UTILITY CURRENT COMPENSATION OF NONLINEAR LOAD BY PV-ACTIVE POWER FILTER COMBINATION USING FUZZY

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Abstract- In this paper, a three-phase three-wire system, as well as a detailed PV generator, dc/dc boost converter to extract maximum radiation power using maximum power point tracking, associate degreed de/ac voltage source converter to act as an APF, is presented. A source is said to be renewable if there's no obvious limit on its availability. It may be used over and over again because it continues to replace itself. Sunshine, wind and water from rain are so renewable, sustainable resource use is that meets our present needs without compromising the power of future generations to satisfy their needs. The photovoltaic (PV) generation is more and more popular these days, while typical loads need additional high-power quality. Basically, one PV generator supply to nonlinear loads is desired to be integrated with a function as an active power filter (APF). The instantaneous power theory is applied to design the PV-APF controller, that shows reliable performances. Here fuzzy logic is used for controlling compared to other controllers. The MATLAB/SimpowerSystems tool has proved that the combined system will at the same time inject maximum power from a PV unit and compensate the harmonic current drawn by nonlinear loads.

INDEX TERMS Active power filter (APF), instantaneous power theory, photovoltaic (PV), power quality, renewable energy.

INTRODUCTION
A PHOTOVOLTAIC (PV) system directly converts sunlight into electricity. The basic device of a PV system is the PV cell. Cells may be grouped to form panels or arrays. The voltage and current available at the terminals of a PV device may directly feed small loads such as lighting systems and DC motors. More sophisticated applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid-connected systems, and mainly to track the maximum power point (MPP) of the device. In order to study electronic converters for PV systems, one first needs to know how to model the PV device that is attached to the converter. PV devices present a nonlinear I–V characteristic with several parameters that need to be adjusted from experimental data of practical devices. The mathematical model of the PV device may be useful in the study of the dynamic analysis of converters, in the study of MPP tracking (MPPT) algorithms, and mainly to simulate the PV system and its components using circuit simulators. The first purpose of this paper is to present a brief introduction to the behavior and functioning of a PV device and write its basic equations, without the intention of providing an in depth analysis of the PV phenomenon and the semiconductor physics. The introduction on PV devices is followed by the modeling and simulation of PV arrays, which is the main subject of this paper with distorted compensation capability, that makes currents injected/absorbed by the utility to be sinusoidal. Therefore, the harmonic compensation function is realized through flexible control of dc/ac VSC. instantaneous power theory has successfully completed active power filter (APF) designing with good performance. However, the PV-APF combination has simply been gradually developed for several years. this combination is capable of simultaneously compensating power factor, current imbalance, and current harmonics, and also of injecting the energy generated by PV with low total harmonic distortion (THD).

Even once there is no energy available from PV, the combination will still operate to enhance the power quality of the utility. After that, the control techniques are improved in some later efforts to develop PV inverters with real power injection and APF features. However, their research did not show consistent results obtained by their projected theories, and they are applicable for a single-phase PV only. The PV-APF system helps the utility supply a unity power issue and pure curved currents to the local nonlinear loads by generating the oscillating and imaginary components. once there's an excess power, that PV unit can only inject average power to the utility. As a result, this system is considered as a distributed APF, which is a better solution than adopting passive filters or centralized APFs. the most contributions of this paper are threefold.

1) For the first time, a fully complete PV-APF combination system is presented.
2) The controller based on instantaneous power theory and instantaneous power balance is proposed to replace the conventional dq-current controller for a
PV unit.  
3) Flexible operation modes of the PV-APF combination system are possible in the proposed model.  

II. PV-APF COMBINATION SYSTEM  
The detailed PV-APF configuration is shown in Fig. 1, which consists of the following.  
1) The PV series-parallel array, which is Sun Power SPR-305-type, delivers a maximum of 10- [kW] power at 1000-W/m2 solar irradiance, assuming that there is no battery storage system connected to the dc bus.  
2) ASEPIC converter (dc/dc) implements MPPT by an incremental conductance integral regulator technique, which automatically varies the duty cycle in order to generate the required voltage to extract maximum power.  
3) The dc bus is connected to a two-level three-phase dc/ac VSC with a CVSC capacitor. The dc/ac VSC converts the ac supplying to local nonlinear loads and connects to a stiff utility.  
4) A capacitor bank filters out switching harmonics produced by the dc/ac VSC.  
5) The loads include a three-phase diode rectifier supplying a current at dc side and one phase diode rectifier connecting between phase A and phase B to make an overall unbalanced load.  
6) This PV-APF combination system is connected directly to the utility for shunt active filter implementation.  

