IMPROVED CONTROL STRATEGIES FOR THREE-PHASE GRID-CONNECTED PHOTOVOLTAIC SYSTEMS UNDER GRID-FAULT CONDITIONS

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DEDICATION

To my beloved parents for their love, support, encouragement and exceptional dedication

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ABSTRACT

During grid fault conditions, a distributed generation should remain connected for a pre-determined amount of time, and also provide reactive power to support the grid voltage. This is called low-voltage ride through (LVRT). LVRT control method for wind power generation systems under unbalanced and harmonic conditions is a well-developed research topic. However, too little attention has been paid to the LVRT control method for three-phase grid-connected photovoltaic (PV) systems under grid fault conditions. This thesis proposes improved control methods for a three-phase three-leg and a three-phase four-leg PV power converter under grid fault conditions. For a three-phase three-leg PV system, an improved positive-negative-sequence control scheme and an instantaneous active-reactive power control strategy are suggested. These schemes are used to cancel the double grid frequency oscillations in the active power and reactive power of a three-phase grid-connected PV during unbalanced grid condition. These methods are also effective to reduce the oscillations of Direct Current (DC)-link voltage that can be detrimental for DC-link capacitor. In order to track the desired unbalanced or harmonic reference current, enhanced proportional resonant (PR) current controllers with harmonic compensator have been designed using Bode frequency analysis. This study also suggests enhanced control method for a three-phase four-leg grid-connected PV system under unbalanced fault conditions using the combination of proportional integral (PI) and enhanced PR controllers using symmetrical components. Enhanced synchronization method for a three-phase four-leg grid-connected PV power converter operating in a three-phase four-wire system under unbalanced grid fault conditions using the magnitude and the phase angle of the positive, negative and zero sequence components is also presented. The proposed control strategy for the three-phase three-wire PV has the ability to cancel the double grid frequency oscillations in the active power, reactive power and also up to 55.5% reduction in the amplitude of the voltage oscillations under unbalanced grid fault conditions. The enhanced scheme for three-phase four-leg PV power converter operating in a three-phase four-wire system under unbalanced grid fault conditions has also the ability to cancel the oscillation of both the active and the reactive powers simultaneously.

ABSTRAK

Dalam keadaan kegagalan grid, penjanaan teragih sepatutnya kekal berada dalam keadaan tersambung bagi satu tempoh masa yang telah ditetapkan, disamping menyediakan kuasa reaktif untuk menyokong voltan grid tersebut. Ini digelar sebagai voltan rendah tunggang lalu (LVRT). Kaedah kawalan LVRT bagi sistem penjanaan kuasa angin yang berada dalam keadaan tidak stabil dan berharmonik adalah satu topik kajian yang telah diselami dengan dalam. Namun begitu, tumpuan amat kurang diberikan kepada teknik kawalan LVRT bagi sistem fotovoltaik (PV) sambungan grid tiga-fasa di dalam keadaan kegagalan grid. Tesis ini mengusulkan kaedah kawalan yang lebih baik bagi penukar kuasa PV tiga-fasa tiga-kaki dan tiga-fasa empat-kaki di dalam keadaan kegagalan grid. Bagi sistem PV tiga-fasa tiga-kaki, skim kawalan urutan positif-negatif yang ditambahbaik dan strategi kawalan serta-merta kuasa aktif-reaktif adalah dicadangkan. Skim-skim ini digunakan untuk memansuhkan ayunan kekerapan grid berganda dalam kuasa aktif dan kuasa reaktif bagi sebuah PV sambungan-grid tiga-fasa dalam keadaan grid tidak seimbang. Kaedah ini juga efektif dalam mengurangkan ayunan voltan pautan-arus terus (DC) yang mana ia boleh menjejaskan kapasitor pautan-DC. Untuk mengesan ketidakseimbangan yang diperlukan atau arus rujukan harmonik, pengawal arus resonan berkadar (PR) yang dipertingkatkan dengan pemampas harmonik telah direkabentuk menggunakan analisis frekuensi Bode. Kajian ini juga mencadangkan kaedah kawalan yang pertingkatkan bagi sistem PV sambungan-grid tiga-fasa empat-kaki dalam keadaan kegagalan tidak seimbang menggunakan kombinasi integral berkadar (PI) dan pengawal PR yang dipertingkat menggunakan komponen simetri. Kaedah penyelarasan yang dipertingkat bagi penukar kuasa PV sambungan-grid tiga-fasa empat-kaki yang beroperasi dengan sistem tiga-fasa empat-wayar di dalam keadaan ketidakseimbangan sesar grid menggunakan magnitud dan sudut fasa bagi komponen positif, negatif dan urutan kosong juga turut dibentangkan. Strategi kawalan bagi PV tiga-fasa tiga-wayar yang diusulkan mampu untuk memansuhkan ayunan frekuensi grid berganda dalam kuasa aktif, kuasa reaktif dan juga pengurangan amplitud ayunan voltan sehingga 55.5% di bawah keadaan tidak seimbang kegagalan grid. Skim yang dipertingkatkan bagi penukar kuasa PV tiga-fasa empat-kaki yang beroperasi dalam sistem tiga-fasa empat-wayar di dalam keadaan ketidakseimbangan sesar grid juga mempunyai kebolehan untuk memansuhkan ayunan bagi kedua-dua kuasa aktif dan reaktif secara serentak.

