CURRENT CONTROL STRATEGY OF GRID-CONNECTED INVERTER FOR DISTRIBUTED GENERATION UNDER NONLINEAR LOAD CONDITIONS

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To my beloved parents, who without their enthusiasm and encouragement, I would never step in this way

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ABSTRACT

Distributed generation (DG) has become more important in recent years for supplementing traditional fossil energy resources for power generation. The DGs include microturbine (MT), fuel cell, photovoltaic (PV) arrays, wind turbine and storage devices. The DG units can operate in parallel to the main grid or in a microgrid (MG) mode. The MG is a discrete energy system consisting of DG and loads that are capable of operating in parallel with, or independently from the main grid. Meanwhile, Grid-Connected Inverters (GCIs) are typically used as the interfaces to connect each DG to the common bus in an MG mode. In the ongoing effort to improve the performance of MG, control strategy of three-phase GCI under nonlinear load conditions has become a mature and well-developed research topic, and some control strategies have been implemented in several countries. A new approach is proposed to control the GCI of DG in an MG under nonlinear and unbalanced load conditions. The proposed control strategy features the synchronous reference frame method. The primary advantage of this method is its ability to effectively compensate for the harmonic current content of the system currents and MG without using any compensation devices, such as an Active Power Filter (APF) or passive filter. In this system, the control strategy is designed to eliminate the main harmonics as well as to cancel the remaining harmonics. Furthermore, correction of the system unbalance is another key feature of the proposed strategy. Fast dynamic response, simple design, stability, and fast transient response are other key features of the presented strategy. The current total harmonic distortions were reduced from above 37.8% to less than 1% with the proposed control strategy under nonlinear load conditions. The proposed control method can be used on the GCI of MT and PV; and has the ability to reduce the complexity, size and cost of the control method in comparison with APFs.

ABSTRAK

Penjanaan Teragih (DG) semakin penting sejak beberapa tahun kebelakangan ini sebagai sokongan kepada sumber tenaga fosil tradisional untuk penjanaan kuasa. Jenis-jenis DG ini meliputi Mikroturbin (MT), sel bahan api, tatasusunan fotovolta (PV) dan turbin angin, serta peranti storan. Setiap unit DG mampu beroperasi selari dengan grid utama atau dalam mod Mikrogrid (MG). MG merupakan sistem tenaga diskrit yang terdiri daripada beberapa DG dan beban yang mampu beroperasi secara selari dengan, atau secara berasingan dari grid utama. Sementara itu, Penyongsang Tersambung Grid (GCIs) sering digunakan sebagai antara muka untuk menyambung setiap DG kepada bas sepunya dalam mod MG. Dalam usaha yang berterusan untuk menambah baik prestasi MG, strategi kawalan GCI tiga fasa dalam keadaan beban tak linear kini merupakan topik kajian yang matang dan maju, malah beberapa strategi kawalan kini dilaksanakan di beberapa buah negara. Suatu pendekatan baru dicadangkan untuk mengawal GCI suatu DG di dalam MG dalam keadaan beban tak linear dan tak seimbang. Kaedah kawalan yang dicadangkan ini mempamerkan kaedah rangka rujukan segerak. Kelebihan utama kaedah ini adalah ia mampu memampas kandungan arus harmonik dalam arus sistem dan MG dengan berkesan tanpa menggunakan sebarang peranti pemampas, seperti Penapis Kuasa Aktif (APF) dan penapis kuasa pasif. Dalam sistem ini, kaedah kawalan ini direkabentuk untuk menyisihkan arus harmonik utama serta membatalkan arus harmonik yang masih berbaki. Tambahan pula, keupayaan untuk membetulkan ketidakseimbangan sistem merupakan satu lagi ciri penting dalam strategi yang dicadangkan. Tindakbalas dinamik yang pantas, reka bentuk yang mudah, kestabilan, dan tindakbalas fana yang pantas merupakan ciri-ciri utama lain bagi strategi yang dicadangkan. Bacaan Jumlah Herotan Harmonic arus berjaya dikurangkan dari setinggi 37.8% hingga lebih rendah 1% dengan strategi kawalan yang dicadangkan dalam keadaan beban tak linear. Kaedah kawalan yang dicadangkan ini boleh diaplikasikan bersama GCI bagi MT dan PV, serta berkebolehan mengurangkan kerumitan, saiz, dan kos sistem kawalan jika dibandingkan dengan APF.

