Power Quality Conditioner of a Single-Phase Voltage Controlled Grid Connected Photovoltaic System with Fuzzy Logic Controller

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Abstract: The output power of photovoltaic (PV) module varies with module temperature, solar isolation and load changes etc. In order to control the output power of single-phase grid-connected PV system according to the output power PV arrays, this paper presents a single-phase photovoltaic system that provides grid voltage support and Compensation of harmonic distortion at the point of common coupling (PCC) with fuzzy controller. The output power provided by the PV panels is controlled by a Maximum Power Point Tracking (MPPT) algorithm based on the incremental conductance method specifically modified to control the phase of the PV inverter voltage. A control circuit is developed and the performance of the control circuit is investigated in MATLAB-SIMULINK. The Matlab simulation results show that, the proposed method has good performance.

Keywords: single-phase PV inverter, Fuzzy controller, Photo Voltaic System, MPPT algorithm.

I. Introduction

Among the renewable energy sources, a noticeable growth of small PV power plants connected to low-voltage distribution networks is expected in the future [1-2], as a Consequence, research has been focusing on integration of extra functionalities such as active power filtering into PV inverters operation [3-4]. Anyway, distribution networks are less robust than transmission network and their reliability, because of the radial configuration, decreases as voltage level decreases. Hence, usually it is recommended to disconnect low-power systems when the voltage is lower than 0.85 pu or higher than 1.1 pu [5]. For this reason PV systems connected to low-voltage grids should be designed to comply with these requirements but can also be designed to enhance the electrical system offering “ancillary services” [6]. Hence they can contribute to reinforce the distribution grid maintaining proper quality of supply which avoids additional investments. However low-voltage distribution lines have a mainly resistive nature and, when a distributed power generation system (DPGS) is connected to a low-voltage grid, the grid frequency and the grid voltage cannot be controlled adjusting active and reactive power independently.

The present paper proposes to solve this issue using a voltage controlled converter that behaves as a shunt controller improving the voltage quality in case of small voltage dips and in presence of nonlinear loads. Shunt controllers can be used as static var generators for stabilizing and improving voltage profile in power systems and to compensate current harmonics and unbalanced load current [10-18].

Along with this shunt controller we are proposed new controller fuzzy, for improving power quality in efficient manner.
In this paper fuzzy logic principles have been used. Fuzzy logic is a powerful and versatile tool for representing imprecise, ambiguous and vague information. It also helps to model difficult, even intractable problems. Fuzzy controllers have been applied to many industrial fields, and it does not need mathematical model of the controlled system. In the fuzzy controller instead of the traditional hysteresis controller is proposed. By using of distributed fuzzy logic controllers in this structure makes that it has adaptive properties in distribution systems. Fuzzy control is a practical alternative for a variety of challenging control applications since it provides a convenient method for constructing nonlinear controllers via the use of heuristic information. A fuzzy logic controller used in this research consists of the rule base, fuzzification, inference engine, and defuzzification. The rule base collects the control rules which describe experts’ knowledge and experience in the fuzzy set. In the fuzzification process, the numerical inputs are converted into linguistic fuzzy values. Then, from the fuzzy values and the already established rule base, linguistic control values are generated in the inference engine. Because these linguistic inference results cannot be used in the actuator directly, they should be converted into numerical output again in the defuzzification process. MAX-MIN composition and the center of gravity method are used in the inference engine and defuzzification of this fuzzy logic, respectively.

In this paper the PV inverter supplies the power produced by the PV panels but also improves the voltage profile as already pointed out [19]. The presented topology adopts a repetitive controller [20-23] able to compensate the selected harmonics. Among the most recent MPPT algorithms it has been chosen an algorithm based on incremental conductance method. It has been modified by fuzzy logic controller in order to take into account the power oscillations on the PV side and it controls the phase of the PV inverter voltage.

II. SHUNT CONTROLLERS FOR VOLTAGE DIPS MITIGATION

Shunt devices are usually adopted to compensate small voltage variations which can be controlled by reactive power injection. The ability to control the fundamental voltage at a certain point depends on the grid impedance and the power factor of the load. The compensation of a voltage dip by current injection is difficult to achieve, because the grid impedance is usually low and the injected current has to be very high to increase the load voltage.

