PROPORTIONAL RESONANT CURRENT CONTROLLER FOR 7-LEVEL MULTILEVEL INVERTER WITH REDUCED SWITCHING

ABDUL KHAIRI BIN ABDUL RAHMAN

A project submitted in partially fulfilment of requirement for the award of the Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering

University Tun Hussein Onn Malaysia

JANUARY 2018

ACKNOWLEDGEMENT

Alhamdulillah, thanks to Allah for his greatness and graciousness and all praise to Allah SWT for the sources and guidance and I managed to complete this report as scheduled.

I would like to take this opportunity to express my sincere appreciation to my supervisor Dr. Shamsul Aizam Bin Zulkifli, for generously spending his precious time and offering his evaluable and encouragement during the completion of this project.

I am also expressing my deepest appreciation to my beloved parent Abdul Rahman Haji Ahmad and Dayang Khabibah Awang Sallam for their help and morale support during the time I need it the most.

Apart from this, my sincere thanks to all my friends, especially my classmate for supporting me and cheering me during hard times and always there for me when they are needed.

ABSTRACT

This project is describing the recently introduced Proportional Resonant (PR) controller and its performance in the application of 7-level multilevel inverter controller system. The performance of the PR controller is measured based on the ability of the controller to reduce the harmonic distortion in the inverter system with non-linear load connected at the output of the inverter. This is because of the ability of the PR controller system to have additional selective harmonic compensator. In this project, a new topology of 7-level multilevel inverter is used to prove the efficiency of this topology to provide a symmetric 7-level multilevel inverter with has low Total Harmonic Distortion (THD) due to the reducing of the number of switches used in the inverter circuit. This project consists of the simulation process of the PR controller for symmetric 7-level multilevel inverter with non-linear load. The system is then also been implemented in a hardware setup with the application of Texas Instrument (TI) C2000 microcontroller as the controller of the inverter circuit. The simulation and the downloading process of the PR controller system to the microcontroller is done by using MATLAB/Simulink software. The result of the multilevel inverter simulation in MATLAB/Simulink shows that the implementation of the PR controller in the inverter system reduce the total harmonic distortion cause by the system load and the harmonic distortion form the inverter system itself. The hardware result shows that the PR controller system is applicable and functioning.

ABSTRAK

Projek ini membincangkan tentang sistem pengawal resonan berkadar dan prestasinya dalam aplikasi untuk system kawalan untuk inverter bertingkat 7-tingkat. Prestasi pengawal resonan berkadar diukur berdasarkan kemampuan pengawal untuk mengurangkan herotan harmonic dalam system sistem inverter yang disambungkan pada bukan linear pada keluaran inverter tersebut. Ini kerana pengawal resonan berkadar mampu menggunakan pemampas harmonic untuk harmonic yang tertentu. Di dalam projek ini, topologi baru untuk inverter bertingkat 7-tingkat digunakan untuk membuktikan topopogi tersebut mampu menurunkan kadar total herotan harmonik dsebabkan oleh pengurangan bilangan suis separa pengalir yang digunakan. Projek ini mempunyai bahagian simulasi untuk inverter bertingkat 7-tingkat dengan pengawal resonan berkala yang disambung dengan beban tidak linear. Sistem tersebut kemudiannya diimplimenkan ke dalam litar sebenar dengan bantuan mikropengawal Texas Instrument (TI) C2000 dimana sistem pengawal inverter diprogramkan kedalamnya. Proses simulasi dan transaksi sistem kedalam litar sebenar dilakukan dengan bantuan perisian MATLAB/Simulink. Hasil dari simulasi di dalam perisian MATLAB/Simulink, penggunaan sistem kawalan resonan berkala di dalam sistem inverter bertingkat 7-tingkat telah mengurangkan kadar total herotan harmonic yang disebabkan oleh beban pada sistem dan herotan harmonic dari dalam sistem inverter tersebut sendiri. Hasil daripada eksperimen ke atas sistem yg telah diadaptasikan ke dalam litar sebenar menunjukkan bahawa sistem kawalan resonan berkala berfunsi.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Introduction

In a power system, inverter is used especially in AC microgrid where there is application of renewable energy source. This is because, most renewable energy source or generator produces a DC voltage. Other than that, the inverters are also needed in the energy storage system where storage energy is in DC form [1].

