DEVELOPMENT OF INTEGRATED PHOTOVOLTAIC BASED DSTATCOM FOR HARMONIC MITIGATION

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

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2024

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AC	Alternating Current
DSTATCOM	Distribution Static Synchronous Compensator
DFT	Discrete Fourier Transform
DC	Direct Current
FFT	Fast Fourier Transform
PV	Grid-Connected Photovoltaic
HCC	Hysteresis Current Control
IGBT	Insulator gate bipolar transistor
LPF	Low-pass filter
PCC	Point of common coupling
PQ	Power quality
PV	Photovoltaic
THD	Total Harmonic Distortion
VRC	Voltage Reference Configuration
VSI	Voltage Source Inverter

LIST OF SYMBOLS

C	Capacitor
C_{DC}	DC capacitor
L	Inductor
L_f	Interface Inductor
R	Resistor
V_{DC}	DC link voltage

PEMBANGUNAN FOTOVOLTA BERASASKAN DSTATCOM BERSEPADU UNTUK PENGURANGAN HARMONIK

ABSTRAK

Tesis ini membentangkan algoritma kawalan Konfigurasi Rujukan Voltan (VRC) berasaskan Jelmaan Fourier Pantas (FFT) untuk Pengagihan Kompensator Statik tiga fasa (DSTATCOM) ke dalam sistem fotovolta solar tersambung grid untuk peningkatan kualiti kuasa di bawah beban tidak linear dan beban tidak seimbang dalam sistem agihan. Penyelidikan ini bertujuan untuk menangani isu-isu kualiti kuasa yang dicirikan oleh herotan voltan, arus, atau frekuensi, yang boleh menyebabkan kegagalan peralatan elektrik. Walaupun grid utiliti konvensional menyediakan bentuk gelombang sinusoidal bersih untuk operasi yang boleh dipercayai, kehadiran beban tidak linear memperkenalkan herotan harmonik, menyebabkan pemanasan lampau transformer, kerosakan grid, dan banyak lagi. FFT mengekstrak komponen harmonik dari arus beban untuk dibekalkan kepada pengawal arus histeresis untuk tujuan mengawal Penyongsang Punca Voltan (VSI). Sistem yang dicadangkan telah dimodelkan dan digunakan untuk mensimulasikan tindak balas yang diingini untuk pelbagai keadaan operasi iaitu beban tidak linear, beban tidak seimbang, sinaran solar yang berubah dan sistem dua mod fotovolta solar tersambung grid berasaskan DSTATCOM (GCPV berasaskan DSTATCOM). Prestasi algoritma kawalan yang dicadangkan telah disimulasikan dalam persekitaran MATLAB menggunakan Simulink. Di bawah keadaan mantap, DSTATCOM yang menggunakan algoritma kawalan VRC berasaskan domain frekuensi menunjukkan pengurangan penyelewengan harmonik yang ketara dari 20.34% kepada 1.87%. Ia juga mengawal gangguan dengan berkesan semasa senario beban tidak seimbang, mengekalkan Jumlah Harmonik Terkandungan (THD) di bawah 5% walaupun apabila arus beban fasa 'b' terputus secara tiba-tiba. Keputusan dari simulasi dan ujian perkakasan menunjukkan bahawa teknik kawalan yang dicadangkan berjaya memenuhi piawaian IEEE-519 dengan menghapuskan harmonik dan mengekalkan nilai THD dalam had yang ditetapkan iaitu 5%.

DEVELOPMENT OF INTEGRATED PHOTOVOLTAIC BASED DSTATCOM FOR HARMONIC MITIGATION

ABSTRACT

This thesis presents a Fast Fourier Transform (FFT) based Voltage Reference Configuration (VRC) control algorithm for the three phase Distribution Static Compensator (DSTATCOM) into grid-connected solar photovoltaic system for power quality improvement under nonlinear load and unbalanced load in distribution system. This research aims to address power quality issues characterized by voltage, current, or frequency distortions, which can lead to electrical equipment failures. While conventional utility grids provide clean sinusoidal waveforms for reliable operation, the presence of nonlinear loads introduces harmonic distortions, causing transformer overheating, grid malfunctions, and more. The FFT extracting the harmonic component from the load current to fed to a hysteresis current controller for the purpose of controlling the Voltage Source Inverter (VSI). The proposed system is modelled and used to simulate the desired responses for various operating conditions which are nonlinear load, unbalanced load, varying solar irradiances and dual mode of grid-connected solar photovoltaic system based DSTATCOM (GCPV based DSTATCOM). The proposed control algorithm performance is simulated in the MATLAB environment using Simulink. Under steady-state conditions, the DSTATCOM employing the frequency domain-based VRC control algorithm demonstrates a significant reduction in harmonic distortion from 20.34% to 1.87%. It also effectively controls disturbances during unbalanced load scenarios, maintaining the Total Harmonic Distortion (THD) below 5% even when a sudden disconnection occurs in phase ‘b’ load current. The results from the simulations and hardware tests show that the proposed control technique successfully meets the IEEE-519 standard by eliminating harmonics and keeping the THD value within the prescribed limit of 5%. This research contributes to the advancement of power quality improvement techniques in photovoltaic systems, ensuring reliable and efficient operation under varying load conditions.

