DEVELOPMENT OF dSPACE-BASED FUZZY LOGIC THREE-PHASE INVERTER CONTROLLER FOR PHOTOVOLTAIC APPLICATION ENHANCEMENT

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PEMBANGUNAN PENYONGSANG TIGA FASA PENGAWAL LOGIK KABUR BERASASKAN dSPACE UNTUK PENINGKATAN APPLIKASI FOTOVOLTA

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TESIS YANG DIKEMUKAKAN UNTUK MEMPEROLEH IJAZAH
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DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

5th August, 2014

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ABSTRACT

Fossil fuel which is the conventional energy source that is used to generate electricity is exhausting and therefore finding alternative energy sources is of a great concern for present and future energy demand. Photovoltaic (PV) is one of the promising renewable energy sources, especially for remote areas. It is a dc source and requires an inverter for converting it to usable power for ac loads. Its nonlinearity characteristic and output fluctuation, pose challenges in the PV inverter design. In this research, an inverter control system is designed and developed in such a way that the impact of PV output fluctuation towards the inverter performance is minimized. Issues concerning inverter such as output harmonic, power factor, switching scheme and losses, and system implementation need to be addressed in the inverter design. To achieve a robust and simple implementation of inverter control which does not require plant mathematical model, a fuzzy logic controller (FLC) is employed in the PV inverter control system. By utilizing the FLC for the inverter voltage control scheme algorithm, the duty cycles of the IGBTs are optimized according to the desired voltage. The duty cycle generation algorithm which is based on the sinusoidal pulse-width modulation technique enables the control system to lower down the inverter output harmonic content. Prior to the prototype development, the inverter model and control system were developed, simulated, and verified in MATLAB/Simulink. A three-phase inverter prototype acquiring a maximum capacity of 3 kW has been built to justify the capability of the control algorithm in generating and stabilizing a quality sinusoidal output waveform of required voltage and frequency. In doing so, a dSPACE DS1104 controller board was employed, to which the developed inverter control algorithm was linked and loaded. The system operation was tested using the 2 kW PV array as the dc input power. The experimental results have shown that the inverter control system was capable of generating and stabilizing sinusoidal voltage of 415 V at a frequency of 50 Hz. Investigations have been made on the inverter performance with and without the utilization of output filter. With the filter, the level of total harmonic distortion (THD) of the inverter output voltage is kept to 2.5% which complies with the IEEE Std 519-1992. The developed inverter performance results are validated with that of the simulation results as well as compared with PV-based inverter control system, in terms of THD, power factor, switching technology, hardware, and system environment. It is found that, the developed inverter control system is more capable and efficient in converting the PV power to usable power for ac loads. This proves the efficacy of the developed control algorithm and therefore is very effective and suitable to be utilized for PV power conversion applications. The dSPACE-based developed inverter prototype is designed and developed in such a way that it is flexible and practical, whereby both the hardware and control system are fully alterable to accommodate the needs for new and future designs especially the control system. The developed inverter with the control system has great potential and prospective to be used in remote areas for providing power to ac loads. Besides, it can be utilized as an interface device for contributing and feeding PV power to the utility grid, such as in the grid-connected system.

