DEVELOPMENT OF HYSTERESIS CURRENT CONTROLLER FOR POWER QUALITY ENHANCEMENT IN GRID CONNECTED PV SYSTEM

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ABSTRACT

The integration of distributed generation like solar and wind are increasing nowadays due to fossil fuel reduction and increased carbon emission. Many integration issues arise of connecting Solar PV to the grid out of which power quality is the important factor. Higher PV injection causes undesirable technical impacts on the distribution networks which leads to power quality issues. This paper studies the impact of PV on the power quality of the utility grid with different levels of penetration of solar energy into the grid. The power quality of the grid is studied using the Total harmonic distortion (THD) by performing Fast Fourier Transform (FFT) analysis. This paper deals with the development of controllers for boost converter and grid tied inverters which minimizes the harmonics due to solar PV system and power converters in grid connected PV system. The Maximum Power Point Tracking (MPPT) for boost converter and Hysteresis current control (HCC) for inverter has been designed and implemented in grid connected PV system. The hysteresis current controller for the inverter has been specifically designed to reduce the THD of the system meeting IEEE519_1992 regulations. The simulation model of the grid connected PV system has been designed in MATLAB 2018b version. The comparison studies are carried out in the PV system with and without hysteresis current controller, after which it can be

concluded that, after the incorporation of the hysteresis current controller, the performance of the system is better in terms of power quality.

Key words: Grid connected PV system, Hysteresis current controller, Maximum power point tracking, Total harmonic distortion.

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1. INTRODUCTION

Solar power is one of the most readily available forms of renewable and clean energy source. The Indian subcontinent is the recipient of about 200 MW/km square of solar energy. This energy is spread throughout an expanse of 3.827 million-km square which amounts to 657.4 million MW per year. India receives about 2,300-3,200 hours of daylight per year thus there is very high scope for clean energy generation via solar power plants. The solar installed capacity reached 34.404 GW according to the latest news within the Indian subcontinent. The statistics also show that India has the lowest capital cost for every mega- Watt for setting up of solar power plants. The extraction of power from renewable energy resources involves several power conversions stages. The conversion stages lead to distortions in the performance parameters that may be harmful for the power electronic components.

Shiva et al [1] gives a description of the power quality scenario of the entire country and how it is very important to integrate renewable energy to the existing grid to curtail the need for the ever-increasing population of the country. It gives a clear idea of the difficulties and issues faced by the integration of solar power to the grid system and suggests a control scheme using shunt active power filters and PI controller to improve the power quality of the system. Pekik et al [2] proposes a hysteresis current control scheme for single phase bridge inverters. The proposed scheme allows equal switching frequency among the various switching power devices. The paper also proposes the modification of the hysteresis double-band which helps in reduction of harmonics of the system and increasing the quality of power.

Raja et al [3] provides a study of a solar photovoltaic system connected with grid under both HCC(hysteresis current control) and HVC(hysteresis voltage control) to reduce the harmonics in the system. Raju et al [4] presents a concept using reactive power compensation and SAPF(Shunt Active Power Filter). This method uses fourier block for reference current generation with the help of advanced adaptive HB(Hysteresis Band) current controller which helps in tracking the reference current.

Chinmay et al [5] uses a current control technique for grid integrated half bridge inverter. The simulation has been carried out in PSIM software using Hysteresis Band current control. Devaraj et al [6] compares the hysteresis voltage control and hysteresis current control and concludes that how both the controllers are effective in their own way. Devaraj et al [7] explain the design of boost converter in Stand-alone system in an elaborate manner. Pandey [8] uses the Clarke transform and elaborates how it is advantageous for a 3-phase system.

Dash R et al [9] presents a freshly developed robust control system for concepts including Microgrid and Smart grid. S Pradhan et al [10] shows a grid integrated pv system having the control algorithm DNLMS(Decorrelation Normalized Least Mean Square) which improves the system performance under conditions which are unfavourable.