CHAPTER 1 : INTRODUCTION

1.1 Background Literature

The power quality (PQ) is a significant concern among power engineers due to the industrial, commercial, and domestic loads, which are primarily nonlinear, which induce harmonics in the power source component (Alzubaidi & Ramana Rao, 2020; R. Kumar et al., 2017). Harmonics are steady-state distortions to current and voltage waveforms that recur every cycle. Current harmonics are more crucial problems than voltage harmonics because voltage harmonics can only emerge when a current harmonic is present. Therefore, current harmonics are affected by the nonlinear load connection in the distribution system (A.Yuvaraj, 2007; Zainuri et al., 2016). Typically, an odd integer multiple of power frequency is present in the power system. Therefore, it affects the amplitude and waveform of the signal. Therefore, the harmonic current injection from customers loads into the utility supply system caused harmonic distortion in the power supply system. As a result, it affected the utility system and customer's equipment, leading to power quality problems (Ingale, 2014).

Custom power is a strategy, which is intended principally to convene the requirement of industrial and commercial consumers. The concept of the custom power is tools of application of power electronics controller devices into power distribution system to supply a quality of power, demanded by the sensitive users. These power electronics controller devices are also called custom power devices because through these valuable powers is applied to the customers (Gupt, 2012). The solution for power quality problems such as harmonic distortion and unbalanced load caused by the nonlinear load in the distribution system is Distribution Static Synchronous Compensator (DSTATCOM).

DSTATCOM is a part of the custom power devices used to improve various PQ issues (Kazmierkowski, 2015; N. Kumar et al., 2020).

The grid-connected photovoltaic system-based Distribution Static Synchronous Compensator (PV based DSTATCOM) features are voltage source inverter (VSI) integrated with the photovoltaic (PV) array. PV based DSTATCOM can improve the power quality problem by reducing the harmonic distortions, reactive power compensation, supply active power, and load balancing in the three-phase distribution system (Singh et al., 2018). Nevertheless, the integration of the solar PV system with the distribution system has negatively impacted distribution systems. The current and voltage of harmonics, voltage fluctuation, protection from grid islanding, and other power quality issues have been discussed (Karimi et al., 2016). Therefore, integrating the solar PV system with DSTATCOM proved to accommodate the growing electrical energy demand. At the same time, mitigate the problem of power quality in the distribution system (Gajjar & Zaveri, 2019).

The control algorithm is an essential component in DSTATCOM to mitigate the power quality problem (Banerji et al., 2012b). There are two traditional methods found in DSTATCOM's control algorithm for reference signal estimation are the time domain and frequency domain. The frequency-domain method follows the principle of Fourier analysis principle. The frequency-domain uses a Fast Fourier Transform (FFT) algorithm to determine the harmonious component of the load current. Sampling the harmonic content of load can be done separately. Therefore, this method can be used in a single phase, 3-phase 3-wire (3P3W), and 3-phase 4-wire system (3P4W) (Fathi et al., 2006). Moreover, the frequency domain is often used for power quality monitoring due to having accurate analytical capabilities. As a result, the frequency domain is also suitable to handle DSTATCOM (Han, 2009).

In this research, the effectiveness of the frequency domain-based Voltage Reference Configuration (VRC) control algorithm to solve the power quality (PQ) is validated by using three-phase three-wire PV based DSTATCOM. This control algorithm improves the power quality by extracting the harmonic component from the load current. It tested under weak grid conditions and maintained the Total Harmonic Distortions (THD) value less than 5% based on the IEEE 519:2014 standard. The IEEE 519:2014 standard sets a Total Harmonic Distortion (THD) limit of 5% for current THD. By accurately extracting harmonic components from load currents, this control algorithm contributes to maintaining THD levels below the specified threshold, even under challenging conditions such as weak grid scenarios. Furthermore, the proposed PV based DSTATCOM with frequency domain based VRC control algorithm will be simulated with MATLAB/Simulink environment and experimentally validated.

