FAULT ANALYSIS ON THREE PHASE THREE LEVEL SVPWM BASED GRID CONNECTED PHOTOVOLTAIC SYSTEM

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ABSTRACT

Solar energy has become a major source of energy with the advancements in pv cell efficiency and reduction in cell cost; grid-connected photovoltaic (PV) systems does not require bulk and lossy battery bank. High voltage Distributed generation and on-site supply of PV system reduces distribution losses, and mitigates environment pollution. This paper presents a Dynamic model of grid-connected PV system using Matlab/Simulink. Based on the accurate system modeling, optimum control and fault analysis are studied. The simulation studies verify the effectiveness of the proposed system, and demonstrate that the proposed control system has good static as well as dynamic performance.

Keywords: Grid-Connected Photovoltaic System; Three Level SVPWM Inverter; Matlab/Simulink.

I. INTRODUCTION

Now a days, renewable energy sources especially wind and solar energy gaining momentum and improving its share in world energy demand. Moreover, photovoltaic systems are eco-friendly noise free source of electricity; Distributed PV generation would have to meet challenges associated with power quality and system security issues not only on the distribution network but also on the transmission grid.

There are two types of the photovoltaic system; stand-alone pv system and grid-connected pv system. Both systems have almost similar functional characteristics, but are different in terms of control structure and operation. The former is used for off-grid applications with battery storage. Its control algorithm must have an ability of bidirectional operation, which is battery charging and inverting, and the later i.e., grid-connected pv system, on the other hand, converts dc to ac and transfers electrical energy directly to power grid. The output voltage, frequency and phase of the inverter should be in synchronism with the voltage frequency and phase of the distribution grid.
But in case of grid connected system, the nonlinear nature of PV cell may inject harmonics into grid and deteriorates the power quality, and faults on the external system that will affect the stability and security of the pv system which must therefore be considered carefully.

This paper emphasizes on mitigation of nonlinearities of pv cell by using feed forward loop. Harmonic content in the output of inverter is reduced by implementing three-level inverter with neutral point clamping and giving firing pulses using three-level SVPWM (Space Vector Pulse Width Modulation) [6], so that the output voltage obtained is more compared to ordinary PWM techniques. A model of PV array capable of simulating their response to changes in irradiance and temperature is presented. For maximum power point tracking (MPPT) P&O algorithm is used which gives pulses to boost converter, so that output voltage of pv array is controlled and operating PV array at maximum power point thus used to maximize the efficiency.

![Fig 1: Grid-connected photovoltaic system](image1)

**II. DYNAMIC MODEL FOR GRID CONNECTED PV SYSTEM**

Fig.1 represents a typical single-stage grid-connected PV system. A PV array is connected to a 6.6KV distribution network with a three level voltage source converter.

**A. Photovoltaic array model**

When cell exposed to light, the DC current is generated. The typical equivalent circuit of PV cell is shown below.

![Fig 2: Equivalent circuit of Solar Cell](image2)

PV arrays consist of Ns series connected solar cells per string and Np such strings are connected in parallel which forms a pv array. Thus the equivalent circuit is represented by a current source parallel to an ideal diode.
The mathematical model of PV arrays is given as

\[ i_{pv} = n_p l_{ph} - n_p l_{rs} \left[ \exp \frac{q v_{dc}}{A k T} \left( v_{dc} + \frac{n_s R_s i_{pv}}{n_p} \right) - 1 \right] - I_{rsh} \]  

(1)

\[ l_{ph} = [l_{scr} + K_v (v - v_r)] \cdot \frac{S}{100} \]  

(2)