There are many type of inverter as inverter varies with the topology used. The application of the inverter determines the topology used for the inverter as each topology has its own advantages and disadvantages. Based on numbers of research paper, a multilevel inverter is the most efficient type of inverter as it solves the drawback faced by a conventional inverter [2].

However, multilevel inverter needs more numbers of switches compared than conventional inverter. The switching operation will create harmonics distortion to the inverter system [3]. In [4], the implementation of PI controller in to control the current is not effective as the control system will be unstable during the variation of attenuation and resonant frequency of the filter.

Thus, a more efficient type of controller to be used to reduce the harmonic distortion in the inverter system is the Proportional Resonant (PR) controller is proposed in this project. With the present of infinite gain at the resonant frequency, PR controller are able to ensure zero steady-state error which in other hand it will minimize the load current distortion and harmonic content in the inverter system [5].

Another mitigation that can be done in the reduction process of harmonic distortion is by decreasing the number of switching pattern used in the multilevel inverter. The reduction of switches number means a new topology of multilevel inverter and a new design of inverter circuit. The modulation strategy of the circuit will be differed from the conventional multilevel inverter. This is to ensure that even if the inverter circuit is modified to have less number of switches, the inverter must produce the same desired output waveform which is in staircase waveform. The 7-level multilevel inverter with the least number of switches used was introduced by which are the inverter topology of symmetric 7-level multilevel inverter with five switches [6].

Therefore, this project focuses on the PR current controller strategy and the 7-level multilevel inverter with minimum switching pattern. In order to analyse the performance of the PR controller in reducing Total Harmonic Distortion (THD), the inverter system THD value will be increased until it exceeds more than 2% of the previous THD value without non-linear load by connecting the inverter to a non-linear load. Figure 1:*1* shows the block diagram of the overall project setup.

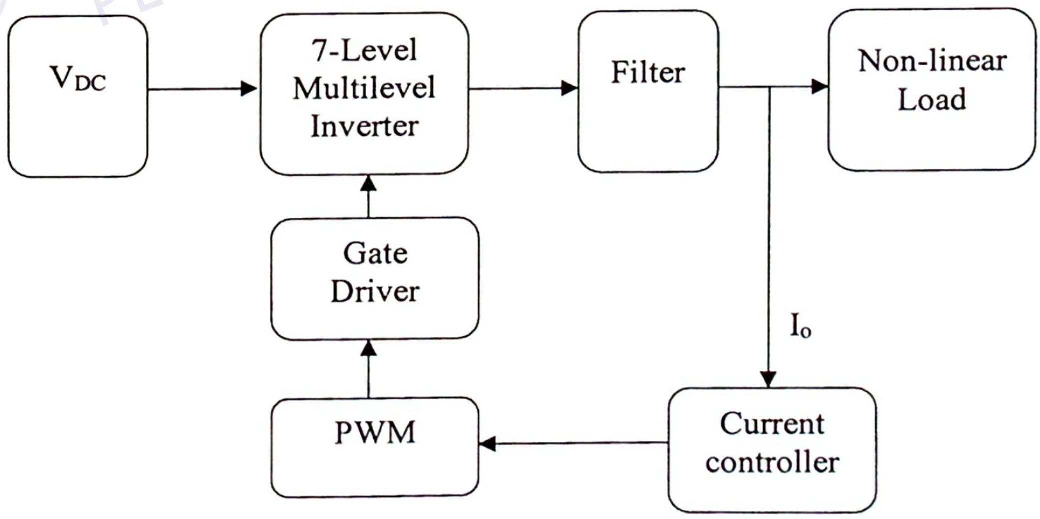

Figure 1:1: Block diagram of Multilevel Inverter with PR Controller

1.2 Problem Statement

In application of inverter, the type of inverter plays an important role especially in the aspect efficiency. Multilevel inverter is a type of inverter with the efficiency as it has the ability to produce the best waveform outputs which are close to sinusoidal waveform. However, the conventional multilevel inverter needs more switches compare to conventional two-level inverters. Semiconductor switches produce significant harmonic current as they chop voltage waveforms during their transition between cut-off and conducting state.

The different circuit configuration of an inverter means a different circuit modulation strategy. Therefore, a new configuration of PWM system must be created to allow the inverter circuit to produce the desired staircase waveform.

