POWER QUALITY IMPROVEMENT IN GRID-CONNECTED PV SYSTEM USING FILTERS WITH CONTROL AND ENERGY MANAGEMENT

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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) using filters. 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.

I. 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 PVinverters.

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 reactive power generated by local loads. In the same context of power quality enhancement, Patsalides et al. (2016) have proposed a generic transient PVS model that can be tuned in order to represent accurately the dynamic behavior of PVSs for both balanced and unbalanced conditions.

Harmonics were also incorporated into the model to highlight its capability for use in complete power quality studies. Hamrounia et al. (2017), have suggested also an approach of a grid connected PV control scheme, that provides optimal PV power and high quality of current injected into the grid and, therefore, high power quality. This task has been performed by combined current control and power control loops. One can also cite the work of Nirmal Mukundan and Jayapraksh (2017), that has addressed a solar PV fed cascaded h-bridge multilevel inverter used in a two stage 3-phase grid connected PVS to ensure MPPT operation and power quality improvement. In this contribution, the system is controlled to generate active power and improve power quality of the grid by injecting reactive power, balancing source currents and supporting harmonic demand of load. Furthermore, a hybrid combination of filters using passive and active filters has been used for the development of power quality. In Patra et al. (2016), the authors have suggested a comparative assessment for power quality that can be achieved with two types of circuits; a dual stage that consists of a boost based VSI and a single stage grid connected PVS using a Z-Source Inverter. In this paper, the power quality of signals in both circuits is analyzed during transient variations of solar intensity and load conditions, with and without the use of a hybrid filter (composed of active and passive filters). As can be seen, power-quality issues are addressed by passive filters and/or more advanced filtering technologies (such as static synchronous compensator, APF, and unified power quality conditioner). However, the shunt APF is the most dominant and efficient solution against problems of power quality, with reactive power and current harmonics compensation. The majority of the above reported solutions use additional tools (passive filter, APF, unified power quality conditioner) instead of exploiting the system PCS to do this task. In addition, the implication of DC bus voltage stability and smoothness, and current commands calculation have not been determined on-line to operate the PVS under its full capability in terms of active power generation, reactive power compensation and active filtering (which is very important in the case of large scale PVSs that will be an ancillary service provider in the near future) to permit an efficient use of such systems in terms of power generation and power quality improvement.

In this paper, a basic decoupled control strategy of active and reactive powers of a large scale PVS (Hokuto mega-solar station) is presented and validated by experimental data of Konishi (2014) and Konishi et al. (2011). Then, the whole system power capacity has been delimited in the (PQ) power plane on the basis of available PVS power; electronics converters rated powers and DC bus voltage smoothness and stability for different operating conditions. Besides, a management procedure is suggested to achieve an on-line full capability operation of SECS in terms of power generation, reactive power compensation and active filtering of non linear load harmonic currents. This strategy is used to pilot the PWM inverter in order to manage the SECS energy function's priorities. 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 PCC. Finally, the maximal capability of the SECS is fully exploited (if needed), without any overrating of power electronics converters or risk of DC voltage instability, by using a procedure that calculates on-line the inverter command currents on the basis of the possible operating zone delimited previously. In summary, here are the main contributions of this paper:

- A hierarchical power management strategy that gives top priority to active power generation, then reactive power compensation and finally active filtering has been proposed.
- The whole system capacity in terms of active and reactive powers is successfully delimited in the (PQ) power plane in order to avoid the system components over-rating and/or instability.
- A control strategy is developed to operate on-line the SECS at its full capacity of power.

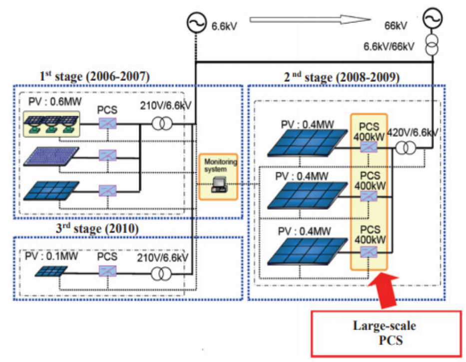

Fig. 1. Configuration of Hokuto mega-solar station.