Where \( v_r \) is the cell reference temperature, \( v_{dc} \) is output voltage, \( R_s \) is series resistance and \( R_{sh} \) is the shunt resistance of the single solar cell, \( n_p \) and \( n_s \) are the number of PV cells connected in parallel and in series respectively and \( I_{rsh} \) is the current flowing through the shunt resistance, \( I_{scr} \) is the short-circuit current of PV cell at a reference temperature and irradiation level, \( l_{ph} \) is the photocurrent of a pv cell which is proportional to both illumination and surface area, \( I_{rs} \) is the reverse saturation current of diode which is related to temperature and \( K_v \) is a temperature coefficient, \( k \) is Boltzmann constant (1.38e-23, in Joules per Kelvin), \( q \) is electric charge (1.602e-19, in Coulombs), \( T \) is operating temperature, \( A \) is P-N junction ideal factor. Neglecting the losses in inductance and the resistance of the VSC interface, the dynamic equations of the PV system are:

From equation (1)&(2), the power delivered by the PV array is expressed as a nonlinear equation, which reflects the nonlinear characteristics of pv array.

\[ (i.e., P_{pv} = v_{dc} i_{pe}) \] is expressed as:

\[ P_{pv} = f (v_{dc}, S, v) \]  

(3)

\[ n_p l_{phv_{dc}} - n_p l_{rs} v_{dc} \left[ \exp \left( \frac{q v_{dc}}{k T A n_s} \right) - 1 \right] \]  

(4)

For a given irradiation level, \( P_{pv} \) is zero at \( v_{dc} = 0 \), but increases as \( v_{dc} \) is increased.

**Fig 3:** I-V and P-V characteristics of a PV array for different irradiance levels.[2]

The aforementioned behavior suggests that \( P_{pv} \) can be controlled/maximized by the controlling \( v_{dc} \). This technique is referred to as the “maximum-power-point tracking” (MPPT). In this paper by using perturbation and observation algorithm MPPT is implemented. The dc-link voltage dynamics are described, from principle of power balance,
\[ \frac{c}{2} \frac{d^2 v_{dc}}{dt^2} = f(v_{dc}, S, v) \]  

(5)

Where denotes the power delivered to the dc side of VSC. Ignoring the VSC power loss, \( P_{dc} \) can be assumed to be equal to \( P_t \). The VSC ac-side terminal voltage can be controlled as

\[ v_t = \frac{v_{dc}}{m} \]  

(6)

B. Distribution Network Model

Distribution network in this paper is of 6.6kv is referred as the composition of distribution line, transformer Tr1 and the filter and load capacitors \( C_f \) and \( C_l \) respectively. Distribution network is supplied by a utility substation which is represented by voltage 3phase voltage source \( U_g \).

If \( v_s, v_t, i_{g1}, i_{g2} \) and are chosen as the state variables, the following state-space model can be derived for the distribution network:

\[ C_f \frac{dv_s}{dt} = i - N i_{g1} \]  

(7)

\[ C_l \frac{dv_t}{dt} = i_{g1} - i_{g2} - i_l \]  

(8)

\[ L_1 \frac{di_{g1}}{dx} = -R_1 i_{g1} + N v_s - v_t \]  

(9)

\[ L_2 \frac{di_{g2}}{dx} = -R_2 i_{g2} + v_l - v_g e^{j\omega_0 t} \]  

(10)

Where the PV system ac-side current \( i' \) and the load current \( i_l \) act as exogenous inputs to the distribution network subsystem. It is assumed that \( v_{gabc}(t) \) is a balanced three-phase voltage whose amplitude and phase angle are \( v_g \) and \( \omega_0 \), respectively.

Using the above equations can be represented in decoupled form as shown below:

From Fig.1.1, we can get the reference model of the distribution network as follows:

\[ \frac{di_{g1d}}{dt} = -\frac{R_1}{L_1} i_{g1d} + \frac{\omega}{L_1} i_{g1q} + \frac{N}{L_1} u_{sd} - \frac{1}{L_1} u_{td} \]  

(11)

\[ \frac{di_{g1q}}{dt} = -\frac{R_1}{L_1} i_{g1q} - \frac{\omega}{L_1} i_{g1d} + \frac{N}{L_1} u_{sq} - \frac{1}{L_1} u_{tl} \]  

