COMPARATIVE ANALYSIS OF VOLTAGE AND CURRENT SOURCE INVERTER TOPOLOGIES FOR STANDALONE SYSTEM.

by

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A thesis submitted in fulfillment of the requirements for the degree of Master of Science in Electrical System Engineering.

Faculty of Electrical Engineering Technology
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2022

ACKNOWLEDGEMENT

First and foremost, praise and thanks to God, for His showers of blessings throughout my master research journey. All difficulties throughout my research were calmly solved with His guidance and knowledge as well as good health.

I would like to express my deepest appreciation to my research supervisor, Dr Syahrul Ashikin, for providing invaluable guidance to my research. Her understanding and quality base policy urged me to deliver the best outcome regarding this research. I also would like to thank my co-supervisor, Dr Leong Jenn Hwai, who convincingly conveyed a spirit of adventure regarding research and encourage me in completing the research.

I am extremely grateful to my parents for their love, prayers, caring and support throughout my master research. Also, I express my thanks to my siblings for their moral support and encouragement that gives me the strength to finish my master journey. My compliments also go to my friends for supporting me and they indirectly give me lots of ideas to complete the research.

A courteous acknowledgement to the Faculty of Electrical Engineering Technology of UniMAP for providing me with a chance to continue my master research. I am especially thanks to all the Dr, lecturers and staff at FTKE. Their expect and guidance regarding my work are highly appreciated. Lastly, I sincerely apologise for all those whom I might not have mentioned here and thank everyone who had been a part of my success.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Alternating current
α	Real
β	Imaginary
CSI	Current source inverter
CM EMI	Common-mode electromagnetic interference
CMV	Common-mode voltage
DC	Direct current
DC-DC	Direct current to direct current
EMC	Electromagnetic
FFT	Fast Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-gate bipolar transistor
IMDs	Integrated motor drives
LCI	Load-commutated inverter
MCS	Minimal switching counts
MTBF	Mean Time Between Failures
NEM	Net Energy Metering
PI	Proportional integral
PID	Proportional-integral-differential
PLL	Phase locked loops
PR	Proportional-resonant
PV	Photovoltaic
PWM	Pulse width modulation
rms	Root mean square
SEDA	Sustainable Energy Development Authority
Si	Silicon
SiC	Silicon carbide
SOP	Superior output performance
SPWM	Sinusoidal pulse width modulation
STATCOM	Static compensator
SVM	Space vector modulation
THD	Total harmonic distortion
THIPWM	Third-harmonic injection pulse width modulation

TNB	Tenaga Nasional Berhad
UniMAP	University Malaysia Perlis
VSI	voltage source inverter
WBG	Wide-bandgap
ZCS	Zero-current switching

LIST OF SYMBOLS

C	Capacitance
C_f	Filter capacitance
f	Output frequency
$f_{carrier}$	Carrier signal frequency
f_h	Normalized frequencies
f_o	Fundamental frequency
$f_{reference}$	Reference signal frequency
f_{sine}	Sine wave signal frequency
f_{sw}	Switching frequency
f_{tri}	Triangular wave signal frequency
$g_1, g_2, g_3, g_4, g_5, g_6$	Gating signal
I_{dc}	Input current
$I_ø$	Phase current
$I_{ø,peak}$	Peak phase current
$I_{ø,rms}$	Phase current in rms
k_i	Integral gain
K_{max}	Minimum value that cause sustained oscillation
k_p	Proportional gain
L	Inductance
L_f	Filter inductance
m_a	Amplitude modulation index
m_f	Frequency modulation index
P	Active power
P_{rated}	Rated power
pu	Per unit
Q	Reactive power
R_{load}	Resistor
$S_1, S_2, S_3, S_4, S_5, S_6$	Switch
T_s	Sampling period
v_{cr}	Triangular carrier wave
V_{dc}	Input voltage
$V_{d,in}$, $V_{q,in}$	Output signal in *dq* frame
$V_{d,ref}$, $V_{q,ref}$	Output reference in *dq* frame
V_{L-L}	Line-to-line voltage
$V_{L-L,peak}$	Peak line-to-line voltage