II.LITERATURE SURVEY

In this study, several recently published topologies are analyzed for reactive power generation capability. It has been found that some of the topologies with their conventional modulation strategies are not suitable for reactive power applications. These are not able to generate zero voltage states during negative power flow. As a result, current is distorted and PV inverter injects current with high total harmonic distortion (THD) into the grid. In order to overcome these problems, modified modulation technique is proposed to achieve reactive power capability without having distortion in injected grid current. It provides path for current to flow in order to generate zero voltage states during negative power flow. With improved modulation strategies, reactive power generation is achieved in inverter topologies without any alteration on the converter structures. The controller software of these topologies is only required to be updated for reactive power generation. The implementation and generation of the proposed improved modulation techniques are straightforward and it can easily be realized. Moreover, single phase transformerless inverter topologies are classified for first time on the basis of reactive power handling capability. In order to verify the theoretical explanations, simulations have been carried out in Matlab/Simulink environment and validated through an experimental setup.

III. BOOST CONVERTER:

A boost converter is DC-to-DC steps up converter which can be improving the output voltage more than its input voltage. The class of switched-mode power supply consists of at least two switches (a diode and a transistor) and at least one energy storage element, like inductor, capacitor or the two combinations.

DC sources are used supplying power to the boost converter, like batteries, solar panels, rectifiers and DC generators. The process of converting a level of DC voltage in to a different level of DC voltage is known as DC to DC conversion. The boost converter is a step-up DC to DC converter with an output voltage greater than the source voltage.

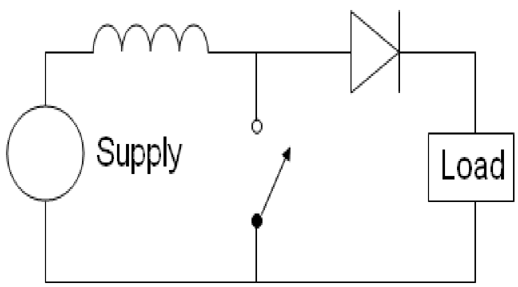

Fig.2 The basic schematic of a boost converter

IV.FUZZY

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision support systems, and portfolio selection. To understand why use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic.

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with un sharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of FL. Even in its more narrow definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

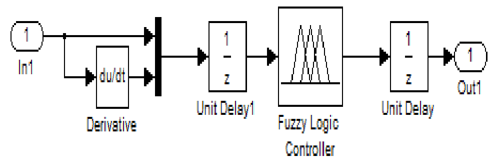

Fig.3Fuzzy interference system

V.PROJECT DESCRIPTION AND CONTROL DESIGN

5.1 Description of the studied grid connected PVS

Large-scale PVSs have become a major development area for research. The power of this kind of energy systems has increased progressively over the last decade with frequent new capacity records. As of January 2017, the largest PVS (Longyangxia Dam Solar Park in China) power in the world is about 850 MW. Then, one can state the Kamuthi Indian photovoltaic power station with a capacity of 648 MW, it was the largest PV power plant in the world in 2016 in front of the Topaz Farm of California (550 MW), previous holder of this title (Porrometo, 2017). The large scale PV grid-connected system studied in this article is one of the PVS high penetrations into the high voltage transmission grid in Japan. It is the Wakkanai project central station PVS. Wakkanai is the northernmost city (Hokuto) in Japan. It is the symbol city of renewable energy because there are large wind-farms and this mega-solar station. This station can develop a capacity of 1.9 MW.

The area of this PVS is of 95.656 m2 , it is installed on the period 2006–2010 and performed on three stages; see Fig. 1 (Konishi et al., 2007): The 1st stage was achieved in the period from 2006 to 2007 and is characterized by a capacity of 0.6 MW. The 2nd stage with a capacity of 1.2 MW was installed in the period 2008–2009. The 3rd stage is the final step of this project. It is characterized by a power of 0.1 MW and was achieved in the period from late 2009 to early 2010. Let us take the 2nd stage, size it again and model its PV generators. This stage contains three PCSs. The schematic of each conditioner and its specifications are given by Fig. 2 and Table 1. respectively (Konishi et al., 2011). It consists of two choppers of 200 kW each and an inverter

Table 1
Specifications and developing targets of a PCS.

Capacity	420 kVA/400 kW
AC voltage	420 V ± 10%
Permissible DC voltage	600 V
Input DC voltage	230–600 V
Switching frequency	4–6 kHz
Conversion efficiency	> 95% from 30 to 100% of the output power
Control functions	MPPT by choppers Minimizing harmonics

with an output rated power of 420 kVA; is connected to a 420 V/6.6 kV transformers. This latter is in turn connected to another step-up transformer of 6.6 kV/66 kV.

