Abstract—This paper proposes an adaptive modified least mean fourth (MLMF) control scheme with perturb and observe (P&O) technique for a voltage source converter (VSC) connected to solar photovoltaic array (SPV), three single-phase non-linear loads in a three-phase, 4-wire system with DSTATCOM (Distributed Static Compensator) capabilities. The adaptive control scheme based on MLMF shows low mean square error and converges faster. The system is modelled and simulated for power factor correction and zero voltage regulation modes. Due to single stage topology, the system shows high efficacy at high voltages. The neutral load current is well compensated by the VSC’s fourth leg current. The harmonics in grid currents are well under the IEEE-519 standard.

Index Terms—VSC, P&O, SPV, PFC, ZVR and Power Quality.

I. INTRODUCTION

The increasing crisis of depleting non-renewable energy resources have led to a hunt for reliable and renewable sources of energy. The solar energy, being the most easily available and affordable, is the most dominant over all other replenishable sources [1].

A solar photovoltaic (SPV) array can be connected to the grid or can be operated as a stand-alone unit. An integration to the grid, provides a freedom to the SPV user regarding the usage of generated electricity to sell it to the grid or use it in self-premises. A single-stage topology of the system also shows enhanced efficiency for high voltages as compared to double-stage topologies [2]. To extract the maximum power from the SPV array, a perturb and observe (P&O) MPPT is used. This algorithm utilizes the voltage-power characteristics of the SPV and helps in maintaining the maximum power [3].

The SPV is integrated to a three-phase, 4-wire system with a voltage source converter (VSC). For the control of VSC, different control schemes like Icosφ algorithm [4], modified instantaneous symmetrical component theory [5], etc. are devised. An adaptive filter control theory like least mean fourth (LMF) with fixed step size [6], combined least mean square-least mean fourth (LMS-LMF) [7] are also proposed for three-phase, 3-wire systems, which show better performance than other adaptive control theories. Moreover, a new variable step-size filtered-x LMS algorithm [8] converges faster than a fixed step LMS. Based on similar grounds, modified LMF with variable step size is used in this paper.

In this paper, a control scheme is developed for a three-phase, 4-wire system integrated to a SPV array via a VSC with DSTATCOM capabilities. Using simpower toolbox, this system is then simulated in MATLAB/Simulink. The system’s response is obtained for power factor correction (PFC) mode and zero voltage regulation (ZVR) mode under various operating conditions such as disconnection of load in a phase, solar insolation variation, etc.

II. PROPOSED TOPOLOGY AND CONTROL APPROACH

The main components in the proposed system are three-phase, 4-wire grid tied SPV system, feeding three single-phase nonlinear loads as shown in Fig. 1. The VSC is connected to the system through interfacing inductors, which help in minimizing ripples in current. A ripple filter (Rf & Cf) is also connected in order to reduce ripples in the grid voltages. The reference DC link voltage is controlled by P&O MPPT algorithm as shown in Fig. 2. The switches of the VSC are gated by the pulses generated using MLMF. A fourth leg is provided in the VSC for the neutral connection of the system.

At first step, the terminal voltage, \( V_t \) is evaluated using the grid phase voltages \( (v_{ga}, v_{gb}, v_{gc}) \) [9] as:

\[
V_t = \frac{2}{\sqrt{3}} \left( v_{ga}^2 + v_{gb}^2 + v_{gc}^2 \right)
\]  

978-1-4799-5141-3/14/$31.00 ©2016 IEEE
Fig. 1. Proposed Topology

$V_t$ is then utilized to find the unit in-phase components of grid phase voltages,

$$u_{ia} = \frac{v_{go}}{V_t}, u_{ib} = \frac{v_{go}}{V_t}, u_{ic} = \frac{v_{go}}{V_t}$$

(2)

The unit quadrature-of-phase components of the voltages are evaluated as,

$$u_{ra} = \frac{-u_{ia} + u_{ib} - u_{ic}}{3}; u_{rb} = \frac{-u_{ia} - u_{ib} + u_{ic}}{3}; u_{rc} = \frac{-u_{ia} + u_{ib} + u_{ic}}{3}$$

