Design and Performance Analysis of Grid Connected Photovoltaic (GCPV) based DSTATCOM for Power Quality Improvements

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Abstract. Solar energy has become the most prominent renewable energy for electrical power generation of the sustainable development agenda. This project focuses on power quality improvement in the low voltage distribution network by using a three-phase three-wire Distributed Static compensator (DSTATCOM) supplied by a single-stage grid-connected solar photovoltaic (GCPV) system. The instantaneous reactive power theory (IRPT) or P-Q theory will be used as the control algorithm of the PV based DSTATCOM to eliminate the harmonic current caused by the non-linear loads in the distribution system. This control method has great impact on the accuracy of the harmonic current and reactive power compensation for harmonic current elimination according to the requirement of THD limit set by IEEE 519-2014. Sizing of the grid-connected solar PV system based DSTATCOM will be presented and capable to deliver the active power demand to the utility grid under variation of solar irradiances. This system is modelled and simulated in the MATLAB/Simulink environment.

1. Introduction

Climate change and depleted resources of conventional fossil fuels for electrical power generations have created critical demand for the conventional energy sources to be replaced with renewable energy sources. Conventional fossil fuels are commonly used to generate electricity. However, these non-sustainable energy resources are depleted and there is an urgent need for sustainable resources to meet the energy demand. Besides, conventional fossil fuels have damaging impacts to the environment and public health \cite{1}\cite{2}. Researchers have found the solutions for these problem with renewable energy resources such as solar, wind, and biomass. The most prominent renewable energy resource for the replacement of conventional fossil fuel is solar energy. Solar energy system converts the sunlight into electricity by using the solar photovoltaic (PV) panels. Installation of solar PV systems at the utility grid has tremendous growth recently due to the decreasing cost of solar PV panels and government's financial solar incentive schemes through rebates, subsidies and tax exemptions \cite{3}. There are two types of solar PV system which are grid connected and standalone system. In grid connected system, the utility grid will ensure reliability of electricity supply but for the standalone system, batteries are required to maintain the reliability of supply \cite{1}. The integration of renewable energy batteries enable operation of
the system in standalone mode when not being connected to the utility grid, then it will deliver continuous and clean power to the load [4]. However, high penetration of solar PV system will impose several power system issues such as power quality and stability issues. These problems will mostly occur at low voltage (LV) distribution system due to the PV output variation when connected with nonlinear loads. The most common power quality issues are unbalance, harmonics dips and swells [5]. Moreover, modern sources of non-linear loads are widely used at the distribution system such as adjustable speed drive (ASDs), switched mode power supplies, data processing equipment and high efficiency lighting. Higher usage of these power electronic based equipment have increased probability in occurrence of resonance, neutral overload in 3-phase systems, overheating of all cables and equipment, loss of efficiency in electric machines, electromagnetic interference with communication systems, measurement errors in average meter readings and nuisance tripping of thermal protections [6][7][8].

GCPV is capable to inject active power into the grid from solar PV array. Usually, this system consists of PV array, boost converter and voltage source inverter (VSI) [6]. However, this system is unable to solve power quality problems such low power factor and unbalanced loads which may increase the grid currents’ THD (Total Harmonic Distortion) values beyond the specified limit [7]. These problems can been solved by using a DSTATCOM (Distributed Static compensator) and proper control techniques such as IRPT (Instantaneous Reactive Power Theory), and LMS-LMF (Least Mean Square- Least Mean Fourth) [9][10][11].

In this project, the proposed single stage grid-connected solar PV (GCPV) system with Distributed Static Compensator (DSTATCOM) for harmonic elimination under nonlinear load at the Point of Couple Coupling (PCC) in the LV distribution system [12]. There are two types of GCPV topologies which are single stage and double stage. Single stage GCPV is the direct connection from the PV array to the VSI whereas double stage has boost converter between PV array and VSI to boost the output from the PV array. The single stage GCPV system has higher efficiency and lower switching losses as compared to double stage GCPV topology [13]. However, the single stage GCPV system has higher initial cost for installation of larger solar PV array at the same amount DC output voltage injected at the DC side of the VSI. The solar PV system used the perturbation and observation (P&O) MPP tracking techniques (MPPT) to ensure that the system functions at its maximum power point under various operating conditions. The technique of perturbation and observation (P&O) is used due to reduced complexity and simple implementation [14]. The steady state and dynamic simulation have been performed by using MATLAB/Simulink [15]. The simulation results are analysed to evaluate the performance of the IRP (PQ) theory for DSTATCOM in eliminating harmonic distortion according to IEEE standard 519-2014 by limiting the Total Harmonic Distortion (THD) to be less than 8% at PCC under non-linear loads with varying solar irradiances. The PCC is also known as the interface between sources and the load in electrical systems. It is always be assumed as the closest point to the consumers in power system.