5.2Modelling of the SECS

The synoptic scheme of the studied system is shown in Fig. 3. It is composed of a PV field, a DC–DC boost chopper, a three-phase PWM inverter and a nonlinear load connected to the PCC of the electric grid. Let us now describe and model this PVS.

5.2(A) Photovoltaic generator description

The PV generator is composed of three fields of 2000 PV modules. The rated power of each PV panel is of 200 W. Thus, the output power of each field is about 0.4 MW and the total generated PV power is 1.2 MW. On the other hand, each PV field includes Ns modules in series and Np parallel branches that can be calculated as follows:

$$\begin{cases} N_s = \dfrac{V_{maxDC}}{V_{maxM}} \\ N_p = \dfrac{I_{maxDC}}{I_{maxM}} \end{cases} \tag{1}$$

where VmaxDC is the maximum input voltage of the PCS, (VmaxDC = 600 V) and VmaxM is the module voltage corresponding to the maximum power operating point (it is equal to 24.5 V in this case). Thus, the series modules number is: Ns = 25. Afterwards, the total number of parallel branches is deduced: Np = 80. So, each field of the PVS comprises 80 parallel arms of 25 modules in series. This implies that each chopper is powered by a half of the PV field (40 parallel strings of 25 modules in series).

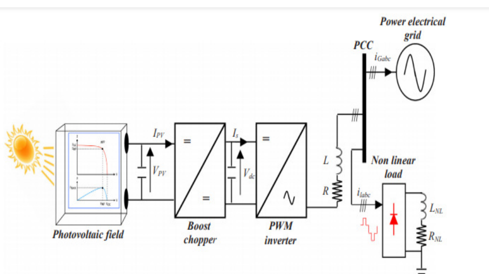

Fig. 3. Synoptic scheme of the studied system.

5.2(B) Photovoltaic array modelling

The PV cell is the basic unit of a photovoltaic module; it transforms the sun rays or photons directly into electric power. The equivalent circuit of a practical PV cell is shown in Fig. 4 (Ramalingeswara Rao and Srikanth, 2014). It comprises a current source, an anti-parallel diode, a series resistance and a shunt resistance. Based on the Shockley and Queisser diode equation, the Ipv – Vpv characteristic equation of a PV cell is given by Patra et al. (2016):

$$I_{pv} = I_{ph} - I_0\left[\exp\left(\frac{V_{pv} + R_s I_{pv}}{nV_T}\right) - 1\right] - \frac{V_{pv} + R_s I_{pv}}{R_p} \tag{2}$$

where Iph is the current generated by the incident solar radiation, I0 is the reverse saturation or leakage current of the diode; it is given by the following expression (VimaRadha Vignesh and VigneshRam, 2014),

$$I_0 = \frac{I_{cc}}{\left[\exp\left(\frac{V_{co}}{nV_T}\right) - 1\right]} \tag{3}$$

with:
Rs is the intrinsic series resistance of the solar cell, Rp is the equivalent shunt resistance of the solar array (its value is usually very larged) and VT is the thermal voltage of the PV module, it is given by the following equation:

$$V_T = \frac{KT_c}{q} \tag{4}$$

where K is the Boltzmann constant (K = 1.38 × 10–23 J/K), q is the electron charge (q = 1.6 × 10–19 C), Tc is the absolute temperature in Kelvin, and n is the diode ideality factor (1 < n < 1.5). Elsewhere, the value of the short-circuit current expressed for other conditions of solar intensity and temperature is given by Kumar et al. (2012):

$$I_{cc}(G) = I_{ccref}\frac{G}{G_{ref}} \tag{5}$$

$$I_{cc}(T) = I_{ccref}\left(1 + \alpha(T - T_{ref})\right) \tag{6}$$

where Gref, Tref, Iccref are the standard values of solar intensity, cell temperature and short-circuit current respectively, and α is a temperature coefficient (A/K). Similarly, the saturation current is expressed, for a given temperature level, as (Bouzelata et al., 2015):

$$I_0(T) = I_0(T_{ref})\left(\frac{T}{T_{ref}}\right)^{\frac{3}{n}}\left(\exp\left(\frac{-qE_g}{nK}\right)\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)$$

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PV cells connected in parallel increase the total output current of the PV module whereas cells

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connected in series augment the total output voltage of the cell.