$V_{L\text{-}L,rms}$	Line-to-line voltage in rms
$V_{m,carrier}$	Amplitude of the carrier signal
$V_{m,reference}$	Amplitude of the reference signal
$V_{m,sine}$	Amplitude of the sine wave signal
$V_{m,tri}$	Amplitude of the triangular wave signal
v_o	Output voltage
V_{phase} / $V_{ø}$	Phase voltage
$V_{phase,peak}$ / $V_{ø,peak}$	Peak phase voltage
V_r	Modulating vector
v_{ra}, v_{rb}, v_{rc}	Sinusoidal reference waves
$[v_r]_{abc}$	Line modulating signals
$v_{ref,THIPWM}$	THIPWM reference signal
$V_{ø,ref}$	Reference output phase voltage
$V_{ø,rms}$	Phase voltage in rms
Ω	Ohms
ω	Angular frequency

Analisis Perbandingan Topologi Penyongsang Sumber Voltan dan Arus untuk Sistem Kendiri.

ABSTRAK

Penyongsang tiga fasa memainkan peranan yang penting dalam sistem kendiri. Ia menukar masukan arus terus (AT) menjadi keluaran arus ulang-alik (AU) yang boleh dimasukkan ke dalam grid atau luar grid untuk kegunaan komersial atau domestik. Penyongsang tiga fasa dikelaskan kepada penyongsang punca voltan (VSI) dan penyongsang punca arus (CSI). VSI kebiasaannya digunakan di dalam industri kerana kestabilan operasi dan kos yang rendah. Walau bagaimanapun, VSI perlu beroperasi dengan tambahan penukar iaitu penukar AT-AT untuk tujuan peningkatan voltan. Sebaliknya, CSI mewarisi keupayaan meningkatkan voltan yang boleh menjadi pilihan alternatif kepada VSI dengan penukar AT-AT. Namun, tidak banyak penyelidikan ke atas CSI berkaitan dengan keupayaan peningkatan voltan. Penyongsang tiga fasa diketahui beroperasi dengan sistem kawalan bagi mengekalkan voltan keluaran dan frekuensi dalam had spesifikasi standard. Walau bagaimanapun, VSI terkawal voltan konvensional dan CSI terkawal arus konvensional bukanlah perbandingan yang mudah kerana parameter terkawal keluarannya adalah berbeza. Satu CSI dikawal voltan telah dilaporkan tetapi tiada usaha terbaru dalam membandingkannya dengan VSI dikawal voltan. Oleh itu, penyelidikan ini memberi tumpuan kepada perbandingan keupayaan peningkatan voltan CSI dengan VSI di dalam keadaan gelung terbuka dan gelung tertutup. Bagi keadaan gelung tertutup, satu sistem voltan terkawal dicadangkan untuk kedua-dua penyongsang. Prestasi VSI dan CSI disimulasikan menggunakan MATLAB/Simulink. Tiga jenis teknik-teknik modulasi iaitu SPWM, THIPWM dan SVM dilaksanakan untuk menyiasat ciri keupayaan peningkatan voltan bagi kedua-dua penukar. Kemudian, reka bentuk sistem kawalan PI rangka segerak terkawal voltan yang sama dicadangkan untuk VSI dan CSI. Di bawah operasi keadaan mantap gelung terbuka, CSI mempunyai keupayaan meningkatkan voltannya secara tersirat dengan memberikan output asas yang secara purata 55% lebih tinggi daripada VSI. Namun, CSI mengalami kesan buruk peratusan THD yang tinggi berbanding VSI pada frekuensi pensuisan yang sama. Kekurangan THD yang tinggi ini boleh diatasi dengan mudah dengan menggunakan penapis CL yang ringkas. Seterusnya, di bawah operasi sistem kawalan gelung tertutup, VSI dan CSI dengan sistem kawalan PI rangka segerak terkawal voltan dibuktikan mempunyai penjejakan rujukan dan penolakan harmonik yang bagus dan sesuai dilaksanakan untuk aplikasi isi rumah atau sistem kendiri. Menariknya, CSI dengan sistem kawalan PI rangka segerak terkawal voltan boleh mencapai julat keluaran yang lebih luas kerana keupayaan meningkatkan voltan tersirat dan memberikan kualiti bentuk gelombang keluaran yang lebih baik berbanding VSI. Penyelidikan ini menyimpulkan bahawa CSI mempunyai keupayaan meningkatkan voltan tersirat yang menyediakan output asas secara purata 55% lebih tinggi daripada VSI dan memberikan kualiti bentuk gelombang keluaran yang lebih baik. Analisis perbandingan VSI dan CSI dalam penyelidikan ini memainkan rujukan penting dalam pemilihan topologi penyongsang yang sesuai untuk memenuhi penggunaan industri atau aplikasi luar-grid.