(12)

\[ \frac{di_{g2d}}{dt} = -\frac{R_2}{L_2} i_{g2d} + \frac{\omega}{L_2} i_{g2q} + \frac{N}{L_2} u_{sd} - \frac{1}{L_2} u_{td} \]  

(13)

\[ \frac{di_{g2q}}{dt} = -\frac{R_2}{L_2} i_{g2q} - \frac{\omega}{L_2} i_{g2d} + \frac{N}{L_2} u_{sq} - \frac{1}{L_2} u_{tl} \]  

(14)
\[
\frac{du_{sd}}{dt} = \omega u_{sq} + \frac{1}{c_f} i_d - \frac{N}{c_f} i_{gld}
\]
\[
\frac{du_{sq}}{dt} = -\omega u_{sd} + \frac{1}{c_f} i_q - \frac{N}{c_f} i_{glq}
\]
\[
\frac{du_{td}}{dt} = -\frac{1}{c_l} i_{gld} - \frac{1}{c_l} i_{g2d} + \omega u_{td} u_{td}
\]
\[
\frac{du_{tq}}{dt} = \frac{1}{c_l} i_{glq} - \frac{1}{c_l} i_{g2q} - \omega u_{td} u_{tq}
\]

Where \(i_{g1d}\) and \(i_{g1q}\) are d and q-axis components of the current between the VSC interface and the load, \(i_{2gd}\) and \(i_{g2q}\) are d- and q-axis components of the current between the load and the grid, \(R_1\) and \(L_1\) are resistance and inductance between the VSC interface and the load, \(R_2\) and \(L_2\) are resistance and inductance between the load and the grid, \(u_{td}\) and \(u_{tq}\) are d and q-axis components of load voltage, \(N\) is the transformer turns ratio, and \(\omega\) is the dq-system angular speed.

C. Load Model

The load model considered is a series R-L circuit, load current i.e. inductor current as the state variable. Thus, it is shown as follows:

\[
L_i \frac{di_l}{dt} = -R_l i_l + v_l
\]

Using the above equations can be represented in decoupled form as shown below:

\[
\frac{di_{td}}{dt} = \omega i_{td} - \frac{R_l}{L_l} i_{td} + \frac{1}{L_l} u_{td}
\]
\[
\frac{di_{tq}}{dt} = -\omega i_{tq} - \frac{R_l}{L_l} i_{tq} + \frac{1}{L_l} u_{tq}
\]

Where \(R_l\) and \(L_l\) are resistance and inductance of the load, \(i_{td}\) and \(i_{tq}\) are d- and q-axis components of the load current.

III. CONTROL STRATEGY

The main objective of this control strategy is to regulate/control the dc link voltage to maximize the power extracted from PV array. VSC, three level SVPWM inverter and control (current control) are synchronized to the network voltage through a phase locked loop (PLL) Categorized into two Strategies as current control & voltage controls. In order to control the grid current efficiently, it is necessary to transform the three-phase ac signals into proper dq-frame counterparts.
A. VSC Current Control

Current-control scheme is developed to ensure that $I_d$, $I_q$ and rapidly track their references $I_{dref}$ and $I_{qref}$ commands. The current-control strategy also improves protection of the VSC against overload and external faults provided that $I_{dref}$ and $I_{qref}$ are limited it is achieved as follows by parks and Clarke’s transformations: at first,

![Simulink Diagram of dq-frame current control](image)

Fig 4: Simulink Diagram of dq-frame current control.[1]

$u(s)$ is decomposed into d- and q-axis component, and then $u_{sq}$ passes through a compensation device to get $\omega$, which is the differential coefficient of reference angle of dq-axis $\rho$.

$$\Omega(s) = G_p(s)U_{sq}(s) = \left[\frac{s+1}{s^2+1}\right]U_{sq}(s)$$  \hspace{1cm} (22)

Where $\Omega(s)$ and $u_{sq}(s)$ correspond to the Laplace transform of $\omega$ and $u_{sq}$, respectively. The dynamics of $i_d$ and $i_q$ are coupled and non linear are coupled due factor $L\omega$ and nonlinear. To decouple and linearize the dynamics $m_d, m_q$ and are determined based on the following control laws.