Nelson A. Patel et al [11] proposes a Hysteresis Current control algorithm for both AC and DC converters. A.Arias et al [12] presents a new method for hysteresis band current control which has been verified experimentally and is based on second input current error derivatives for the choice of zero voltage vectors. Renukadevi V et al[13] provides a dynamic model for PV Generation system. Simulink model has been designed in MATLAB and the results have been provided.

2. STRUCTURE OF GRID- TIED PV SYSTEM

The system discussed is a grid connected PV system. In the system there are following components: PV array, Boost converter with MPPT control, Inverter with Hysteresis Current Controller (HCC), Utility grid, Linear and non-linear loads and active filters. The schematic of the grid connected PV system is shown in figure 1. The PV module is connected to the converter (boost) which increases the voltage of PV to higher level. The switching of converter is done by MPPT algorithm which gives a range of duty cycle and extract the maximum power from the PV module irrespective of the factor that whatever condition the PV module falls under. The boost converter output is fed to the Inverter which converts DC to AC power and makes it suitable for feeding to the grid. The three-phase inverter's switching is controller using HCC. The HCC compares the feedback current extracted from the grid side and the generated reference current and develops a band width. The switching of the converter is such that the current which is being fed to grid is limited within the bandwidth of hysteresis controller, also known as Hysteresis Band, thus, current harmonics are reduced.

Figure 1 Schematic diagram for Grid-tied Solar PV system

3. MODELING OF GRID CONNECTED PV SYSTEM

The modeling of the grid connected PV system for all the components is designed and is provided below:

3.1. PV Array Modeling

The equivalent circuit of solar PV cell is shown in figure 2 and the corresponding PV and IV characteristics is shown in figure 3.

Figure 2. Equivalent of solar cell

Figure 3 PV cell characteristic curve

3.2. Boost Converter Model

Figure 4 DC-DC boost converter

The boost converter is connected in between PV panel and Inverter. A capacitor is always given after PV panel when it is connected with a grid system since it reduces the ripple current. The inductor and capacitor are designed as follows:

$$\text{Duty cycle, } D = 1 - \left(\frac{V_{out}}{V_{in}} \right) \quad (1)$$

$$\text{Inductance, } L = \frac{(V_{in} * (V_{out} - V_{in}))}{\Delta I_l * f_s * V_{out}} \quad (2)$$

$$\Delta I_l = (0.2 \text{ to } 0.4) * I_{out} * \left(\frac{V_{out}}{V_{in}}\right) \quad (3)$$

$$\text{Capacitance, } C = \frac{(I_{out} * D)}{f_s * \Delta V_{out}} \quad (4)$$

Where,

V_{in} = Input Voltage

V_{out} = Desired Output voltage

f_s = Switching frequency

ΔI_l = Change in ripple current

I_{out} = Output current / boost current

C =Capacitor

D = Duty cycle

3.3. Three Phase Voltage Source Inverter (VSI) Model

Inverter converts the DC power obtained from the boost converter to AC power. Three phase inverter used in the system uses six MOSFET switches. The MOSFET's gate pulses are provided by the hysteresis controller, which controls the switching of the inverter switches such that distortions in output AC waveform is reduced.

Figure 5 Three phase VSI

Referring figure 5, VDD, -VDD of the inverter terminals represents the output terminals of the boost converter. G1, G2, G3 are the gate pulses obtained from the inverter controller in this case hysteresis current controller. The upper switches Q1, Q3, Q5 are supplied with the gate pulses and the lower switches Q2, Q4, Q6 are supplied by NOT of the gate pulses. Sequential switching on and off of the inverter switches with the help of inverter control insures distortion less and production of pure sinusoidal AC waveform.