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ABSTRAK

Bahan api fosil merupakan sumber tenaga konvensional digunakan untuk menjana elektrik, kini semakin menyusut. Pencarian sumber tenaga alternatif adalah perlu bagi permintaan tenaga masa kini dan masa depan. Fotovolta (FV) adalah salah satu sumber tenaga alternatif harapan, terutama di pedalaman. Ia merupakan arus terus dan memerlukan penyongsang untuk menghasilkan kuasa yang berguna untuk beban arus ulang-alik (AU). Ciri ketaklelurusan dan keluaran yang turun-naik, adalah cabaran dalam rekabentuk penyongsang FV. Oleh itu, dalam kajian ini, kawalan penyongsang direka supaya kesan turun-naik keluaran FV terhadap prestasi penyongsang, seperti kestabilan keluaran dan kualiti kuasa dapat diminimakan. Isu-isu penyongsang seperti kandungan harmonik keluaran, faktor kuasa, skim pensuisan, kehilangan kuasa, dan pelaksanaan sistem mesti dipertimbangkan dalam rekabentuk penyongsang. Dengan ciri yang teguh, mudah dilaksanakan, dan tidak memerlukan model matematik, pengawal logic kabur (PLK) digunakan dalam kawalan penyongsang FV, yang mana objektif kajian ini dicapai. Menggunakan PLK bagi algoritma kawalan voltan, kitaran tugas peranti IGBT dapat dioptimumkan mengikut voltan yang dikehendaki. Algoritma penjanaan isyarat sinusoidal modulasi lebar denyut membolehkan system kawalan merendahkan kandungan harmonik keluaran penyongsang. Sebelum prototaip dibangunkan, model penyongsang dan kawalan telah dibangunkan, disimulasi, dan disahkan menggunakan MATLAB/Simulink. Prototaip penyongsang tiga fasa berkapasiti maksima 3 kW telah dibina untuk justifikasi keupayaan algoritma kawalan menjana dan menstabilkan keluaran sinusoidal voltan dan frekensi yang diperlukan. Untuk itu, pengawal dSPACE DS1104 telah digunakan, yang mana algoritma kawalan penyongsang tersebut telah dimuat turun kepadanya. Operasi ini telah diuji menggunakan 2 kW tatasusun FV. Keputusan eksperimen menunjukkan kawalan penyongsang mampu menjana dan menstabilkan voltan sinusoidal 415 V pada frekuensi 50 Hz. Kajian telah dijalankan terhadap prestasi penyongsang dengan dan tanpa penapis keluaran. Dengan penapis, tahap jumlah herotan (JHH) voltan keluaran penyongsang ditetapkan pada 2.5% dan mematuhi IEEE Std 519-1992. Prestasi penyongsang disahkan dengan simulasi dan juga perbandingan dengan kawalan penyongsang FV, dari segi JHH, factor kuasa, teknologi pensuisan, perkakasan, dan pelaksanaan. Didapati sistem kawalan penyongsang ini lebih berupaya dan berkesan dalam penukaran kuasa FV kepada kuasa yang bermanafaat untuk mengoperasikan beban AU. Ini telah membuktikan keberkesanan algoritma kawalan penyongsang tersebut dan oleh itu ia adalah amat berkesan dan sesuai digunakan dalam aplikasi FV. Prototaip penyongsang yang dibangunkan berasaskan pengawal dSPACE ini adalah fleksibel dan praktikal, di mana perkakasan dan kawalannya dapat diubahsuai sepenuhnya untuk menampung keperluan rekabentuk baru dan juga rekaan masa depan. Penyongsang dengan sistem kawalan tersebut mempunyai potensi besar dan prospek untuk digunakan di pendalaman bagi membekalkan kuasa kepada beban AU. Selain itu, ia juga boleh digunakan sebagai peranti antaramuka untuk menyumbang kuasa FV kepada grid utiliti, seperti dalam sistem yang tersambung ke grid.

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LIST OF ABBREVIATIONS

ac	alternating current
ADC	Analog-to- Digital Converter
AVR	Automatic Voltage Regulator
CCM	Continuous Conduction Mode
COG	Center-of-Gravity
CPU	Central Processing Unit
CSI	Current-Source Inverter
DAC	Data Acquisition Card
dc	Direct current
DG	Distributed Generation
DISO	Double-Input-Single-Output
DSP	Digital Signal Processor
ECU	Electronic Control Unit
FFT	Fast Fourier Transform
FLC	Fuzzy Logic Controller
FPGA	Flat-Package Gate Array
GTO	Gate-Turn-Off Thyristor
GUI	Graphical User Interface
IC	Integrated-circuit
I/O	Input-Output
IGBT	Insulated-Gate Bipolar Transistor
LOH	Lower Order Harmonic
mod	Moderate
MOSFET	Metal-Oxide Field Effect Transistor
MPPT	Maximum Power Point Tracking
P&O	Pertube and Observe
PC	Personal Computer
PAS	Programmable ac source
PCI	Peripheral Component Interconnect
PI	Proportional-Integral

