

$$\begin{aligned}&(L_2 - L_1)Cs^3 + (aL_1C + aL_2C + L_2/R_{load} - L_1/R_{load})s^2 \\ &+[(1-D)^2 + aL_2/R_{load} + aL_1/R_{load})s + a(1-D)^2 = 0\end{aligned} \tag{4.9}$$

From Eq. (4.9), it can be concluded that there are two factors affecting the stability, (1) Values of the simulated and real impedance and (2) Time delay in the PHIL. Applying Routh rule to Eq. (4.9), and considering that in this PHIL, time delay is 15 μs, R_{load} is 28 Ω and C=12940 μF, therefore, the stable conditions is

$$0 < (L_2 - L_1) < 7 \tag{4.10}$$

4.3. Accuracy Analysis of PHIL Simulation

4.3.1 Error Introduced in the PHIL Simulation

Comparing circuits of the Fig. 4.1 (original real boost chopper) and Fig. 4.4 (PHIL simulation built for this boost chopper), it is obvious that the accuracy of PHIL simulation are mainly defined by two factors. (1) The first is the non-ideal transfer of signals V_1 to V_2 in the feedforward loop and I_2 to I_1 in the feedback loop. This depends on: calculation time of V_1; the type of hold circuit of of d/a converter (DAC), time delay of DAC; bandwidth and dynamic range of power amplifier; bandwidth, sampling period and conversion time delay of ADC, etc.

This type error is named as transfer function deviation (TFD) (2) the second error is mainly caused by the sensor noise when the current I_2 is measured. This error is named as noise deviation (ND).

4.3.2 Transfer Function Deviation (TFD)

Assuming that all signals transfer ideally and the error is only caused by the time delay and non-ideal of the power amplifier, the block diagram of PHIL can be drawn as Fig. 3.13, in which the dashed line means introduced errors by TFD.

In this PHIL, it is assumed intersted signal is the real inductor current I_2. Considering that the investigated system is a dc boost chopper, therefore, the interested characteristic of I_2 is its magnitude under switching frequency. Defining I_2 as reference value and $I_{2\text{-TFP}}$ as the value with TFD, a reasonable approach to evaluate the accuracy can be defined by following equation:

$$\varepsilon_{I2-TFD} = \left| \frac{|I_{2-TFD}| - |I_2|}{|I_2|} \right| \tag{4.11}$$

$$= \left| \left(\left| \frac{e^{-sT_{d1}}}{Z_2 + Z_1 e^{-sT_d}} \right| - \left| \frac{1}{Z_1 + Z_2} \right| \right) / \left| \frac{1}{Z_1 + Z_2} \right| \right| \tag{4.12}$$

Eq.12 clearly shows that the error caused by TFD is a function of frequency and the it varies with the difference of frequency. Moreover, it also a function of time delay T_{d1}.

4.3.3 Noise Deviation (ND)

Supposing that all signals in the PHIL simulation transfer ideally except that there is a sensor noise when the real current I_2 is measured, the block diagram of the PHIL can be drawn as Fig. 3.16. Treating the sensor noise as white noise ε and assuming I_2 is interested signal, PHIL simulation error can be evaluatd by following eqution:

$$\varepsilon_{I2-ND} = \left| \frac{|I_{2-ND}| - |I_2|}{|I_2|} \right| \tag{4.13}$$

$$= \left(\left| \frac{1}{Z_1(1+\varepsilon) + Z_2} \right| - \left| \frac{1}{Z_1 + Z_2} \right| \right) / \left| \frac{1}{Z_1 + Z_2} \right| \tag{4.14}$$

It should be noted that usually this white noise ε is defined by the quality of the current sensor.

4.4. Experiment of PHIL Simulation and Results

4.4.1 PHIL Simulation of Boost Chopper

To verify previous stability and accuracy analysis, four PHIL simularions as Fig. 4.3 were carried out with differrent value of the simulated inductor and real inductor. PHIL simulation conditions are summerized in table 4.2. Table 4.3 summarized the values of used inductors . It should be noted that to meet the stable condition (Eq. 4.10), L_1 should be always smaller than L_2. The fouth experiment was instable and there was no results obtained.