5.3 Power control and management strategy

In 1983, Akagi suggested a new concept called the p–q theory. First, uses the Clarke transformation to transfer three-phase voltages and currents from abc coordinate to αβ coordinate in order to compensate the harmonics and negative components (Belaidi et al., 2011). The real and imaginary instantaneous powers theory is based on time-domain analysis, what makes it valid for operation in steady-state and transient regime, as well as for generic voltage and current power system waveforms (Sreerami Reddy and Hameed, 2015). The Clarke transformation can be expressed for a three phase system (voltage/current/non linear load current) as follows (Sreerami Reddy and Hameed, 2015; Tahmi et al., 2014):

Then, previous (voltage/currents) components in the α-β coordinateare transformed into d-q coordinate as shown in the following equations (Ibrahim et al., 2013):

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \quad (13)$$

Moreover, the instantaneous active and reactive powers delivered to the grid have been calculated as follows (Sezen et al., 2014):

$$P = v_d i_d + v_q i_q \quad (14)$$

$$Q = v_d i_q - v_q i_d \quad (15)$$

Elsewhere, different MPPT methods dedicated to pilot PVSs have been proposed in the literature and can be classified into direct and indirect methods. Indirect methods require prior knowledge of the PV array characteristics under different irradiance/temperature conditions. In contrast, direct methods use voltage and current measurements from the PV array to achieve the optimal operation point (Franco et al., 2017). On the other hand, several techniques have been used to perform a decoupled control of PVS active and reactive powers injected to the grid such as PI controller (which is simple to implement but underperforming and less robust against parametric and operating point variation) and advanced strategies (such as sliding mode, adaptive control, optimal control) which are high-performing but more complicated. The fuzzy logic control is a good between these techniques in terms of effectiveness and robustness. In this paper, a DC-DC converter has been controlled using a fuzzy robust controller proposed by Benlarbi et al. (2004) to ensure the MPPT operation for different climatic conditions (irradiation and temperature). This technique permits a 'blind piloting' of the chopper by adjusting its duty cycle; it can replace the well known pilot cell used for MPPT purposes, see Fig. 5. Furthermore, the fuzzy logic technique has been applied to guarantee an effective decoupled control of the PVS output active and reactive powers injected into the electrical grid through the PWM inverter for different operating conditions. This converter is controlled to ensure also an active filtering of the non linear load harmonic current. Consequently, the SECS depicted in Fig. 5

- Capture a maximum of power from the fluctuating solar energy (MPPT mode).
- Inject different levels of active and reactive powers into the grid through a PWM inverter.
- Compensate reactive power and improve the power quality via current harmonic filtering.

In addition, Fig. 6 shows the details of the PWM inverter control block of Fig. 5. The available power of the PVS (Pmax) and the power reference Pref are used to determine the effective power command Pref * of the PWM inverter. Moreover, the reactive command power Qref * is determined on the basis of the reactive reference, whilst the whole system capability. Then, the two fuzzy logic controllers generate dq current references idref and iqref. To achieve the active filtering operation these currents commands must be added in tandem with harmonic current dq components to be filtering (ildh, ilqh). The total references idreft and iqreft are limited by idrefmax and iqrefmax, respectively to gives the effective commands of the inverter output currents in the dq frame (idreft* and iqreft*). The limitations applied on the current references idreft and iqreft are based on the whole system capability in terms of power and the block priority management of different operations (active power generation, reactive power compensation and active filtering). This strategy is presented in details in Section 4.2.

5.4 Active filtering operation

There are various methods to identify the harmonic currents of a nonlinear load. Practically, a Selective Pass Band Filter (SPBF) or a Low Pass Filter (LPF) can been used to extract the harmonic currents components (Boutoubat et al., 2013). Frequency domain compensation, which is based on Fourier analysis, is not very used because it requires more real time processing power (Prabhakar and Bhattar, 2015). The most classical methods are "instantaneous power theory p-q" or "d-q or synchronous detection method". In our case, the harmonic current components in the (d-q) reference frame are obtained after subtracting the LPF outputs (direct current components) from the dq currents of the non linear load (the whole currents are composed of a fundamental part which is constant in the dq frame and a harmonic part), as depicted in Fig. 7

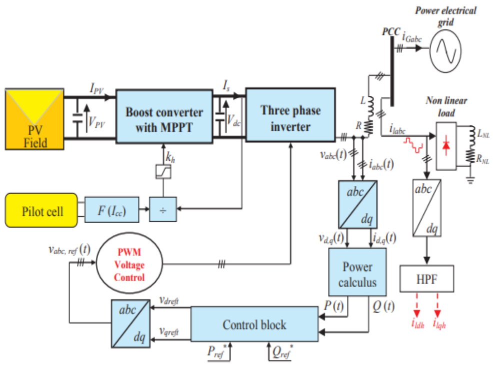


Fig. 5. Control scheme of the PWM inverter for power generation and harmonic mitigation.