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PID	Proportional-Integral-Derivative
PLL	Phase Locked Loop
p.u.	per unit
Prog	Programming
PV	Photovoltaic
PWM	Pulse-Width Modulation
RMS	Root Mean Square
RTI	Real-Time Interface
RTW	Real-Time Workshop
SPWM	Sinusoidal Pulse-Width Modulation
SVPWM	Space Vector Pulse-Width Modulation
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply
VSI	Voltage-Source Inverter

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CHAPTER I

INTRODUCTION

1.1 RESEARCH BACKGROUND

The growth of human population of the earth has resulted significant rise of energy demand. Fossil fuel, the conventional energy source, is one of the resources used to generate electricity. In fact, this resource is exhausting, (Salas et al. 2009) thus, finding alternative energy sources has become a great concern for catering the present and future energy demand. Based on the current consumption, it is estimated that the petroleum has less than 50 year's reserves (Sheehan et al.1998). Moreover, the fossil-based energy generation indirectly introduces adverse side-effects to the environment which degrades the environment air quality. Some of the fossil energy resources are petroleum, natural gas, coal, etc (Demirbasi 2009). The consumption of this fossil-based energy by the fuel-based machines and engines such as automobiles and generators, releases the harmful carbon dioxide to the atmosphere which causes air pollution and indirectly leads to the phenomenon like global warming. Therefore, the green, clean and pollution-free environment has to be preserved for future generations. Of course, this can be realized with the utilization and implementation of the pollution-free renewable energy resources, e.g. solar PV. Extensive research works in the area of renewable energy technology have led to the development and utilization of the green energy sources such as the PV, biomass, geothermal, hydropower, and wind. These energy resources have the great potential to be harvested for providing alternative energy. These future energy resources have their own advantages and disadvantages. Depending on these advantages and feasibility, they can be fully utilized to become part of the energy resources for providing the rising energy demand.

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Among the available renewable energy resources, PV is the most important renewable energy resources and has notably increased in industry over the past few years (Salas et al. 2009). PV is one of the promising renewable energy sources, especially for remote areas where utility power is unavailable. It is a pollution-free kind of energy resource and cost-effective especially for the application in remote areas where the power utility is unavailable (Ahmad et al. 2003). In addition, with proper equipments and method, the harvested energy can also be delivered to the utility grid in a grid-connected system. Unlike fossil-fuel energy, PV energy resource is abundantly available and can be considered as maintenance-free energy source. It is a dc power source and in order to utilize its usefulness, especially for the ac-related applications, a device called inverter is required for converting it to the ac power source (Blaabjerg et al. 2004). An inverter is an electronic device which converts the dc power to ac power at a desired output voltage or current and frequency. The applications of this inverter are mostly found in the adjustable speed ac devices, induction heating, UPS, laptop computers, printers and other personal productivity electronics and electrical products. In the area of renewable energy such as the PV, this inverter plays the important roles in ensuring the operability of the above products and applications. In these applications, it is very important that the inverter produces a clean sine wave output waveform at a precise voltage over controlled frequency ranges, within a certain load variations. The features of the PV inverter characteristics are very important and must be taken into account in designing the inverters. Some of the PV inverter system design features include simple design (non-complex algorithm, less switching devices), stable, flexible control, high reliability, ease of maintenance and testing, high efficiency, low waveform THD, unity power factor and low cost (Tao et al. 2011). In addition, smaller size and lower weight inverter system are important features in designing inverters (Martins 2013). Besides, the PV nonlinearity characteristic and fluctuation in the output, pose challenges in PV inverter design (Letting et al. 2012). The inverter control system should be designed in such a way that the impact of the output fluctuation toward the inverter performance, e.g. stability and power quality is minimized. For a PV with a low output voltage, a dc to dc boost converter is incorporated in the power conversion system (Sanjeevikumar et al. 2008).