A. DYNAMIC MODEL OF PV ARRAY  
The dynamic model of PV cell is shown in Fig. 2. PV array consists of N string connected in parallel and every string consists of M number of modules connected in series.  

The output-terminal current I is equal to the light generated current IL, less the diode-current Id and also the shunt leakage current (or ground-shunt current) Ish. The series resistance RS represents the internal resistance to the current flow. The shunt resistance RSh is inversely related to leakage current to the ground. In an ideal PV cell, RS = zero (no series loss) and RSh is infinite (no outpouring to ground), in a typical high-quality 1-in2 silicon cell, RS = 0.05–0.10 and RSh = 200–300.  

The PV conversion efficiency is sensitive to small variations in RS, however is insensitive to variations in RSh. A little increase in RS will decrease the PV output considerably. the 2 most significant parameters mostly used for describing the cell electrical performance are the open-circuit voltage Voc = Vout + RSI obtained once the load current is zero (I = 0) and also the short-circuit current Isc. Ignoring the little diode and the ground-leakage currents below zero terminal voltage, the short-circuit current below this condition is that the photocurrent IL, the basic equation describing the I–V characteristic of a practical PV cell is  

\[
I = I_L - I_D - I_{sh} - I_{D} \left[ \frac{V_{DC}}{e^{kT} - 1} - \frac{V_{out} + IR_{S}}{R_{sh}} \right]
\]

where ID is the saturation current of the diode, Q is the electron charge (1.6 × 10^-19 C), A is the curve fitting constant (or diode emission factor), K is the Boltzmann constant (1.38×10^-23 J/◦K), and T (◦K) is the temperature on absolute scale. The ISh, that, in practical cells, is smaller than IL andId, can be ignored.  

B. MPPT IN DC/DC CONVERTER  

Figure 3. I–V curve and remarkable points.  

The MPPT control method in two stage PCS schemes is presented with the following assumptions: the DC link voltage regulation control speed is much faster than the MPPT loop, and the efficiency of the boost converter is almost constant throughout the operating point. shows the proposed two stage PCS control schematic. As in a conventional scheme, the inverter has the voltage loop to regulate the input DC link voltage and the current loop to control the output current to be in-phase with the line voltage for the high power factor. By maintaining the DC link voltage constant, the output of the voltage loop, determines the output current amplitude, and thus controls the level of power processed by the PCS. For the constant DC link voltage, the input current of the inverter is directly proportional to the solar array output power. Thus, using ref I V, the MPP can be tracked without calculating the solar array power. Also, the boost converter can stabilize the solar array operating point by the switch duty command from the MPP tracker. The proposed method is quite simple because it performs MPPT control without
calculating any operations and the boost converter does not need feedback control circuit.

Figure 4. Controller mechanism of the boost converter.

III. INSTANTANEOUS POWER BALANCE

Instantaneous power flow among the components of the PV-APF system simplified in Fig. 5 may be a compromise between technical constraints and designed targets.

Figure 5. Instantaneous powers flows among the PV-APF system.

II. LITERATURE SURVEY

The combined operation of the active power filter with the photovoltaic generation system is expressed [1]. The proposed system consists of a PV power plant, a DC–DC boost converter, and an active power filter [2]. A novel control strategy for the DC–DC converter has been developed in order to extract the maximum amount of power from PV arrays [6]. Also, a novel the overall efficiency of photovoltaic (PV) systems connected to the grid depends on the efficiency of direct current (DC) of the solar modules to alternate current (AC) inverter conversion [4]. The requirements for inverter connection include: maximum power point, high efficiency, control power injected into the grid, high power factor and low total harmonic distortion of the currents injected into the grid [7]. An approach to power factor control and reactive power regulation for PV systems connected to the grid using field programmable gate array (FPGA) is proposed. According to the grid demands: both the injected active and reactive powers are controlled [9]. A new digital control strategy for a single-phase inverter is carried out. This control strategy is based on the phase shift between the inverter output voltage and the grid in order to control the power factor for a wide range of

the inverter output current and consequently the control and the regulation of the reactive power will be achieved. The advantage of the proposed control strategy is its implementation around simple digital circuits [10]. The various compensation strategies for shunt active power filter using a generalized theory of instantaneous reactive power. A general instantaneous vector expression for filter current in terms of active and reactive powers has been derived. The general time domain algorithm for filter reference currents in terms of source powers has been given. It is shown that the algorithm works under balanced and unbalanced source voltages while producing a set of balanced three-phase source currents at a desired power factor [8]. Power-electronics-based zonal direct current (dc) power distribution systems are being considered for sea and undersea vehicles. The stability of the dc power-electronics-based power distribution systems is a significant design consideration because of the potential for negative-impedance-induced instabilities. In this paper, the dynamic properties and control of a buck converter feeding a downstream dc–dc converter are studied. The controller in this system combines an instantaneous current feedback loop using hysteresis with a proportional–integral (PI) algorithm to regulate the output voltage of the converter. Based on a large-signal-averaged model of the converter, the stability-in-large around the operation point is presented. The complete analysis is carried out considering a buck dc–dc converter operating with a constant power load (CPL). Simulations and experimental results are provided to verify the analysis.

