INTERCONNECTION AND DAMPING ASSIGNMENT PASSIVITY-BASED CONTROLLER FOR MULTILEVEL INVERTER

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To my lovely mother, who gave me endless love, trust, constant encouragement over the years, and for her prayers.

To my husband, kids, my mother in law and siblings, for their patience, support, love, and for enduring the ups and downs during the completion of this thesis.

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ABSTRACT

This thesis proposes an Interconnection and Damping Assignment Passivity-Based Controller (IDA-PBC) to control a 5-level Cascaded H-Bridge Multilevel Inverter (CHMI). The proposed IDA-PBC uses the Port-Controlled Hamiltonian (PCH) theory to modify the CHMI system energy by adding damping, thereby modifying dissipation structures related to dynamics and stability. The objective is to maintain output voltage regulation, resulting in fast response and low Total Harmonic Distortion (THD) values. Although the proposed IDA-PBC control algorithm showed outstanding performance during transient and nonlinear load condition, further improvements are required during no-load condition. To address this, improvements in the form of modification to the proposed IDA-PBC algorithm was made by adding a single loop Proportional-Integral (PI) controller at the voltage side, which was aimed at regulating the voltage before it was fed back into the IDA-PBC. In order to verify the viability of the proposed IDA-PBC-PI controller for the CHMI, a simulation study was conducted using MATLAB/Simulink at a 20 kHz switching frequency and 1 µs sample time. The controller was tested at five load conditions, namely, steady state, no-load to full-load, load uncertainty, structural uncertainty and nonlinear load condition. The performance of the proposed controller showed regulated output voltage while maintaining THD values below 5% in all load conditions and a maximum of 220 µs response time during load uncertainty. The simulation results revealed the superiority of the proposed controller compared to the conventional double loop PI controller and the conventional IDA-PBC in terms of transient response, THD value, as well as regulation of the output voltage. The feasibility of the proposed IDA-PBC-PI controller was validated by developing its proof-of-concept hardware prototype. The simulation and experimental results obtained based on a 3 kHz switching frequency and 38 µs sample time were found to be consistent, which confirmed the capability of the proposed controller in controlling the 5-level CHMI output voltage.

ABSTRAK

Tesis ini mengusulkan Penetapan Terhadap Sambungan dan Redaman bagi Pengawal yang Berasaskan Konsep Pasif (IDA-PBC) untuk mengawal 5-aras Penyongsang Jejambat-H Pelbagai Aras (CHMI). IDA-PBC yang diusulkan menggunakan teori Kawalan-Port Hamiltonian (PCH) untuk mengubah suai tenaga CHMI dengan menambah redaman dan mengubah suai struktur pelesapan yang berkaitan dengan dinamik dan kestabilan. Objektif kawalan adalah untuk mengekalkan aturan voltan keluaran, serta menghasilkan masa tindak balas yang cepat dan Jumlah Gangguan Harmonik (THD) yang rendah. Walaupun algoritma kawalan IDA-PBC yang diusulkan menunjukkan prestasi cemerlang semasa keadaan peralihan dan beban yang tidak linear, penambahbaikan diperlukan semasa keadaan ketiadaan beban. Oleh itu, pengubahsuaian kepada algoritma IDA-PBC yang diusulkan telah dilaksanakan dengan menambah kawalan Berkadar-Kamiran (PI) pada bahagian voltan, untuk mengawal selia voltan sebelum ia disuap-balik ke dalam IDA-PBC. Bagi mengesahkan kebolehupayaan kawalan ini, kajian simulasi dijalankan menggunakan MATLAB/Simulink pada frekuensi pensuisan 20 kHz dan 1 μs sampel masa. Pengawal ini diuji pada lima keadaan beban iaitu pada keadaan tetap, tiada beban kepada beban penuh, beban yang tidak menentu, ketidakpastian struktur dan beban yang tidak linear. Prestasi pengawal yang diusulkan menunjukkan voltan keluaran adalah teratur selain mengekalkan nilai THD bawah 5% dan masa tindak balas maksimum sehingga 220 μs. Keputusan simulasi mendedahkan keunggulan pengawal yang dicadangkan berbanding pengawal PI dua gegelung konvensional dan pengawal IDA-PBC konvensional dari segi masa tindakbalas, nilai THD serta aturan voltan keluaran. Semua pelaksanaan pengawal IDA-PBC-PI yang dicadangkan telah disahkan dengan membangunkan perkakasan prototaip berdasarkan konsep-pembuktian. Keputusan simulasi dan eksperimen yang diperolehi berdasarkan frekuensi pensuisan 3 kHz dan 38 μs sampel masa adalah didapati konsisten, yang mengesahkan keupayaan pengawal yang dicadangkan dalam mengawal voltan keluaran bagi 5-aras CHMI.

