A Double Frequency Tuned SOGI Based Control Approach for Roof Top S-DSTATCOM

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Abstract — This paper deals with single phase roof top S-DSTATCOM (Solar Distribution Static Compensator). The proposed S-DSTATCOM feeds solar energy into the distribution system along with active power filtering thereby improving power quality at CPI (Common Point of Interconnection). It consists of a boost converter, which serves the purpose of MPPT (Maximum Power Point Tracking) and a VSC (Voltage Source Converter), which performs reactive power compensation, harmonics elimination and feeding solar energy into the grid. A DFTSOGI (Double Frequency Tuned Second Order Generalized integrator) based control algorithm is proposed for the control of VSC. The DFTSOGI produces feed-forward for the average power consuming component of the load current. Moreover, feed forward term for the solar contribution is also used to improve the dynamic response in case of climatic change. A PI (Proportional-Integral) controller is used to regulate the DC link voltage to desired value. A wide range of simulation studies are presented to demonstrate all features of proposed system. The system is tested under various dynamic loading and climatic conditions. The performance of proposed system is found satisfactory for various linear and nonlinear loads. The THD (Total Harmonic Distortion) of grid current is observed well under IEEE-519 standard under all loading conditions.

Keywords — Power quality; Harmonics mitigation; SPV.

I. INTRODUCTION

The monotonically increasing cost of conventional fuels and their continuous consumption has moved the world in a new era of energy crisis. The solar energy provides a green energy based solution to the problem of energy crisis. The recent research and reports show that the SPV (Solar Photo-voltaic) systems are reaching grid parity [1]-[2].

The solar PV array offers nonlinear V-I characteristic at its output terminals. There is a single operating point at which the power output from a given PV array is maximized. Moreover, that point is dependent on surrounding climatic conditions. Therefore in order to optimize the utilization of PV array, MPPT (Maximum power point Tracking) techniques are used. A review of MPPT techniques is shown in [3]. The incremental conductance (InC) based MPPT technique is widely used because of simplicity, fast convergence and comparatively lower calculations. Therefore, the InC is used in this work also.

The shunt grid tied VSCs (Voltage Source Converters) are used for several applications such as, STATCOM (Static Synchronous Compensator), active filter, grid tied SPV (Solar Photo-voltaic) system [4]-[6]. A review on STATCOM technology and further research potential is addressed in [4]. Various control approaches for distribution grid tied VSCs are shown in [5]-[6]. The increasing nonlinear loads have raised the demands of power filters. A simple peak detection based approach for DSTATCOM (Distribution Static Compensator) is shown in [5]. A frequency shifter based control approach for multifunctional grid tied solar energy conversion system is shown in [6]. In both [5]-[6], in order to estimate average power consuming component of load current, the load current is multiplied by corresponding phase voltage and the output of multiplier is passed through LPF (Low Pass Filter). The cutoff frequency of LPF has to be kept very low (10 to 15 Hz second order LPF) to filter out second harmonic component present in the output of multiplier. Therefore, there is a tradeoff between steady state accuracy and dynamic performance due to low cut off frequency of LPF.

The use of SOGI (Second Order Generalized Integrator) for orthogonal signal generator in single-phase PLL is shown in [7]. However, in this paper a DFTSOGI (Double Frequency Tuned Second Order
Generalized Integrator) based control approach is used for S-DSTATCOM (Solar-DSTATCOM). The proposed S-DSTATCOM serves the purpose of distributed generation by solar energy source along with harmonics compensation, reactive power compensation and overall unity power factor operation with respect to CPI (Common Point of Interconnection). The DFTSOGI based approach is an extension of control approaches shown in [5]-[6], wherein problem of tradeoff of steady state and dynamic performance is solved by judiciously inserting a SOGI to selectively suppress the inherent second harmonic in the single-phase systems. A wide variety of results are shown to demonstrate all the features of the proposed system. The THD (Total Harmonic Distortion) of grid current is observed well under IEEE-519 standard [8] even under nonlinear loads at CPI.

II. SYSTEM CONFIGURATION

The system configuration for proposed two-stage S-DSTATCOM is shown in Fig. 1. The solar PV array is connected to the first stage i.e. to the boost converter. The output of boost converter is connected to the DC link of second stage (grid tied single-phase VSC). The VSC is connected to the grid via an interfacing inductor. Moreover, some local loads to be compensated are also connected at the CPI. A ripple filter is also connected at the CPI to absorb the switching ripples generated by the VSC. The VSC instantaneously transfers all available solar energy into the grid along with objective of load compensation. The proposed system serves feature of PV inverter and DSTATCOM simultaneously, hence it is named after as S-DSTATCOM.