$$m_d = \frac{2}{v_{dc}}(v_d - L\omega i_q + v_{sd})$$ \hspace{1cm} (23)

$$m_q = \frac{2}{v_{dc}}(v_d - L\omega i_d + v_{sq})$$ \hspace{1cm} (24)

Introduce $i_{dref}$ and $i_{qref}$, which are two new control inputs. Regulating $i_d$ and $i_q$ to track their corresponding reference value $i_{dref}$ and $i_{qref}$, shows that the control signal $v_d$ is the output of a compensator $K_d(s)$, processing the error signal, thus current control is completed.

$$e = i_{dref} - i_d$$

$$K_d(s) = K_q(s) = \frac{k_p s^2 + k_i}{s}$$ \hspace{1cm} (25)

And then active and reactive outputs of PV system are expressed as:

$$P_s = \frac{3}{2}U_{sd}i_d$$ \hspace{1cm} (26)

$$Q_s = -\frac{3}{2}U_{sd}i_q$$ \hspace{1cm} (27)
B. VSC Voltage Control

The purpose of voltage control is to make dc-link voltage track the voltage which corresponds to the maximum power point. In this case, \( i_q = 0 \), dc link voltage is adjusted by regulating the d-axis component of \( I \), reactive power becomes zero in the steady state and the PV system exhibits a unity power factor to the distribution network. The unity power-factor operation also results in a minimized magnitude for the VSC line current, for a given real-power flow. In a steady state, \( u_{sq}(s) \) is forced to 0.

\[
G_i(s) = \frac{I_d(s)}{I_{qref}(s)} = \frac{1}{\tau_i s + 1} \tag{28}
\]

![Fig 5: Simulink Diagram of dc-link voltage control](image)

The detailed modeling of voltage control is taken from [1]. feed forward compensator in voltage controller is responsible in mitigating the pv system non linearities.

The purpose of the MPPT system is to sample the output of the dc terminal voltage of pv array and apply a resistance (load) to obtain maximum power for any given environmental conditions.

MPPT can effectively improve the solar energy conversion efficiency of PV systems. Perturb-and-observe (P&O) method is used to achieve this function. P&O method first measures the current output power of the array, and then adds a small perturbation to the original output voltage, after that, compares the current power with the original one.

IV. FAULT ANALYSIS

In grid connected PV system Faults are classified as internal or DC side faults and external of AC side or system faults. DC side faults are the faults due to change in irradiation or change in temperature of the PV array, it generally affects dc voltage and ac side as well. Faults on ac side are the faults generally occur in ac system but near to point of common coupling (PCC) here in this paper Faults on both dc and ac side are discussed and the outputs are depicted. Important component is the residual current device-earth leakage. It assures protection to people and installations against fault current to earth. Micro-breaker should be installed between inverter and grid, and its rated fault current should be between specified limits.
V. SIMULATION RESULTS

The switched model is also used to verify the linearized model of the overall system, which is implemented in Matlab/Simulink.

PV system Parametric Values are as shown below:

A user defined embedded matlab code block is taken to insert the code for the P&O algorithm, and the algorithm is explained. Different types of Faults on DC as well as AC side are discussed below.

At $t = 0.2s$, as a result of disturbance, the reference power provided by MPPT scheme is suddenly increased from 2.15MW to 2.3MW. We can see this process shows the responses of dc voltage. When there is a disturbance, $u_{dc}$ tracks its reference value smoothly, and reaches its original value in less than 0.01 second. After the required voltage achieved $u_{dc}$ remain stable. it is although an internal fault ,change in terminal ac side voltage at $t=0.2s$ is considerably low value. The simulation results show that the control method achieve the design requirements