2. Methodology

1.1 DSTATCOM System Configuration

DSTATCOM can provide harmonic current mitigation, reactive power compensation, power factor correction and load balancing in low voltage AC distribution system. DSTATCOM consists of a voltage source inverter (VSI) with DC link capacitor at the DC side of the VSI. VSI is the key factor of DSTATCOM performance. Three phase three wire DSTATCOM is connected to three phase AC mains and three phase non-linear load. The AC output of the VSI is attached with the interfacing inductor (Ld) to minimize the output current ripple. The combination of the capacitor (Cd) and resistor (Rd) is the ripple filter mounted on the PCC parallel to the load to avoid high frequency noise of the PCC voltage switching. The compensating current (ic, ib, ic) injected by DSTATCOM will compensate the load
reactive power and eliminate harmonics of the load current. Figure 1 presents the system configuration of GCPV based DSTATCOM.

![Three Phase Three Wires GCPV based DSTATCOM](image)

**Figure 1.** Three Phase Three Wires GCPV based DSTATCOM.

### 1.2 Parameters of VSI based DSTATCOM

DC bus voltage, $V_{dc}$, should be higher than the amplitude of main voltage supply to control the PWM of three-phase VSI based DSTATCOM which can be calculated by using Eq. (1). Moreover, the design of DC bus capacitor, $C_{dc}$ depends on the stability control of $V_{dc}$ in the event of load application. The value of $C_{dc}$ can be determined by Eq. (2) by using energy conservation principle where $a$ is the overloading factor, $V_{dc, \text{cal}}$ is the minimum level of $V_{dc}$, $V_{ph}$ is the phase voltage, $I$ is the VSI phase current and $t$ is time required to regulate the $V_{dc}$ [16][10]. Then, there are two main parameters in considering the value of AC inductance, $L_f$ which are ripple current, $i_{\text{crpp}}$ and the switching frequency, $f_s$ as defined in Eq. (3).

$$V_{dc} = \left(2(2V_d)\right)^{1/2}\left((3m)\right)^{1/2}^{-1}$$  \hspace{1cm} (1)

$$0.5C_{dc}[V_{dc}^2 - (V_{dc, \text{cal}}^2)] = k[3V_{ph}(aI)t]$$  \hspace{1cm} (2)

$$L_f = (3mV_{dc})^{1/2}(12af_sI_{\text{crpp}})^{-1}$$  \hspace{1cm} (3)

### 1.3 Instantaneous Reactive Power (P-Q) Theory

Instantaneous Reactive Power can be representing to the three phase system properties which are active power, $P$ and reactive power, $Q$. However, the power is relying on the independent phenomena even without harmonic distortion which are voltage and current phase shift, permanent energy transmission and line current asymmetry due to load unbalance. Instantaneous Reactive Power theory is based on the Clarke Transform of voltage and current in three phase systems the calculation of $P$ and $Q$ instantaneous power. The controller will be supplied with input data from supply voltages ($V_a$, $V_b$, $V_c$) and load currents ($i_{La}$, $i_{Lb}$, $i_{Lc}$) to produce reference currents. Besides, the line currents ($i_{La}$, $i_{Lb}$, $i_{Lc}$) will be injected into hysteresis controller for pulse width modulated (PWM) signal generation for DSTATCOM signal switching. There are several processes that involved in the Clark Transformation. Eq. (4) is applied to construct the block set of $V_{\alpha\beta\gamma}$ and $I_{\alpha\beta\gamma}$. Within Clark transformation, the measured voltage and...
current signals will be in three phase condition and then, it will convert into alpha and beta signals and convert back into $V_{alpha}$ and $I_{alpha}$:

$$
\frac{V_a}{V_b} = \left(\frac{2}{3}\right)^{1/2}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & (3)^{1/2}(2)^{-1} & -(3)^{1/2}(2)^{-1} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}
$$

$$
\frac{I_a}{I_q} = \left(\frac{2}{3}\right)^{1/2}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & (3)^{1/2}(2)^{-1} & -(3)^{1/2}(2)^{-1} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}
$$

Then, there are two parts for power loss calculation in real and imaginary instantaneous power which are DC (average power) and AC which can be defined as $\bar{p}$ and $\bar{q}$ average power due to component $I_{ap}$ and $I_{aq}$ respectively, whereas $\bar{p}$ and $\bar{q}$ are oscillating power due to component $I_{ap}$ and $I_{aq}$:

Real power: $p = \bar{p} + \bar{p}$

Imaginary power: $q = \bar{q} + \bar{q}$

1.4 Design of GCPV based DSTATCOM

Table 1 shows the design parameters of the proposed GCPV based DSTATCOM. Equation (7) and (8) have been used to calculate the number of PV panel in parallel to achieve the peak power capacity, $P_{OUT}$ which is 33 kW.