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LIST OF ABBREVIATIONS

AARC	-	Average Active-Reactive Control
AC	-	Alternating Current
BPSC	-	Balanced Positive-Sequence Control
CB	-	Circuit Breaker
CMPN	-	Continuous Mixed P-Norm
DC	-	Direct Current
DSRF	-	Decoupled Synchronous Reference Frame
DDSRF	-	Double Decoupled Synchronous Reference Frame
DSOGI	-	Dual Second Order Generalized Integrator
DGs	-	Distributed Generations
DERs	-	Distributed Energy Resources
FB	-	Full-Bridge
FLC	-	Feedback Linearizing Control
FLL	-	Frequency Locked Loop
FRT	-	Fault Ride Through
GW	-	Gigawatt
HC	-	Harmonic Compensator
HVRT	-	High Voltage Ride Through
IARC	-	Instantaneous Active-Reactive Control
IEC	-	International Electrotechnical Commission
IEEE	-	Institute of Electrical and Electronics Engineers
IGBT	-	Insulated-Gate Bipolar Transistor
IncCond	-	Incremental Conductance
LV	-	Low Voltage
LVRT	-	Low Voltage Ride Through
MIMO	-	Multi-Input-Multi-Output
MPP	-	Maximum Power Point
MPPT	-	Maximum Power Point Tracking
NF	-	Notch Filter
NPC	-	Neutral Point Clamped

NSRF	-	Negative Synchronous Reference Frame
P&O	-	Perturb and Observe
PCC	-	Point of Common Coupling
PEIs	-	Power Electronic Interfaces
PD	-	Phase Detector
PI	-	Proportional Integral
PID	-	Proportional Integral Derivative
PLL	-	Phase-Locked Loop
PN	-	Positive-Negative
PNCR	-	Positive and Negative Current Regulator
PNSC	-	Positive- and Negative-Sequence Control
PR	-	Proportional Resonant
PSRF	-	Positive Synchronous Reference Frame
PV	-	Photovoltaic
PWM	-	Pulse Width Modulation
QSG	-	Quadrature Signal Generator
QZS	-	Quasi-Z Source
RERs	-	Renewable Energy Resources
RESs		Renewable Energy Sources
SCCs	-	Symmetrical Component Calculators
SISO	-	Single-Input-Single-Output
SMC	-	Sliding Mode Control
SOGI	-	Second Order Generalized Integrator
SRF	-	Synchronous Reference Frame
SVM	-	Space Vector Modulator
THD	-	Total Harmonic Distortion
VCO	-	Voltage-Controlled Oscillator
VSI	-	Voltage Source Inverter
VSC	-	Voltage Source Converter