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LIST OF ABBREVIATIONS

APCT	-	Active Power Component Theory
APFs	-	Active Power Filters
APLC	-	Active Power-Line Conditioners
ASD	-	Adjustable Speed Drive
AFC	-	Alkaline FC
BPF	-	Band-Pass Filters
CPL	-	Constant Power Load
CHC	-	Current Harmonic Compensation
CSI	-	Current Source Inverter
CPC	-	Current's Physical Components
DB	-	Dead-Beat
DoE	-	Department of Energy
DFT	-	Discrete Fourier Transform
DERs	-	Distributed Energy Resources
DGs	-	Distributed Generators
EPRI	-	Electric Power Research Institute
EPQ	-	Electrical Power Quality
ES	-	Energy Storage
FUT	-	Filtered Unit Template
FDG	-	Flexible DG
FC	-	Fuel Cell
FPS	-	Fundamental Positive Sequence
FLC	-	Fuzzy Logic Controller
GHG	-	Greenhouse Gas
GCI	-	Grid-Connected Inverter
HDN	-	Harmonic Decoupling Network

HC	-	Hybrid Compensation
HCF	-	Hybrid Compensator Filter
HF	-	Hybrid Filter
INC	-	Incremental Conductance
IRP	-	Instantaneous Reactive Power
IGBT	-	Insulated-Gate Bipolar Transistor
IEC	-	International Electrotechnical Commission
LBC	-	Low Bandwidth Communication
MPP	-	Maximum Power Point
MPPT	-	Maximum Power Point Tracking
MG	-	Microgrid
MT	-	Microturbine
MCFC	-	Molten Carbonate FC
NLLs	-	Nonlinear Loads
PFs	-	Passive Filters
PMSG	-	Permanent Magnet Synchronous Generator
PLL	-	Phase-Locked Loop
PAFC	-	Phosphoric Acid FC
PV	-	Photovoltaic
PCC	-	Point of Common Coupling
PEM	-	Polymer Electrolyte Membrane
PI	-	Proportional-Integrate
PEMFC	-	Proton Exchange Membrane FC
PRF	-	Pulse Repetition Frequency
PWM	-	Pulse Width Modulation
RoCoF	-	Rate of Change of Frequency
RERs	-	Renewable Energy Resources
RC	-	Repetitive Controller
SOGI	-	Second-Order Generalized Integrator
SAPF	-	Shunt Active Power Filter
SOFC	-	Solid Oxide FC
SMES	-	Superconducting Magnetic Energy Storage
SRF	-	Synchronous Reference Frame
THD	-	Total Harmonic Distortion

UFDG	-	Unified FDG
UPQC	-	Unified Power Quality Conditioner
VPI	-	Vector-Proportional-Integral
VSI	-	Voltage Source Inverter
VF	-	Voltage-Frequency
WT	-	Wind Turbine

LIST OF SYMBOLS

u	-	Grid Voltage
P	-	Real Power Injected
Q	-	Reactive Power Injected
θ	-	Power Angle
C	-	Capacitor
ω	-	Angular Frequency
L	-	Transformation Matrix
i_r	-	Reference Current
ω_f	-	Frequency of Rotation of the Reference Feed Forward
v_D	-	DC-link Capacitor Voltage
P_{in}	-	Input Power
P_o	-	Output Power
PI	-	Proportional Integral
K_p	-	Proportional Gain
K_i	-	Integral gain of the PI controller
i_a, i_b and i_c	-	Three-Phase Load Currents
$\bar{I}_d$ and $\bar{I}_q$	-	Fundamental Active and Reactive Current Components
$\tilde{I}_d$ and $\tilde{I}_q$	-	Harmonic Active and Reactive Current Components
i_S^* , i_S^* and i_S^*	-	Extracted Reference Current Signal
v_d and v_q	-	Voltages at the Point of Common Coupling
I_d and I_q	-	Currents at the Point of Common Coupling
I_d^* and I_q^*	-	Reference currents
P^+	-	Positive Sequence Active Power
Q^+	-	Positive Sequence Reactive Power
ω_c	-	Rated Angular Frequency