3.4. Design of Filter

Two filters are used before feeding power to grid. One series active filter is used and one parallel active filter is used. The series active filter injects voltage which is produced in series with the supply. It manages or compensates the voltage sags and swells on the grid and the load side. This enhances the power quality. RL filter has been used in the model for series filter. The parallel active filter is used for reactive power compensation for nonlinear loads of the system. It provides reduction of harmonics in current. RC filter is used for parallel active filter.

$$RL = 1.5e^{-3} \cdot P_{base} \quad (5)$$

$$L = \frac{0.15 \cdot P_{base}}{2 \cdot \pi \cdot f} \quad (6)$$

$$\text{Where } P_{base} = V_{base}^2 / P \quad (7)$$

V_{base} is the base value of the voltage for which the grid is designed.

$$Q_c = 0.1 \times P \quad (8)$$

$$P_c = \frac{Q_c}{50} \quad (9)$$

Where P is the real power of the system in Watt.

4. DESIGN OF CONTROLLER

4.1. MPPT Controller (Maximum Power Point Tracker)

Figure 6 FLOWCHART of P&O

MPPT checks what type of PV module is given and check it's characteristics. From PV curve of the module, it tries to gain the MPP of the curve by substituting $dP/dV = 0$. By solving the derivative we get the maximum power and maximum voltage of the curve. MPPT is given a range of duty cycle which helps to set the output voltage of the converter as per whatever reference value is given. There are several algorithms for achieving the maximum power of the PV system. The Perturb and Observe algorithm has been implemented in this paper.

This algorithm measures the V and I of the PV module from checking the characteristics. From PV curve of the module, it tries to gain the MPP of the curve by substituting $dP/dV = 0$. It calculates the PV power by multiplying voltage and current. It compares the present and previous value of the power and checks whether it is greater than zero. The same process is followed for the voltage. After the voltage is set, the duty cycle is calculated which is fed to the switch of the converter.

4.2. Design of Hysteresis Controller

Hysteresis Current Controller compares the feedback current, the current being fed to the grid, with the generated reference current. The output of the comparison is fed to a relay defining the Upper Hysteresis Bound (UHB) and Lower Hysteresis Bound (LHB) of the hysteresis band. The controller makes the feedback current follow the reference current waveform. The output of the relay is fed to the gate terminal of the inverter switches. The HCC generates gating or switching pulses.

Figure 7 Hysteresis Current Controller

When the current error crosses or touches the upper limit, a voltage is applied less than 0 (or negative voltage) by the VSI to the grid. This results to decrease in current at the grid side. When the current error crosses or touches the lower limit, a voltage is applied greater than 0 (positive voltage) leading to the grid side and this results in increase in current at the grid side. For three phases, three current controllers are used which operate independently. Current ramps up and down in the grid which is shown in the figure 8. The current reference extraction is the proposed algorithm used in HCC and Load balancing is applied on the development of the Hysteresis controller for better real power injection into the utility grid by the PV system.

Figure 8 Hysteresis Band (HB)

Table 1 Inverter Switching Logic based on HB

Status of the comparator	Status of the switch
$\geq$ Upper HB	ON - Upper Leg OFF- Lower Leg
$\geq$ Lower HB	OFF - Upper Leg ON- Lower Leg

4.2.1. Current Reference Extraction

Figure 9 Simulink of Current Reference Extraction

The input voltage of VSI is compared with a voltage (reference) and injected to the Proportional Integral controller. PI controller is used because it is useful to obtain zero steady state error. The output of the PI controller is fed to the current compensating block. Compensation current block is used to generate reference current. It is a very important part in the hysteresis control method. It is a time domain method and is less complicated than frequency domain method. The p-q conversion to $\alpha\beta$ frame is known as the Clarke Transformation. It transforms the “abc” (3-phase) voltage and current into $\alpha\beta$ stationary reference frame. After performing Clarke’s transformation we apply a Low Pass Filter (LPF) to cancel out all the high frequency disturbances, and then again perform an Inverse Clarke’s transformation. Inverse Clarke’s Transformation is where we get the compensated three phases again. The compensated current is the reference current for the hysteresis controller.