The shunt controller can be current or voltage controlled. When the converter is current controlled it can be represented as a grid-feeding component (Fig. 2(a)) that supports the grid voltage by adjusting its reactive output power according to the grid voltage variations. When the converter is voltage controlled it can be represented as a Grid-supporting component (Fig. 2(b)) which controls its output voltage. However also in this second case the control action results in injecting reactive power in order to stabilize the voltage. The vector diagrams of a shunt controller designed to provide only reactive power are reported in Fig. 3. When the grid voltage is 1 pu the converter supplies the reactive power absorbed by the load and the vector diagram of the current or voltage controlled converter is the same, in the first case it controls the compensating current IC, in the second one it controls the load voltage as underlined in Fig. 3(a) and Fig. 3(b).
When a voltage sag occurs, the converter provides reactive power in order to support the load voltage and the grid current $I_g$ has a dominant reactive component

$$\bar{I}_g + \bar{I}_c = \bar{I}_{load}$$  \hspace{1cm} (3)

The amplitude of the grid current depends on the value of the grid impedance since

$$\bar{I}_g = \frac{V_{Lg}}{j\omega L_g}$$  \hspace{1cm} (4)

where $V_{Lg}$ is the inductance voltage drop shown in Fig. 3(c). If the shunt controller supplies the load with all the requested active and reactive power, in normal conditions it provides a compensating current $I_c = I_{Load}$, hence, the system operates as in island mode and $I_g = 0$

Fig. 2 Use of a shunt controller for voltage dips compensation: (a) simplified power circuit of the current controlled shunt controller; (b) simplified power circuit of the voltage controlled shunt controller

Fig. 3 Vector diagram of the shunt controller providing only reactive power: (a) current controlled converter in normal conditions; (b) voltage controlled converter in normal condition; (c) vector diagram for compensation of a voltage dip of 0.15 pu.

In case of a voltage dip, the converter has to provide the active power required by the load and it has to inject the reactive power needed to stabilize the load voltage as shown in Fig. 4(b). The grid current in this case is reactive. It can be seen that

$$V_{load} = E + V_{Lg}$$  \hspace{1cm} (5)

Hence, during voltage sag, the amount of reactive current needed to maintain the load voltage at the desired value is inversely proportional to $\omega L_g$. This means that a large inductance will help in mitigating voltage sags, although it is not desirable during normal operation.
Fig. 4. Vector diagram of the shunt controller providing both active and reactive power: (a) normal conditions; (b) vector diagram for compensation of a voltage dip of 0.15 pu.

III. IMPLEMENTATION OF FUZZY LOGIC CONTROLLER (FLC)

FLC are formed by simple rule based on “If x and y then z”. These rules are defined by taking help from person’s experience and knowledge about the system behavior. The performance of the system is improved by the correct combinations of these rules. Each of the rules defines one membership which is the function of FLC. More sensitivity is provided in the control mechanism of FLC by increasing the numbers of membership functions. In this study, the inputs of the fuzzy system are assigned by using 3 membership functions and the fuzzy system to be formed in 9 rules. Hence, the sensitivity in the control mechanism is increased. The fuzzy control system is divided into three main sections. These sections are explained in the following.

A. Error Calculation

The error signal (errA) is calculated from the difference between the Current value and the reference value obtained from Repetitive controller. Beside, the error rate signal (RerrA) is the differences between the variation of error at current sampling and its previous sampling. These signals of Current for each phase are measured and converted into per unit (pu.) value.

B. FLC

The section of FLC is divided in three subsections. These subsections are given as summarized in the following:

Fuzzification: The numeric input-variable measurements are transformed by fuzzification part into the fuzzy linguistic variable, which is a clearly defined boundary with a crisp. These linguistic variables of error/error rate are shown in Fig 5.
**Fig 5: fuzzy Logic Membership functions of inputs and Outputs**

The basic if-then rule is defined as “If (error is very small and error rate is very small) then output”. The signals error and error rate are described as linguistic variables in the FLC such as large negative (neg), zero (zero), positive (post). These are shown in Fig. In the same way, the input values of the fuzzy controller are connected to the output values by the *if-then* rules.

The relationship between the input and the output values can be achieved easily by using *Takagi-Sugeno type inference* method. The output values are characterized by memberships and named as linguistic variables such as negative big (bneg), Negative (neg), zero (zero), positive (post), and positive big (bpost). The membership functions of output variables and the decision tables for FLC rules are seen in Table I.