III. CONTROL APPROACH

The proposed DFTSOGI based control approach is shown in Fig. 2. The six quantities sensed for feedback and control of proposed system are CPI voltage ($v_c$), grid current ($i_g$), load current ($i_L$), dc link voltage of VSC ($v_{dc}$), PV string voltage ($v_{pv}$) and the current ($i_{pv}$). All sensed signals are processed according to block diagram as shown in Fig. 2. There are two main power circuits in the proposed system and the control approaches for these two power circuits are independent. The boost converter is control via MPPT algorithm, whereas VSC is controlled to achieve objective of transferring solar power instantaneously, harmonics mitigation and reactive power compensation and over all UPF operation with respect to CPI. The description for control algorithm is given in the following section.

A. Maximum Power Point Tracking

An InC (Incremental Conductance) based MPPT (Maximum Power Point Tracking) algorithm is used in this work. The InC based MPPT technique possesses advantages such as easy to implement and good dynamic response under fast varying climatic conditions. Governing equations are as,

$$\frac{\Delta I}{\Delta V} = -\frac{I_{pv}}{V_{pv}}, \text{at MPP} \quad (1a)$$

$$\frac{\Delta I}{\Delta V} > -\frac{I_{pv}}{V_{pv}}, \text{Left of MPP on } P_{pv} vs V_{pv} \text{ curve} \quad (1b)$$

$$\frac{\Delta I}{\Delta V} < -\frac{I_{pv}}{V_{pv}}, \text{Right of MPP on } P_{pv} vs V_{pv} \text{ curve} \quad (1c)$$

where $\Delta I$ and $\Delta V$ are change in PV current and voltages in two consecutive samples. The reference PV array voltage is decided by this MPPT algorithm, which is then used to estimate the reference duty ratio of the boost converter. The duty

![Fig. 1 System Configuration](image-url)
ratio is then compared with a saw-tooth waveform to generate switching pulses for the boost converter.

B. Control Algorithm for Grid Connected VSC

The VSC in the proposed S-DSTATCOM is controlled to achieve the objective of feeding solar energy instantaneously and active filtering simultaneously. The S-DSTATCOM is controlled such that grid current is sinusoidal and at unity power factor with respect to CPI voltage, even when local loads are nonlinear and offering poor power factor. In order to achieve this objective, the reference grid current is estimated assuming that only real power is exchanged at CPI. The reference current is compared with sensed grid current and an indirect current control is used to generate the switching pulses for the VSC.

The reference DC link voltage is kept above the amplitude of CPI voltage to ensure proper current control. The reference voltage is decided as 400 V in the proposed work. A PI controller is used to regulate the DC link voltage. In steady state condition, the output of PI controller is designated as loss component of VSC. The governing equation for estimating PI controller output is as,

\[ I_{\text{loss}} = I_{\text{ref}} - I - K_{\text{p}} v_{\text{ac}} - K_{\text{i}} v_{\text{ac}}^\prime - I \]  \hspace{1cm} (4)

The effects of climatic changes are considered using a PV feed-forward (PVFF) term which ensures simultaneous reflection of PV array parameter on the reference grid current. The PVFF is estimated as,

\[ I_{\text{PVFF}} = \frac{2P_{\text{PV}}}{V_{\text{n}}} \]  \hspace{1cm} (5)

The DFTSOGI algorithm is used for estimation of average power consuming component (I_{Lp}) of load current. The load current (i_p) is multiplied with the \( u_p \) for estimation of I_{Lp}. The output of multiplication (i_p) consists of three components, which are DC component (I_{Lp}), second harmonic component and high frequency component corresponding to load harmonics. In order to estimate I_{Lp} just from i_p conventionally a LPF (Low Pass Filter) is used. However, to suppress the second harmonic content the cutoff frequency of the low pass filter has to be very low (of order of 10 Hz second order LPF). Therefore, there is a tradeoff between steady state and dynamic performance. The proposed DFTSOGI algorithm selectively suppresses the second harmonics content and hence only LPF_{h} (50 Hz second order LPF) is required which improves the dynamic response for same steady state response. The governing equations for DFTSOGI algorithm are as,

\[ i_p = i_f + \sum_i t \]  \hspace{1cm} (6)

where \( i_f \) fundamental component of load current which can be rewritten as,

\[ i_f = i_{f0} \sin \omega_0 t + i_{f1} \cos \omega_0 t \]  \hspace{1cm} (7a)

\[ i_p = i_{f0} \sin \omega_0 t + i_{f1} \cos \omega_0 t \sin \omega_0 t + \sum_i \times \sin \omega_0 t \]  \hspace{1cm} (7b)

The transfer function for SOGI algorithm tuned at second harmonic frequency is given by,

\[ \frac{I_{\text{L}}(s)}{I_{\text{p}}(s)} = k(2\alpha_0)s / \{ s^2 + 2k\alpha_0 s + (2\alpha_0)^2 \} \]  \hspace{1cm} (8)

In order to ensure this reference grid current are locked with unit sine in phase with CPI voltage. The unit sine in phase with CPI voltage is estimated as,

\[ v_m = \sqrt{v_p^2 + v_q^2} \]  \hspace{1cm} (2)

where \( v_p \) is grid voltage and \( v_q \) is 90° phase lead signal of \( v_p \).

\[ u_p = v_p / v_m \]  \hspace{1cm} (3)

![Fig. 2 Block diagram of proposed control approach.](image-url)
The DFTSOGI algorithm provides unity gain to the second harmonic component and it suppresses the DC and other high frequency component. The $i_{Lh}$ is obtained as a result of subtraction of $i_{2f}$ from $i_p$ hence it contains only the DC component and the high frequency component. The high frequency components are suppressed by $LPF_h$, the output of which is scaled by two to obtain $I_{Lp}$.