1.2 Problem Statement

Harmonic distortion in electronic devices disrupts source currents due to their nonlinear characteristics, producing non-sinusoidal current waveforms with high-frequency harmonics. These harmonics travel back into the source, interact with the power system impedance, and cause current distortion. This distortion can trigger resonance effects, amplifying specific frequencies and worsening the problem. Ultimately, this results in power quality issues such as voltage fluctuations and increased losses in the distribution system, which can impact the performance of sensitive equipment and reduce overall system reliability. Conventional utility grids supply clean sinusoidal waveforms to ensure reliable operation; however, nonlinear loads such as An example of a nonlinear load device is a switched-mode power supply (SMPS), computer, and battery charger with their harmonic components that introduce distortions, leading to transformer overheating, grid malfunctions, and more (Kiss & Balazs, 2014; McGranaghan, 1998). Additionally, unbalanced load currents, arising from various industrial applications, exacerbate the distribution network's complexities (Chandra et al., 2000). The proposed solution seeks to harness the DSTATCOM's capabilities to mitigate voltage fluctuations, harmonics, and load imbalances. This necessitates an intricate analysis of system components and control strategies to effectively enhance power quality, ensuring the seamless integration of solar-generated power while maintaining grid stability.

The integration of the solar PV system into the distribution system triggered power quality issues such as harmonic distortions (Gandhi et al., 2020). The effects of harmonics in power system networks can cause severe long-term effects. The problems identified in the previous works are power inverters interface with PV arrays in power grids that produce harmonic currents. Thus, they may increase the total harmonic distortion of both voltage and currents at the point of standard coupling (PCC) (Tobnaghi & Vafaei, 2016). The frequency domain has been used for measuring the harmonic current in the nonlinear load (Kiss & Balazs, 2014).

Power quality can be defined as any power problem manifested in voltage, current, or frequency deviations that result in failure or malfunction of customers' equipment

(Standards et al., 2009). The power supply provided by the utility grid is clean and sinusoidal waveforms that do not contain sags or spikes, which allows the customers' equipment to operate reliably.

To address harmonic distortion in source currents caused by nonlinear loads in electrical devices, it's crucial to implement effective solutions. One promising approach is integrating Photovoltaic (PV) based Distribution Static Synchronous Compensators (DSTATCOMs) at the Point of Common Coupling (PCC). These devices not only mitigate harmonic distortion but also offer additional benefits compared to traditional active filters. While active filters are effective in reducing harmonic currents, PV based DSTATCOM offer several advantages. Firstly, they provide dual functionality by supplying additional power through photovoltaic generation. Secondly, they offer dynamic control capabilities, adjusting reactive power compensation in real-time, which is essential for handling fluctuations in PV generation and load demand. Additionally, PV based DSTATCOM have a modular design, making them easier to install and integrate into existing distribution networks. Overall, the integration of PV based DSTATCOM presents a comprehensive solution for harmonic elimination while enhancing power quality and network stability.

The frequency domain based VRC control algorithm technique uses Fourier analysis to extract the harmonic component from the distorted voltage or current signal. The frequency domain-based VRC control algorithm is already applied in single-phase and three single-phase active power filters, and it has been proved that this controller is a simpler, robust control scheme and less computational time for extracting reference current signals (Baharudin et al., 2015). A review of works of literature is done to mitigate the power quality issues in the distribution system. The proposed three-phase three-wire PV based DSTATCOM with frequency domain based VRC control algorithm can mitigate the power quality problem in the distribution system.

Choosing Texas Instruments (TI) components for testing in the field of Grid-Connected Photovoltaic (PV) based Distribution Static Synchronous Compensator (DSTATCOM) is a strong decision. TI is known for their advanced electronic solutions and reliability, which align well with the requirements of this area. Their versatile microcontrollers, DSPs, and power management solutions effectively address the complex needs of a PV based DSTATCOM, ensuring strong performance and efficient power management. The availability of development tools, software resources, and reference designs from TI speeds up the design and testing phases, enhancing reliability. TI's components adhere to industry standards, guaranteeing quality and compatibility. Overall, Texas Instruments' technology simplifies integration, providing a strong foundation for successful testing and implementation in this critical application. This choice ensures that the system operates effectively and reliably in a vital application like this.

