IDENTIFICATION AND MODELLING OF TWO-PHASE DC-DC BOOST CONVERTER BASED ON AUTOREGRESSIVE MOVING AVERAGE WITH EXOGENOUS, OUTPUT-ERROR AND TRANSFER FUNCTION MODEL STRUCTURES

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To my beloved parents, thank you.

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ABSTRACT

This research presents the identification and modelling of a two-phase DC-DC boost converter based on the autoregressive moving average with exogenous (ARMAX), output-error (OE) and transfer function (TF) model structures for low-voltage applications. The goals that led to this study were to reduce the time taken to design the controller and analyse the output of constant K_p and K_i generated from the auto tuning method. A two-phase boost converter employs as 180-degree phase shift from each phase to drive the power switch. This research focused more on the system identification approach to generate mathematical models from the open-loop response. The generated models were from the TF, ARMAX and OE model structures. The mathematical models were generated from the pulse-width modulation (PWM) input and voltage output of the two-phase boost converter itself in the time domain data. After the best model order was found to replace the two-phase boost converter with a mathematical model, the controller design took place. Some closed-loop blocks were designed for the mathematical models in MATLAB/Simulink software, which were also used to perform the auto-tuning of the proportional-integral (PI) controller. However, tuning methods such as the Ziegler-Nichols and the Cohen-Coon methods are more time-consuming. After the best values for constants K_p and K_i were determined, the values were used in the real hardware to analyse the output responses. The findings showed that K_p and K_i from the TF model showed 19% overshoot compared with those of the ARMAX and OE models, which were 25.36% and 24.6%, respectively. All of the output responses from the different K_p and K_i values resulted in less than 5% ripple voltage. It can be concluded that the best model from the system identification approach was the TF system model, since it had the lowest overshoot and the lowest percentage of output voltage ripple.

ABSTRAK

Penyelidikan ini membentangkan pengenalpastian dan pemodelan penukar rangsangan dua fasa berdasarkan model ARMAX (*autoregressive-moving Average with Exogenous)*, model OE *(output-error)* dan model TF *(transfer function)* untuk aplikasi voltan rendah. Isu yang membawa kepada penyelidikan adalah seperti mengurangkan masa yang diambil untuk menala pengawalan dan mengkaji keluaran daripada K_p dan K_i melalui pendekatan kawalan automaik. Penukar rangsangan dua fasa menggunakan anjakan fasa 180 darjah dari setiap fasa untuk menghidupkan suis. Walau bagaimanapun, kajian ini akan lebih tertumpu kepada pendekatan pengenalan sistem untuk menjana model matematik daripada sistem tanpa pengawal. Model yang akan dihasilkan adalah daripada model *TF*, model *ARMAX* dan model *OE*. Model matematik ini akan menggunakan data masukan daripada *pulse-width modulation* (PWM) dan data keluaran daripada voltan keluaran penukar rangsangan dua fasa itu sendiri. Selepas berjaya memperolehi model matematik terbaik daripada sistem pengenalpastian untuk menggantikan penukar rangsangan dua fasa, pengawal arus voltan akan dihasilkan. Selain itu, dengan mencipta beberapa bentuk pengawal voltan untuk model matematik dalam perisian MATLAB/Simulink, ia akan digunakan untuk menala pengawalan *proportional-integral* (PI) secara automatik. Kaedah kawalan seperti Ziegler-Nichols dan Cohen-Coon lebih memakan masa untuk mendapatkan nilai penalaan PI. Selepas mencari nilai terbaik untuk K_p dan K_i, nilai tersebut akan digunakan dalam sistem sebenar untuk menganalisis keluaran. Data daripada kajian menunjukkan bahawa K_p dan K_i daripada model TF menunjukkan 19% lebihan berbanding model *ARMAX* dan *OE* iaitu 25.36% dan 24.6%. Tambahan pula, semua tindak balas keluaran daripada K_p dan K_i yang berbeza menghasilkan tekanan voltan kurang daripada 5%. Dapat disimpulkan bahawa model terbaik daripada pendekatan pengenalan sistem adalah daripada model *TF* kerana ia mempunyai lebihan voltan dan tekanan voltan keluaran yang paling kurang.