Comparative Analysis of Voltage and Current Source Inverter Topologies for Standalone System

ABSTRACT

A three-phase inverter plays an important role in the standalone system. It converts the variable direct current (DC) input into alternating current (AC) output that can be fed into on-grid or off-grid for commercial or domestic usage. Three-phase inverters are classified into voltage source inverter (VSI) and current source inverter (CSI). VSI is commonly used in industrial due to its stable operation and low cost. However, VSI need to operate with an extra converter stage which is a DC-DC converter for the voltage boosting purposes. In contrast, CSI inherits voltage boosting capability may become an alternative option to VSI with a DC-DC converter. Yet, there are not many research on CSI that dedicated on the voltage boosting capability. A three-phase inverter is knowingly work with control system to maintain the output voltage and frequency within the standard specification limits. However, the conventional voltage-controlled VSI and current-controlled CSI are not a straightforward comparison due to their different output-controlled parameters. A voltage-controlled CSI has been reported yet there is no recent work reported in comparing with a voltage-controlled VSI. Thus, this research focuses on comparing the voltage boosting capability of CSI and VSI in both open-loop and closed-loop conditions. For closed-loop condition, a voltage-controlled is proposed for both inverters. The performance of VSI and CSI are simulated using MATLAB/Simulink. Three types of modulation techniques namely SPWM, THIPWM and SVM are implemented to investigate the voltage boosting capability feature of the inverters. Then, the same design of voltage-controlled synchronous frame PI control system is proposed for both VSI and CSI. Under open-loop steady-state operation, CSI has implicit its voltage boosting capability by providing a fundamental output that is on average 55% higher than VSI. Yet, CSI suffer high THD percentage as compared to VSI for the same switching frequency. This high THD shortcoming can be easily resolved by using a simple CL filter. Next, for closed-loop control system operation, VSI and CSI with voltage-controlled synchronous frame PI control system are proved to have good reference tracking and harmonic rejection and suitable to be implemented for household application or for a standalone system. Interestingly, CSI with voltage-controlled synchronous frame PI control system able to achieve a wider range of output due to the voltage boosting capability and provide a better quality of output waveform as compared to VSI. This research concludes that CSI has implicit voltage boosting capability that provides a fundamental output on average 55% higher than VSI and provide a better quality of output waveform. A comparative analysis of VSI and CSI in this research plays an important guidance in the selection of suitable inverter topology to fulfil industrial usage or off-grid application.

CHAPTER 1 : INTRODUCTION

1.1 Introduction

Recently, the energy crisis and environmental issues such as global warming and pollution have rising the concern on renewable energy power generation. Renewable energy is defined as energy that comes from sources that can replenish themselves over a short period. Mostly renewable energy sources provide clean energy and are friendly to the environment with low greenhouse gases emission. For example, solar energy, wind energy, geothermal energy, wave energy, tidal energy, biomass energy and hydroelectric energy. These renewable energy source power generation plants are now established worldwide.

As a country locates at the Earth's equatorial, Malaysia is rich in solar energy. This encourages the development of solar energy power generation in Malaysia. The Sustainable Energy Development Authority (SEDA) Malaysia also play an important role in the renewable energy industry. SEDA has introduced lots of programmes to promote the renewable energy industry, for example the Solar Rooftop Programme (under Feed-in Tariff scheme), Net Energy Metering (NEM) programme, and various technical training programmes (SEDA, 2021). These programmes promote Malaysia's solar industry has grown tremendously over the past decade.