I_p^+, I_q^+	-	Positive-sequence active-reactive current amplitude
I_p^-, I_q^-	-	Negative-sequence active-reactive current amplitude
i_d^+, i_q^+	-	Positive-sequence d-axis and q-axis components of the inverter current
i_d^-, i_q^-	-	Negative-sequence d-axis and q-axis components of the inverter current
i_{dc}	-	Phase current flowing through DC-link capacitor
P^*	-	Active power reference
Q^*	-	Reactive power reference
P_{MPP}	-	Maximum allowable active power
V^+, V^-	-	Positive-negative-sequence voltage amplitude
v_d, v_q	-	dq components of the inverter voltage
i_d, i_q	-	dq components of the inverter current
i_a, i_b, i_c	-	Instantaneous values of phase currents
V_a, V_b, V_c	-	Three-phase inverter pole voltages
V^*	-	Reference voltage
V_{dc}^*	-	DC-link reference voltage
$abc/\alpha\beta$	-	"abc" to "$\alpha\beta$" transformation
abc/dq	-	"abc" to "dq" transformation
$I_{g\alpha}^*, I_{g\beta}^*$	-	Reference current signals in $\alpha\beta$ reference frame
$V_{g\alpha}^*, V_{g\beta}^*$	-	Reference voltage signals in $\alpha\beta$ reference frame
I_d^*, I_q^*	-	Reference currents
R_d	-	Passive damping resistance series with filter capacitor
k_p	-	Proportional gain
k_i	-	Integral gain
k_{RHP}	-	Right hand-plan pole gain
ω_c	-	Cross-over frequency
G_i	-	Transfer function of current control loop

N_p	-	Number of panels connected in parallel
N_s	-	Number of panels connected in series
V_t	-	Solar cell thermal voltage
I_{ph}	-	Solar cell photocurrent
r_{PV}	-	Dynamic resistance of PV system
$v_{\perp}$	-	Orthogonal voltage
$\|v\|^2$	-	Norm of the grid voltage vector signal
s	-	Laplace variable
D_c	-	Duty cycle
m	-	Modulation index of PWM algorithm

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CHAPTER 1

INTRODUCTION

1.1 Background of the Research

One of the most significant current discussions in the field of electric power systems, in recent years, is the deployment of renewable energy technologies to reach sustainable development [1, 2]. Among different types of renewable energy resources, solar photovoltaic (PV) is a suitable choice, due to the possibility of direct conversion of sunlight into electricity using power electronic devices straightforwardly [3]. Furthermore, PV systems are highly popular because they contribute to world energy security, decreasing the nation's dependency on fossil fuels, preventing global warming in the world and providing a full range of voltage regulation [4, 5]. Despite some disadvantages such as the relatively high cost of solar modules and variable power output, PV systems have been commercialized in numerous countries for technical, economic and environmental reasons [6]. They are being installed in a wide-ranging power capacities either in grid-tied or islanded mode to improve overall power quality and reliability of the main grid [7].

Grid-tied PV power systems are important renewable energy resources (RERs) in the distribution networks, and play a key role in stability, security and power quality of the power system. Nonetheless, to attain a reliable operation during both normal and grid fault conditions, some regulatory and technical problems have to be resolved before PV systems can become commonplace. In other words, the PV systems must be able to stay connected to the main grid for power quality enhancement even under grid faults [8]. The unregulated output power of PV power station under abnormal conditions can be regulated through grid-friendly converters, and the power system reliability can be guaranteed depending on the performance of these power converters.

Numerous research works have been published on the development and analysis of improved control systems for PV power converters during the last decades [9, 10]. In this regard, a growing body of literature has also suggested and analysed for grid synchronization, reference generation methods and current control of PV power converters [11]. When operated in power system applications, the PV power converter will be exposed to disturbances, transients and interruptions that propagate through the distribution network. Hence, PV systems should be controlled properly using power converters at their point of common coupling (PCC) under grid faults to keep PV systems connected to the utility grid. Grid faults can result in unbalanced grid voltages at the PCC of a PV power generator [12]. In other words, the delivered currents into the main grid by the PV power station lose their sinusoidal appearance as a consequence of abnormal grid conditions. Oscillations in the output power is a challenging control issue arising from grid fault conditions, and the main cause of tripping PV systems from the network.