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LIST OF SYMBOLS AND ABBREVIATIONS

θ	-	Time delay
A_q	-	Random number 1
B_q	-	Random number 2
C_q	-	Random number 3
D_q	-	Random number 4
E_q	-	Random number 5
F_q	-	Random number 6
N	-	Various numbers
ADC	-	Analog to digital converter
AC	-	Alternating current
ARMAX	-	Autoregressive-moving Average with Exogenous model
ARX	-	Autoregressive with Exogenous model
ASIC	-	Application-specific integrated circuit
BCM	-	Boundary Conduction Mode
BJ	-	Box-Jenkins
C	-	Capacitor
CCM	-	Continuous conduction mode
D	-	Duty cycle
D	-	Derivative
DC	-	Direct current
D_1	-	Diode 1
D_2	-	Diode 2
DSP	-	Digital signal processing
DCM	-	Discontinuous conduction mode
EMI	-	Electromagnetic interference
FPGA	-	Field Programmable Gate Array
FFT	-	Fast Fourier Transform

f	-	Frequency
f_s	-	Switching frequency
HDL	-	Hardware Description Language
Hz	-	Hertz
I	-	Integral
ID	-	Integral Derivative
I_{Lmax}	-	Maximum current
I_{Lmin}	-	Minimum current
$\mathrm{I_{L(average)}}$	-	Average inductor current
$\mathrm{i_c}$	-	Current through capacitor
$\mathrm{i_d}$	-	Current through diode
I_L	-	Inductor current
i_{L1}	-	Inductor current through L_1
i_{L2}	-	Inductor current through L_2
K	-	Process gain
K_p	-	Proportional gain
K_d	-	Proportional derivative
K_i	-	Proportional integral
L	-	Inductor
L_{crit}	-	Minimum inductor
L_1	-	Inductor 1
L_2	-	Inductor 2
MOSFET	-	Metal-Oxide-Semiconductor Field-Effect Transistor
MPPT	-	Maximum power point tracking
OE	-	Output-Error
P	-	Proportional
PI	-	Proportional Integral
PD	-	Proportional derivative
P	-	Power
PV	-	Photovoltaic
PID	-	Proportional-integral-Derivative
PWM	-	Pulse-Width Modulation
r	-	Ripple factor

R	-	Resistor
RMS	-	Root-mean-square
RTI	-	Real-Time-Interface
S	-	Power switch
S_1	-	Switch 1
S_2	-	Switch 2
T	-	Switching period
T_{off}	-	Switch off time
T_{on}	-	Switch on time
t	-	Time constant
t_r	-	Rise time
t_f	-	Fall time
TF	-	Transfer Function
UPS	-	uninterruptable power system
V_{in}	-	Input voltage
V_s	-	Supply voltage
V_o	-	Output voltage
V_{Loff}	-	Inductor voltage time switch off
V_{Lon}	-	Inductor voltage time switch on
V_{out}	-	Output Voltage
V_{max}	-	Maximum voltage
V_{min}	-	Minimum voltage
V_{ref}	-	Reference voltage

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Chapter 1 presents the detailed information related to the proposed research, which consists of the background of the study, problem statement, objectives and scope of the study.

1.2 Background of Study

Boost converters have been used in numerous applications, such as personal electronics appliances [1], [2], automotive [3], [4], communications [5] and enterprise systems. Boost converters are also widely applied in PV cells [6]–[9] and wind power systems [10]–[12]. However, conventional boost converters have drawbacks, such as high current ripple occurring on the switches and the output diode, inability to distinguish between switch voltage stress and output voltage and large switching [13], [14]. Research in power electronics has established ways to effectively increase the performance and efficiency of boost converters to generate better output, such as using multiphase DC-DC boost converters or interleaving techniques [15]–[18].