Table 4.2 Parameters of PHIL simulation

V_{dc}	75 V	K_{iv}	0.16
V_{out}	130 V	K_{pv}	1.6
Rated power	600 W	K_{pi}	3
Capacitor	12940 μF	K_{ii}	8
Total inductor (L_1+L_2)	1.984 mH	f_s	18 kHz

Table 4.3 Values of L1 and L2 used in the PHIL simulations

experiment	Case 1	Case 2	Case 3	Case 4
L_1 (mH)	0	0.312	0.624	0.992
L_2 (mH)	1.984	1.672	1.36	0.992

4.4.2 Results of the PHIL Simulation

Fig. 4.6 shows waveforms of inductor currents of these PHIL simulations. The reference value was obtained by the experiment of the whole real chopper (Fig. 4.1) with its controller (Fig. 4.2).

4.4.3 Offline Simulation of the PHIL simulation

In order to analyze the accuracy, offline simulation of the whole PHIL,which is shown as Fig. 4.7, was also carried out based on PSCAD/EMTDC. In the offline simulation, the time delay of the PHIL is included. The simulation is also carried out as same conditions in table 4.2 and table 4.3. Simulation results also verify that the forth experiment (L_1=L_2=0.992 mH) is unstable. Results are shown in Fig. 4.8.

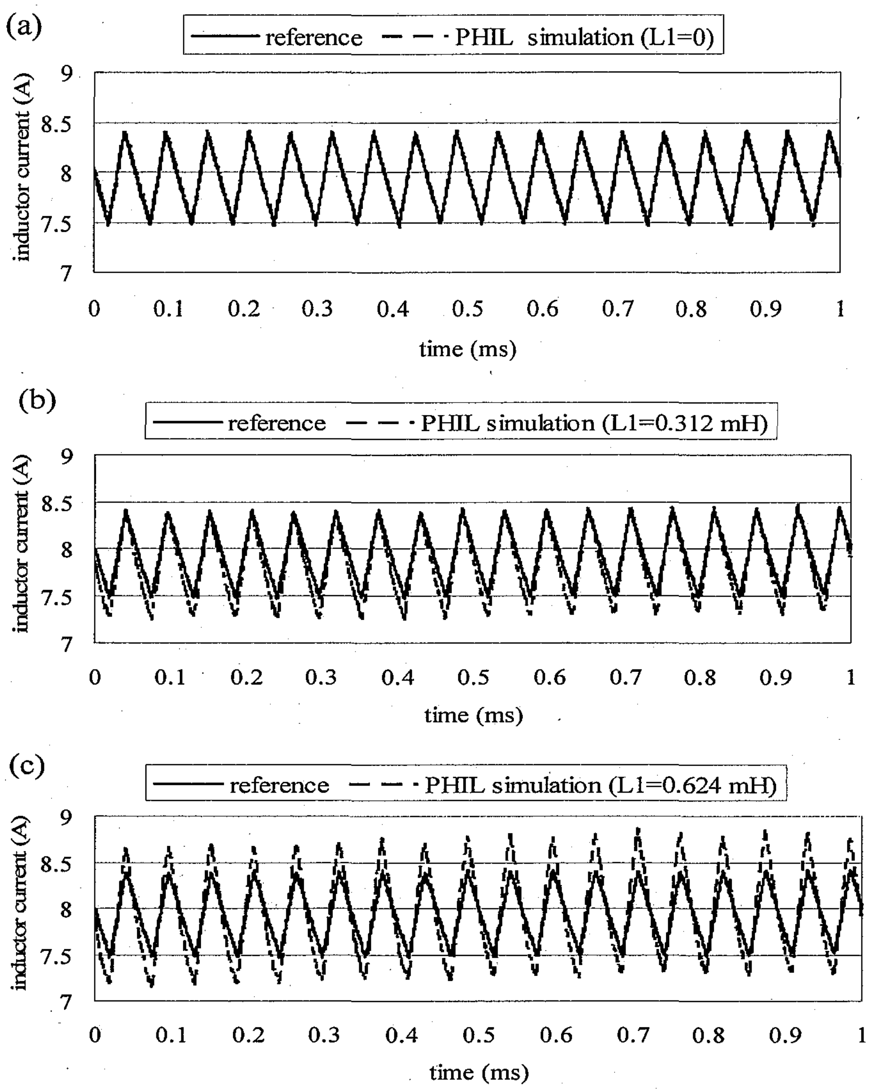
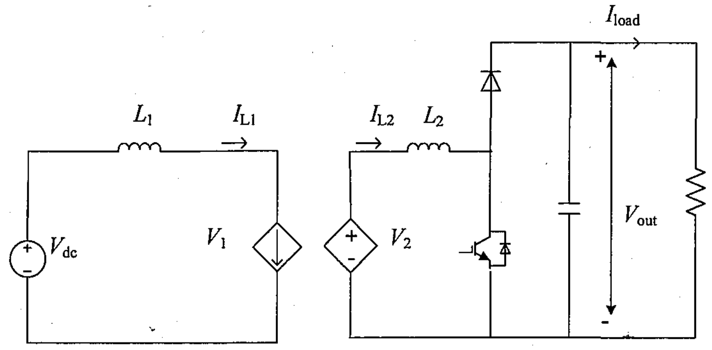


