Design of A Grid Integrated PV System with MPPT Control and Voltage Oriented Controller using MATLAB/PLECES

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Abstract: This paper presents model of a grid-integrated photovoltaic array with Maximum Power Point Tracker (MPPT) and voltage oriented controller. The MPPT of the PV array is usually an essential part of PV system as MPPT helps the operating point of the solar array to align its maximum power point. In this model, the MPPT along with a DC-DC converter lets a PV generator to produce continuous power, despite of the measurement conditions. The neutral-point-clamped converter (NPC) with a boost converter raises the voltage from the panels to the DC-link. An LCL-filter smoothen the current ripple caused by the PWM modulation of the grid-side inverter. In addition to the MPPT, the system has two more two controllers, such as voltage controller and a current controller. The voltage control has a PI controller to regulate the PV voltage to optimal level by controlling the amount of current injected into the boost stage. Here, the grid-side converter transfers the power from the DC-link into the grid and maintains the DC-link voltage. Three-phase PV inverters are used for off-grid or designed to create utility frequency AC. The PV system can be connected in series or parallel to get the desired output power. To justify the working of this model, the grid-integrated PV system has been designed in MATLAB/PLECS. The simulation shows the P-V curve of implemented PV Array consisting 4 X 20 modules, reactive, real power, grid voltage and current.

Keywords: PV Array, MPPT, NPC, MATLAB/PLECES.

1. INTRODUCTION

A photovoltaic (PV) system with a maximum power point tracker (MPPT) integrated to the grid is shown in Fig. 1. Power electronics inverters are transform DC from the PV system into AC and then inject into the grid. There are special standards and necessities regarding the PV connection to the grid. In [1] presented simulation which helps in selection of operating principle, sizes and cost when utilizing PV in small isolated system. In [3] provided a review on recent development in photovoltaic technology. It also discussed its advantages by comparing with the conventional sources. Similarly, [4] described a complete solar photovoltaic power electronic conversion system. It also defined a circuit-based simulation model for a PV cell in order to allow the interaction between proposed converters (with its associated control arrangement). The model shows the I-V characteristics for that particular cell with irradiance and temperature as variable parameters [5]. The main aim is to find the parameters of the nonlinear I–V equation by adjusting the open circuit, maximum power, and short circuit current.
2. GRID INTEGRATED PV SYSTEM

2.1 Basic Controls of Three-Phase Grid-Connected PV System

The main controllers are MPPT control, reactive power control, grid synchronization, and grid supporting features. The control objectives of a three-phase system [6] can be divided into PV controller to extract the maximum power from the input source, grid controller control the active power delivered to the grid, reactive power interchange with the grid, high efficiency and quality of the injected power, anti-islanding protection and grid synchronization. The control system applied to the three-phase PV inverters has two cascaded loops as follows. (a) Inner Current Control Loop (ICCL) and (b) Outer Current Control Loop (OCCL) for Current Reference Generation. The ICCL controls the power quality issues and current protection of the inverter. The existing controllers, such as Proportional Resonant (PR), Resonant Control (RSC), Repetitive Controller (RC), and Deadbeat Controller (DB) can be adopted directly [6-7].

Park transformation ($\alpha\beta$ to $dq$) lead the Proportional Integral (PI) controllers to regulate the injected current, and again inverse Park transformer ($dq$ to $\alpha\beta$) is applied. The PR controller with Harmonic Compensators shows good performance in terms of fast dynamic response and accurate tracking compared to the PI controller [8]. Whereas the OCCL generates a current reference used in the inner current control loop to shape the injected grid current.

Fig.1. PV system control structure with additional diagnostic functions

2.2 Controller In Synchronous Reference Frame

Park transformation to a three-phase voltage and current controls the $dq$ for a three-phase system. It uses the reference frame transformation module (abc to $dq$) to transform the grid voltage and current waveforms into a reference frame which rotates synchronously with the grid voltage. This makes control variables as DC quantities. Every deviation in the grid voltage and current will be shown to the corresponding d-axis and q-axis components, hence it filters out by controlling using PI. In Fig.2 (a), the DC-link voltage is controlled according to the desired output power. This output is used as the reference for the active current controller, whereas the reactive current reference is set to zero in normal operation. When the reactive power has to be controlled then reactive power reference must be given to the control system. A Phase-Locked Loop (PLL) system is added in this control structure to synchronize the grid current and voltage and also generates phase angle which is necessary in abc to $dq$ transformation. For this controller, the drawback is the poor compensation capability of the low-order harmonics in the case of PI based controllers even when cross-coupling terms and voltage feed-forward control are adopted to improve the performance [7].
2.3 Implementation of Controller In Stationary Frame

