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Control and energy management of a large scale grid-connected PV system for power quality improvement

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ABSTRACT

Power quality is highlighted as an important parameter in modern power systems. Moreover, grid-connected photovoltaic power plants are increasing significantly in size and capacity. Elsewhere, due to the progressive integration of nonlinear loads in the grid, the principal role of a Solar Energy Conversion System (SECS) is not only to capture the maximum power from solar but, also to ensure some ancillary services and improve the quality of power. This paper presents a novel strategy dedicated to improve the management of active power generation, reactive power compensation and power quality of a SECS, while guaranteeing the possibility of exploiting the full capacity of the Power Conditioning System (PCS) and the PhotoVoltaic System (PVS). The proposed control algorithm is applied to a large scale PVS connected to the grid through a cascade of a DC-DC converter and a PWM inverter. This control strategy manages the SECS function's priorities, between main active power generation, reactive power compensation and active filtering in such a way to guarantee a smooth and stable DC voltage and ensure a sinusoidal grid current. Top priority is given to the active power production over power quality improvement. Then, priority is given to reactive power compensation over mitigation of current harmonics absorbed by the non-linear load connected to the Point of Common Coupling (PCC). Moreover, the whole system upper limits of active and reactive powers have been determined in the (*PQ*) power plane on the basis of PVS available power, converters rated power and DC bus voltage smoothness and stability. Finally, a control procedure dedicated to the calculation of the inverter current commands is proposed in order to exploit the full capacity of the SECS and respect the determined power limits. Simulation results confirm the effectiveness and the performance of this control strategy and prove that the SECS can operate at its full power whilst the power quality can be improved by reactive power compensation and active filtering.

1. Introduction

Global energy crisis and environmental concerns from conventional fossil fuels have pushed researchers to alternative energy sources which are cleaner, inexhaustible and produce less environmental impact (Kandemir et al., 2017). Among these alternative sources, solar PV energy based generation is one of the most popular and readily available renewable energy sources. In particular, large-scale grid-connected PVSs have increased and expected to grow rapidly in future due to several advantages such as ease of installation, noiseless operation, safer operation with lower operational costs, and environmental benefit (Liu et al., 2015a; Roy and Mahmud, 2017). In spite of numerous advantages of PVSs connected to the utility grid through power electronics converters, it is necessary to control the grid current during normal/faulty conditions and ensure grid synchronization (Lakshmi and Hemamalini, 2016). Moreover, it is known that the extensive use of modern electronic devices and nonlinear loads leads to the problem of no sinusoidal current and reactive power drawing from the source. This behavior causes voltage distortion that affects other loads connected at the same PCC. Hence, the power quality issue has captured increasing attention in power engineering in recent years. Note that, the measure of power quality depends upon the needs of the equipment that is being supplied (Sezen et al., 2014; Arul Murugan and Anbarasan, 2014).

In the literature, several research studies in the area of power generation and power quality improvement (reactive power compensation and/or harmonic filtering) using SECS, have been performed. Concerning the harmonic filtering, passive filter is one of the most used devices to address this issue. For example, Hanif et al. (2014) have used an active damping technique for LCL filter based grid connected PVSs to achieve effective active damping for three phase grid-connected PV

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Nomenclature

APF	active power filter
HPF	high pass filter
LPF	low pass filter
MPPT	maximum power point tracking
PCC	point of common coupling
PCS(s)	power conditioning system(s)
PI	proportional integral
PVS(s)	PV System(s)
PWM	pulse width modulation
RMS	root mean square
SECS	solar energy conversion system
SPBF	selective pass band filter
THD	total harmonic distortion
G	irradiation
I	current modulus
i	(a, b, c) three-phase inverter current
i_d	d-axis inverter output current
$i_{drefmax}$	d-axis maximal reference current
i_{dreft}	d-axis total reference current
i_G	(a, b, c) three-phase grid current
i_{ld}	d-axis nonlinear load current
i_{ldh}	d-axis current harmonic component
I_{max}	maximal current modulus
I_{PV}	PV field current
i_q	q-axis inverter output current
$i_{qrefmax}$	q-axis maximal reference current
i_{qreft}	q-axis total reference current
i_{lq}	q-axis nonlinear load current
i_{lqh}	q-axis current harmonic component
I_s	DC bus current
k_h	chopper ratio
P, Q	active and reactive powers
P_{max}	maximum of active power
P_{lim}	active power limit
L	line inductance
L_{NL}	nonlinear load inductance
Q_{max}	maximum of reactive power
Q_{lim}	reactive power limit
R	line resistance
R_{NL}	nonlinear load resistance
T	temperature
v	(a, b, c) three-phase inverter voltage
v_d	d-axis inverter output voltage
V_{dc}	DC bus voltage
v_q	q-axis inverter output voltage
V_{PV}	PV field voltage