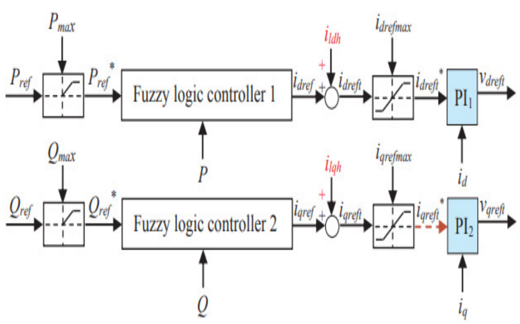


Fig. 6. Control block of the PWM inverter.

5.5 SECS capabilities and power quality improvement

Due to the integration of nonlinear loads in the grid, the SECS is not used only to capture the maximum power from the sun, but also to participate in power quality improvement. In this section, the whole system power capacity will be delimited in the (PQ) plane to manage the power of the PVS and improve its quality within the possible limits. 4.2.1. Active and reactive power capabilities of the SECS To avoid the over-rating of the SECS components during its control for both MPPT power generation and power quality improvement, it is required to know its active and reactive powers capabilities. The area of Fig. 8 shows the whole system capabilities in terms of active and reactive powers limits that will be respected. The circle centered at the point A with a radius of 420 kVA delimits the set of the PWM inverter possible operating points.

The two DC-DC converters of the system and the PVS rated power (2 × 200 kW = 400 kW) determines the active power maximum limit of the system. Moreover, simulation tests have been performed for different active power levels in order to determine the maximal reactive power that can be generated by the system at the output of the PWM inverter without destabilizing the DC bus voltage. This limit of reactive power (Qmax) delimits the upper edge of the trapezoidal shaded area of Fig. 8. An energetic analysis can be used for the delimitation of the whole system reactive power capability in the (PQ) plane. It may be performed on the basis of the DC bus voltage energy balance. For a given active power, on can express the energy to be stored and given back by the DC bus capacitance per cycle. This energy corresponds to a DC bus voltage ripples level. Then, the reactive power that gives a DC bus voltage variation (inside the values permitted by the inverter due to its operation according to the grid ac voltage) can be taken as the upper limit of reactive power (Qmax). Under the upper limit of reactive power, the DC bus voltage remains smooth and stable. Note that, in the case of a pure generation of reactive power, the system can inject up to 220 kVAr. So, the shaded area that specify the powers limitations of the whole system is determined by the PVS available powers (for a temperature of 25 °C and an irradiation of 1000 W//m2), the DC-DC converters rated power (2 × 200 kW), the inverter rated power and the DC bus voltage (600–900 V) smoothness and stability.

4.2.2. Management of PVS function’s priorities

The capability of the SECS in terms of power is characterized by a maximal current modulus Imax that can be calculated on the basis of the power limits Plim and Qlim of Fig. 8. One can write:

$$I_{max} = \sqrt{2}\,\frac{\sqrt{P_{lim}^2 + Q_{lim}^2}}{3V_{PCC}} \quad (16)$$

where VPCC is the bus-bar RMS voltage, Plim and Qlim are the active and the reactive powers limits of the SECS for a given operating point. To manage the SECS energy, the first priority is given to active power production over power quality improvement. Thus, the maximum value of the available reactive current to be used for reactive power compensation and harmonic currents mitigation is calculated from the following equation (Gaillard et al., 2009):

$$i_{qrefmax} = \sqrt{I_{max}^2 - I_{drefmax}^2} \quad (17)$$

In order to exploit the SECS at its full capacity in terms of power, it is proposed in this paper to express the total references of the d-q currents for active power production, reactive power compensation

Table 2
Grid current THD for different operating points of the studied system.