IV. CONTROLLERS FOR DC/AC CONVERTER

In this section, the controllers for dc/ac VSC based on instantaneous power theory and instantaneous power balance are presented. In a conventional way, the dq-current controller is used to inject maximum real power from PV and zero reactive power to keep unity power factor of the utility. While a nonlinear load is connected close to PV position, the proposed unique PV-APF controller should be used to compensate the harmonics and help transfer the PV power. At night (no irradiance and no battery) or when there is no PV array, the APF controller is switched into the system in order to operate the CVSC capacitor just for an APF purpose.

A. PV-APF CONTROLLER

The dc/ac VSC integrated by an APF function should provide the harmonic elimination and reactive power compensation and simultaneously inject the maximum power generated by PV units. The controller is established based on the instantaneous power theory, where all the parameters
are processed instantaneously. The input signals of that controller include utility voltages (vabc), nonlinear load currents (iabcL), output currents of dc/ac VSC (iabcUti), and dc-link voltage VVSC (to prevent overcharge dc-link capacitor).

\[
\begin{align*}
\{ p_L &= pVSC + pUti \\
q_L &= qVSC + qUti 
\end{align*}
\]  

(2)

Since the target is laid on the load, its consuming power is continuously measured and analyzed. Using the Clarke transformation, the instantaneous real power (pL) and imaginary power (qL) of the load can be calculated, as shown in the following equations:

\[
\begin{align*}
\left[ v_a(i_a) \right] &= \sqrt{2} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\
0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \left[ v_a(i_{aL}) \right] \\
\left[ v_p(i_p) \right] &= \begin{bmatrix} v_a(i_{aL}) \\
v_b(i_{bL}) \\
v_c(i_{cL}) \end{bmatrix} \\
p_L &= v_a(i_a) - v_p(i_p) \\
q_L &= v_p(i_p) - v_a(i_a) 
\end{align*}
\]  

(3)

(4)

In general, the real and imaginary power include two parts: 1) an average (superscript -) one, and 2) an oscillating (superscript ˜) one, which are realized through an LPF (or rarely a high-pass filter). The LPF cutoff frequency must be selected carefully as to the inherent dynamics of loads that lead to compensation errors during transients. Unfortunately, the unavoidable time delay of the LPF may degrade the controller performance. In practice, a fifth-order Butterworth LPF with a cutoff frequency between 20 and 100 [Hz] has been used successfully depending on the spectral components in oscillating part that is to be compensated.

\[
\begin{align*}
\{ p_L &= \bar{p}L + pL \\
q_L &= \bar{p}L + qL 
\end{align*}
\]  

(5)

The average part derives from the fundamental component of nonlinear load current, while the oscillating part results from the harmonics and negative-sequence components. After successful compensation, the imaginary power and the oscillating part of the real power will come from the dc/ac VSC. The utility, in that case, supplies only one fraction of the average power required from the load. The rest is supposed to be from the PV array. In addition, the dc-link voltage regulator determines an extra amount of real power (p̄ loss) that causes additional flow of energy to (from) the dc-link capacitor CVSC in order to keep its voltage around a fixed reference value (VVSCref ). Eventually, reference powers are passed to a current references calculation block. These ideas make the following equations:

\[
\begin{align*}
\{ pL + \bar{p}L &= pVSC + \bar{p}VSC + pUti + \bar{p}loss \\
qL + \bar{q}L &= qVSC + \bar{q}VSC + qUti 
\end{align*}
\]  

(6)

(7)

If the p̄ loss is supplied VSCd by the PV unit and the PV-APF combination compensates all imaginary power of load demand, is changed to

\[
\begin{align*}
\{ pVSC &= pL - \bar{q}Uti - \bar{p}loss \\
qVSC &= -qL - \bar{p}Uti \\
\bar{p}VSC &= \bar{p}L \\
\bar{q}VSC &= \bar{q}L 
\end{align*}
\]  

(8)