As per the direction of the indicated grid current, the load and the loss components are demanded from the grid whereas the PV array component is fed into the grid. Therefore, considering the reference directions the amplitude of reference grid current is estimated as,

$$I_{r} = I_{Lp} + I_{loss} - I_{pv}$$  \hfill (9)

The estimated peak value of reference current is then multiplied with per unitized signal ($u_p$) to estimate the instantaneous reference grid current. The estimated reference current and sensed grid current are then given to current controller to generate switching pulses for VSC.

C. Comparison of Proposed and Conventional Algorithm

The conventional approach [5]-[6] to estimate $I_{Lp}$ is shown at the bottom of Fig. 2. All salient internal signals of the proposed algorithm are shown in Fig. 3. It is easily observable from Fig. 3 that $i_p$ contains huge second harmonics component along with required DC component and higher order harmonics. The internal signals for removal of second order harmonics by DFTSOGI are shown in Fig. 3. It can be easily observed (from $I_{Lp}$) that the proposed DFTSOGI based method provides fast dynamic response as compared to conventional approach for same peak to peak ripples (from zoomed $I_{Lp}$) under steady state conditions.

IV. RESULTS AND DISCUSSION

The simulation results for steady state and dynamic conditions are shown in Fig. 4. The PV array peak power is considered as 4 kW and the load power is considered as 2 kW for this simulation study. The results for reactive power compensation, load variation and insolation variation are shown to demonstrate all the feature of the S-DSTATCOM. The system parameters are given in Appendix.

A. Behavior of System under Linear Loads at CPI

The behavior of S-DSTATCOM under linear loads at CPI is shown in Fig. 4 (a). Before, $t = 0.35$ s, the system is operating under steady state condition. It can be observed that the load current is lagging CPI voltage, however the grid current is out of phase of CPI voltage confirming unity power factor operation. The VSC supplies reactive power required by the load and the active power corresponding to SPV. At $t = 0.35$ s, the load is removed. The grid current increases in order to feed extra power corresponding to load power. No significant effect of load removal is observed on the DC link voltage and PV array parameters.

B. Behavior Under Nonlinear Loads and Insolation Variation

The behavior of S-DSTATCOM under nonlinear loads at CPI is shown in Fig. 4 (b). Before $t = 0.35$ s, the system is operating under steady state condition. One can observe that the load current is square wave but the grid current is sinusoidal. The VSC supplies the harmonics content of load current and sinusoidal current corresponding to solar power. At $t = 0.35$ s, the load is removed. The grid current is increased after load removal to feed the same solar power. The VSC current becomes sinusoidal after load removal as there are no load harmonics. No significant effect
of load removal is observed on the DC link voltage and PV array parameters.

The performance for insolation variation is also shown in Fig. 4 (b). At $t=0.5\ s$, the insolation is changed from $1000 \ W/m^2$ to $500 \ W/m^2$. The grid currents and the VSC current are decreased after decrease the in solar insolation. The decrease in PV power and the PV array current are clearly visible.

C. Harmonics Analysis

Figs. 4 (c)-(d) show the harmonics spectra of load current and grid current. Fig. 4 (c) shows
harmonics spectra of current fed load current. The THD of this load current is found around 41%. However, irrespective of this load current distortion, the THD of grid current is less than 1% which can be observed in Fig. 4 (d).

V. CONCLUSION
A single-phase two-stage DFTSOGI based control approach for S-DSTATCOM has been proposed. The proposed system not only feeds solar energy into the grid but also helps in power quality improvement at CPI. A wide variety of simulation results are shown to demonstrate all the features of the proposed system. The proposed approach solves the problem of tradeoff between steady state and dynamics performances, by providing fast dynamic response for similar steady state performance. A comparative study of proposed and conventional approach proves feasibility of the claim. The dynamic and steady state performances for the proposed S-DSTATCOM have been found satisfactory. The grid current THD is found well below 5% even under nonlinear load at CPI.

APPENDIX
Parameters for simulation: Single-phase grid voltage 230V, frequency = 50Hz, supply inductance = 2.5 mH and supply resistance = 0.8 Ω, interfacing inductor = 5 mH, ripple filter R = 5 Ω, C = 5µF, K_p = 0.4, K_i = 0.2, PV array open circuit voltage: 330 V, PV array short circuit current: 17 A PV array peak power: 4 kW, linear load: 2 kW, 0.8 lag, Current fed nonlinear load: diode bridge rectifier with RL load, 2 kW (R=21 Ω and L= 200 mH).

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