In promoting the solar energy power generation plants, a photovoltaic (PV) standalone system has been introduced for rural areas where the electric grid cannot be accessed. Figure 1.1 shows the PV standalone system. PV standalone system can supply power to direct current (DC) or alternate current (AC) loads. For AC loads, an inverter is necessary to convert the DC power from solar panel or battery to AC power so that it can feed to AC loads. The inverter can be classified as voltage source inverter (VSI) and current source inverter (CSI) based on their input source. These two types of inverters provide some significant advantages in respectively industrial usage.

Inverter plays an important role to ensure system stability when operation faults and power disturbance occurs, moreover it improves the performance of the entire system. The efficiency of the inverter is determined by modulation techniques and control systems. The selection of modulation techniques improves the energy utilization of the inverter. A control system function is to ensure system stability during faults and power disturbances.

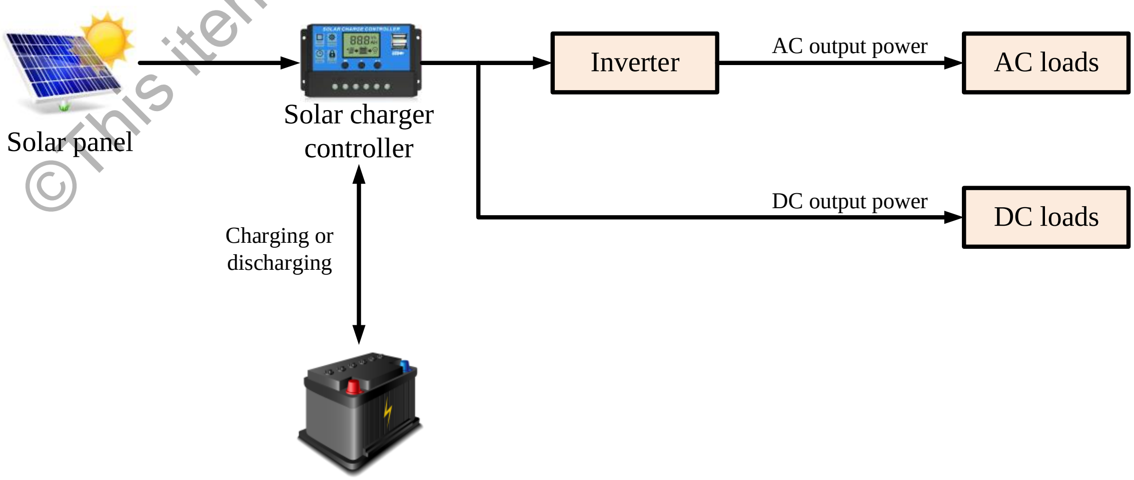

Figure 1.1: Photovoltaic (PV) standalone system.

1.2 Problem Statement

Three-phase inverters can be classified into voltage source inverter (VSI) and current source inverter (CSI). VSIs are by far the dominant topology used in industrial fields due to its operation stability, ease of control, low power losses and low cost. However, VSI normally required an extra DC-DC converter in renewable energy power distribution system thus it worked as two-stage converters (Zeb et al., 2018). On the other hand, CSI does offer the specific advantages on ability to inherit voltage boosting capability and it can work as a single-stage converter (Lin Luo & Ye, 2013; Lorenzani et al., 2017; Mohr & Fuchs, 2005). The voltage boosting capability has increased interest in CSI as an alternative option to VSI with a DC-DC boost converter. Yet, there are not many research on CSI, particularly on the analysis of its voltage boosting capability. This intrigues a deep interest in investigating this feature of CSI.