Even if the total number of switches in the inverter system is reduced, the harmonic current is still more than one switches needed in the inverter circuit. Harmonic distortion can still be form from the operation of the switches. Moreover, the present of non-linear could also lead to the production of harmonic current in the system [7]. This will eventually increase the THD level of the system. Therefore, the inverter system must have a type of controller system which can detect the changes in the output waveform and reduce the harmonic distortion.

1.3 Project Objectives

Based on the problem statements, there are three objectives that are going to be achieved. The objectives of this project are;

1. To construct a minimal switching single phase 7-level multilevel inverter with non-linear load circuit using MATLAB/Simulink.
2. To reduce the THD on the inverter system and non-linear load using Proportional Resonant (PR) controller.
3. To construct and proof the concept in hardware setup for reduced switching single phase 7-level multilevel inverter with non-linear load and PR controller.

1.4 Project Scopes

This project is to develop a Proportional Resonant (PR) controller for 7-level multilevel inverter with minimum switching pattern. The application of the PR controller in the inverter system is used to reduce the harmonic distortion when a non-linear load is connected to the inverter system. Thus, PR controller and 7-level multilevel inverter with minimum switching pattern is proposed to study as stated below;

- The construction of symmetric 7-level multilevel inverter is using MATLAB/ Simulink.
- The simulation of symmetric 7-level multilevel inverter is be conducted with and without non-linear load.
- The output current THD level will be analyse and the harmonic produced by the inverter and non-linear load will be ensured exceed overall THD of at least 2% higher than the inverter without non-linear load.
- After implementing the PR controller in the inverter system, the output of the symmetric 7-level multilevel inverter with PR controller will be determined and analysed to identify the THD value
- The PR controller and the inverter topology will be implement in hardware using Texas Instrument (TI) C2000 microcontroller.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will focus on studies, fact and research project on a topic on this project title. The chapter will also review on four major themes which frequently emerge throughout the literature reviewed. These themes are single-phase multilevel inverter, proportional-resonant controller, software and C200 Texas Instrument microcontroller.

2.2 Multilevel Inverter

Multilevel inverter is a type of power electronic converter which can provide or produce desired Alternating Current (AC) voltage level at the output of the converter using numbers of lower level Direct Current (DC) voltage source as input [8]. Multilevel inverter has a high power and voltage range which is as shown in Figure 2:1. This kind of capability instantly solves the problem faced by the normal inverter which is facing difficulty in connecting single power semi-conductor to the medium-voltage network.

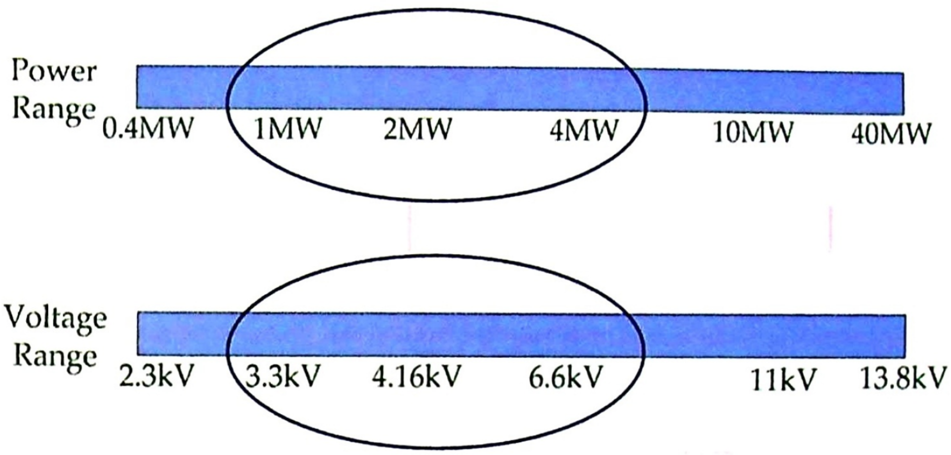

Figure 2:1: Power and voltage range of multilevel inverter

Multilevel inverter starts from the three-level inverter which was introduced by Nabae in [9]. There are many types of multilevel inverter as the level of the inverter increase from three to as many as possible. This chapter will review more on 7-level multilevel inverter as it is going to be the one that will be used in this project. The variety of multilevel inverter will increase as they are many topologies that are available. This chapter will review is the common topologies used for 7-level multilevel inverter which is cascade H-bridge multilevel inverter and the new symmetric multilevel inverter which is going to be used in this project.