### Table I: Fuzzy Rules

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**Defuzzification:** In the defuzzification process, the controller outputs represented as linguistic labels by a fuzzy set are converted to the real control (analog) signals. In the created fuzzy model, “*Sugeno’s Weighted Average*” method which is the special case of “*Mamdani Model*” is selected for the de-fuzzification process.

**C. Signal Processing**

The control signals are produced from the output of FLC process. They are used in the generation of switching signals for converter by comparing with carrier signal.

**IV. PV SYSTEM WITH SHUNT-CONNECTED MULTIFUNCTIONAL CONVERTER**

In case of low power applications it can be advantageous to use the converter which is parallel connected to the grid for the compensation of small voltage sags. This feature can be viewed as an ancillary service that the system can provide to its local loads.

The proposed PV converter operates supplying active and reactive power when the sun is available. At low irradiation, the PV converter operates only as harmonic and reactive power compensator.

It is difficult to improve voltage quality with a shunt controller since it cannot provide simultaneously control of the output voltage and the output current. Besides, a large rated Converter is necessary in order to compensate voltage sags. However this topology is acceptable in PV applications since the PV shunt converter must be rated for the peak power produced by the panels.

In the proposed system the PV converter operates as a shunt controller; it is connected to the load through an LC filter and to the grid through an extra inductance \( L_{g^*} \) of 0.1 pu as shown in Fig.

Usually in case of low power applications, the systems are connected to low voltage distribution lines whose impedance is mainly resistive, but, in the proposed topology, the grid can be considered mainly inductive as a consequence of \( L_{g^*} \) addition on the grid side. However, since the voltage regulation is directly affected by the voltage drop on the inductance \( L_{g^*} \), it is not convenient choosing an inductance \( L_{g^*} \) of
high value in order to limit the voltage drop during grid normal conditions. It represents the main drawback of the proposed topology.

![Diagram](image)

**Fig 6: Grid-connected PV system with shunt fuzzy controller functionality.**

(a) Control of the converter

The proposed converter is voltage controlled with a repetitive algorithm. An MPPT algorithm modifies the phase displacement between the grid voltage and the ac voltage produced by the converter in order to force it to inject the maximum available power in the given atmospheric conditions. Hence the current injection is controlled indirectly. The amplitude of the current depends on the difference between the grid voltage and the voltage on the ac capacitor $V_c'$. The phase displacement between these two voltages determines the injected active power (decided by the MPPT algorithm) and the voltage amplitude difference determines the reactive power exchange with the grid. The requested reactive power is limited by the fact that a voltage dip higher than 15% will force the PV system to disconnect (as requested by standards). The active power is limited by the PV system rating and leads to a limit on the maximum displacement angle $\delta_{mppt}$.

Moreover the inverter has its inner PI-based current control loop and overcorrects protections. A phase-locked-loop (PLL) detects the amplitude $V_{peak}$ and phase $\delta_{grid}$ of the grid voltage. Then the phase displacement $\delta_{mppt}$ is provided by the MPPT algorithm described in Section B. The voltage error between $V_{ref}$ and $V_c'$ is pre-processed by the repetitive controller which is the periodic signal generator of the fundamental component and of the selected harmonics: in this case the third and the fifth ones are compensated (Fig.6). The proposed repetitive controller is based on a finite impulse response (FIR) digital filter [20]; it is a “moving” or “running” filter, with a window equal to one fundamental period, defined as

$$F_{RPT}(z) = \frac{2}{N} \sum_{i=-N_h}^{N_h} \left( \sum_{i=-Na}^{Na} \cos \left( \frac{2\pi}{N} (i+N_a) \right) \right) z^{-i}$$

where $N$ is the number of samples within one fundamental period, $Nh$ is the set of selected harmonic frequencies and $Na$ is the number of leading steps determined to track the reference exactly. The repetitive controller ensures a precise tracking of the selected harmonics and it provides the reference for the inner loop. In it a proportional-integral (PI) controller improves the stability of the system offering low-pass filter function. The PI controller $G_c$

$$G_c(z) = \frac{k_p + \frac{k_i}{z}}$$

is designed to ensure that the low frequency poles have a damping factor of 0.707. The open-loop Bode diagram of the system is shown in Fig. 6(b): the stability is guaranteed since the phase margin is about 45 degrees. In normal operation mode the shunt-connected converter injects the surplus of active power in the utility grid and, at the same time, it is controlled in
order to cancel the harmonics of the load voltage. At low irradiation, the PV inverter acts only as a shunt controller eliminating the harmonics. Controlling the voltage $V_c'$, the PV converter is improved with the function of voltage dips compensation. In presence of a voltage dip, the grid current $I_g$ is forced by the controller to have a sinusoidal waveform which is phase shifted by $90^\circ$ with respect to the corresponding grid voltage.

