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A Control Architecture and Performance Analysis of a Grid Integrated Photovoltaic System

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Abstract— For an utility-scale photovoltaic (PV) systems, the control objectives, such as maximum power point tracking, synchronization with grid, current control, and harmonic reduction in output current, are comprehended in single stage for high efficiency and simple power converter topology. Globally Grid Connected PV based system, the inverter is a critical component responsible for the control of electricity flow between the dc source, and loads or grid. This paper proposes a control architecture for a three-phase, photovoltaic (PV) system that is connected to a distribution network. The control is based on a current-regulating technique and a dc-link voltage regulator with a modified control strategy, which includes compensation for grid voltage dip and reactive power injection capability. The real and reactive powers are controlled by using dq components of the grid current. The current-control technique decouples the PV system dynamics from those of the network and the load deviations. The dc-link voltage-control scheme enables control and maximization of the real power output. A feed forward compensation mechanism is proposed for the dc-link voltage-control loop, to make the PV system dynamics immune to the PV array nonlinear characteristic. Simulation results of the PV system during system disturbances and fast solar irradiation changes authorize that the proposed control algorithm for PV inverters can provide appropriate real power services and ensure PV DC voltage stability during dynamic system operation and atmospheric conditions.

IndexTerm— photovoltaic (PV), voltage-source converter (VSC) Renewable energy sources (RES), Maximum power point tracking(MPPT), Point of Common Coupling (PCC), phase-locked loop (PLL), proportional-integral-derivative (PID), Phase Look Loop (PLL)

I. INTRODUCTION

Global warming has become the real matter of concern, all over the world due to increase in greenhouse gases in the environment. As a result there is a continuous increase in temperature, strong effect on ozone layer depletion, rise in sea level and climate change. Depletion of fossil fuel and increase in energy demand has created an energy security issue which can be solved through renewable energy sources.

Therefore, it has become essential to rely more upon the renewable energy sources for power generation than conventional energy sources. One of the greatest advantage of using of renewable source is that, it is free of cost and rich availability.

The Solar energy is one of the most promising energy resources, due to its freely availability and renewable character. It can play a key role in solving the world energy crisis.

The use of Renewable energy sources (RES), which are environmental friendly and as well pollution free, is increasing worldwide. Outed scale of solar energy, in particular, has seen unique growth. Photovoltaic (PV) systems possess numerous fundamental advantages compared with other means of moving renewable energy [1]. The main advantages of PV systems include the following: 1) static, quiet, and movement-free characteristics; 2) longevity; and 3) low-maintenance costs. Using PV modules individually is not recommended because of minimal power harvest. To provide the load with the precise voltage and current needed, both series and parallel configurations of PV modules are frequently employed [2].

The intelligent control of output voltage and current of a three-phase photovoltaic grid connected inverter is essential to be considered. The output voltage and the voltage-current relationships on the PV depend on various levels of solar radiance and various cell temperatures. The voltage-current characteristic is a difficult and nonlinear function and difficult to identify the dynamic model [3]. In this scenario, one of the foremost issues is the optimal integration of PV energy resources in prevailing electrical distribution systems. This tactic needs high voltage rated devices for the inverter. To overcome this issue, the step-up transformer is necessary. This system enables to use the low voltage rated devices for inverter and then boosting the voltage by transformer. Reference [14] has discussed analysis and control of PV system integrated with IEEE 14-bus system, utilizing two-stage power conversion topology. In [15], control strategy is used, and sensitivity analysis is performed with distribution network modeled as an RLC circuit in PSCAD environment.

II. PV SYSTEM CHARACTERISTIC AND MODELING

A. Basic Characteristics of a PV Cell

PV cell is a current source that produce electrical energy shown in Fig. 1. A PV cell can be represented by an equivalent single diode model [4].
The mathematical expression for the equivalent circuit model is shown below

\[ I_{PV} = I_{ph} - I_d - I_{sh} \]  
\[ I_{PV} = I_{ph} - I_0 \left( e^{\frac{(V_{PV}+I_{PV}R_s)}{AT_{c}}} - 1 \right) - \frac{V_{PV}+I_{PV}R_s}{R_{sh}} \]  

A PV array consists of several PV modules connected in series to produce a higher voltage and in parallel to increase the current. So the current equation of PV system become

\[ I_{PV} = N_p I_{ph} - N_p I_0 \left( e^{\frac{(V_{PV}+I_{PV}R_s)}{AT_{c}}} - 1 \right) - \frac{V_{PV}+I_{PV}R_s}{R_{sh}} \]  

Where \( I_{PV} \) is the PV system output current. \( I_{ph} \) is the photocurrent, \( I_d \) is the diode current, \( I_0 \) is the reverse saturation current, \( V_T = k*(T_c/q) \) is the thermal voltage, \( T_c \) is the actual cell temperature (K), \( k \) is Boltzmann constant (1.381×10^{-23} J/K), \( q \) is electron charge (1.602 ×10^{-19} C). “A” is the ideality factor. \( N_s \) is the number of PV cells connected in series and \( N_P \) is the number of cells connected in parallel.