Implementation of the controller in a stationary reference frame, also known as αβ control, which is shown in Fig.2 (a). The control structure, the control variables are transformed using the abc to αβ module. The resultant αβ frame are sinusoidal. Other controllers should be added since the PI controller does not eliminate the steady-state error when the signal is time variant. The PR controller has the capability of eliminating the steady-state error when controlling sinusoidal waveforms (αβ). Harmonic Compensators (HC) connected in parallel for low-order harmonics like 3rd, 5th, and 7th order for improving the injected current quality.

The transfer function of a PR with HCs controller is shown as follows.

\[ G(s) = k_p + k_r \frac{s}{s^2 + \omega_0^2} + \sum_{h=3,5,7,...} k_{rh} \frac{s}{s^2 + (h\omega_0)^2} \] (1)

where, \( k_p \) is the proportional gain, \( k_r \) is the fundamental resonant control gain, \( k_{rh} \) is the control gain of the h-order resonant controller, \( \omega_0 \) is the grid fundamental frequency.

![Fig.2. (a) General Structure of a three-phase PV inverter with stationary frame control and (b) Three-phase PV inverter with natural frame control [7]](image)

2.4 Control Structure In Natural Reference Frame

In this control strategy (abc-control), an individual controller is applied to each phase grid current. Implementation of abc-control is shown in Fig.2 (b). The DC-link voltage is controlled to generate the active current reference in dq-frame which are transformed into three current references using the inverse Park transformation and the phase angle of the grid voltages. The error signal produced by comparing with the corresponding measured grid current goes into the current controller. These individual current controllers are necessary to produce the duty cycles for the PWM. Any of the controllers like PI controller, PR controller, hysteresis controller, dead-beat controller and repetitive controller [6, 9], can be adopted as the three current controllers in the natural reference frame control structure based on the control complexity and its dynamic performance.

2.5 Grid Synchronization

In grid synchronization an internal reference signal is generated by the control algorithm of a grid-connected power converter. Synchronization ensures that the current injected in the grid is sinusoidal and in phase with the grid voltage having unity power factor. In fig. 3 (a), the dq PLL uses the Park’s transformation, as shown in Eq. 2, to translate the abc natural rotating reference frame into the dq-Synchronous Reference Frame (SRF).
In this PLL, either direct axis or quadrature axis component of voltage can be used for frequency or phase angle estimation. A crucial aspect of the transformation is that the voltage of the d-axis \((V_d)\) has to lie on the voltage of phase A. Proportional-Integral (PI) controller is used to track q-axis \((V_q)\) to zero and estimate the frequency and phase of dq PLL. The PI controller used here controls the frequency error signal which gives the output as phase angle in dq. It tracks the phase angle and works well if there is balanced fault but the drawback is seen when there is unbalanced fault. It is because of the oscillation of the negative sequence present which fails to match the \(V_d\) with positive sequence component.

The model of inverter shown in fig. 3 (b) has the state-space representation \([5]\) as

\[
\begin{align*}
\frac{\dot{a}}{L} &= -\frac{R}{L}i_a - \frac{1}{L}e_a + \frac{V_{pv}}{3L}(2S_a - S_b - S_c) \\
\frac{\dot{b}}{L} &= -\frac{R}{L}i_b - \frac{1}{L}e_b + \frac{V_{pv}}{3L}(-S_a + 2S_b - S_c) \\
\frac{\dot{c}}{L} &= -\frac{R}{L}i_c - \frac{1}{L}e_c + \frac{V_{pv}}{3L}(-S_a - S_b + 2S_c)
\end{align*}
\]

where \(S_a, S_b, S_c\) are the switching signals of each phase and is operated as shown below.

\[
S_i (i = a, b, c) = 1 \text{ if } S_i^T \text{ is ON}, S_i^B \text{ is OFF} \\
= 0 \text{ if } S_i^T \text{ is OFF}, S_i^B \text{ is ON} \ldots (4)
\]

where T is top and B is bottom switch.