There are many advantages of multilevel inverter. One of them is that this type of inverter can produce a low distortion output voltage. It also draws input current with low distortion. Another advantage of this inverter is that it can operate with a lower switching frequency [10].

2.2.1 7-Level Multilevel Inverter

As mention earlier, 7-level multilevel inverter is used in this project. The 7 -level inverter is chosen as it has moderate number of level which makes the output of the inverter is almost sinusoidal and only require simple filter to produce smooth sinusoidal AC current and voltage [2]. There will be two types of 7-level multilevel inverter that are going to be reviewed in this subtopic. The first one will be the conventionally used cascade H-bridge multilevel inverter and the new symmetric multilevel inverter. The staircase waveform of the 7-level multilevel inverter is as shown in Figure 2:2.

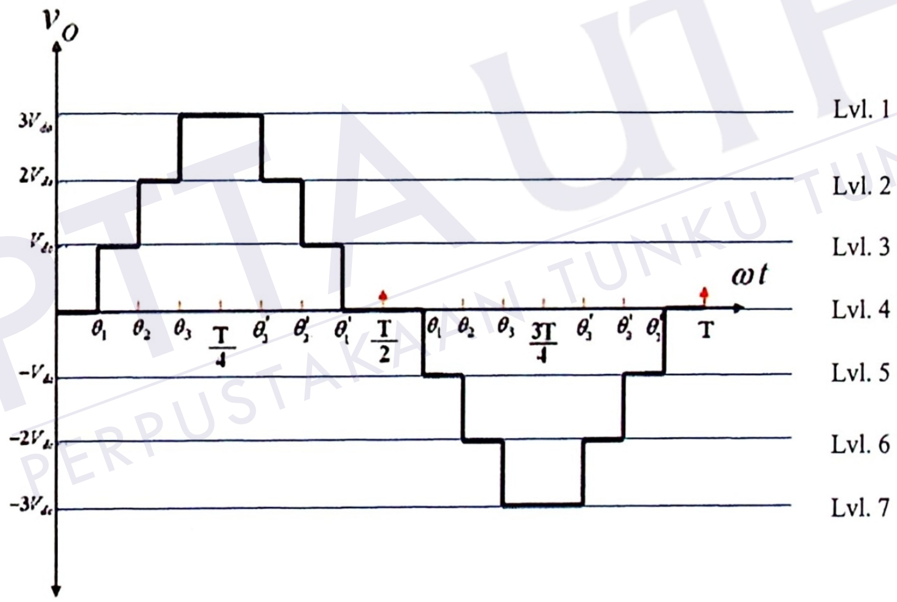

Figure 2:2: Output waveform of 7-level multilevel inverter

2.2.1.1 Cascade H-Bridge Multilevel Inverter

Cascade H-bridge multilevel inverter is the one of the basic and commonly used topology for multilevel inverter. This topology can be used in both single and three phase system conversion. The inverter circuit consist of H-Bridge (HB) power converter with DC source and capacitor. This topology gives the inverter the ability to produce multiple levels of output voltage to form AC output depending the number of level that are suitable for the system.

Figure 2:3 shows the schematic diagram of cascade HB multilevel inverter. Each HB cell consists of four switches and four diodes. Different combination of switch positions determines the level of output voltages. For 7-level multilevel inverter, three HB cells are required which gives a total of 12 switches that must be controlled in the process of producing 7 level staircase waveforms.