Three characteristic operation points for the PV system: open circuit, MPP and short circuit are shown in Fig. 1. Isc is the short circuit current; Voc is the open circuit voltage; \( V_m \) and \( I_m \) are voltage and current at the MPP, respectively. The corresponding mathematical equation is given in above Eq. (2) [5].

\[ P_{PV} = I_{PV} \times V_{PV} \]

\( V_{PV} \) is nothing but voltage across Capacitor that means \( V_{PV} \) is equal to \( V_{dc} \), therefore power can be expressed as a function of

\[ P_{PV} = f(I_{PV}, V_{dc}) \]
\[ =N_p I_{ph}V_{dc} - N_p I_0V_{dc} \left( e^{\frac{(V_{PV}+I_{PV}R_s)}{AT_{c}}} - 1 \right) - \frac{V_{PV}+I_{PV}R_s}{R_{sh}} \]  

In the above equations, the parallel resistance (\( R_{sh} \)) generally has a high value and sometimes assumes infinity in PV module modeling because of its slight impression. Whereas the value of series resistance (\( R_s \)) cannot be neglected because of its effect on output power. [6]

Therefore the value of term \( \frac{V_{PV}+I_{PV}R_s}{R_{sh}} \) is very less which can be treated as zero, so that above equation becomes

\[ P_{PV} = N_p I_{ph}V_{dc} - N_p I_0V_{dc} \left( e^{\frac{(V_{PV}+I_{PV}R_s)}{AT_{c}}} - 1 \right) \]  

The changing temperature and irradiation level has effect on both of these characteristic curves and operating point. When \( PV \) module is connected to the load, it has a single operating point where the values of current and voltage results in maximum power output and is specified by the intersection point between the load line and I-V curve of the PV panel called maximum power point (MPP). The MPP is given by the product of MPP voltage (\( V_m \)) and MPP current (\( I_m \)).

When source impedance matches with the load impedance, maximum power theorem circuit generates maximum power. Therefore, MPPT regulates the duty cycle and feed to the converter so that the load line crosses the I-V curve at the MPP and maximum power is delivered to the load.

**B. Photovoltaic Array Modeling**

The power delivered by the PV array is

\[ P_{PV} = I_{PV} \times V_{PV} \]

The PV module has nonlinear characteristics whose maximum power generated depends on temperature and solar irradiation. Fig. 2 shows two main current-voltage (I-V curve) and power voltage (P-V curve) characteristic curves.
Above figure shows the variations of $P_{PV}$ as a function of $V_{DC}$, for different levels of the solar irradiation. Fig. 3 shows that for a given irradiation level, $P_{PV}$ is zero at $V_{DC}=0$, but increases as $V_{DC}$ is increased. However, this trend continues only up to a certain voltage at which $P_{PV}$ reaches a peak value; beyond this voltage, $P_{PV}$ decreases with the increase of $V_{DC}$. The aforementioned behavior suggests that $P_{PV}$ can be controlled/maximized by the control of $V_{DC}$. This is referred to as the “Maximum-Power-Point Tracking” (MPPT) in the technical literature [7].

III. CONTROL TECHNIQUES OF GRID CONNECTED PV SYSTEM MODEL

The configuration of a three-phase PV system connected to the utility grid is shown in Fig. 4. The power electronic interface has a DC-to-AC converter. The PV array which is shown in the figure supplies DC current to the capacitor across the PV system which in terms generate equivalent DC power and feed to the inverter at a voltage level of $V_{PV}$ and current level $I_{PV}$. A DC link capacitor $C$ is located between the PV array and the inverter. The PV inverter is connected through a transformer with the grid at Point of Common Coupling (PCC). The utility grid is a voltage source $V_s$ with a system impedance. Both the phase angle and magnitude of the inverter output voltage are controlled to regulate the PV inverter real power and the reactive power supplied to the grid. The PV inverter real power is equal to the (PV array output power) - (the inverter losses) because of the energy balance between PV inverter DC input and AC output.

Let us consider the voltage at PCC is $v_t$ while the PV inverter transformer output voltage and current are $v_c$ and $i_c$, respectively.