Time (hour)	P (kW)	Q (kVAr)	THD (%)
13:00	341.67	64.91	2.68
14:09	50	9.5	2.94
15:00	275	52.25	2.73

harmonic mitigation by the following equations:

$$i_{dreft} = i_{dref} + k_0 i_{ldh}$$

$$i_{qreft} = i_{qref} + k_0 i_{lqh} \quad (18)$$

where k0 is a positive gain which can vary between 0 and 1. Then, the second priority is given to compensate the reactive power over harmonic mitigation. Hence, one can distinguish the following situations: (a). First, if the reactive current command iqreft verifies:

$$i_{qreft} \geqslant i_{qrefmax} \quad (19)$$

Then iqreft* = iqreftmax and the SECS operates at its full capacity in terms of power. In this case only active power production and reactive power compensation are practically possible (i.e. k0 = 0). And the total PWM inverter current commands are given by

$$i_{dreft} = i_{dref} \quad (20)$$

$$i_{qreft} = i_{qref}$$

(b). Second, if the reactive current command iqreft verifies:

$$i_{qreft} < i_{qrefmax}$$

Then a portion of reactive current is available and can be used for harmonic filtering. Two cases can be distinguished:

1. The first case occurs for:

$$(i_{dref} + i_{ldh})^2 + (i_{qref} + i_{lqh})^2 \leqslant I_{max}^2 \quad (22)$$

In this situation, the PWM inverter can be used for both reactive power compensation and total harmonic current filtering (i.e. k0 = 1) without any over-rating of the system capability. Consequently, the total current commands are expressed by the following equations:

$$i_{dreft} = i_{dref} + i_{ldh}$$

$$i_{qreft} = i_{qref} + i_{lqh} \quad (23)$$

2. The second case verifies:

$$(i_{dref} + i_{ldh})^2 + (i_{qref} + i_{lqh})^2 > I_{max}^2 \quad (24)$$

In this situation, the SECS can be used to compensate the total reactive power and to filter a portion of harmonic currents without overpassing the system limits. For this purpose an appropriate gain k0 (0 < k0 < 1) which verifies the following equation is determined:

$$(i_{dref} + k_0 i_{ldh})^2 + (i_{qref} + k_0 i_{lqh})^2 = I_{max}^2$$

The value of k0 can be found by solving this second order equation. Then, the total current commands are calculated from Eq. (18).

VI. SIMULATION RESULTS

6.1. Simulation results of a decoupled power control of the PVS

To show and validate the decoupled power control performance used to manage the PVS energy in terms of decoupling and power limitations, simulation results have been carried out in the same experimental tests conditions presented in Konishi, (2014). In this case, the following operating points (note that the power levels considered here are evaluated per PCS) of Hokuto mega solar plant have been chosen from Fig. 7 of this reference: (P = 341.67 kW; Q = 64.91 kVAr), (P = 50 kW; Q = 9.5 kVAr) and (P = 275 kW; Q = 52.25 kVAr). These three operating points have been recorded at 13:00, 14:09 and 15:00 respectively (see Fig. 7 of Konishi (2014)). The PVS powers are controlled by the line current components id and iq, the phase angle between the active and reactive powers is chosen equal to φ = 10.76° (tgφ = Q/P = 0.19), (see Fig. 7 of Konishi et al. (2011)) and the switching frequency of the PWM inverter is fixed to 4 kHz (see Table 1. of Konishi (2014)) as in the experimental conditions. Step changes in the active and reactive power commands (Pref, Qref) are introduced and the actual active and reactive powers delivered by the inverter are presented in Fig. 9(a). One can note that P and Q track properly their commands (Pref, Qref) respectively in the steady state after a rapid transient of few milliseconds. Moreover, the current amplitude changes depending on the required apparent power, under practically a constant power factor (see Fig. 9(b)). Elsewhere, the grid current THD is calculated for these operating points, see Table 2. Note that in all cases, the calculated grid current THD is closer to the experimental measurement (THD = 2.8%), see Fig. 8 of Konishi (2014).

6.2. Simulation results of reactive power compensation and harmonic mitigation in the case of non-saturated current commands