The interest in multiphase interleaved boost converter topologies has increased in recent years, where the boost converters employ phase-shifted pulse-width modulation (PWM) to control the metal-oxide-semiconductor field-effect transistors (MOSFETs). This is frequently used in designs where the paralleling of components is necessary [19]. This thesis focused on the two-phase DC-DC boost converter, where the PWM signals of the two-phase boost converter were phase-shifted by 180 degrees at each phase to turn on and turn off the MOSFETs. The advantages of the *N*-phase boost converter topology compared with the conventional boost converter topology are the ability to reduce input and output current ripples [20], reduce the stress on the switches and improve load transient responses [21], [22].

In designing a boost converter, it is important to provide sufficient information to ensure the reliability, effectiveness, and robustness of the system. The controller must be designed in the simulation to obtain the gain constants of K_p, K_i and K_d. The most popular method to tune the proportional-integral-derivative controller is via the Ziegler-Nichols tuning method [23]. However, this method provides less information about the internal system. Deficient information about the open-loop system of the two-phase boost converter, such as the transient response and frequency response, will lead to inaccurate controller design. In addition, designing such hardware in the simulation will be time-consuming. Mathematical modelling can solve this issue when designing a proper controller for two-phase boost converters in low-voltage applications.

Basically, there are two ways to obtain the mathematical model, which are the first principle model, as the example of physical laws, and empirical model, as the example of system identification [24]. System Identification is a tool used to build mathematical models based on input and output signals. The signal can be measured in the time or frequency domain depending on the data measured. In general, a few steps must be followed in order to perform the identification technique. The step consists of input and output data collection, model selection, model order determination, model validation and lastly model evaluation. In this study, the model was selected from the ARMAX, TF and OE model structures [25].

Subsequently, the model from the system identification was used to design the controller. The values of constants K_p and K_i for designing the PI controller were determined by using the auto-tuning method. The auto-tuning method consumed less time in building the controller. This was due to the tuned values of K_p and K_i from the mathematical model generated from the system identification method. After the values of constant K_p and K_i were successfully obtained, the values were tested using the prototype controller.

1.3 Problem Statement

A DC-DC boost converter has a significant role in solar power system, where its main function is to increase the voltage gain [26]. A DC-DC boost converter is extensively used in many applications, such as the photovoltaic (PV) panel [27], wind power system [28], an uninterruptable power system (UPS) [29] and electric drive [30]. However, there are issues arising from conventional converters, such as large current at the low-voltage side, high voltage stress on the switches and high current ripple, all of which are major concerns in DC-DC boost converters [31]. The most practical way is by using the multiphase boost converter, as explained in [22], [31], [35] and [36].

The application of physical laws in system modelling might cause inaccuracies in designing the mathematical model. System identification can be used to address the issue, such as by analysing [34], designing, verifying and evaluating the generated mathematical model. System identification is more facile, where it only uses input and output data to generate the mathematical model, unlike using physical laws, which derives the mathematical model of a physical system and hence is more complex [35]. In addition, small amount of data can cause errors in the modeling state. Hence, by increasing the sample data can improve the model of the two-phase boost converter.

In designing the controller in this study, firstly, the mathematical model of the two-phase boost converter must be obtained. Then, the mathematical model was simulated. The auto-tuning method from the mathematical model was used to find constant K_p and K_i values. The auto-tuning method provided an easier way to construct the constants' values, since this technique would tune the system according to the study's desire. Using this approach saves more time in designing the controller compared with using the Ziegler-Nichols and Cohen-Coon tuning methods.

In addition, system identification can provide access to improve or test the internal structure of the system in term of rise time and overshoot of the system.

Therefore, the proposed two-phase DC-DC boost converter was combined with the system identification to observe the relationship. Three models were addressed to develop the system using system identification, which were the ARMAX, OE and TF model structures. The models were chosen because they would give a better output model compared with other models in the system identification approach.