Clarke's transformation is used in the system and preferred as compared to dq transform because, this transformation does not lose any information even if a system imbalance occurs. Clarke transformation is an isomorphism thus there is no loss of information which means the zero sequence is considered whereas in dq transformation the zero sequence is omitted. Clarke transformation is the basis for the p-q theory that is used in the control loop of the inverter in the system for unbalance compensation. Clarke transformation converts the abc quantities in the matrix form, during the calculation of conversion of abc to two frame reference system, such that zero appears in the off diagonal terms of the matrix, making the computation easier. This transformation provides a stationary reference frame, in which compensation, balancing and elimination of harmonics are easily performed.

Table 2 Equations for Clarke and Inverse Clarke Transform

CLARKE TRANSFORM	INVERSE CLARKE TRANSFORM
<ul style="list-style-type: none"> • $V_0 = \frac{(V_a + V_b + V_c)}{\sqrt{3}}$ • $V_\alpha = \left(V_a - \frac{V_b}{2} - \frac{V_c}{2} \right) * \sqrt{2/3}$ • $V_\beta = \frac{(V_b - V_c)}{\sqrt{2}}$ • $I_{l0} = \frac{I_{al} + I_{bl} + I_{cl}}{\sqrt{3}}$ • $I_{l\alpha} = \left(I_{al} - \frac{I_{bl}}{2} - \frac{I_{cl}}{2} \right) * \sqrt{\frac{2}{3}}$ • $I_{l\beta} = \frac{I_{bl} - I_{cl}}{\sqrt{2}}$ • $I_0 = I_{l0}$ • $P_0 = V_0 * I_{l0}$ (Dot multiplication : *) • $P = V_\alpha * I_{l\alpha} + V_\beta * I_{l\beta}$ • $Q = V_\beta * I_{l\alpha} - V_\alpha * I_{l\beta}$ 	<ul style="list-style-type: none"> • $V_0 = \frac{(V_a + V_b + V_c)}{\sqrt{3}}$ • $V_\alpha = \left(V_a - \frac{V_b}{2} - \frac{V_c}{2} \right) * \sqrt{2/3}$ • $V_\beta = \frac{(V_b - V_c)}{\sqrt{2}}$ • $I_\alpha = \frac{(V_\alpha * P + V_\beta * Q)}{V_\alpha^2 + V_\beta^2}$ • $I_\beta = \frac{V_\beta * P - V_\alpha * Q}{V_\alpha^2 + V_\beta^2}$ • $I_{ac} = \sqrt{\frac{2}{3}} * \left(\frac{I_0}{\sqrt{2}} + I_\alpha \right)$ • $I_{bc} = \sqrt{\frac{2}{3}} * \left(\frac{I_0}{\sqrt{2}} - \frac{I_\alpha}{2} + \sqrt{3} * \frac{I_\beta}{2} \right)$ • $I_{cc} = \sqrt{\frac{2}{3}} * \left(\left(\frac{I_0}{\sqrt{2}} - \frac{I_\alpha}{2} - I_\beta \right) * \sqrt{3}/2 \right)$

Where ,

V_0, V_α, V_β are $\alpha\beta$ transformation voltage component,

P and Q is real power and reactive power respectively.

I_0, I_α, I_β are $\alpha\beta$ transformation current component.

I_{ac}, I_{bc}, I_{cc} is reference current components for AC waveform.

5. CONCEPT OF LOAD BALANCING

In the proposed model, two loads are connected at the grid side for the compensation of reactive power. The control of the reactive power is defined as reactive power compensation, which leads in the improvement on the performance of AC system. In the proposed system, the reactive power compensation is performed using the load support technique. In load support technique, load balancing is performed so that the power factor of the system improves, which leads to balancing the real power at the inverter side thereby improves the regulation of voltage. Compensation of the reactive power improves the system stability by improving the power being fed to the grid and loads. As the reactive power is needed to support system voltage, consumption of more reactive power, by both load and grid, will lower the voltage. On the contrary, if there is more reactive power produced by the inverter and fed to the grid and loads and the consumption is less by the load and grid, then in the

system there will be more reactive power which gets circulated which can lead to high system voltages. Controlling the voltage is critical for safe operation of the power system as devices are designed to operate within a specific voltage range. The loads connected in the grid side are RC loads, 5kW active load power. The benefit of having inductive load (grid) and capacitive loads (RC loads) in the system, is that the inductive lagging reactive power is inverse to the polarity of leading capacitive power. The capacitive load stores, and then supplies power to the inductive load decreasing the reactive power which the source has to supply and hence power factor correction is carried out.