ω^*	-	Reference of Angular Frequency
E_C	-	Rated Voltage Amplitude
$\emptyset_C$	-	Rated Phase Angle
E	-	Amplitude of the Inverter Output Voltage
S	-	Laplace Variable
m_P	-	Active Power Proportional Coefficient
m_D	-	Active Power Derivative Coefficient
n_P	-	Reactive Power Proportional Coefficient
E^*	-	Voltage Amplitude Reference
$\emptyset^*$	-	Voltage Phase Angle Reference
n_P	-	Reactive Power Proportional Coefficient
m_I	-	Active Power Integral Coefficient
n	-	Harmonic Order
B	-	Bandwidth
f_n	-	Tuning Frequency
Q_C	-	Reactive Power
f_1	-	Fundamental Frequency
k_p	-	Proportion Coefficient of Reactive Power
k_p	-	Proportion Coefficient of Active Power
k_i	-	Integral Coefficient of Active Power
k_i	-	Integral Coefficient of Reactive Power
$k_{r\ \kappa}$	-	Resonant Coefficients of the Voltage
$k_{r\ \kappa}$	-	Resonant Coefficients of the Current
R_V^h	-	Virtual Resistance in h Order Harmonic
v_C^{h*}	-	Generated Separately
H_I^h	-	Harmonic Distortion Index Related
$I_{C_\alpha}^1$	-	The Main of h Current of Axis α
$I_{C_\alpha}^h$	-	Harmonic Components of h Current of Axis α
$H_{I,m}^h$	-	Maximum Value of H_I^h
I_α	-	Real Inductor Current
V_α	-	Real Output Voltage
I_β	-	Imaginary Inductor Current

V_β	-	Imaginary Output Voltage
δ	-	Power Angle
Z_V	-	Virtual Impedance
Z_{o1}	-	Virtual Impedance in the Main Frequency
L_D	-	Direct Inductance
K_1	-	Gain of Proportional Controller
ω_t	-	System Angular Frequency
v_o	-	Output Voltage of the Inverter
v_r	-	Reference Voltage of the Inverter
G_P	-	Transfer Function of the Proportional Controller
f_s	-	Switching Frequency
X	-	State Variable Vector
ψ	-	Angle of the α / d Transformation
ω_c	-	Voltage Central Angular Frequency

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CHAPTER 1

INTRODUCTION

1.1 Overview

Due to climate changes, such as global warming and increased CO_2 emissions, there is an urgent need for power production based on renewable energy sources. One such concept is to generate electricity closer to the customer, known as distributed energy generation. Generating energy closer to the load reduces the need for long distance power lines. Making a reliable connection between renewable energy sources and the utility grid, however, may be a challenge.

New Renewable Energy Sources (RESs), such as Photovoltaic cell (PV), Microturbine (MT), Fuel Cell (FC), and Wind Turbine (WT) are often intermittent. These energy systems can be combined or connected to a local energy storage system to maintain a continuous power flow between the mains grid and the local network.

Even though RES usage adds complexity to the aforementioned optimality condition, they offer various technical, economical [1] and environmental [2] advantages as well. Such benefits might be in the form of reducing line losses, improving voltage profiles, enhancing power quality, shaving demand peaks, increasing system reliability, and rising grid security [3].

A Microgrid (MG) is a discrete energy system that consists of distributed energy sources (e.g., renewables, conventional, storage) and loads, which are capable of operating in parallel with, or independently from the main grid. The MG's primary purpose is to ensure reliable and affordable energy for commercial, industrial, and residential consumers. The benefits that extend to utilities and the community at large may include lower Greenhouse Gas (GHG) emissions, and lower stress on the transmission and distribution systems.