1.4 Objectives

The main objectives of this research are as follows:

a) To identify the optimum mathematical model of the two-phase boost converter based on the system identification approach using the TF, ARMAX, and OE model structures.
b) To analyse the performances of PI controller for the two-phase boost converter based on the TF, ARMAX and OE models in terms of transient response, overshoot and undershoot.

1.5 Scope of Study

This study focused on modelling a two-phase boost converter to obtain the mathematical model for the controller design. The scope of the study is as follows:

a) The software solutions used to perform the simulation and hardware implementation of the two-phase boost converter were MATLAB/Simulink, ControlDesk and Quartus II software.
b) Measurement data were extracted from the PWM input and voltage output of the two-phase boost converter.
c) The model structure was selected from the TF, ARMAX and OE model structures.
d) The order for the mathematical model was limited to the 20th order.
e) The model structure was evaluated.

f) The circuit comprised power input, MOSFETs, inductor, capacitor, resistor and diode.

g) The parameters were as follows:

- Input voltage = 15-40 V
- Output voltage = 45-60 V
- Output power = 20-200 W
- Switching frequency = 100 kHz
- The passive components used were a 470 μF inductor and a 220 μH capacitor.

1.6 Thesis outline

This thesis consists of five chapters. The outline of this thesis is illustrated below.

In Chapter 2, readers are briefed on research-related matters, such as reviews on some basic concepts about the step-up DC-DC boost converter. These are isolated/non-isolated converters, unidirectional/bidirectional converters and techniques to improve the DC-DC boost converter. In addition, the difference between various phases will be explained. Next, some theories on the modelling approach are presented, which are on-line/off-line, structural/behavioural and non-parametric/parametric system identification approach. Next, the system identification loop is explained, which includes the steps to be followed in order to perform the identification technique. Reviews on the PID control algorithm and on DSP and FPGA are presented. Finally, previous research works related to the proposed topic are discussed.

In Chapter 3, the overall methodology of the research study is explained. It consists of the research flowchart to give a better understanding on how this research was done. Next, the design and the principle of the operation of the two-phase boost converter will be explained. In this subtopic, the modes of operation, which were the continuous conduction mode and the discontinuous conduction mode, are described. The subtopic on the two-phase data acquisition will show how input and output data were retrieved from the two-phase boost converter. In addition, the steps to generate the system model by using the system identification toolbox will be described in detail. Next, the signal for the MOSFET design using

Quartus II software will be explained. The controller design using MATLAB/Simulink is also shown. Finally, the equipment and the components used in the experiment will be discussed in this chapter.

Chapter 4 presents the analysis and the discussion on both the experiment and the simulation in the proposed research. The mathematical model for the ARMAX, TF and OE model structures is shown. The percentage similarity between the model and the data from the two-phase boost converter via the simulation is also shown. The experiment would show the responses from the two-phase boost converter by using the constants K_p and K_i obtained from the system model. Some of the experiment's output values were compared with the output from the simulation to verify the responses in the experiment.

Chapter 5 presents the conclusion of the proposed research, as well as its contributions. Recommendations for future work are also included in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the literature review is presented to help give information for implementing the identification and modelling of the two-phase DC-DC boost converter for low-voltage applications. The classification of step-up DC-DC converters, which are non-isolated and isolated DC-DC converters, unidirectional and bidirectional DC-DC converters, and non-isolated and isolated DC-DC converters, are explained. In Subchapter 2.3, the difference between various phases of the DC-DC boost converter is explained. Subchapter 2.4 presents the theory of modelling approach, which consists of on-line and off-line identification, structural and behavioural models, and non-parametric and parametric identification. System identification loop and classification of polynomial parametric estimation will be explained in Subchapter 2.5 and Subchapter 2.6. In Subchapter 2.7, the control system algorithm is discussed. DSP and FPGA will be explained in Subchapter 2.8. Subchapter 2.9 presents the gap of study related to the proposed research.