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LIST OF ABBREVIATIONS

A	-	Ampere
A_c	-	Amplitude of the carrier signal
A_m	-	Amplitude of the modulating signal
A/D	-	Analog/Digital
CHMI	-	Cascaded H-bridge Multilevel Inverter
CPU	-	Central Processing Unit
DC	-	Direct Current
DSP	-	Digital Signal Processor
EMI	-	Electromagnetic Interference
EV	-	Electric Vehicle
FFT	-	Fast Fourier Transform
FPGA	-	Field-Programmable Gate Array
I/O	-	Input/Output
IGBT	-	Insulated-Gate Bipolar Transistor
kHz	-	kilo Hertz
m	-	Number of staircase level
m_a	-	Amplitude modulation ratio
MLI	-	Multilevel Inverter
N	-	Harmonic order
PS-PWM	-	Phase-shift Pulse Width Modulation
PV	-	Photovoltaic
PWM	-	Pulse Width Modulation
$r1$, $r2$	-	Random number in a range of 0 to 1
n	-	Number of single phase full bridge inverters
THD	-	Total Harmonic Distortion
V	-	Volt
Var	-	Volt amperes reactive
VDC1	-	DC supply module 1
VDC2	-	DC supply module 2

Vc	-	Capacitor output voltage of CHMI
W	-	Watt
μs	-	micro seconds
θ	-	Angle

CHAPTER 1

INTRODUCTION

1.1 Introduction

The rapid evolving industry in recent years has demanded higher power equipment which now reaches up to Megawatt level. These high power applications need to be connected to medium-voltage power electronics devices. In order to cater the demand, multilevel inverter has been introduced [1]. Multilevel inverters are built by a row of power semiconductors and voltage sources. This inverter structure is able to create staircase sinusoidal like voltages. The required output voltage of the inverter can be obtained by summing up the total of the DC voltage sources. This structure allows the multilevel inverter to produce higher output voltage, with less voltage for each semiconductor device to withstand. Thus, multilevel inverter structure increases the capability of the power converters to operate in medium-voltage grid.

Since its introduction in 1981 [1], its amazing and interesting properties in medium and high power application has attracted a large interest among researchers. This includes its capability to operate in higher voltage operation with low switching losses and reduced harmonics [2], [3]. As compared to conventional inverters, multilevel inverters are also preferred due to the low voltage stress on the power switches where lower $\frac{dV}{dt}$ is applied to the components since the voltages are divided into smaller values to perform the switching [4]. This cost-effective solution not only enables the inverters to meet high power ratings, but also capable to operate in low power operations such as in renewable energy application [5]–[7]. Other applications include tractions [8], [9], active power filtering [4], [10], VAR compensation [11], flexible AC transmission system [12] and induction motor drives [13].

Providing a clean and stable sinusoidal output voltage regardless of any perturbations is the main requirement of a well-designed multilevel inverter. It is also important to ensure that the multilevel inverter can provide fast transient recovery time caused by load uncertainties or disturbances. Moreover, in the case of the presence of a non-linear load, the multilevel inverter will produce a highly distorted load current and in return will cause deterioration in the output voltage quality. The severe effects of the current and voltage distortion in power system quality have been reported in various cases [14], [15]. Thus, it is very important to maintain a regulated output voltage with fast transient response and low Total Harmonic Distortion (THD) of below 5% [16]. In order to achieve these, a reliable closed-loop control scheme is needed.

There are two main approaches of ensuring output regulation of a multilevel inverter which are; linear or nonlinear strategies. One of the most frequently applied linear controllers is the Proportional Integral (PI) controller of which control objective is to regulate the output signals and reduce the steady state error to zero [17]. Although offering the advantage of constant switching frequency, this controller, however, is very sensitive to perturbations and variations of a system's parameters. Since the mathematical model of the inverter itself is nonlinear, it is strongly agreed that a nonlinear control strategy from the nonlinear structure of the system will lead to better achievement in terms of performance. An example of a commonly used nonlinear approach is determining the inverter switching by using hysteresis comparator. This method has been proven to achieve a good dynamic response in multilevel inverter applications [18], [19]. However, the variable switching frequency has become a major drawback of this approach.

Another nonlinear controller that has gained researcher's interest in recent years is a method based on energy function shaping known as Passivity-based Controller (PBC). The growing interest in PBC implementation in power electronics devices [20]–[22] has resulted in a very successful development of the so-called Interconnection and Damping Assignment PBC (IDA-PBC). This controller produces a closed-loop system based on Hamiltonian structure. In this structure, the closed-loop energy is required to have a minimum desired equilibrium point to assure its stability. The main advantage of the IDA-PBC algorithm is that the Lyapunov function is obtained naturally by the dynamic structure of the system itself, leading to the desired operating point, rather than imposing external dynamics which conventional controllers mostly do. The IDA-PBC has proven to be useful and efficient to meet regulatory objectives in various applications [22]–[25].

1.2 Problem Statement

The nonlinear nature of the multilevel inverters' nonlinear equations is caused by the multiplication of the state variables by the control inputs. Traditional linear control methods as presented in [17], [27] often neglect the nonlinear characteristics of the multilevel inverter and physical characteristics of the LC filter. This in turn, leads to instability problems on the power converter system. In comparison to the linear controller, nonlinear controllers deal with a wider class of systems that are nonlinear, time-variant or both. It is generally applied to real-world systems that are often governed by nonlinear equations [28].