inverters. In Naveena and Kuthsiyatjahan (2015), a double-tuned parallel resonant circuit has been proposed to attenuate the second and fourth order harmonics at the inverter DC side, improve the power quality and enhance the system efficiency. In this paper, a modified carrier based modulation technique for the current source inverter was used to magnetize the DC-link inductor by shorting one of the bridge converter legs after every active switching cycle. Moreover, an optimization technique is suggested by Mishra and Ray (2016) to tune the LCL filter parameters of a photovoltaic fed distributed static compensator. In this work, the design procedure includes harmonic elimination, power factor improvement, and transient behavior enhancement. In another case presented in Sakar et al. (2017), hosting capacity of a distorted distribution system due to photovoltaic connection has been addressed. According to this study, the passive filter is used to increase the harmonic-constrained hosting capacity which then improves the voltage waveforms, and power factor, and filters current harmonics.

Elsewhere, the reactive power compensation is essential for the next-generation of grid connected PV inverters in order to allow high penetration of PVS. In fact, Liu et al. (2015b) have shown the effect of optimized reactive power compensation on PVS operation performance. This study evaluates mainly the effect of this compensation on system reliability and power quality.

In addition, numerous research papers have dealt with reactive power capability of photovoltaic generation systems. Almost all these papers have proposed various control schemes in single-phase and three phase grid-connected PVS to inject/absorb reactive power to/from the grid through PV inverters without discussing the limitations of the PVS in terms of reactive power (Lal et al. 2013; Freddy et al. 2017; Ahmad and Singh, 2018). However, the reactive power capability is subject to several limitations (resulting from voltage, current, and climatic conditions) that change with the system operating point. To address this issue, some studies have been recently performed to analyze and estimate the PVS limits in the (*PQ*) power plane. In Delfino et al. (2009), a sort of capability chart of the whole grid connected system (PV panel + inverter + transformer) in terms of active and reactive power produced at the AC side has been defined. On the basis of a simplified model, this analysis has been carried out to delimit the points set in the (*PQ*) plane, at steady state without over-rating all the involved devices. Albarracin and Alonso (2013) have studied also the reactive power limits of PV inverters by considering inverter current and voltage limits, and PV active power limit. In this study, the capability to inject/absorb reactive power in order to reduce over-voltages when PV generators are disconnected has been addressed. Once more, the analysis is developed by considering only PV generator and inverter limitations. Elsewhere, the reactive power capability of PV plants is analyzed in Huang et al. (2015). In this paper, the reactive power of a PVS is assumed to be limited only by the capability of inverters and internal transmission losses (unit transformers, main transformer and collector lines). In order to calculate the capability of PVS in terms of reactive power, the limits of the power factor at the output of PV inverters have been fixed to ± 0.85 (that corresponds to reactive power limits of ± 0.46 pu according to the inverter apparent power limit). Another study has been developed by Cabrera-Tobar et al. (2016) where the PV inverters capability curves of a PV generator is obtained by considering variable solar irradiance, temperature, DC bus voltage level and inverter modulation index. In this case of a direct coupled inverter to the PV generator, limitations of current, voltage, active power and reactive power have been considered. The DC input voltage is constrained between the two limits required by the inverter which reduce the range of the PV generator output power (since there is no DC-DC converter to tune this voltage). In addition, a simple phasor diagram of the PV inverter interconnected with the grid has been used to delimit also the whole system capability in terms of reactive power in the (*PQ*) plane.

Elsewhere, a PVS operating in the MPPT mode, connected to a three phase grid and incorporating a shunt Active Power Filter (APF) has been presented in several works (Ibrahim et al., 2013; Sreerami Reddy and Hameed, 2015; Bouzelata et al., 2015; Bag et al., 2016; Bhole et al., 2017; Aboudrar et al., 2017; Tareen et al., 2017). In all these works, the PVS is used to generate power from the sun array and feed to the grid while the shunt APF is used to improve the power quality of the photovoltaic generation based on *d-q* theory.

Besides, different control approaches for reactive power compensation and harmonic filtering techniques of grid connected PVSs are reported in literature. In Renukadevi et al. (2015), harmonic filtering and reactive power compensation of a grid connected PVS have been studied. In this work, a synchronous reference frame strategy is chosen and the grid connected photovoltaic generation system is controlled to send active power to the grid, compensate harmonics and absorb