The RESs are connected to the utility network or an MG by an interface converter. An MG is a local grid composed of Distributed Generators (DGs), energy storage systems, and loads that can operate in both grid-connected [4], and islanded modes [5]. Power quality problems are a specific concern with MGs because distortion within the harmonic sources represent a high proportion of the total loads or Nonlinear Loads (NLLs) in small-scale systems [6]. The main limitation associated with MGs occurs when exchanging the current from the grid to the MG; this exchange is considered a source of harmonic distortion in a Grid-Connected Inverter (GCI) [7].

Several approaches have been proposed to improve the power quality in MGs. Installing Passive Filters (PFs) in appropriate locations, preferably closer to the harmonic generator, can lead to the trapping of the harmonic currents near the source, which can reduce their distribution throughout other parts of the system [8]. Active Power Filters (APFs) are flexible solutions for compensating the harmonic distortion caused by various NLLs in power distribution systems. Hybrid Compensation (HC) has the advantages of both passive and active power filters for the improvement of power quality problems [9]. Traditionally, the GCIs used in MGs that are connected to the main grid behave as current sources [10].

The GCI controller should be able to correct an unbalanced system, and cancel the main harmonics to meet the waveform quality requirements of the local loads and MGs [7]. The primary goal of a power-electronic interface inverter is to control the power injection [11]. However, compensation for power quality problems, such as current harmonics, can be achieved through appropriate control strategies. Consequently, the control of DGs must be improved to meet the requirements when connected to the grid [12].

Due to these issues, this study was focused on a new inverter control method for harmonic compensation. The proposed control strategy consist of a Synchronous Reference Frame (SRF) method, which was proposed to control the power injection to the grid, to provide harmonic current compensation, and to correct the unbalanced system. The focus of the present study was to reduce the Total Harmonic Distortion (THD) in the current flowing between the Point of Common Coupling (PCC) and the MG.

1.2 Background of the Study

Electricity plays an important role in our modern, industrialized society. With the increase in size and capacity, power systems have become more complex, thus leading to reduced Electricity Power Quality (EPQ).

Distributed generation is a new approach in the electricity industry, which involves power sources that range between 1 kW and 50 MW [13]. Such power source can be connected to a distribution network or installed close to consumption centers. Although there is no agreement on the exact definition of distributed generation, several attempts made in the literature to define this concept [14–16]. Any type of small-sized power convertor, which is directly connected to the distribution network or to the consumer’s side of the electric network, is referred to as a DG. In response to global warming, and the zeal to diverse their energy resources, most countries have aimed to incorporate a considerable amount of DGs into their power systems [17]. DGs can generate power locally using RESs, which include wind energy [18], solar energy [19], small hydro power [20], and biomass [21]. There are also other nonrenewable sources, such as small size gas and micro-turbines [22], and fuel cells [23]. The renewable or non-conventional electricity generators used in DG systems are known as Distributed Energy Resources (DERs) [24].

When smaller producers are connected to grids via distributed electricity generation methods and can produce their own share of electricity, planning for this increase in Distributed Energy Resources (DERs) is one of the unavoidable future problems. Nonetheless, integrating DERs has become a priority in these stand-alone distribution networks. The diffusion of DERs with the MG concept has evolved into clusters of loads and paralleled DERs that can operate as a single power system to provide power to its local area [25].

1.2.1 Structure of Microgrid

The past decade has seen the rapid development of MG in many countries due to the considerable attention they have been receiving. These low-power distribution systems offer various advantages, such as enhanced reliability, scalability, and flexible control of power compared to larger, centralized power systems [26]. The structure of a typical MG is depicted in Figure 1.1, which may include DERs and controllable loads. The DERs typically consist of a variety of MTs, WTs, FCs, PVs, and Energy Storage (ES) units, such as batteries [27].