B. PV UNIT PERFORMANCE

V. FUZZY LOGIC CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC.

<table>
<thead>
<tr>
<th>Change in error</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PM</td>
<td>PM</td>
<td>PS</td>
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<tr>
<td>NM</td>
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<td>PM</td>
<td>PS</td>
<td>PS</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
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<tr>
<td>Z</td>
<td>PB</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td>NS</td>
<td>NM</td>
<td>NB</td>
</tr>
<tr>
<td>PS</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td>NS</td>
<td>NM</td>
<td>NB</td>
<td>NB</td>
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<td>NS</td>
<td>NM</td>
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<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>PB</td>
<td>Z</td>
<td>NS</td>
<td>NM</td>
<td>NM</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
</tr>
</tbody>
</table>

TABLE I: Fuzzy Rules
Fuzzification: Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The partition of fuzzy subsets and the shape of membership function adapt to appropriate system. The value of input error and change in error are normalized by an input scaling factor.

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular E(k) input there is only one dominant fuzzy subset. The input error for the FLC is given as

\[ E(k) = \frac{P_{ph}(k) - P_{ph}(k-1)}{V_{ph}(k) - V_{ph}(k-1)} \]  

(9)

\[ CE(k) = E(k) - E(k-1) \]  

(10)

Inference Method: Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

Defuzzification: As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, “height” method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output

The set of FC rules are derived from

\[ u = [-\alpha E + (1-\alpha)C] \]  

(11)

Where \( \alpha \) is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable. A large value of error E indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible. One the other hand, small value of the error E indicates that the system is near to balanced state.

VI. SIMULATION VALIDATION

The main parameters of the system used in the simulation study are indicated in Table 1. The simulation is run in a period of 0.75 s. The important time instances are: 1) at 0.05 s, turn ON MPPT and VSC dq-current controller; 2) at 0.35 s, activate MPPT; 3) at 0.5 s, switch VCS dq-current controller to PV-APF controller; 4) at 0.6 s, switch to APF controller without PV; 5) at 0.7 s, switch PV-VSC out of system; and 6) at 0.75 s, stop simulation.

![Figure 6. simulation model of proposed system](image)

**TABLE 1. System parameters in simulation.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (Vdc)</td>
<td>260V</td>
</tr>
<tr>
<td>Frequency (f)</td>
<td>60HZ</td>
</tr>
<tr>
<td>Rs, Ls</td>
<td>ideal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DC/AC VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC link voltage (Vdc)</td>
</tr>
<tr>
<td>DC link capacitor (C)</td>
</tr>
<tr>
<td>SHAF filter (R, L)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unbalanced non linear load</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 phase diode rectifier</td>
</tr>
<tr>
<td>Constant DC current, ( I_{dc} )</td>
</tr>
<tr>
<td>1 phase diode rectifier</td>
</tr>
<tr>
<td>Constant DC current, ( I_{dc} )</td>
</tr>
</tbody>
</table>

| Fuzzy controller |

![Figure 7. Operation modes of simulation.](image)

![Figure 8. Output power of PV during running time](image)
Active power filter performance

Figure 9. Duty cycle and VPV changed by MPPT.
(a) Output voltage of PV unit. (b) Duty cycle of MPPT

Figure 10. Utility supplied current waveform.

Figure 11. Utility supplied current and PCC voltage waveform.

Figure 12. THD in four modes of PV system operation while utility supplies power. (a) dq-current mode. (b) PV-APF mode. (c) APF mode. (d) Only utility supplies load.

Figure 13. PV supplied current waveform.

Figure 14. Real power from the (a) utility, (b) PV unit, and (c) load, while the utility supplies power.

Figure 15. Imaginary power from the (a) utility, (b) PV unit, and (c) load, while the utility supplies power.
VI. CONCLUSION

In this paper, a PV-APF combination system with a local controller is proposed. To compensate the utility current without any harmonics, the controller implements 2 purposes, that are active power from the PV unit and filtering the harmonics of the local nonlinear load. The new controller based on instantaneous power balance has been explained consequently. The MATLAB/SimPower Systems simulation shows sensible performances of this controller. Here fuzzy controller is used compared to alternative controllers because of its accurate performance. The positive influence of MPPT on increasing PV power output is additionally valid. The shift among 3 controllers to dc/ac VSC brings different current waveforms. As a result, the conventional dq-current controller should not be applied once PV is connected to a local nonlinear load regarding power-quality viewpoint, whereas a PV unit is deactivated, the APF function will still operate. It is, therefore, technically possible for these power electronics-interfaced DG units to actively regulate the power quality of the distribution system as an auxiliary service, which will certainly make those DG units extra competitive.

REFERENCES