The average real power and average reactive power output of the PV inverter to the grid can be expressed

\[ P = \frac{V_{dc}V_C}{X_{TF}} \sin \alpha \]  \hspace{1cm} (6)

\[ Q = \frac{V_{dc}V_C}{X_{TF}} (V_C \cos \alpha - V_t) \]  \hspace{1cm} (7)

When the phase angle $\alpha$ between the PCC voltage and inverter output voltage is small, they can be approximated as

\[ P = \frac{V_{dc}V_C}{X_{TF}} \alpha \]  \hspace{1cm} (8)

\[ Q = \frac{V_{dc}V_C}{X_{TF}} (V_C - V_t) \]  \hspace{1cm} (9)

Where $V_s$ and $V_C$ are the RMS values of the PCC terminal voltage $v_t$, and inverter output voltage $v_c$, $\alpha$ is the phase angle difference of $v_c$ and $v_t$, and $X_{TF}$ is the equivalent reactance of the transformer [8].

A. PV System Control

For the PV system of Fig. 4, the main control objective is to regulate the dc-link voltage to control/maximize the power extracted from the PV array. The real power and reactive power of the PV inverter can be controlled simultaneously and independently.
Depending on the control objectives, the MPP of the PV arrays or a fixed amount of real power could be the control goal for the real power control. For the reactive power, the control goal could be maintaining the local PCC voltage at some reference setting or providing a fixed amount of reactive power. In this paper, a proportional-integral-derivative (PID) feedback control is implemented in the PV system controller [8]. Fig. 4 indicates that: 1) the VSC PWM and control are synchronized to the network voltage through a phase-locked loop (PLL) [9]. Thus, the three-phase ac signals are transformed into proper-frame counterparts, and the controllers process dc equivalents rather than original sinusoid-ally-varying signals and 2) the error between (the square of) the dc-link voltage and its corresponding reference value is processed by the PID compensator whose output is augmented by a feed forward signal to issue the current command \(i_{dref}\). The feed forward compensation counteracts the destabilizing and nonlinear characteristic of the PV array and enhances the PV system stability. The dc-link voltage reference is usually obtained from an MPPT scheme and is permitted to vary from a lower limit to an upper limit. The limits on the dc-link voltage ensure proper and safe operation of the VSC; and 3) the command \(i_{dref}\) is delivered to a \(dq\)-frame current-control scheme that forces \(i_d\) to track \(i_{dref}\). The control of \(i_d\) enables the control of \(i_{PV}\).

A saturation block limits \(i_{dref}\) to protect the VSC against overload and external faults. For analysis and control purposes, space-phasor variables in the models of the Grid connected PV system, are projected on a \(dq\)-frame. This is achieved by replacing each space-phasor by its \(dq\)-frame equivalent, as above.

The details of the aforementioned control schemes are discussed in MATLAB SIMULINK in the below figure.

Fig. 5 Control logic of DC Voltage Regulator Matlab Simulink

\[ i_{dref} = u_{pid} + P_{PV} \frac{2}{3v_d} \]  
\[ u_{pid} = f(e_u = v_{ref}^2 - v_{dc}^2) \]

Where \(v_d\) is the disturbance voltage at point of coupling to transformer. Regulation of \(v_d\) at zero also has the effect that the expression for the PV system real-power output becomes

\[ P_S = \frac{3}{2} v_d i_d \]  

In the above equation \(P_S\) is controlled to regulate the dc-link voltage and to control/maximize the power extracted from the PV array. Subsequently, the control of \(P_S\) is in result to the control of \(i_d\).

B. VSC Current Regulating Loop

A current-regulating scheme is devised to ensure that \(i_d\) and \(i_q\) rapidly track their respective reference commands \(i_{dref}\) and \(i_{qref}\). The current-regulating strategy also enhances protection of the VSC against overload and external faults, provided as that of by means of limiting \(i_{dref}\) and \(i_{qref}\).

Fig. 6 Current Control Scheme in dq-axis in Matlab Simulink

The current-control scheme also forces \(i_q\) to track \(i_{qref}\). The unity power-factor operation also results in a minimized magnitude for the VSC line current, for a given real-power flow for that sake of result in this paper \(i_{qref}=0\), as shown in the above figure.

Where \(m_d\) and \(m_q\) are the control inputs, and \(v_d\) and \(v_q\) are the disturbance inputs from bus bar-1 as shown in the fig.4. To decouple and linearize the dynamics of \(i_d\) and \(i_q\), \(m_d\) and \(m_q\) are determined based on the following laws

\[ m_d = (u_d - (.9156)i_d - v_d) \]  
\[ m_d = (u_q - (.9156)i_q - v_q) \]

Where \(u_d\) and \(u_q\) are two new control inputs. Which is output of the PID Compensator.
C. PLL Technique

Nowadays, the PLL technique is the state-of-the-art method to extract the phase angle of the grid voltages. The PLL is implemented in dq synchronous reference frame, and its schematic is illustrated in Fig. 7. As it can be noticed, this structure needs the coordinate transformation from abc → dq. A regulator, usually PID, is used to control this variable, and the output of this regulator is the grid frequency. After the integration of the grid frequency, the utility voltage angle is obtained, which is fed back into the αβ → dq transformation module to transform into the synchronous rotating reference frame.