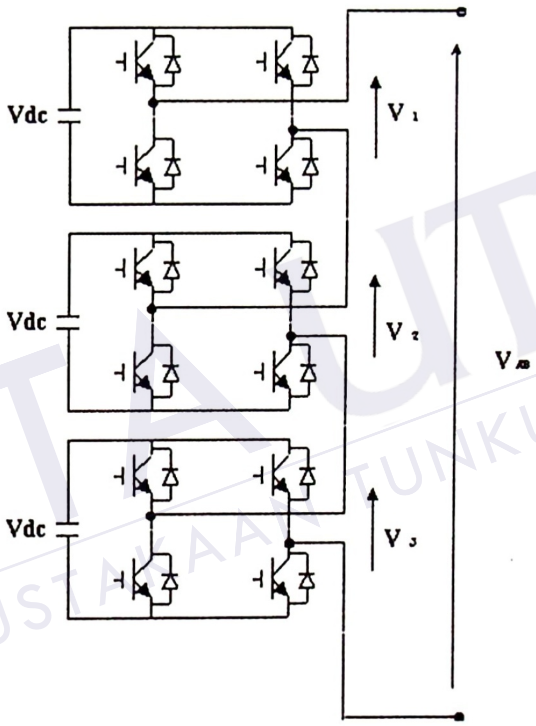

Figure 2:3: Cascade H-Bridge multilevel inverter

One of the advantages of this inverter is that the number of levels can be increased simply by increasing the number of HB. As the number of level increase, the total harmonic distortion can be reduced. The only drawback of doing so is that the higher the number of levels mean a more complex circuit modulation strategies [11]. This is due to the increase number of switches that needs to be control. Other than that, the number increase number of switches also will encourage the presents of harmonic due to switching process.

2.2.1.2 Symmetric Multilevel Inverter

For a 7-level multilevel inverter, designing a system or strategy to control 12 switches could be burdensome. Other than that, high number of switches can also cause harmonic distortion. Therefore, numbers of researches have been conducted to reduce the switching number for the 7-level multilevel inverter. This is because the reduction of the number of switches can reduce the complexity of the circuit modulation system and reduce the Total Harmonic Distortion (THD).

Basically, reducing switches in multilevel inverter can be done by modifying the circuit of the inverter. Paper [12] successfully archives the reduction of three switches which makes only nine switches in needed. An improvement is then made by Lakshi by reducing the number of switches for 7-level multilevel inverter from nine to seven [12]. Then, another successful improvement had been made by Rokan who had successfully reduce the number of switches to six [13]. However, the circuit design of the 7-level multilevel inverter with the least number of switches was made by Umashankar. He reduce the number of switches to five switches and at the same time produce a multilevel inverter with lowest THD value as stated in his research entitle " A New 7-Level Symmetric Multilevel Inverter with Minimum Number of Switches" [6].

A 7-level symmetric multilevel inverter as shown in Figure 2:*4* is a redesigned circuit of an existing 6-switch topology. The switch that are connected parallel to the load was removed as the production of 7-level staircase voltage waveform can also be done but with only modifying the modulation of the circuit strategy.

From the circuit diagram, it is shown that the polarity of the load can be controlled by giving the polarity reversal role to switch 4 and 5. Generally, the expression for the output voltage levels is as shown in equation (1) and (2) where m is the number of output voltage level, n is the number of switches and v is the number of dc source.

$$m = (2n - 3) \tag{2.1}$$

$$m = (2v - 1) \tag{2.2}$$

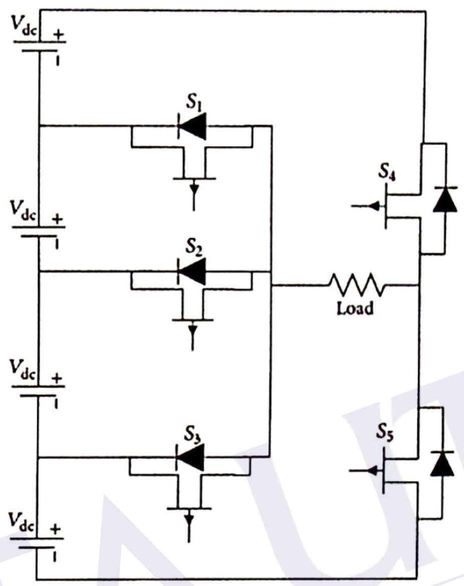

Figure 2:4: Circuit diagram of 7-level symmetric multilevel inverter

Reduced switches had made the circuit compact and simpler. However, the circuit needs four dc sources in order for the circuit to produce 7-level staircase waveform.

Table 2:1: Switching scheme for 7-level symmetric multilevel inverter

SL no.	S_1	S_2	S_3	S_4	S_5	Output voltage
1	OFF	OFF	ON	OFF	ON	$+V_{dc}$
2	OFF	ON	OFF	OFF	ON	$+2V_{dc}$
3	ON	OFF	OFF	OFF	ON	$+3V_{dc}$
4	OFF	OFF	OFF	OFF	OFF	$0V_{dc}$
5	ON	OFF	OFF	ON	OFF	$-V_{dc}$
6	OFF	ON	OFF	ON	OFF	$-2V_{dc}$
7	OFF	OFF	ON	ON	OFF	$-3V_{dc}$

2.3 Proportional-Resonant (PR) Controller

In the operation of the 7-level multilevel inverter, there is a presence of harmonic distortion in the AC output of the inverter. Conventionally, Proportional Integral (PI) controller is used in the 7-level multilevel inverter to reduce the total harmonic distortion at the output of the inverter. However, the PI controller has a limited bandwidth which unable the controller remove or reduce the low current harmonic [14].