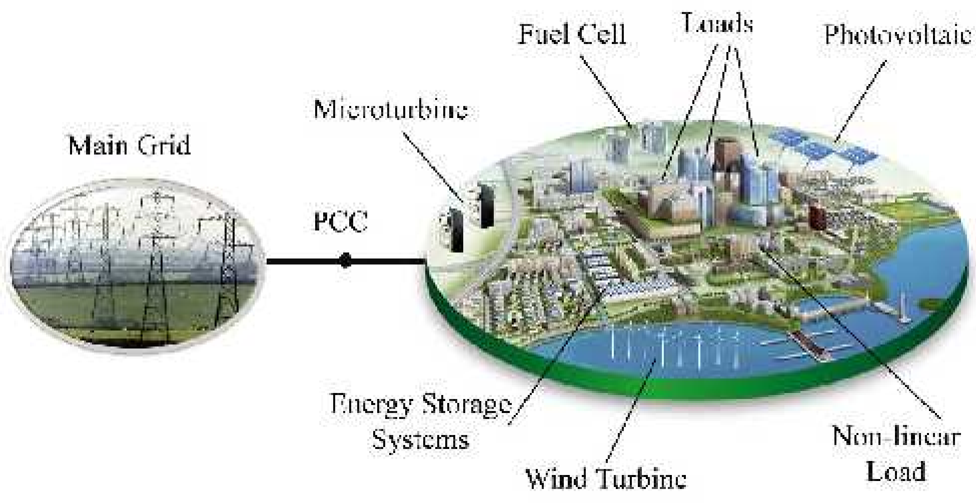

Figure 1.1 Structure of a typical microgrid

As in the archetypal MG architecture, MT, WT, FC, PV, and ES hybrid systems also make use of the complementary features of DERs to reduce storage capacity, and deliver a reliable and consistent service. These features allow the MG to be operated in the grid-connected mode to exchange power with the main power

[28,29]. MG can also be operated in the islanded mode [30–33], where power can be exchanged between the MG and the grid. Therefore, whenever a power disruption or an external attack occurs within the grid, the MG could still operated autonomously by being disconnected from the rest of the distribution system at the PCC. In another mode, the frequency of the MG and the voltage at the PCC are determined by the grid [34]. In the grid-connected mode, the MG control's main responsibility is to regulate the active and reactive powers, which are generated by the DERs. The grid cannot allow voltage regulation by the DER to avoid any interaction with the same functionality provided by the grid [35]. Hence, the GCI is the component that connects the DERs to the MG or to the grid because they are effective interfaces for DERs [36].

1.2.2 Grid- Connected Inverter

The increasing demand for electrical energy is exhausting fossil energy reserves. In addition, the increase in energy prices have necessitated the use of current energy resources in a more efficient way. Power electronic converters are finding increased use as the essential equipment to convert and control electrical power in the wide power range from milliwatts to gigawatts with the help of power semiconductor devices. Nowadays, more than 70% of all electricity is processed through power electronics [37]. Therefore, highly efficient, sustainable, reliable and cost-effective power electronics systems are needed to reduce energy waste, to improve power quality, and to reduce costs in power generation, power transmission/distribution and end user application. With increasing power densities, challenges related to the quality of the power electronic systems have been more significant. The power electronic converters are often used in microgrids to control the flow of power, and to convert it into suitable DC or AC form [38].

1.2.3 Control Methods of Grid Connected Inverter

Load flow calculations are vital for power flows, voltage profile, and losses determination. These calculations are also used to assess voltage regulation issues, and the basic capacity that is incorporated into the distributed generator interconnection. These calculations can also support other analyses, such as reliability, contingency, as well as power quality or transients. By finalizing these calculations, the model of the power system can be tuned according to its operational limits. Adjustments may consist of selecting different transformer taps, generator working set points, reactive power compensators, and spinning reserve.

The addition of significant levels of renewable generators, such as PVs or WTs, may increase the complexity of these analyses due to the uncertain nature of the energy sources. For example, the time and location dependency of wind generators require extra care when combined with feeder location and load variability. Thus, further studies are required to determine the operating conditions that the new power systems will experience. This situation gets even worse when energy storage devices are employed. In such conditions, the calculations may be done over a longer period.