2.2 Classifications of step-up DC-DC converters

By adding the voltage-boosting capability in a DC-DC converter, the converter can be used in numerous power conversion applications. The step-up DC-DC converter achieved popularity in the late 1960s with the advent of semiconductor switches in the 1950s [36]. A pulse-width-modulated (PWM) boost converter, a

basic step-up of DC-DC voltage converter with some features that make it reasonable for many applications from low- to high-power devices [37]. The converter has the capability of operating either in the continuous conduction mode (CCM) or the discontinuous conduction mode (DCM).
The step-up DC-DC converter can be categorised as shown in Figure 2.1.

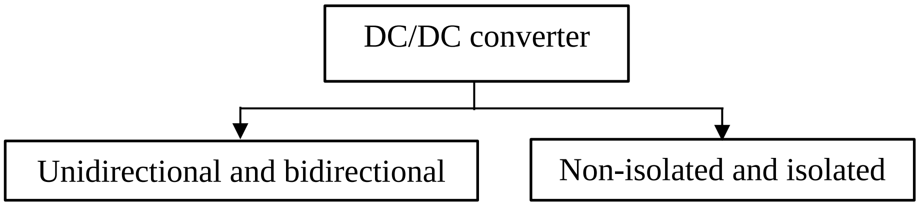

Figure 2.1: Step-up DC-DC converters based on categorisation

2.2.1 Non-isolated and isolated DC-DC converters

A PWM boost converter, which comprises three basic components (switch, inductor and diode), is an effective non-isolated converter to step up voltage, which is suitable for many applications. Basically, boost converters and other non-isolated converters are suitable only for low-voltage conversion with the reduction in cost and size [38], [39]. A non-isolated converter can be set up either with or without magnetic coupling. If efficiency is not a major problem and high-voltage step-up is not considered, non-isolated converters without magnetic coupling can be a solution, which consist of only passive components and a switching device. Nevertheless, it is important to address the magnetic coupling in high-power systems to improve efficiency and reliability [37]. For example, in [40], the improvement in system performance was done by sharing the connection between the non-isolated input and the output of the converter.

Applications such as renewable-energy-based power conditioning systems and electric vehicles apply isolated DC-DC converters in their interior designing [41]–[43]. Electrical isolation in several applications is important to reduce electromagnetic interference (EMI) and to ensure low noise during the power transfer [37]. Normally, isolated converters can be designed as a single structure or as two structures separated by a transformer or a coupled inductor. Some of the

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APPENDIX G

LIST OF PUBLICATION

1) **M. A. N. Amran**, A. A. Bakar, M. H. A. Jalil, M. U. Wahyu, and A. F. H. A. Gani, "Simulation and modeling of two-level DC/DC boost converter using ARX, ARMAX, and OE model structures," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 18, no. 3, p. 1172, Jun. 2020, doi: 10.11591/ijeecs.v18.i3.pp1172-1179.
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APPENDIX H

AWARDS

1) Best Paper Award, 2021, 4th International Conference on Engineering and Computing (ICEEComp2021) –Virtual Mode 24-25 April 2021, Malaysia "Power Losses Analysis of Multiphase Interleaved DC-DC Boost Converter using OrCAD PSpice Software".
2) Best Paper Award, 2019 13th International Power Engineering, Optimization & Computing Conference, "Design and Development of PWM Switching For 5-Level Multiphase Interleaved DC/DC Boost Converter", Indonesian Journal of Electrical Engineering and Computer Science.

APPENDIX I

VITA

The author was born on May 5, 1995, in Selangor, Malaysia. He went to Maktab Rendah Sains Mara Pengkalan Hulu, Perak, Malaysia, for his secondary school. He pursued his bachelor's degree at Universiti Tun Hussein Onn (UTHM), Johor, Malaysia, and graduated with B.Eng. (Hons) in Electronic and Electrical Engineering in 2019. Then, he pursued his master's degree at Universiti Tun Hussein Onn (UTHM) in the power electronic field. He has interests in power electronics, digital control, renewable energy and control system.