One of the solution that can be used to overcome the limitation of the PI controller operation is by applying the second order Generalized Integrator (GI) as reviewed in [15]. Xiaoming Yuan conclude that using stationary-frame generalized integrator based PI controller will give a zero steady-state error for current harmonic.

This project is purposing the application of Proportional-Resonant (PR) current controller in the 7-level multilevel inverter. The different between PR and PI controller is that the PR controller has a different way of taking part in integration action. The integrator will integrate the frequencies that are close to the resonance frequency. The PR current controller is represented by

$$G_{PR}(s) = K_P + K_I \frac{s}{s^2+(\omega_0)^2} \tag{2.3}$$

PR controller is quite similar with the common PI controller. From the Bode plot of PR controller shown in Figure 2:5 shows that PR have very high gain in a narrow frequency band centred around resonance frequency. K_i which is the integral time constant will affect the width of the frequency band. The higher the K_i, the wider the band [16].

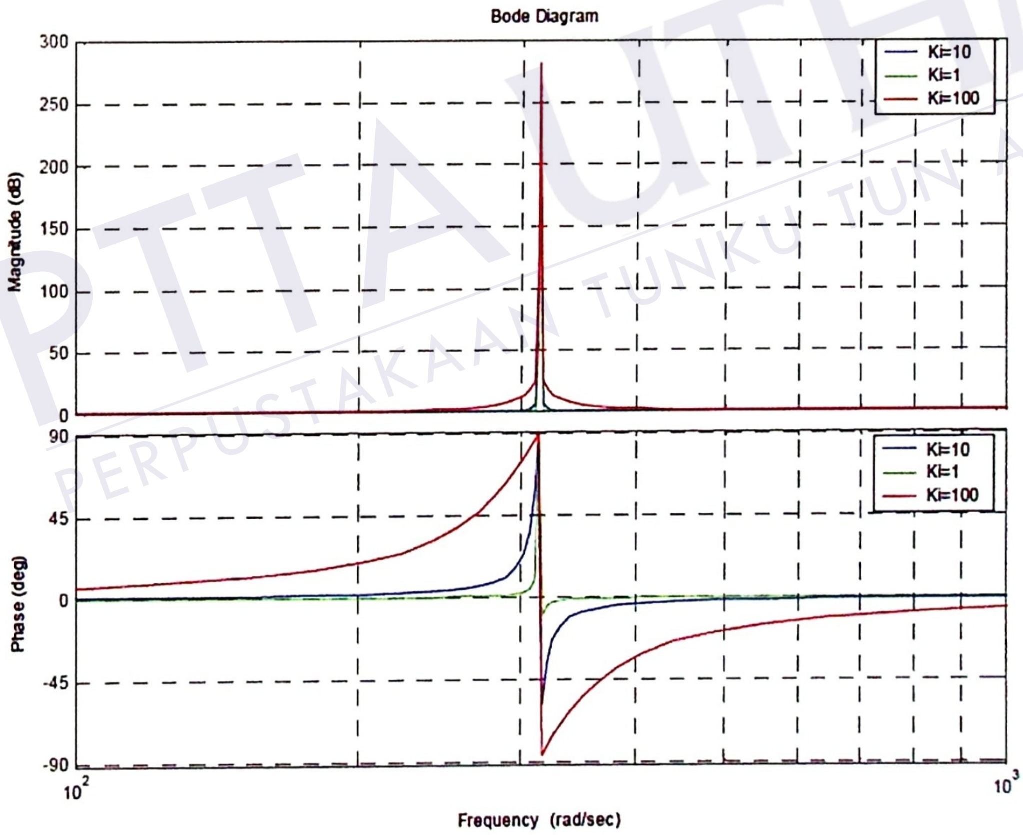

Figure 2:5: PR controller bode graph[14]