DG creates several challenges in load flow calculations such as modeling of the transmission or sub-transmission system, simulating the equipment's for voltage-control, embedding single and two-phase lines, single-phase loads, which in the general view cause unbalanced systems in calculations. Therefore a proper load flow tool for a system containing distributed renewable generation, beside the conventional power system components, must contain a vast number of various generation and energy storage models combined with analysis capabilities.

1.3 Problem Statement

Based on an extensive literature review related to the field of MG, extensive studies are required to develop better control strategies for GCI, while preserving the accuracy within distributed generators. These aspects will be discussed in the following paragraphs in this section.

Control of three-phase grid-connected inverters is now a mature and well-developed research topic. Nevertheless, applications of microgrids with grid-connected inverters, in the presence of nonlinear load and practical DGs are not well-established. Most had only been studied using simple models, and for a limited number of DGs.

Hybrid compensation has the advantages of both passive filter and active power filter for the improvement of power quality problems. Moreover, hybrid filters have several drawbacks, including higher cost, larger size, higher power switch count, and complex control algorithms and interface circuits to compensate for unbalanced and nonlinear loads.

Most of the current references only reported the implementation of DGs for the injection of active and reactive power into the grid. No strategy has been devised to deal with the application of these devices to completely remove the harmonics at the grid.

1.4 Objectives of Research

Aforementioned gaps in researches lead us to choose the following objectives for this study:

i- To develop a microgrid system based on practical DG model.

ii- To develop a control strategy for the harmonic current compensation and the correction of the system and MG without the use of any compensation devices.

iii- To improve current control strategy for a three-phase GCI of distributed generation sources such as PV and MT.

1.5 Scope of Research

The motivation for this study is to improve the current control strategy for a three-phase PV and MT grid-connected inverter under unbalanced and nonlinear load conditions. The proposed control method would enable the grid-connected inverter to inject balanced and clean currents to the grid, even when the local loads are unbalanced and/or nonlinear. It can also compensate for the harmonic currents. The main scopes of this study are listed as follows:

i- The proposed method can be used for photovoltaic and MT grid-connected inverter at the MG. Moreover, the distributed generators, energy storage systems, and nonlinear loads which have been operated in grid-connected modes, were taken into consideration in this study.

ii- The grid and MG voltage were not considered for the network model, while the grid current and MG were taken into account. Therefore, the voltage was assumed to be sinusoidal.

iii- Network regulation and responsibility for RESs integration, operation, maintenance, and other financial and economic aspects were not considered in this study.

iv- It was fact that the various types of RESs in this study were not the same, and they can produce active and reactive power, then they can be integrated in the MG as a practical model.

v- This study was focused on current control strategy for a separate three-phase PV and MT grid-connected inverters at the MG. However, the fuel cell and the wind turbine were connected to the grid by an ordinary interface converter without the control strategy.

vi- All DG models were extracted from the MATLAB/Simulink power system toolbox.

1.6 Organization of Thesis

This thesis is organized into five chapters. The research motivations, brief and conclusive description of the study background, the problem statement, and the research objectives are explained in the current chapter, chapter 1.

An elaborative literature review is illustrated in chapter 2 with the focus on DGs in macrogrid for distributed generations, which would consist of renewable energy sources. In addition, a review is presented on current control methods for grid-connected inverters.

Chapter 3 presents the design of the proposed control strategy. This chapter is categorized into several subsections: modeling and decoupling of a three-phase Voltage Source Inverter (VSI), control strategy for a three-phase grid-following unit under unbalanced load conditions, harmonic compensation control strategy for a three-phase grid-following unit, distributed SRF control scheme, descriptions of test systems, and the software used for simulations.

Chapter 4, illustrates the performance of the proposed control strategy. It also includes the simulation results, and discussions on the outcomes of the improved control strategy for GCI. Furthermore, three case studies were taken into consideration as: a) Case study I: without any compensation device, b) Case study II: with an APF and distributed PFs, and c) Case study III: without any compensation devices, such as APF and PFs, and with only the proposed control method on the PV and microturbine. The results were compared with benchmark results from previous literatures that can prove their validity. Finally, last chapter, chapter 5, concludes the addressed issues, and the results of the proposed solutions. Recommendations for future works are also presented.

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