By applying KCL to the DC link capacitor node, the state-space equation for capacitor voltage is obtained as

\[
\frac{\dot{V}_{pv}}{C} + i_{dc} + i_c = 0
\]

\[
\frac{\dot{V}_{pv}}{C} = \frac{1}{C}(i_{pv} - i_{dc}) \ldots (5)
\]

Assuming the switching and conduction losses of the inverter to be negligible, the input current of the inverter is equal to the output current

\[
i_{dc} = i_aS_a + i_bS_b + i_cS_c \ldots (6)
\]

\[
\frac{\dot{V}_{pv}}{C} = \frac{1}{C}(i_{pv} - i_aS_a - i_bS_b - i_cS_c \ldots (7)
\]

Fig.3. (a) Structure of the dq PLL and (b) Model of inverter
3. RESULTS & DISCUSSIONS

The result of PV curve of implemented PV array of 4 X 20 modules has been shown in Fig. 4 (a). As the irradiance is decreasing the power and current level decreases. The single PV string ultimately has maximum power of 2.5 kW in consequent with four PV string connected with inverter delivers a power output of 9.5 kW to the grid with the maximum current of 19 A and constant dc-link voltage of 800 V as shown in Fig. 4 (b).

Fig. 4 (a) P-V Curve of implemented PV Array consisting 4 X 20 modules and (b) Performance of waveform according to insolation at t = 4 s starts increasing

Table I. Setting of the parameter for the simulated grid-integrated PV system

| Parameters                      | Values | Parameters                      | Values | Parameters                      | Values | Parameters                      | Values |
|---------------------------------|--------|---------------------------------|--------|---------------------------------|--------|---------------------------------|--------|
| Power of the single PV string   | 2.5 kW | PV Voltage                      | 690 V  | Grid Resistance                 | 2 ohm  | DC-Link Capacitance             | 55 µF  |
| Power of four PV string         | 10 kW  | Inverter Output Voltage         | 800 V  | Grid Inductance                 | 1 mH   | DC-Link Voltage                 | 800 V  |
| PV current                      | 14 A   | Grid Voltage                    | 325 V  | Grid Frequency                  | 50 Hz  | Switching Frequency             | 5 kHz  |

The NPC-Inverter is achieved with constant output voltage of 800 V as shown in Fig. 5 (a). The steady state simulation of the proposed control strategy of synchronization of inverter voltage and grid voltage of Phase A is shown in Fig.5 (b). In Fig.6 (a), output current of phase A is shown and it is clear that the proposed inverter can inject the filtered output current into the utility grid with unity power factor and low THD with the help of LCL filters. Similarly, Fig 6 (b) shows the phase output of PLL.

Fig. 7 (a) and (b) shows the real and reactive power respectively. Switching loss occurs because of the transition from on-state to off-state and vice-versa. The switching loss of boost converter is shown in Fig. 8 (a). With the increasing demand in power electronics in terms of packaging and high power density temperature control is necessary. With the help of PLECS environment, thermal design for the boost converter is validated and the voltage sourced converter is imposed in order to provide a cooling. From the thermal analysis results of the boost converter, the temperature rises to around 80°C with the conduction loss of 23 W. During the transition time, current and voltage are larger than zero which cause power loss. The NPC-inverter shows conduction loss of 19 W at 90°C as shown in Fig. 8 (b).
Fig. 5 (a) Output Voltage of the NPC-Inverter and (b) Simulated synchronized inverter voltage with grid voltage

Fig. 6 (a) Filtered output current of Phase A and (b) Phase output of PLL

Fig. 7 (a) Real power of the Grid and Reactive Power of the grid

Fig. 8 (a) switching loss of Boost converter and (b) switching loss of NPC-Inverter
This paper describes about the grid-integrated solar PV system modeling, construction of controllers in refining the dynamic response output. In the controller, the harmonic capacitor is tracked to maintain the nominal harmonics. The synchronization performance of SRF-PLL with the inverter output into the grid is few milliseconds. The pure sinusoidal waveform is produced as the harmonics are reduced by LCL filter. During the transition period switches are continuously operated, due to this the temperature is increased with high losses therefore thermal analysis has been found out in the converters.

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4. CONCLUSION

CONCLUSION

This paper describes about the grid-integrated solar PV system modeling, construction of controllers in refining the dynamic response output. In the controller, the harmonic capacitor is tracked to maintain the nominal harmonics. The synchronization performance of SRF-PLL with the inverter output into the grid is few milliseconds. The pure sinusoidal waveform is produced as the harmonics are reduced by LCL filter. During the transition period switches are continuously operated, due to this the temperature is increased with high losses therefore thermal analysis has been found out in the converters.