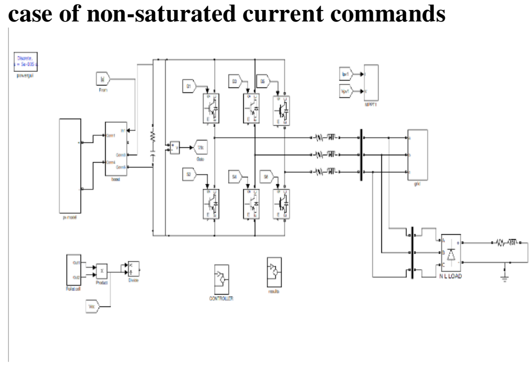


Fig7:proposed Simulation diagram

This segment discusses the reimbursement of reactive control and harmonic mitigation without saturated current commands. A non-linear load of 80 kW is attached to the PCC; it is supplied through the PWM inverter by the PVS and continually draws harmonic currents. Fig. Fig. 10 displays the non-linear load, its fundamental portion, and the harmonic element that the active filtering current compensates. The injection voltage in the grid is 200 kW and the reactive capacity is 100 kVAr (Pref = 200 kW and Qref = 100 kVAr). The DC bus voltage is held virtually constant until active filtering is done, and PVS control monitors its commands properly (see Figure 11(b) and(a)). Fig, on the other side. 11(c) displays the latest inserted waveform in the grid until the filtering operation is enabled. The existence of the non-linear load renders it non-sinusoidal. In comparison, Fig. 11(d) with an inverter swapping frequency of 4 kHz displays the harmonic range of the current with a THD of 6.77 percent. Notice that the instantaneous d-q currents monitor their references appropriately (see Fig. 11(e, f)).

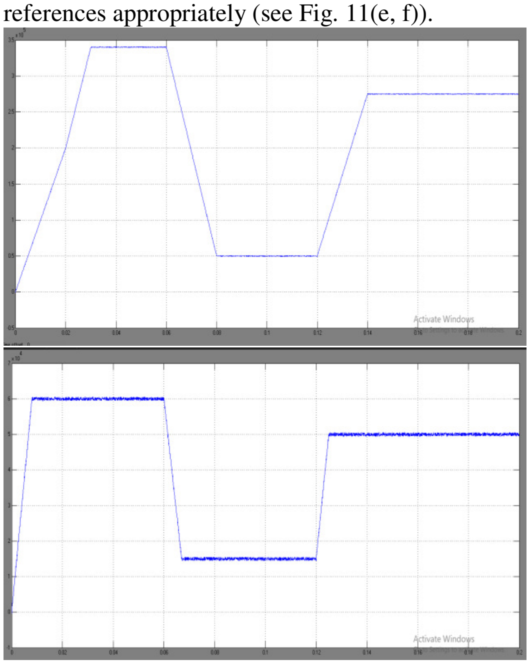


Fig8: Simulation results of a decoupled power control of the PVS: (a) Active and reactive powers in (kW) and (kVAr) respectively

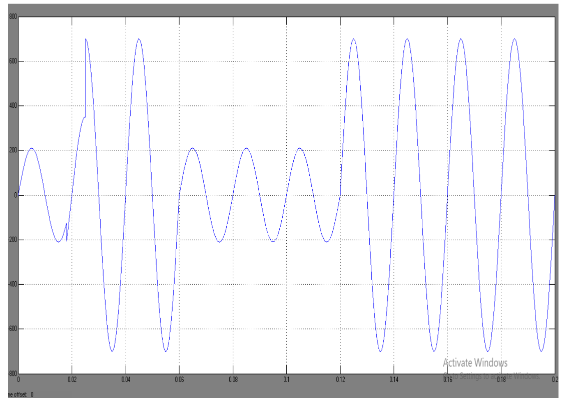


Fig9: Phase current ia (A) at the output of the inverter.

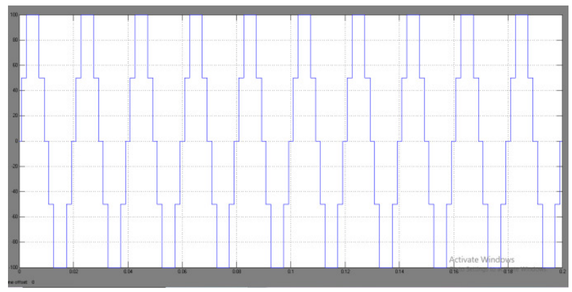


Fig10: Characteristics of the studied non linear load: Phase current component ila

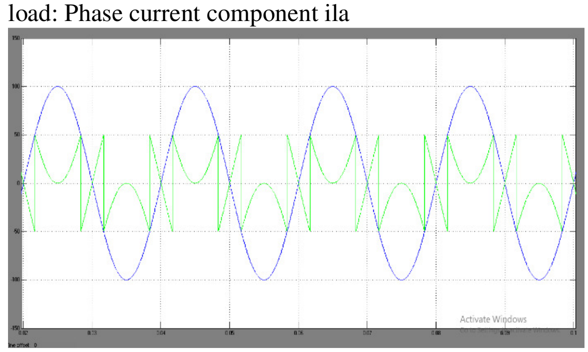


Fig: Fundamental and harmonic components of ila (A).