Fig. 4.6 Results of PHIL simulation (a) L_1=0, L_2=1.984 mH (b)L_1=0.312 mH, L_2=1.672 (c)L_1=0.624 mH, L_2=1.36 mH



$$V_2 = V_1 e^{-sT_{d1}} \qquad I_{L1} = I_{L2} e^{-sT_{d2}}$$

Fig.4.7 Offline simulation of PHIL based on PSCAD/EMTDC

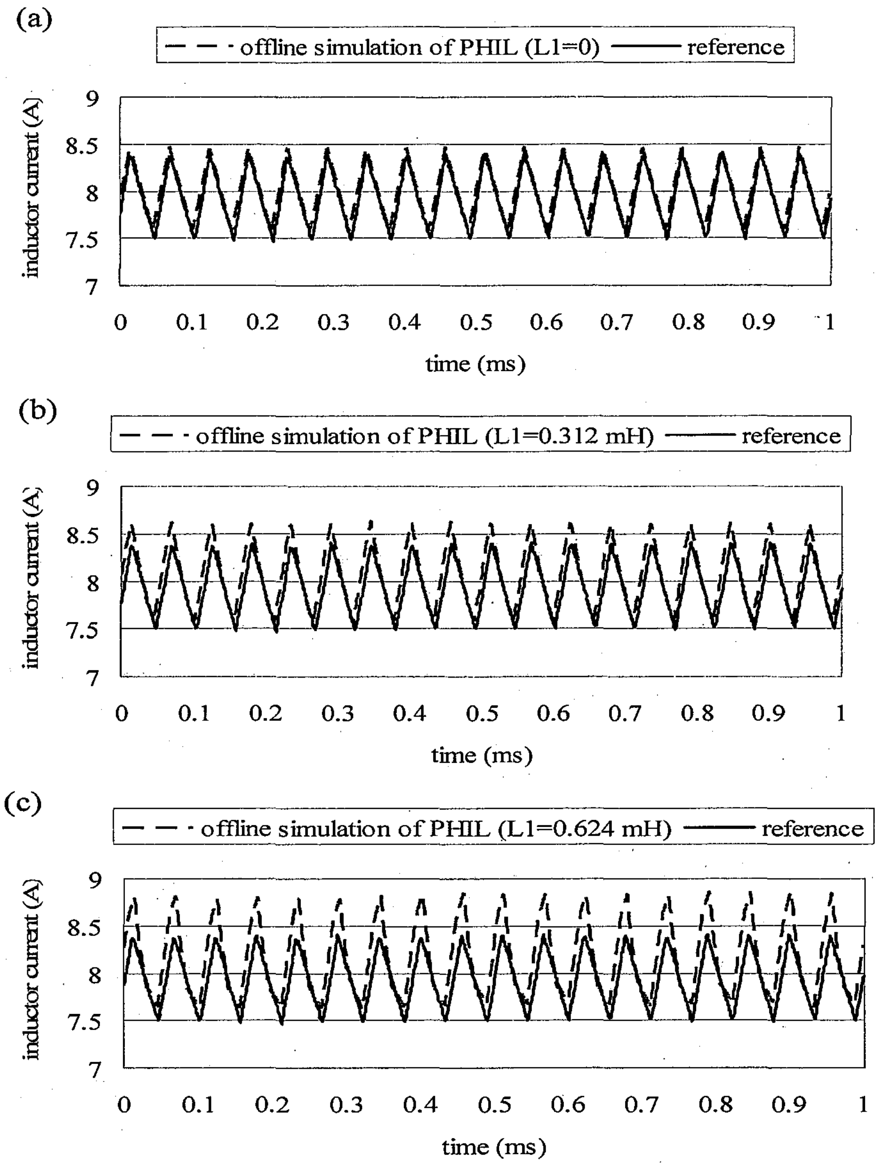


Fig. 4.8 Results of offline simulation of PHIL (a) L_1=0, L_2=1.984 mH (b)L_1=0.312 mH, L_2=1.672 (c)L_1=0.624 mH, L_2=1.36 mH

4.4.4 Analysis of Errors in PHIL Simulation

4.4.4.1 TFD of different simulated inductors L_1

Both the results of PHIL (Fig. 4.6) and simulation of PHIL (Fig. 4.8) show that the increasing of simulated L_1, which means a decreasing of L_2, will lead to higher error in the PHIL system. Fig 4.9 shows the TFD (calculated by Eq. (4.11) and (4.22)) versus frequency when the