The proportional gain K_p can be tuned the same way to tuned the similar gain in PI controller. K_p determines the order in harmonic the PR is used for harmonic compensation. In this case, it can be used to regulate harmonics without disturbing the stability limit. This can be done by cascading several GI tuned to resonate at the desired frequency. The most significant affecting harmonics in current spectrum are 3^{rd}, 5^{th}, and 7^{th}. The transfer function in (2.4) is the typical harmonic compensator transfer function for 3^{rd} and 5^{th} harmonics.

$$G_h(s) = \sum_{h=3,5,7} K_{Ih} \frac{s}{s^2 + (\omega . h)^2} \tag{2.4}$$

2.4 Non-Linear Load and Harmonic Distortion

Nowadays, non-linear load can be easily found in common daily appliance. Some of most commonly used single phase non-linear are rectified input, switching power supplies and electronic lighting ballasts and so forth.

Non-linear load is a type of load which its impedance varies with the applied voltage. This means that the current drawn by the load will not be sinusoidal. This situation also occurs even if the load is connected to and AC voltage source. The non-sinusoidal current contains harmonic current that interacts with the impedance of the specific system which creates distortion. This distortion will affect the distribution system equipment and eventually affect the performance of the elements in the system.

Harmonic distortion is defined with respect to the fundamental frequency. This statement is based on IEEE Standard 519. The magnitude of fundamental frequency is much larger than any individual harmonic frequency. the RMS sum of the harmonics are also much larger. To measure the level of total distortion in a system, Total Harmonic Distortion (THD) calculation is usually used. THD is the ratio of RMS sum of all harmonic frequencies to the RMS value of the fundamental frequency[17]. The calculation of THD is as shown in equation (2.5).

$$THD = \frac{\sum(All\ RMS\ Harmonic\ Frequencies)}{Fundamental\ Frequency} \tag{2.5}$$

REFERENCE

[1] C. A. R.-P. J.D. Bastidas-Rodríguez, "Tipos de inversores y topologías para aplicaciones de microrredes Types of inverters and topologies for microgrid applications," Rev. UIS Ing., vol. 16, no. 1, pp. 7–14, 2017.

[2] K. Sato, H. Haga, and S. K. Nagaoka, "Single-phase 7-level inverter for reducing number of switches," INTELEC, Int. Telecommun. Energy Conf., vol. 2016–Septe, 2016.

[3] R. M. Patil, M. S. Nagaraj, and P. S. Venkataramu, "Analysis of the Effect of Harmonics Due To Switching Devices W . R . T . Experimental & Simulation Point of View," pp. 1454–1461, 2015.

[4] L. Changrong and L. Jih-Sheng, "Low Frequency Current Ripple Reduction Technique With Active Control in a Fuel Cell Power System With Inverter Load," Power Electron. IEEE Trans., vol. 22, no. 4, pp. 1429–1436, 2007.

[5] S. Eren, A. Bakhshai, and P. Jain, "Control of three-phase voltage source inverter for renewable energy applications," 2011 IEEE 33rd Int. Telecommun. Energy Conf., pp. 1–4, 2011.

[6] S. Umashankar, T. S. Sreedevi, V. G. Nithya, and D. Vijayakumar, "A New 7-Level Symmetric Multilevel Inverter with Minimum Number of Switches," Hindawi Publ. Corp., vol. 2, pp. 1–9, 2013.

[7] W. K. W. Kui, G. S. G. Shuhua, H. Q. H. Qian, H. Y. H. Yuanhong, and W. Q. W. Qinfang, "Investigation of harmonic distortion and losses in distribution systems with non-linear loads," 2008 China Int. Conf. Electr. Distrib., pp. 1–6, 2008.

[8] I. BIN MAMAT, DEVELOPMENT OF THREE PHASE BACK TO BACK CONVERTER WITH CURRENT FLOW CONTROL USING RASPBERRY PI MICROCONTROLLER, no. February. Universiti Tun Hussein Onn Malaysia, 2015.

[9] A. Nabae, I. Takahashi, and H. Akagi, "A New Neutral-Point-Clamped PWM Inverter," IEEE Trans. Ind. Appl., vol. IA-17, no. 5, pp. 518–523, 1981.

[10] J. Rodríguez, J. S. Lai, and F. Z. Peng, "Multilevel inverters: A survey of topologies, controls, and applications," IEEE Trans. Ind. Electron., vol. 49, no. 4, pp. 724–738, 2002.