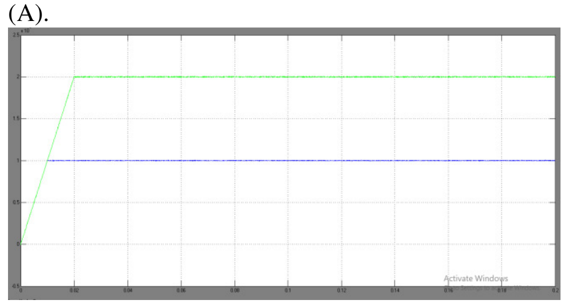
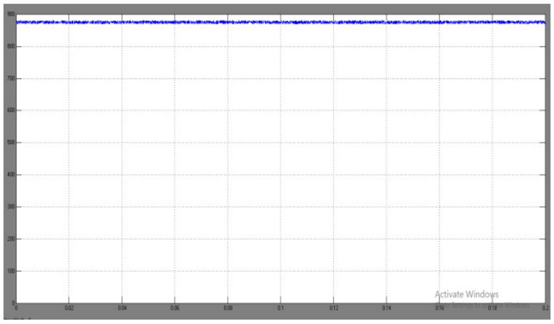
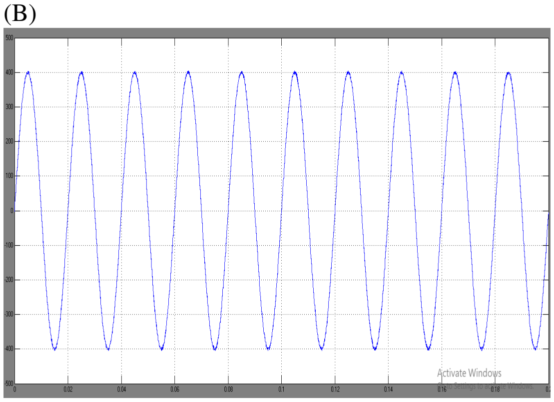


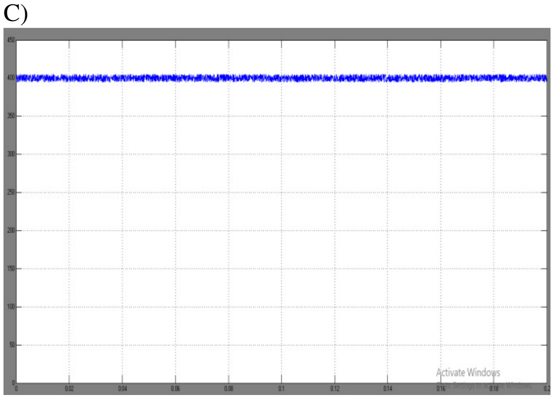
FIG: Active and reactive powers injected into the grid P (W), Q (VAr),



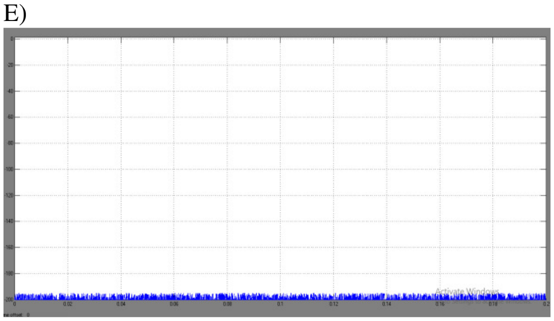
(B)



C)



E)



F)

Fig11.. Simulation results without active filtering under a non-saturated current command: (a) Injecting active and reactive control to P (W), Q (VAr), (b) DC bus voltage Vdc (V), (c) grid current iGa (A), (e) Direct current component id, (f) Quadrature current component iq (A), and command of it.

VII . CONCLUSION

A novel strategy has been proposed to manage and improve the power quality of a grid connected large scale PVS. More accurately, fuzzy logic controllers have been used to guarantee a decoupled control of active and reactive powers injected into the grid using filters. The PWM inverter is controlled in such a way to manage between active power production and power quality improvement without exceeding the whole system power capacity. The proposed priority control block gives top priority to active power production, then reactive power compensation and finally active filtering. The power capability of the whole system has been delimited in the (PQ) power plane (on the basis of the PVS available power, the power electronics converters rated power and the DC bus voltage smoothness and stability) and fully exploited without over-rating, by the calculation of an appropriate portion of current commands in order to ensure a better active filtering quality and keep the inverter current under its limit value corresponding to the whole system power capacity. Simulation results show the effectiveness and the performance of the proposed approach of filters adding in terms of power generation, reactive power compensation and active filtering.

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