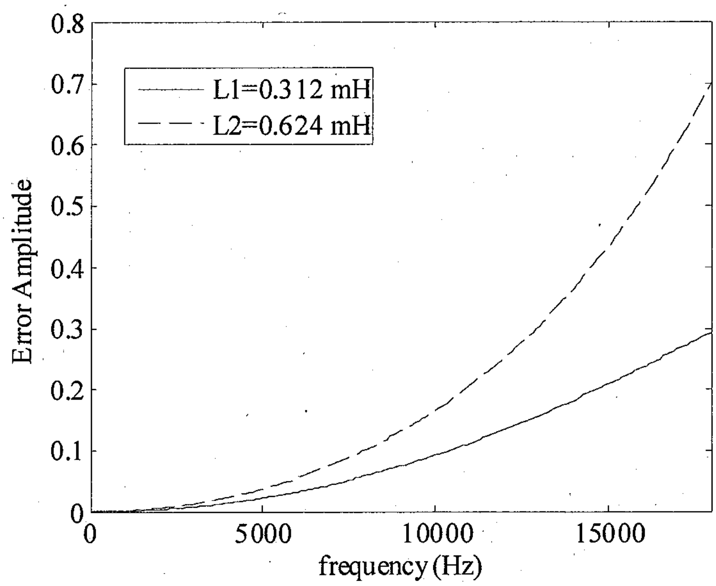


Fig. 4.9 TFD against frequency under different simulated inductor L_1

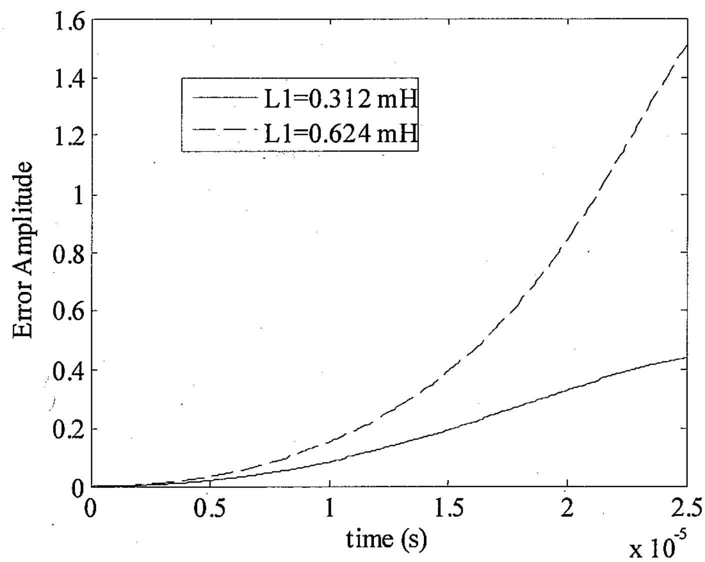


Fig. 4.10 TFD against time delay under different simulated inductor L_1

simulated L_1 is 0.312 mH and 0.624 mH, respectively. Fig. 4.10 shows TFD varies with time delay. It clearly shows the error TFD increases with the increasing of frequency and time dealy. Moreover, the TFD increases dramatically when the simulated L_1 changes from 0.312 mH to 0.624 mH.

4.4.4.2 Comparison of results

To verify the previous method to predict PHIL accuracy, three errors are compared: (1)

predicted error calculated by Eq. (4.12) and (4.14), (2)error in offline simulation of PHIL and (3)error of PHIL simulation. Applying FFT (Fast Fourier Transform) to the results obtained by PHIL simulation and offline simulation of the PHIL, the magnitudes under different frequency can be obtained. Comparing these magnitudes to reference datas, errors of different frequency can be calculated. Since the HUT is a chopper, it is assumed that the typically interesting frequency is dc (0 Hz) and 18 kHz, which is the switching frequency of the chopper. The errors are shown in tables 4.4 ,4.5 and 4.6. Tables 4.4 and 4.5 show errors when frequency is zero and 18 kHz, respectively . Table 4.6 compares the errors of different time delay.

It should be pointed out that when calculating the error by Eq. (4.12) and (4.14), instantaneous modelof chopper in Eqs. 15 and 16 is used instead of the average model. When the IGBT is turn off:

$$V_{in} = R_L i_L + L\frac{di_L}{dt} + V_{out} \tag{4.15}$$

when IGBT is turn on:

$$V_{in} = R_L i_L + L\frac{di_L}{dt} \tag{4.16}$$