The nonlinear control systems can be classified into two major groups which are non-model based and model based. Non-model based controllers do not consider essential information of the system parameters and hence no mathematical model for the controller is needed. The controllers are more robust than their model based counterparts. An example of a non-model based controller in the market is Fuzzy Logic Controllers (FLC) [29]. This technique is useful to approximate a system because the fuzzy sets boundaries can be unclear or indefinite due to the gradual transition between membership and non-membership [30]. In CHMI, FLC has been applied successfully in improving power quality by minimizing the harmonics in the output voltage waveform [31]–[33]. However, these non-model based controllers are lacking in standard design guidelines and are normally designed in heuristic manners. Their performances are quite unpredictable and are generally difficult to optimize [34].

On the other hand, model-based controllers require a precise mathematical model of the multilevel inverter in order to design the controller's algorithm. Its design procedure is systematically structured and is widely accepted by the control system community [35]. A common design environment provided in a model-based controller design enhances general communications between the elements of power systems, provide easier data analysis and allow system verification. The impact of the controller's design and modification in terms of time and cost can be reduced by synthesizing and troubleshooting the errors in the system as early as possible. It is also easier to reuse or upgrade the existing developed system especially for a system with expanded capabilities.

1.3 Thesis Objective

This thesis proposes a model-based nonlinear controller which is a modified IDA-PBC for the control of a Cascaded H-bridge Multilevel Inverter (CHMI). This structured controller model enhances the stability and dynamical performance of the CHMI by adding damping elements and modifying the dissipation structure. The proposed modified IDA-PBC in this thesis improves the transient stability of power systems by proposing a new solution of the matching partial derivative equation through the desired interconnection matrix. The new matrix function for the interconnection and damping matrices shows outstanding performance during transient response and during the presence of a nonlinear load. However, in order to improve the performance of the controller during transition from no load to full load condition, and vice versa, a complementary PI controller is proposed to be added to the voltage part of the controller. This controller is referred to as the IDA-PBC-PI controller which is able to minimize the steady-state error between the actual output voltage with the equilibrium point before it is injected back into the IDA-PBC system. This results in the improvement of the inverter's performance especially during the transition from no load to full load. This controller is able to maintain output voltage regulation with fast transient response while maintaining low THD value with various load conditions. This thesis critically looks into the aspect of the design, analysis, implementation and performance evaluation of both the IDA-PBC and IDA-PBC-PI controllers. The objectives of this thesis are:

1. To study the multilevel inverter concept, topologies and control methods that has been implemented as well as the concept and types of Passivity-Based Controllers (PBC).
2. To implement through simulation and experimental work the concept of Interconnection and Damping Assignment Passivity-Based Controller (IDA-PBC) on Cascaded H-bridge Multilevel Inverters (CHMI).

3. To develop the related IDA-PBC mathematical model, design procedures and control performance evaluation in terms of output voltage regulation and transient response while maintaining the acceptable range of Total Harmonic Distortion (THD) percentage.

1.4 Thesis Scope

The thesis covers the development of the mathematical model and implementation of both the proposed IDA-PBC and IDA-PBC-PI controllers for a 5-level CHMI. Performance evaluation of the controllers is based on maintaining output voltage regulation with fast transient response and low THD under various loading conditions. The performance is verified through both simulation and experimental work of the proposed controllers for the 5-level CHMI.

1.5 Thesis Contribution

In implementing the concept of IDA-PBC as applied to a 5-level CHMI, the following contributions are attained:

- Two new matching equations of damping and injection matrices have been proposed in the controller's algorithm. These equations are obtained by solving the Partial Differential Equation (PDE) derived from the structure of the 5-level CHMI. These two matrices are developed by following propositions that are subjected to the IDA-PBC control law.

- A new IDA-PBC-PI controller to improve the overall CHMI output voltage performance during no load condition. Although IDA-PBC itself is robust and performs well throughout various loading conditions, the PI controller added at the voltage part of the IDA-PBC has shown improved performance.

1.6 Organization of Thesis

This thesis consists of this introductory chapter and four other chapters organized as follows:

Chapter 2 provides literature review on the various multilevel inverter topologies and controllers. The significance of choosing the 5-level CHMI is also included.

Chapter 3 explains the research methodology of the thesis. It is divided into three sections namely, the mathematical model for the 5-level CHMI circuit and the development of IDA-PBC control algorithm, simulation model of the system and the experimental set-up.

Chapter 4 presents the simulation and experimental results of the proposed controllers. The performance of each controller is evaluated in terms of output voltage regulation and THD as well as transient response during no load to full load transition, load uncertainty and structural uncertainty. Comparison of the two proposed controllers with the double-loop PI controller is also included.

Chapter 5 provides conclusions of the thesis and recommendation for future works is also included in this chapter.

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