Generally, three-phase inverters work with an appropriate control system to maintain the output voltage and frequency within the specification standard limits. The conventional VSI and CSI control strategies are primarily on voltage regulation and current regulation respectively. Thus, the comparison of the performance between voltage-controlled VSI and current-controlled CSI cannot be done in a straightforward approach. This is because the output controllable parameter of VSI is voltage, but for CSI, its controllable parameter is current. There was an attempt to implement the voltage regulation control strategies into CSI have been reported (Grogan, Holmes, & Mcgrath, 2010). This voltage-controlled CSI might increase the competitiveness of CSI in industrial fields and standalone system, especially for voltage-controlled systems. However, there is no recent research work in comparing the VSI and CSI with voltage-controlled system. Therefore, it is worth investigating the performance and challenging facing for both inverters in a voltage-controlled system.

1.3 Objective

The objectives of this research are:

i. To design a three-phase voltage source inverter (VSI) and current source inverter (CSI) topologies with the appropriate modulation index and switching frequency.

ii. To design a proportional integral (PI) voltage-controlled-closed-loop system for three-phase voltage source inverter (VSI) and current source inverter (CSI) system.

iii. To evaluate the performance of three-phase voltage source inverter (VSI) and current source inverter (CSI) in term of voltage boosting, fundamental output, total harmonic distortion (THD_v and THD_i) and quality of output waveform.

1.4 Scope

In this research, the main focus is on the comparative analysis of three-phase VSI and CSI for standalone systems in aspect of voltage boosting capability. This research uses MATLAB/Simulink as the main tool for project simulation. In the construction of three-phase VSI and CSI, the DC input of each inverter is assumed stiff and the IGBT switches are assumed as ideal switches. Next, the passive components such as inductors, capacitors and resistors are assumed ideal. This research involves the open-loop steady-state simulation and closed-loop control simulation of three-phase VSI and CSI in a standalone system. Three modulation techniques which are sinusoidal pulse width modulation (SPWM), third-harmonic injection pulse width modulation (THIPWM) and space vector modulation (SVM) are implemented into both inverters in open-loop steady-state simulation. The LC filters for three-phase VSI and CL filters for three-phase CSI are implemented in order to provide a pure sine wave output. However, the designs of LC and CL filters are not included in this research. In closed-loop control simulation, a voltage-controlled synchronous frame proportional-integral (PI) closed-looped control system is proposed for both inverters, but with different control gains. The performance of three-phase VSI and CSI are compared and analysed in terms of fundamental output, output total harmonic distortion (THD) and output waveform by using MATLAB Simulink. The output THD harmonic level is verified based on IEEE Std 519™-2014 standard.

1.5 Thesis Outline

This thesis is covered in five chapters. The organization of each chapter is presented as follows:

Chapter 1 present a general introduction and the problem statements that inspired the research. Then, research objectives that need to be carried out to complete the research are stated. The scopes of research are briefly described in this chapter.

Chapter 2 presents the literature review related to the research. It contains the topology of three-phase VSI and CSI, modulation techniques and PI control system. The standalone system is also briefly described in this chapter. The theoretical details in the literature review are studied through articles, conference papers, journals or books.

Chapter 3 discussed the methodology of research. It is divided into two sections which are open-loop circuit designation and closed-loop circuit designation with the control system. The parameters of the system and modulation techniques used are discussed.

Chapter 4 present the simulation result and analysis of the research. All simulation data are presented and analysed in detail. Then, the comparative analysis of three-phase VSI and CSI has complied.

Chapter 5 summarizes an overall conclusion for the research. Several recommendations for future work are suggested for the improvement of the research.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature review on the three-phase voltage source inverter (VSI) and current source inverter (CSI) for a standalone system. A survey of three-phase VSI and CSI topologies are presented and their features are discussed. The modulation techniques used for three-phase inverters are sinusoidal pulse width modulation (SPWM), third-harmonic injection pulse width modulation (THIPWM) and space-vector modulation (SVM). The switching schemes of these modulation techniques are studied and discussed. Lastly, the synchronous frame proportional-integral (PI) controller and standalone system are studied.

2.2 Three-Phase Inverters

A three-phase inverter converts a DC input power to an AC output power at desired magnitude and frequency. For AC output power, the magnitude, frequency and phase should be controllable. Three-phase inverters are widely used in industrial applications such as adjustable-speed AC motor drives, induction heating, standby power supplies, uninterruptible power supplies, high voltage DC transmission system and stand-alone power systems.