*TFD*1 (IGBT turns off) and *TFD*2(IGBT turns on) are calculated respectively and TFD is defined as:

$$TFD = \max\{TFD1, TFD2\} \tag{4.17}$$

Table 4.4 also indicates that errors of PHIL when frequency is zero are very small and has no relationship to value of L_1/L_2. However, table 4.5 shows that errors increase with the increasing of the ratio of L_1/L_2 when frequency is 18 kHz. Therefore, a smaller value of L_1 not only benefit to stability as discussed in section 2 but also benefit to the accuracy of PHIL.

Table. 4.4 Errors of dc component (f=0)

	Prediction error		Offline simulation	PHIL simulation
	TFD	ND		
L_1=0 mH	0	0	0.8%	0.38%
L_1=0.312 mH	0	0.04%	1.35%	1.43%
L_1=0.624 mH	0	0.04%	2.85%	0.09%

Table. 4.5 Errors of ac component (f=18000 Hz)

	Prediction error		Offline simulation	PHIL simulation
	TFD	ND		
L_1=0 mH	0	0	1.07%	0.6%
L_1=0.312 mH	27.4%	0.8%	30.8%	29.3%
L_1=0.624 mH	70.1%	1.6%	75.1%	73.9%

Table. 4.6 Errors of ac component (f=18000 Hz) under different time delay

Time delay (µs)	L1=0.312 mH		L1=0.624 mH	
	Prediction error	PHIL	Prediction error	PHIL
15 µs	19.4%	18.8%	39.4%	35.4%
16 µs	23.3%	21.6%	46.4%	46.7%
18 µs	28.2%	29.3%	71.7%	73.9%

Because in offline simulation of PHIL, only time delay is considered, the error also displays only the deviation caused by the time delay. From tables 4.4 and 4.5, it can be concluded that the total error of PHIL is mainly originated from time delay.

Table 4.6 indicates that the time delay has significant influnce on the errors of PHIL, especialy when L_1 is large. Under the condition of L_1=0.624 mH, if the time delay shortens from 18 µs to 15 µs, the error reduces more than a half. Therefore, to achieve high accuracy, a short time delay is necessary.