1.3 Objective

The study's objective is to improve the power quality problem in terms of harmonic elimination in the distribution network with the integration of the PV system. In addition, to achieving the goal, these necessary actions are to be taken:

1) To design the system configuration of a grid-connected solar PV system based Distribution Static Synchronous Compensator (PV based DSTATCOM).

2) To develop a frequency domain-based Voltage Reference Configuration (VRC) control algorithm for PV based DSTATCOM for harmonic mitigation at PCC due to nonlinear loads.

3) To evaluate the performance of PV based DSTATCOM for power quality improvement in simulation and hardware validation.

1.4 Scope of Research

The scope of this research is to improve power quality in a polluted distribution system by reducing harmonic currents using a 4 kW grid-connected photovoltaic (PV) based DSTATCOM with a frequency domain-based VRC control algorithm. The project involves both software and hardware implementation.

Modelling and Simulation: The circuit of the three-phase PV based DSTATCOM will be modelled and simulated in the MATLAB/Simulink environment. The frequency domain-based VRC control algorithm for the designed circuit will be developed using Texas Instruments™ (TI) C2000 microcontrollers (MCUs) with Code Composer Studio IDE.

Experimental Evaluation: Experimental work will be conducted to evaluate the performance of the proposed PV based DSTATCOM in improving power quality at the Point of Common Coupling (PCC) under nonlinear loads. The performance will be assessed in terms of harmonic distortion reduction, load balancing, and reactive power compensation during steady-state and dynamic conditions, adhering to the IEEE 519:2014 standard.

Simulation Based on Real Hardware Environment due to hardware limitations for the solar component, the project will simulate the PV system under real hardware conditions, testing the proposed DSTATCOM's performance with nonlinear loads. This approach allows for comprehensive analysis despite the inability to use actual solar hardware in all scenarios.

a) The source voltage will be reduced from 415 V to 220 V based on research indicating better performance and feasibility at this voltage level. This adjustment ensures compatibility with existing hardware constraints and facilitates accurate simulation and testing under practical conditions.

b) Achieve significant improvement in power quality by reducing harmonic distortions in compliance with IEEE-519:2014 standards and ensure active power supply to the utility grid.

c) Maintain the stability of the distribution system at the PCC when connected to nonlinear and unbalanced loads.

d) Ensure robust performance under weak grid conditions, including unbalanced loads and varying solar irradiance.

e) Enhance the utilization factor of the PV based DSTATCOM during periods of low solar irradiance penetration.

By focusing on these aspects, the study aims to provide a comprehensive solution for power quality improvement in distribution systems affected by nonlinear loads, leveraging both advanced simulation techniques and practical hardware testing.

1.5 Dissertation organization

This thesis consists of this introductory chapter and five other chapters arranged as follows:

Chapter 2 covers the literature review and a brief discussion of power quality especially harmonic distortion problems as one of the power quality problems. This chapter also present the survey of custom power devices (CPDs) including topologies and principles operation, highlights the advantages of DSTATCOM and describes the proposed control algorithms as alternative to new control algorithm of DSTATCOM including its topology.

Chapter 3 describes the proposed configuration of three-phase three-wire DSTATCOM system connected to nonlinear load and its design configuration, detailing its design consideration. The design of DSTATCOM based PV system are also described in term of technical and economic evaluation. Furthermore, the proposed Voltage Reference Configuration (VRC) control algorithm is then explained in detail. The DSTATCOM system and its control algorithm are modelled in MATLAB Simulink environment and validated with FPGA-in-the-loop (FIL) which are also enlighten in this chapter. Then, the chapter ends with the description of three phase hardware prototype of the DSTATCOM system.

Chapter 4 presents the results obtained from the PV-based DSTATCOM system's performance analysis. Graphs, tables, and figures illustrate the system's capability to mitigate power quality issues, enhance voltage regulation, and improve overall grid stability. The results are analyzed in relation to the research objectives, shedding light on the effectiveness of the integrated system. Limitations encountered during the study are addressed, offering insights into potential areas of improvement. The chapter facilitates a comprehensive understanding of the system's impact and contributions.

Chapter 5 In the concluding chapter, the research findings are summarized, and their implications for the field of renewable energy integration and power quality enhancement are discussed. The extent to which the research objectives were met is reevaluated, highlighting the achievements of the PV-based DSTATCOM system. Recommendations for future research are proposed, including the exploration of advanced control strategies, real-world implementation, and optimization techniques. The chapter concludes by reinforcing the importance of the study's contributions to advancing sustainable and reliable power distribution systems.