$$
V = \frac{P_{out}}{I_{MPP}}
$$

$$
\text{No. of PV module in Parallel} = \frac{V}{V_{MPP} \times \text{No. of PV module in Series}}
$$

Table 1 Design Parameters of GCPV based DSTATCOM

| Parameter                      | Rating     |
|-------------------------------|------------|
| DC Bus Voltage, $V_{DC}$      | 700V       |
| DC Bus Capacitor, $C_{DC}$    | 20000 µF   |
| AC Inductor, $L_f$            | 2mH        |
| Voltage at maximum point, $V_{MPP}$ | 72.9V     |
| Current at maximum point, $I_{MPP}$ | 5.69A     |
| No. of PV panel in series     | 2          |
| No. of PV panel in parallel   | 40         |

1.5 Perturb and Observe (P&O) MPPT algorithm

Perturb and Observer (P&O) is the maximum power point tracking (MPPT) algorithm used in this GCPV based DSTATCOM system to extract the optimum power from the solar PV array regardless of the solar irradiance as defined in Eq. (9). The peak output voltage from the solar PV array, $V_{pv}$ is perturbed by a fixed quantity followed by the next perturbation based on the solar PV array power, $P_{pv}$. For an effective performance of P&O algorithm, the rate of change in maximum power point ($f_{MPPT}$) must be less than the inverse of the settling time. Extraction of $I_{pv}$ and $V_{pv}$ is performed at a higher frequency than the updating $V_{pv}$. The $f_{MPPT}$ can perform incorrectly since P&O decision is based on the unsettled output which will result in system instability.

$$
P_{pv}(n) = V_{pv}(n) \times I_{pv}(n)
$$
When \( \frac{P_{pv}}{V_{pv}} \) is greater than zero, it will induce positive perturbation, otherwise negative perturbation will occur. It can be concluded that an efficient P&O algorithm can be obtained through these three stages [17].

3. Result and Discussion

The implementation of GCPV based DSTATCOM in harmonic current elimination can be demonstrated in Figure 2 where the distorted line current due to the connected nonlinear load at the PCC is shown in Figure 2(a). After compensation by using GCPV based DSTATCOM, the harmonic currents is eliminated and the line current is improved as presented in Figure 2(b). Table 2 shows the value of THD obtained at the PCC for the three phase line currents \((i_{sa}, i_{sb}, i_{sc})\) and load currents \((i_{La}, i_{Lb}, i_{Lc})\). The effectiveness of the GCPV based DSTATCOM by using IRPT control algorithm can be observed since the THD of the line currents improved significantly from 30.82% to 3.73% after compensation.

![Figure 2](image)

(a) Distorted line current before compensation (b) Improved line current waveform after compensation

### Table 2 Comparison of THD values for GCPV based DSTATCOM

| Phase | Line | Load  |
|-------|------|-------|
| A     | 3.66%| 30.82%|
| B     | 3.73%| 30.82%|
| C     | 3.73%| 30.83%|

The performance of the solar PV system for the proposed system are demonstrated in Figure 3. The I-V curve of the designed GCPV based DSTATCOM indicates that the designed system with P&O MPPT algorithm is capable to provide active power to the utility grid under variation of solar irradiance.
at 1000 Wm⁻², 800 Wm⁻², 600 Wm⁻², 400 Wm⁻², 200 Wm⁻², and 0 Wm⁻². PV output power are directly proportional with solar irradiances since the PV output power is reduced considerably when the solar irradiances are decreased respectively in Figure 4. When the PV output power is decreased, the PV array output voltage will decrease simultaneously. This will affect to $C_{dc}$ at the DC side of the VSI which the IRPT control algorithm will regulated the DC bus voltage to maintain the effectiveness of the proposed system for harmonic current elimination at the PCC according to the specified THD limit set by IEEE 519-2014 which is 5%.

![Figure 3](image1.png)

**Figure 3.** I-V Curve performance for the GCPV based DSTATCOM under variation of solar irradiances.

![Figure 4](image2.png)

**Figure 4.** P-V curve performance for the GCPV based DSTATCOM under variation of solar irradiances.

### 4. Conclusion
Performances of the proposed system of GCPV based DSTATCOM by using IRPT control algorithm are presented in this paper which is capable to provide harmonic current elimination due to connected nonlinear loads in the low voltage distribution system. The P&O MPPT algorithm has successfully extracted the maximum PV output power under varying solar irradiances to inject the active power to the utility grid. The experimental results of this multi-objective GCPV based DSTATCOM system has been successfully performed under steady-state condition which the THD values of the utility grid line currents are achieved within the requirements according to grid code compliance of IEEE 519-2014.

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