[11] Z. Zhibing, L. Yongdong, and D. Bo, "Modeling and control strategy for cascade bi-directional DC/DC converter in Microgrid," Power Electron. Motion Control Conf. (IPEMC), 2012 7th Int., vol. 3, pp. 1747–1751, 2012.

[12] T. V. V. S. Lakshmi, N. George, S. Umashankar, and D. P. Kothari, "Cascaded seven level inverter with reduced number of switches using level shifting PWM technique," Proc. 2013 Int. Conf. Power, Energy Control. ICPEC 2013, pp. 676–680, 2013.

[13] R. A. Ahmed, S. Mekhilef, and H. W. Ping, "New multilevel inverter topology with minimum number of switches," IEEE Reg. 10 Annu. Int. Conf. Proceedings/TENCON, pp. 1862–1867, 2010.

[14] R. Teodorescu and F. Blaabjerg, "Proportional-resonant controllers. A new breed of controllers suitable for grid-connected voltage-source converters," 9th Int. Conf. Optim. Electr. Electron. Equipments, pp. 9–14, 2004.

[15] X. Yuan, W. Merk, H. Stemmler, and J. Allmeling, "Stationary-frame generalized integrators for current control of active power filters with zero steady-state error for current harmonics of concern under unbalanced and distorted operating conditions," IEEE Trans. Ind. Appl., vol. 38, no. 2, pp. 523–532, 2002.

[16] K. C. CHEN, APPLICATION OF PROPORTIONAL RESONANT (PR) CURRENT CONTROLLER IN SINGLE PHASE INVERTER SYSTEM CONNECTED TO NONLINEAR LOAD, vol. 2017. Universiti Tun Hussein Onn Malaysia, 2017.

[17] T. A. Kneschke, "DISTORTION AND POWER FACTOR OF NONLINEAR LOADS," pp. 47–54, 1999.

[18] M. Jafari, Z. Malekjamshidi, G. Lei, T. Wang, G. Platt, and J. Zhu, "Design and Implementation of an Amorphous High Frequency Transformer Coupling Multiple Converters in a Smart Micro Grid," IEEE Trans. Ind. Electron., vol. 46, no. c, pp. 1–1, 2016.

[19] M. Mirhosseini et al., "Resonant Versus Conventional COntrollers in Grid-Connected Photovoltaic Power Plants Under Unbalanced Grid Voltages," vol. 7, no. 3, pp. 1124–1132, 2016.

[20] L. Herman, S. Member, I. Papic, S. Member, and B. Blazic, "A Proportional-Resonant Current Controller for Selective Harmonic Compensation in a Hybrid Active Power Filter," vol. 29, no. 5, pp. 2055–2065, 2014.

[21] D. Sera et al., "Low-Cost Digital Implementation of Proportional-Resonant Current Controllers for PV Inverter Applications Using Delta Operator," pp. 2517–2522, 2005.

[22] R. Teodorescu and F. Blaabjerg, "A New Control Structure for Grid-Connected LCL PV Inverters with Zero Steady-State Error and Selective Harmonic Compensation," vol. 0, no. C, pp. 580–586, 2004.

[23] A. Ajami, M. Reza, J. Oskuee, A. Mokhberdoran, and A. Van Den Bossche, "Developed cascaded multilevel inverter topology to minimise the number of circuit devices and voltage stresses of switches," no. June 2013, 2014.

[24] H. K. Jahan, K. Zare, and M. Abapour, "Verification of a low Components Nine-Level Cascaded-Transformer Multilevel Inverter in Grid- Tie Mode," vol. 6777, no. c, 2017.

[25] S. SAHOO and T. Bhattacharya, "Phase Shifted Carrier Based Synchronized Sinusoidal PWM Techniques for Cascaded H-Bridge Multilevel Inverters," IEEE Trans. Power Electron., vol. 8993, no. c, pp. 1–1, 2017.

[26] A. R. A. Manito, E. O. de Matos, U. H. Bezerra, B. C. Costa, T. Mota Soares, and M. E. de L. Tostes, "Using linear and non-parametric regression models to describe the contribution of non-linear loads on the voltage harmonic distortions in the electrical grid," IET Gener. Transm. Distrib., vol. 10, no. 8,

pp. 1825–1832, 2016.

[27] N. Zhang, H. Tang, and C. Yao, "A systematic method for designing a PR controller and active damping of the LCL filter for single-phase grid-connected PV inverters," Energies, vol. 7, no. 6, pp. 3934–3954, 2014.