6. RESULTS AND DISCUSSION

The complete model of grid connected PV system has been developed and simulated in MATLAB/SIMULINK 2018b. The single line diagram of the PV model is shown in Figure 10. The specification of the PV module is shown in Table 3.

Figure 10 Single Line Diagram for Grid- tied Solar PV system

Table 3 Specification of PV System

Parameters	Specifications
Module	1Soltech 1STH-215-P
Parallel String	4
Series-connected module per string	16
Open circuit voltage (V)	36.3
Short circuit current (A)	7.84
Maximum Power (W)	213.15

The system is a PV Grid connected system maintaining a power of 13.5KW. A varying irradiance of 1000 to 500 W/m² are set at 25°C. Two cases have been considered showing the performance of HCC and MPPT controllers in the system. Both the cases have been simulated and results are discussed below:

- Without MPPT and Hysteresis controller.
- With MPPT and Hysteresis controller

Case 1: Without MPPT and Hysteresis controller

The system is without MPPT controller and Hysteresis Current Controller. Normal pulse signal has been given in place of the controllers. For a 13.5KW system, the real power varies from 0 to 6KW. So much power loss can be seen from the data. From the graph, it can clearly

be seen that the inverter output current is distorted. The THD obtained from the system is 69.40% which violates the IEEE519_1992 regulations. The DC link voltage also exceeds the reference voltage which is 700V.

Figure 11 Inverter input voltage, Inverter output voltage, Inverter current

Figure 12 Real Power

Figure 13 THD

Case 2: Proposed controller model

The system is designed with MPPT controller for the boost converter and Hysteresis Current Controller for the Inverter. From this case, it will be shown how incorporating the HCC affects the system in a better way.

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Figure 14 Inverter input voltage, Inverter output voltage, Inverter current

For a 13.5 KW system, 12.9 KW system is obtained at 1000W/m^2 and when irradiance is decreased to 500W/m^2 , the power decreases to half of what was obtained at 1000W/m^2 . It can be seen how there is so less power loss comparing to case 1. The DC link voltage (inverter input voltage) is maintained below the reference value (700V). The inverter input current has a graph without no distortion which indicates that the system is running efficiently. The efficiency of the system is also proven with the help of THD (total harmonics distortions) which is 0.15% which is less than 5% according to the IEEE519_1992 regulations.

Figure 15 Real Power

Figure 16 THD

Table 4 Comparison of Case 1 and Case 2 at 1000W/m² of 13.5KW system

Parameters	Case 1	Case 2
PV Voltage	560 V	490V
PV Power	6.5KW	13.5KW
DC link voltage	850V	600V
Inverter voltage	415V	415V
Inverter current	-60A to 80A(Distorted)	10A
Real Power	6KW	12.9KW
Reactive Power	Distorted	0 VAR
THD	69.40%	0.15%

7. CONCLUSION

By designing the Hysteresis current controller and MPPT controller, better power quality has been achieved. By using the concept of Load Balancing, the power factor of 1 is achieved. The PV array modeling, boost converter, inverter, filters, control algorithm has been studied and analyzed in detail and designed as per the system requirement. The competency of the proposed algorithm has been proven through the simulation results and validation are done with respect to following standards : IEEE 519 -2014, IEEE -5147 and IEC- 61727. The analysis concludes that with the proposed algorithm, the power quality issues has been resolved.

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