Irrespective of the type and size, one critical component for any PV power station is the effectiveness of its operation under grid faults [13]. Development of the conventional control solutions for power electronic interfaces (PEIs) can fulfil the tight requirements imposed by the grid operator and provide the required stability, reliability and to maintain the specified power quality during transient grid faults. Reactive power support, voltage recovery, frequency stability and ensuring that the PV systems remain connected to the grid without generating overcurrent are the main requirements of PV generation systems under grid faults. Consequently, power and energy engineers everywhere are pondering the challenges of operation of PV power station under abnormal conditions, as it is the most way to improve the power quality, stability and reliability of utility grid with the high penetration of the PV systems [14] To attain the stable operation and appropriate integration, it is required for PV power stations to offer an improved low-voltage ride-through (LVRT) capability and maintain grid functionality throughout fault conditions [15]. In the following sections, the problem statement, thesis objectives, scope and thesis outline of this study are presented.

1.2 Problem Statement

Nowadays, three-phase PV systems are increasingly integrated into distribution networks to generate power locally near the customers. Under normal condition, PV systems operates with unity power factor to generate the maximum of active power. In order to cope with fault circumstances, the PV systems are needed to disconnect from the power system. Nevertheless, grid fault occurrence in distribution networks with high penetration of distributed generations (DGs), the cascade disconnection of all PV systems could trigger more severe grid challenges than the initial event. To overcome such potential issues, new grid codes are used by some countries to provide ancillary services such as voltage and frequency regulation for DGs. LVRT is the ability of PV keeps connected to the utility grid throughout short period during voltage sags. Furthermore, under abnormal conditions this ability control schemes must accurately control the current regulator under unbalanced and harmonic distortion; rapidly detect voltage faults; properly calculate active and reactive current references (reference current generator); prevent overcurrent failure; control the DC-link voltage; and prevent the active and reactive power oscillations.

Different LVRT methods for three-phase three-leg PV power converters in three-wire distribution systems are presented under grid fault conditions. However, the LVRT control methods for three-phase three-leg PV power converter in three-wire distribution systems under abnormal conditions often suffer from slow transient response, complex control algorithm, poor synchronization performance, unsatisfactory performance under harmonic distortions and active and reactive power oscillations. Consequently, it is vital to propose enhanced control methods to mitigate and reduce such disturbances for three-phase three-leg PV power converters in three-wire distribution systems.

The proportional integral (PI) current control is one of the popular current regulator in three-phase PV inverters. However, steady-state magnitude and phase error and limited disturbance rejection ability are the main disadvantages of this controller. When the current controlled inverter is connected to the utility grid, the phase error results in a power factor decrement and the limited disturbance rejection ability leads to the need of grid feed-forward compensation. Nevertheless, the imperfect compensation action of the feed-forward control results in high harmonic distortion of the current and as a result non-compliance with international standards. In addition, designing a proper control for the DC–AC converter to remain connected PV systems to the ac source under grid fault conditions due challenges such as the oscillation of the active and reactive power or the overloaded current is a great challenge. Consequently, it is required the design of an improved current control, synchronization method and power control strategy for three-phase three-leg grid-connected PV power in a three-wire system.

In addition to above-mentioned challenges for LVRT methods for three-phase three-leg PV power converters, too little attention has been paid to the LVRT control techniques for three-phase four-leg PV power converters in three-phase four-wire distribution networks under grid fault conditions because of the presence of positive, negative and zero sequence components. The synchronization control methods and the current controller of three-phase four-leg PV systems in four-wire distribution systems under abnormal circumstances due to the presence of the positive, negative and zero sequence components are more complicated. Additionally, the output active and reactive power control exchanged with the power grid in three-phase four-leg PV systems requires the design of specific reference generation control schemes for determining the current that must be injected into the utility grid by the PV systems. In three-phase three-wire systems, there exist four current control freedoms as the zero-sequence components are omitted due to the structure of power system. Hence, the active and reactive power oscillations cannot be mitigated at the same time. This issue can be more complicated under harmonic distortion. However, in the three-phase four-wire distribution networks with the zero-sequence components, there exist six current control freedoms. Therefore, it is essentially required the design of an improved reference generation control strategy to extend the controllability of the PV system by cancelling the oscillation of both the real and the reactive powers simultaneously.