This algorithm has a better rejection of grid harmonics, notches, and any other kind of disturbances, but additional improvements have to be done to overcome grid unbalance. In the case of unsymmetrical voltage faults, the second harmonics produced by the negative sequence will propagate through the PLL system and will be reflected in the extracted phase angle. To overcome this, different filtering techniques are necessary such that the negative sequence is filtered out. As a consequence, during unbalanced conditions, the three-phase dq PLL structure can estimate the phase angle of the positive sequence of the grid voltages [10]-[12].

D. PWM Gate Pulse Generating

There are many Pulse Width Modulation techniques available in order to synthesize the low frequent grid voltage from a DC supply. For this project the most common techniques have been used:

- Sinusoidal PWM (SPWM)
- Space Vector PWM (SVPWM)

In SPWM the low frequency reference signal is compared with a high frequency triangular carrier signal to generate the switching signals for the semiconductor Gates (Fig. 8) with following duty ratios:

- Sinusoidal PWM (SPWM)
- Space Vector PWM (SVPWM)

IV. Simulation Results

The simulations of the real power control of the PV system under atmospheric condition changes are demonstrated in this section. The outline of the simulation system is shown in Fig. 4. The PCC line-to-line voltage is 480 V and the load is 260 kW. The PV system is composed of solar modules with 14 parallel connections and 17 serial connections. Table I shows the parameters of the PV module. The maximum power of the PV arrays is around 70 kW.
### TABLE 1
THE PARAMETERS OF THE PV MODULE UNDER STANDARD TEST CONDITIONS (STC : IRRADIANCE 1000 W/M², CELL TEMP.=25 DEG. C)

<table>
<thead>
<tr>
<th><strong>PV Parameters</strong></th>
<th><strong>Values</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Qd (Diode Quality Factor)</td>
<td>1.3</td>
</tr>
<tr>
<td>Iph (Photo-Generated Current)</td>
<td>5.9602A</td>
</tr>
<tr>
<td>Isat (Diode Saturation Current)</td>
<td>1.1753*10^-8A</td>
</tr>
<tr>
<td>Rp (Parallel Resistance)</td>
<td>993.51 ohm</td>
</tr>
<tr>
<td>Rs (Series Resistance)</td>
<td>0.037998 ohm</td>
</tr>
<tr>
<td>Voc (Open Circuit Voltage)</td>
<td>64.2V</td>
</tr>
<tr>
<td>Isc (Short-Circuit Current)</td>
<td>5.96A</td>
</tr>
<tr>
<td>Pmax (Maximum Electrical Output)</td>
<td>69.4 KW</td>
</tr>
<tr>
<td>Vmp (Voltage at Maximum Power Point)</td>
<td>54.7V</td>
</tr>
<tr>
<td>Imp (Current at Maximum Power Point)</td>
<td>5.58A</td>
</tr>
</tbody>
</table>

#### A. Real Power Output of PV Module

Fig. 10 show the simulation results for the real power output control of the PV array. As shown in Figure at 5 s, a 20 kW step change is applied to the real power reference. The PV array real power output tracks this change and increases to 60 to 70 kW.

![Power generated by PV Module](image)

**Fig. 10 Power generated by PV Module**

The Fig.12 illustrate the flow of power demand at PCC by means of real power need by the load. When power demand is less than that of PV power at PCC the power is supplied by the PV module only and rest feed to the grid, feeding power to grid shows positive in the figure where as in sometime the load demand exceeds the power generate by the PV system at that time rest power is feed from the grid to the load at PCC, the power feed from grid shows negative in the figure.

![Three-Phase Grid Voltage at the point of Grid Interface](image)

**Fig. 12 Three-Phase Grid Voltage at the point of Grid Interface**
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The current-control strategy permits dc-link voltage regulation and enables power-factor control by taking q-axis reference current into zero. The proposed solution can ensure a stable constant power generation operation. The proposed control strategy forces the PV systems to operate at the left side of the MPP, and thus, it can achieve a stable operation as well as smooth transitions. Experiments have verified the effectiveness of the proposed control solution in terms of fast dynamics.

Future work will concern the derivation of new control (like Artificial Intelligent) strategies for the possible employment of PV units to provide other ancillary services and, more generally, to fully explore the opportunity of using distributed energy resources, and in particular PV units, as custom power devices for the improvement of the power quality.

REFERENCES
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V. CONCLUSION

This paper presents control algorithms for real power and local voltage control of a grid-connected three-phase single-stage photovoltaic (PV) system that is connected to a distribution network. The proposed control strategy adopts an inner current-control loop and an outer dc-link voltage-control loop.