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In general, the success of PV system applications is related to the design and performance of inverters and the controllers. The opportunities are still exist for improving the inverter controller, since inverter failure remains one of the primary causes for PV system failure (Messenger et al. 2004). The conversion process is fully dependent based on controllers and their control algorithms (El-Barbari et al. 1999). Thus, good inverter controllers are necessary for improving the inverter performance in PV or renewable energy applications. There are various types of controllers employed in the implementation of PWM techniques, e.g. SPWM, SVPWM, for generating and regulating output of inverters. The SVPWM method is more complex compared to SPWM especially for multi-levels inverters (Satish et al. 2010). Some of the controllers include analogue circuit controllers, microcomputers, digital circuit controllers, FPGA and DSPs (El-Hefnawi 1997). Globally, researchers continue to develop and improve various areas of inverter, e.g. control algorithm, in effort to support the application of renewable energy.

PV inverters can be employed as standalone power system for providing ac power to residential appliances such as fluorescent lamps, fans and refrigerators (Akkaya et al. 2004). Inverter with a very high quality power output can be operated as main component in the AVR systems, UPS, and PAS (Tzou et al. 1998). In addition, they can be individually used or be part of the DG system in the power system which interfacing and feeds the alternative energy power to the grid system (Poh et al. 2005; Eltawil et al. 2010). Therefore, it is essential that the power electronics-based conversion system (inverter) delivers a proper energy as to provide the effective and efficient connection to the grid (Marei et al. 2004).

1.2 PROBLEM STATEMENT

The main issues concerning PV inverter include the intermittent, fluctuation, dc output nature of PV devices, output voltage regulation, harmonic content and conversion efficiency (El-Barbari et al. 1999). In the PV-based inverter system, the issue of power intermittency and dc nature of the PV must be considered in the inverter design. The intermittent nature of the PV output voltage causes instability in the level of inverter output power which is undesirable especially for the sensitive and critical loads

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(Rajkumar et al. 2013). Some of the methods adopted to lessen the impact of the PV shortcoming are by adopting enhanced inverter control system whereby the variations of the PV output dc voltage are compensated, thus leading to stabilized inverter output voltage. Concerning the issue of self-losses which relates to the efficiency of the inverter, an appropriate switching frequency selection for the power devices must be considered in the system design (Bandara et al. 2012). High switching frequency eases the filtering design which in turns enhances the quality of the inverter output waveform. In fact, this alleviates the issue of high level of harmonic components in the inverter output waveform. On the other hand, high switching frequency leads to higher power loss which reduces the inverter efficiency. Therefore, the selection of suitable switching frequency is crucial and must take into account the inverter output quality and power loss.

The selection of suitable inverter controller is crucial in the inverter design whereby inverter parameters can be optimized effectively. In addition to the issue of the quality of the inverters itself, the flexibility of the inverter control system design is very important so as to provide the inverter designer a platform for further product research and design development. This is something that the commercially available inverters are lacking of. This is an essential feature so that the control system can be fully assessable for upgrading purpose, thus providing inverter parameters improvement such as the voltage, current harmonics content, and power factor. Various types of inverter controller platforms have been presented in the literature such as microcomputer (El-Hefnawi 1997), DSP (Selvaraj et al. 2009) and FPGA (Hassaine, et al. 2014). Besides, the utilization of controllers like microcontrollers (Yousefpoor et al. 2012), microprocessors (Acharya et al. 1986), analogue and digital circuit controllers (Frederick et al. 1979) are also reported in the literature. Most of the controllers required users to have software programming knowledge in order to develop the inverter control algorithm and this is a time consuming task in designing inverters. There should be a design platform whereby the design and development of the inverter control system algorithms can be simplified and the period is shortened.

Owing to these highlighted issues and problems concerning inverters and controllers, a new approach for the PV-based inverter control system needs to be

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designed to acquire promising results such as lower harmonic contents, unity factor, simple hardware implementation, lower loss switching scheme, easy system implementation and shorter product design period. With the high quality output, the inverter has the prospect to be connected and feeding PV power to the utility grid. Furthermore, the proposed system provides vast research area opportunities in further system improvement and upgrading.