1.3 Objectives of the Research

The objectives of this research are:

i. To design an improved current control strategy for a three-phase three-leg grid-connected PV power converter operating in a three-phase three-wire system to cancel the oscillation of the DC-link voltage, active and reactive powers under unbalanced grid fault conditions and harmonic distortions.

ii. To propose enhanced power control strategies for a three-phase three-leg grid-connected PV power converter operating in a three-phase three-wire system to reduce oscillations in active power, reactive power and DC-link voltage under unbalanced grid fault conditions and harmonic distortions.

iii. To design an enhanced power control strategy and synchronization scheme for a three-phase four-leg grid-connected PV power converter operating in a three-phase four-wire system to cancel the oscillation of both the active and reactive power simultaneously under unbalanced grid fault conditions.

1.4 Scope of the Research

The focus of this study is on developing improved LVRT control strategies for three-phase grid-connected PV power converter. The LVRT control strategies are implemented on a three-phase three-leg PV power converter in a three-phase three-wire distribution network and a three-phase four-leg PV power converter in a three-phase four-wire distribution network. Hence, the main focal aspects of the study are listed as follow:

i. This research is focused on current control strategy and power control strategy for grid-connected photovoltaic power converters.

ii. This research is concentrated only on asymmetrical faults, specifically single line-to-ground fault (SLG) which is considered ‘type B’ voltage sag, as well as line-to-line fault (LL) which is considered ‘type C’ voltage sag.

iii. The symmetrical faults such as three-phase fault and three-phase to ground fault are beyond the scope of this research.

iv. In this research both the steady-state and transient conditions are considered.

v. The proposed control schemes are implemented in the three-phase three-wire and four-wire low voltage (LV) power system.

vi. In this study only the grid-connected photovoltaic system is considered as the DG.

vii. All the models are performed using MATLAB/Simulink toolbox and DIgSILENT PowerFactory tools under different grid fault conditions.

1.5 Significance of the Research

The significance of this research can be mainly categorized as follows:

i. The proposed control strategies for the three-leg PV system has the ability to reduce power oscillations in active and reactive power.

ii. The suggested controller for the four-leg PV system can totally mitigate the fluctuations in both the active and reactive power simultaneously.

iii. The proposed control strategies are capable of relieving the current amplitude for the faulty phase without further increasing in the current amplitude in the normal phases.

iv. The proposed control strategies are effective to reduce the oscillations of the DC-link voltage that can be detrimental for DC-link capacitor.

1.6 Thesis Organization

This thesis is organized into five chapters, in which the outline of each chapter is as follows:

Chapter 1 provides the general overview of the study by discussing the research background, problem statement, research objectives, scope and the significance of the research.

The detailed literature review is illustrated in Chapter 2 with the focus on the concept of LVRT in grid-tied PV system and its characteristics, new grid code needs, and reactive power requirements. This chapter also discusses the general control structures of grid side converter for PV systems. Different control strategies for the three-phase grid-connected PV systems, reference frames, synchronization methods, types of inverters, control modification, different topologies for PV system as well as the network under various unbalanced grid-fault conditions are also comprehensively reviewed in this chapter.

Chapter 3 defines and establishes the methodology of the research. This chapter is summarized into several subsections: modelling of grid-connected PV system, control strategy of inverter-based PV systems, design of conventional PI and PR current controllers, control strategy for three-phase three-wire PV grid-tied system, design considerations for the selection of DC-link capacitors, Power control strategy for three-phase four-wire power converter with zero sequence current path, system description, and the software used for the simulations.

Chapter 4 presents the results and discussion. This illustrates the performance of the proposed control strategy. It also includes the simulation results, as well as discussions on the achievements of the improved control strategy for grid-connected PV system. The results are compared with the benchmark results from previous literatures that can prove their validity.

Finally, conclusions are presented in Chapter 5 and the thesis ends with possible recommendations for future works.

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LIST OF PUBLICATIONS

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