The slight difference between the prediction error and the error of offline simulation is caused by the imperfection of the chopper model in the simulation, such as IGBT and inductors.

From these two tables, it can be concluded that analysis in section 4.3 can be used to predict the accuracy of a PHIL when reference data is unavailable.

4.5. Summary

This chapter focuses on the evaluation of PHIL simulation for a boost chopper. To achieve valid accuracy analysis of PHIL, a PHIL of a relatively simple nonlinear load, a boost chopper, is investigated. To broaden the application of PHIL to inductor coupled systems, the inductor in the investigated is divided to a simulation part and a real part.

(1) it is concluded that to achieve stable operation, simulated inductor L_1 must be smaller than L_2. (2) a method to predict PHIL accuracy is also presented. and the validity of it is verified by both the comparison of PHIL simulation and offline simulation of PHIL. Results obtained also show that a large value of the ratio of L_1/L_2 corresponds to a bad accuracy. (3) error of the PHIL is mainly caused by by the time delay introduced in the system. Therefore, to achieve a high fidelity PHIL of an inductor coupled system, a small time delay and a small value of L_1/L_2 are necessary.

References

[1] S. Ayasun, R. Fischl, T. Chmielewski, S. Vallieu, K. Miu and C.Nwankpa: "Evaluation of the Static Performance of a Simulation-Stimulation Interface for Power Hardware in the Loop", IEEE Power Tech Conference Proceedings, 2003 Bologna, Vol.3, issue.23-26, pp.1-8 (March, 2003).

[2] W.Ren, M. Steurer, T. L. Baldwin , "Improve the Stability and the Accuracy of power Hardware-in-the Loop Simulation by selecting Appropriate Interface Algorithms" IEEE Transactions on Industry Applications, Vol.44, No.4 July/Aug 2008. pp: 1286-1294 (July/August, 2008).

[3] W. Ren, M. Steurer, T. L. Baldwin, "An Effective Method for Evaluating the Accuracy of power Hardware-in-the Loop Simulations" IEEE Transactions on Industry Applications, Vol.45, Issue.4 July/Aug 2009. pp: 1484-1490 (July/August, 2009).

[4] M. Hong, S. Horie, Y. Miura, T. Ise, C. Dufour, "A Method to Stabilize a Power Hardware-in-the-loop Simulation of Inductor Coupled System" International Conferrence on Power System Transients (IPST 2009), issue.239, (June, 2009).

Chapter 5 Conclusions

Although the technology of hardware-in-the-loop (HIL) simulation is now used in power system extensively, the application of it is mainly restricted to the design of controller, which is so called controller HIL (CHIL). In comparison to CHIL, the technology of power hardware-in-the-loop (PHIL) is still primary. Two issues, stability and accuracy, severely limit the development of the PHIL simulation.

To develop a PHIL of a gas engine cogeneration system with high fidelity, modeling, stability and accuarcy of the PHIL were investigated in this research. Following achievments were obtained in this research:

1) Numerical models of gas engine (GE) and permanent magnet synchronous generator (PMSG) were built based on MATLAB/Simulink and SimPower System. The validity of the models was verified through experiment. Moreover, to represent the characteristics of GE and PMSG in a "real time" situation, models were modified by an advanced real time solver, ARTEMIS.

2) A PHIL simulation of GECS was built, in which GE and PMSG were replaced by their numerical models and simulated by digital simulator. A real matrix converter (MC), together with its controller, interfaced the numerical models via power amplifier, d/a and a/d converter. In this PHIL, since both simulation part and real part had inductor, it was an inductor coupled system.

3) Stability of PHIL simulation of inductor coupled systems were analyzed and following conclusions were achieved.

(1) Even the real system is stable, the PHIL simulation for it may lose stability due to the introduced time delay.

(2) Two factors affect the stability of a PHIL of inductor coupled systems. One is time delay. The other is the values of the reactance. To achieve stable operation, the simulation inductor must be smaller than the real inductor. Moreover, a larger real inductor also means a larger

stable area for the PHIL simulation.