<table>
<thead>
<tr>
<th>Table 1: System Parameters</th>
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<tr>
<td>PV System Parameters</td>
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<tr>
<td><strong>Transformer:</strong></td>
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<tr>
<td>Nominal power</td>
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<tr>
<td>voltage ratio</td>
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<tr>
<td>leakage resistance</td>
</tr>
<tr>
<td>leakage inductance</td>
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<td><strong>Interface reactor:</strong></td>
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<tr>
<td>Inductance L</td>
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<tr>
<td>Interface resistance including Valves R</td>
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<tr>
<td>Filter capacitance $c_f$</td>
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<tr>
<td>Switching Frequency</td>
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<tr>
<td><strong>PV Array and DC link:</strong></td>
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<tr>
<td>DC link capacitance</td>
</tr>
<tr>
<td>No of cells connected in series, $N_p$</td>
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<tr>
<td>No of cells connected in parallel $N_s$</td>
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<tr>
<td>Cell reference Temperature</td>
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<tr>
<td>$\nu_f$</td>
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<tr>
<td>Cell Short circuit current $I_{sc}$</td>
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<tr>
<td>Reverse saturation current $I_{sr}$</td>
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<tr>
<td><strong>Line Parameters:</strong></td>
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<tr>
<td>Grid Voltage</td>
</tr>
<tr>
<td>Line inductance $L_1 + L_2$</td>
</tr>
<tr>
<td>X/R ratio</td>
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<tr>
<td>Line Length</td>
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At $t=0.2s$, due to sudden fall in temperature from 300K to 200K, there is a fall in dc side voltage output of boost converter. Due to this internal fault, there is a considerable effect on the output side ac voltage and current waveforms.

3-level SVPWM inverter firing 12-pulses ($g_1$ to $g_6$ and $g_{1a}$ to $g_{6a}$); space vector technique makes duty cycle range to be improved [3], harmonic distortion significantly low compare to 2 level SVPWM inverter.
Fig 9: Firing pulses of SVPWM for three legs (4 pulses per leg)

Fig 10: Output waveforms of $V_{abc}$ and $I_{abc}$ on Grid side without fault

Fig.8 show a single phase fault occurs on y-phase at Fault is initiated at 0.2 sec, breaker opens at 0.25s and it is cleared at 0.3 sec. Fault current magnitude is $4.4 \times 10^4$ A at the instant of fault. Fig.9 shows, When a 3 phase fault occurs on grid side, the corresponding change in voltage and current waveforms are shown below. Fault is initiated at 0.2 sec, breaker operated at 0.23 sec and it is cleared at 0.3 sec. The fault current magnitude is $2.65 \times 10^5$ A at the instant of fault. From Voltage waveforms, it takes 2.5 cycles to restore the voltage to its original.

When the fault happens in a inverter side, i.e. at the PCC, the output voltage & current waveforms of the inverter becomes asymmetrical as shown in fig 10.

Fig 11: Output waveforms of $V_{abc}$ and $I_{abc}$ on Grid side for a single phase fault
At the time fault occurs at inverter end, The PV energy system works as a load; it consumes energy from the utility grid. So it is significant to ensure the PV energy system absorb as much energy as possible from sun irradiation to ensure the sufficient high voltage level of the battery so as to get a stable AC output power. Meanwhile, it is necessary to cut it off from the main grid when PV energy system doesn’t produce sufficient energy and the voltage level is lower than the threshold value.

In emergency condition, when PV system must be shutdown the breaker isolates the PV system from the distribution network.

VI. CONCLUSION

In this paper, a grid-connected PV system based on MATLAB has been proposed. Optimum control and fault analysis were studied based on it. The control consists of a voltage control loop and a current control loop. Current control can achieve the dc voltage regulation and power factor control. Voltage control can achieve the maximum power point tracking. The dc-side voltage is controlled through the ac-side d-axis current component which is associated with the real power flow, based on the power balance approach between the ac- and dc-side. Control of $i_d$ enables control of $p_s$ and $p_{pv}$ and a saturation block limits $\delta_{deref}$ to protect the VSC against over load and external faults. Simulation and analysis results show that the model can correctly reflect the system characteristics and the methods can meet the actual needs.
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