1.3 OBJECTIVES AND SCOPE OF STUDY

This research project aims to develop an intelligent-based three-phase inverter control algorithm for PV system application. The research proposes an intelligent control system algorithm which focuses on the three-phase inverter system configured in standalone mode of operation. The objectives of the research are summarized as follows:

i. To develop a fuzzy logic-based inverter control algorithm and integrate with the dSPACE DS1104 controller board which enable the control algorithm to be linked to the inverter prototype.

ii. To develop an inverter simulation model and integrate with the fuzzy logic-based control algorithm which forms the complete inverter system simulation.

iii. To develop a three-phase inverter prototype, including a three-phase filter, so as to justify the functional capability of the developed fuzzy logic-based inverter controller and filter utilization.

iv. To perform testing on the developed inverter prototype and validates the inverter system simulation of objective ii.

This research mainly focuses on the three-phase inverter control system algorithm for PV application system which operates only in a standalone mode supplying ac power to a three-phase resistive load. Furthermore, it concentrates on a non-storage PV system, whereby the generated power from PV is directly transferred

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to the load without the use of back-up batteries. Moreover, a storage PV system required a charge controller development which is considered beyond the scope of this research. In fact, both systems acquire different control system. Indeed, the research engages many aspects of sub-system developments that ensure the effective and proper operation of the PV system. Developing a three-phase inverter simulation model in the MATLAB/Simulink software environment is one of the important tasks in this work, which involves not only the inter-components connections and interactions, but also the effective operability of the control algorithm. It serves as a benchmark stage in translating theoretical ideas into prototypes. Accomplishing this research task, the fuzzy logic control algorithm needs to be designed, simulated and effectively integrated into the whole PV system. By integrating the developed prototype inverter with the dSPACE DS1104 controller board, the inverter design and development period is shortened. Moreover, the implementation of the inverter system is simplified greatly. With the dSPACE system GUI, the inverter and controller parameters real-time monitoring is accomplished. Thus, the inverter and controller can be further improved continuously. With the fuzzy logic-based control algorithm which regulates the inverter direct and quadrature voltage components, the inverter unity power factor feature is achieved. The success of system operation and achieving good simulation results, serves as the validation for the inverter prototype realization. Developing a three-phase inverter prototype including a harmonics-attenuating filter, in conformance with the simulation results, is part of the major concern in this research. Acquiring the filter in the inverter output stage contributes to the generation of a quality ac output voltage and current with low harmonic distortion level. The output quality is enhanced by selecting a suitable filter minimum cut-off frequency of one-tenth of the switching frequency which compromises between the capacitor size and switching loss. Furthermore, implementing the SPWM switching technique in the control algorithm reduces the harmonic content of the inverter output voltage and current. In addition, by utilizing by suitable IGBT switching frequency, the switching loss is reduced. One of the most important tasks is testing and evaluation of the inverter prototype. Among them are voltage and current measurements of PV panels as well as inverter and solar irradiations. After all, one of the major implication aspects of the research development outcome is the possibilities of system

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implementation in remote areas, e.g. islands and villages, where the power utility is unavailable or uneconomical.

1.4 THESIS OUTLINE

Chapter I describe a general overview of the research background and the importance of finding alternatives energy resources for future energy demand. In addition, it explains the necessary method and requirement for harvesting and converting the available energy resources into more usable power. It also discusses the significance of the power converters in PV systems application. Besides, it highlights and discusses the general issues concerning the power converters design quality such as the conversion efficiency, harmonic content, power factor, losses, etc. The importance and future prospect of the power converter which utilizes the renewable energy source is also discussed. This chapter also explains the objectives and scope of the research work. Chapter II presents an overview of previous researches on PV, power converters, control system, controllers, control strategies, and switching devices and techniques. Moreover, it provides the theoretical background of a PV, overview of the dSPACE and fuzzy logic controller, working as well as design principles of commonly used power converters, such as a dc to dc boost converters, and three-phase inverters. Chapter III describes the development of the fuzzy logic-based inverter control algorithm utilizing the dSPACE DS1104 controller board. Besides, it covers the transformation of the control strategy into switching signals for the power devices. The simulation model and hardware implementation of the fuzzy logic-based inverter are discussed in Chapter IV. Chapter V presents the performance evaluation of the three-phase inverter based on the results obtained from simulations, and experimental that integrates the real PV panel. Finally, Chapter V presents the conclusions and recommendations for future research works.

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