(3) In the PHIL simulation built for the GECS, because the simulation inductor (generator inductor) was greater than the real inductor (inductor of MC input filter), the PHIL was unstable. To achieve stable operation of it, a method to stabilize it was proposed. Analysis results showed that this method had no influence on the test of MC. Moreover, this method can improve the accuracy of the PHIL.

4) The results of PHIL simulation were verified by off-line simulation of GECS. From results of PHIL, it was found that the output voltage of the MC had distortion. It was caused by the switch commutation and would be improved in the following research.

5) To verify the accuracy analysis in the previous section, a PHIL simulation of a relatively simple circuit, which was a boost chopper, was investigated.

In this analysis, errors introduced in the PHIL are divided to two types: transfer function deviation and noise deviation. The first is caused by the non-ideal transfer function of the power interface and the second is caused by noise injection in the system.

The PHIL of the boost chopper was carried out and results were compared to those obtained by experiment and offline simulation of the PHIL. The good match of these results verified the validity of the proposed method to predict the accuracy.

6) Results obtained in previous also show that the error of a PHIL is mainly induced by the time delay of the PHIL. The error varies with the time delay. Moreover, the ratio of simulation inductor over real inductor has critical influence on the accuracy. To achieve a PHIL of inductor coupled system with high accuracy, the inductor in the simulation part should much less than the real inductor.

The PHIL simulation of a GECS is meaningful for developing a new power converter system for it. This scheme can also be applied for developing power converter systems with a gas turbine or a wind turbine system.

Furthermore, since inductor coupled systems are the most common systems in power system, such as 1) an AC electric drive system consisting of AC motor, an inverter, transformer and 2) a distribution system consisting of power converter, transformer and transmission line, etc., the achievements of this research can broaden the application of PHIL technology in power systems.

List of publications

Transactions

J-1 Miao Hong, Satoshi Horie, Yushi Miura, Toshifumi Ise, Yuki Sato, Toshinari Momose, Christian Dufour: " Power Hardware-in-the-loop simulation of a Gas Engine Cogeneration System for Developing Power Converter Systems", to be published in IEE of Japan Transactions on Industry Applications, Vol. 130 ,No. 5 (2010)

J-2 Miao Hong, Yushi Miura, Toshifumi Ise, Yuki Sato, Toshinari Momose, Christian Dufour: "Stability and Accuracy Analysis of Power Hardware-in-the-loop Simulation of Inductor Coupled Systems", accepted for publication in IEE of Japan Transactions on Industry Applications.

International Conference

C-1 Miao Hong, Satoshi Horie,Yushi Miura, Toshifumi Ise, Christian Dufour: " A Method to Stabilize Power Hardware-in-the-loop simulation of Inductor Coupled Systems", International Conference on Power Systems Transients (IPST), Kyoto Japan (June, 2009)

C-2 Miao Hong, Jianru Long, Yushi Miura, Toshifumi Ise: "Accuracy Evaluation of a Power Hardware-in-the-loop Simulation of a Boost Chopper", accepted for presentation in International Power Electronics Conference, (IPEC 2010), Sapporo Japan (June,2010).

Domestic Conference

C-3 Miao Hong, Yushi Miura, Toshifumi Ise,Yuki Sato, Toshinari Momose, " Real Time Simulation of a Gas Engine Cogeneration System with a Matrix Converter", National Convention Record IEE Japan, No. 6-253 (March, 2008)

C-4 Miao Hong, Yushi Miura, Toshifumi Ise,Yuki Sato, Toshinari Momose,Christian Dufour: "

Real Time Simulation of a Gas Engine Cogeneration System with a Matrix Converter", Joint Technical Meeting on Semiconductor Power Converter and Industry Electronics Application, IEE, Japan, SPC-08-90, IEA-08-28 (June, 2008)

C-5 Miao Hong, Yushi Miura, Toshifumi Ise,Yuki Sato, Toshinari Momose, "Stability Analysis of a Power Hardware-in-the-loop Simulation"; Kansai-section Joint Convention of Institutes of Electrical Engineering, No. G4-28 (Nov. 2008)