B. MPPT algorithm Power supplied from a PV array depends mostly on present atmospheric conditions (irradiation and temperature), therefore in order to collect the maximum available power the operating point needs to be tracked continuously using a Maximum Power Point Tracker algorithm. To find the maximum power point (MPP) for all conditions, it has been used an MPPT control method based on the Incremental Conductance Method, which can tell on which side of the PV characteristic the current operating point is. The MPPT algorithm modifies the phase displacement between the grid voltage and the converter voltage providing the voltage reference $V_{ref}$, furthermore, there is an extra feature added to this algorithm, which monitors the maximum and minimum values of the power oscillations on the PV side. In case of single-phase systems, the instant power oscillates with twice the line frequency. This oscillation in the power on the grid side leads to a 100 Hz ripple in the voltage and in the power on the PV side. If the system operates in the area around the MPP the ripple of the power on the PV side is minimized. This feature can be used to detect in which part of the power voltage characteristics the system operates. It happens in the proposed control scheme where the information about the power oscillation can be used to find out how close the current operating point is to the MPP, thereby slowing down the increment of the reference, in order not to cross the MPP. A flowchart of the MPPT algorithm is shown in Fig. 7 explaining how the angle of the reference voltage is modified, in order to keep the operating point as close to the MPP as possible. The MMP can be tracked by comparing the instantaneous conductance $I_{pv,k} / V_{pv,k}$ the incremental conductance $dI_{pv}/dV_{pv}$ as shown in the flowchart.

Considering the power-voltage characteristic of a PV array, it can be observed that operating in the area on the left side of the MPP $\delta_{mPPT}$ has to decrease. This decrement is indicated in Fig. 7 with $side = -1$, moreover, operating in the area on the right side of the MPP $\delta_{mPPT}$ has to increase and it is indicated with $side = +1$. The increment size determines how fast the MPP is tracked. The measure of the power oscillations on the PV side is used to quantify the increment which is denoted with incr in Fig. 7.
V. SIMULATION RESULTS

The PV system with power quality conditioner functionality has been tested in simulation with the following system parameters: LC filter made by 1.4 mH inductance and 2.2 µF capacitance and 1 Ω damping resistance; an inductance $L_g^*$ of 0.1 pu; an 1 kW load. The control has been validated in presence of sudden changes of the PV power caused, for example, by irradiation variations. The reported tests show the behavior of the MPPT for a voltage sag. The results refer to the case of inverter controlled in order to collect the maximum available power: 2 kW.

The controller parameters are $k_{FIR} = 0.3$, $N = 48$ (sampling frequency = 6400 Hz) $Na = 0$, $kp = 4.5$, $ki = 48$. The set of test aims to demonstrate the behavior of the system during a voltage sag and the interaction of the voltage control algorithm with the MPPT algorithm.

Fig 7 Flowchart of modified MPPT algorithm

Fig 8: Performance of the voltage controlled shunt converter with MPPT Algorithm:

(a) Grid voltage $E$

(b) Load voltage $V_{load}$
VI. CONCLUSION

In this paper a single-phase photovoltaic system with shunt Fuzzy controller functionality has been presented. The PV converter is voltage controlled with a repetitive algorithm. An MPPT algorithm has been specifically designed for the proposed voltage controlled converter. It is based on the incremental conductance method and it has been modified to change the phase displacement between the grid voltage and the converter voltage maximizing the power extraction from the PV panels. The designed PV system provides grid voltage support at fundamental frequency and compensation of harmonic distortion at the point of common coupling (PCC). An inductance is added on the grid side in order to make the grid mainly inductive, it may represent the main drawback of the proposed system.
VII. REFERENCES


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