(3)

At $(k+1)^{th}$ instant, the active in-phase weight component of the three phases are evaluated as [6],

$$w_{la}(k+1) = w_{la}(k) + \tau_{la}(k) * w_{ia}(k) * e_{la}^*(k)$$

(4)

$$w_{lb}(k+1) = w_{lb}(k) + \tau_{lb}(k) * w_{ib}(k) * e_{lb}^*(k)$$

(5)

$$w_{lc}(k+1) = w_{lc}(k) + \tau_{lc}(k) * w_{ic}(k) * e_{lc}^*(k)$$

(6)

Here, the error $e_{la_0}(k)$ is evaluated as,

$$e_{la_0}(k) = i_{la}(k) - u_{ia}(k) * w_{ia}(k)$$

(7)

$$e_{la}(k) = i_{la}(k) - u_{ia}(k) * w_{ia}(k)$$

(8)

$$e_{la}(k) = i_{la}(k) - u_{ia}(k) * w_{ia}(k)$$

(9)

And $\tau_{w_{la}}(k)$ represents the varying step-size component, where $m$ corresponds to phases, a, b, & c, and is derived by,

$$\tau_{w_{la}}(k) = \tau_{w_{la}}(k-1) - \beta \nabla J(k)$$

(10)

where the objective function $J(k)$ is represented as,

$$J_{la}(k) = \frac{1}{2} e_{la}^2(k) + \frac{1}{2} \alpha \tau_{w_{la}}^2(k-1)$$

(11)

$\alpha$ and $\beta$ being constants, ranging (0,1).

The equivalent value of in-phase active weight component ($w_{L_{la}}$) is given as,

$$w_{L_{la}} = \frac{w_{la} + w_{lb} + w_{lc}}{3}$$

(12)

The weight of PV power component ($w_{p_v}$) is evaluated as,

$$w_{p_v}(k) = \frac{2 P_{p_v}(k)}{3V_t}$$

(13)

The error between the DC Link voltage $V_{dc}(k)$ and the MPPT generated reference DC voltage, $V_{dc}^*(k)$, is fed to a PI (Proportional-Integral) regulator, whose output is taken to be $w_{Ad}$ and is expressed as,

$$w_{Ad}(k+1) = w_{Ad}(k) + K_p [e_{a}(k+1) - e_{a}(k)] + K_i e_{a}(k+1)$$

(14)

where $e_{a}(k) = V_{dc}^*(k) - V_{dc}(k)$

(15)

The total active in-phase weight component ($w_{As}$) is evaluated as,

$$w_{As} = w_{L_{la}} + w_{Ad} - w_{p_v}$$

(16)

The active in-phase reference currents are evaluated as,

$$i_{a_0} = w_{Ad} * u_{ia}; i_{b_0} = w_{Ad} * u_{ib}; i_{c_0} = w_{Ad} * u_{ic}$$

(17)

At $(k+1)^{th}$ instant, the reactive quadrature-of-phase weight component of the three phases are evaluated as,

$$w_{ra}(k+1) = w_{ra}(k) + \tau_{ra}(k) * u_{ia}(k) * e_{ra}^*(k)$$

(18)

$$w_{rb}(k+1) = w_{rb}(k) + \tau_{rb}(k) * u_{ib}(k) * e_{rb}^*(k)$$

(19)

$$w_{rc}(k+1) = w_{rc}(k) + \tau_{rc}(k) * u_{ic}(k) * e_{rc}^*(k)$$

(20)

Here, the error $e_{ra_0}(k)$ is evaluated as,

$$e_{ra_0}(k) = i_{ra}(k) - u_{ia}(k) * w_{ia}(k)$$

(21)

$$e_{ra}(k) = i_{ra}(k) - u_{ia}(k) * w_{ia}(k)$$

(22)

$$e_{ra}(k) = i_{ra}(k) - u_{ia}(k) * w_{ia}(k)$$

(23)

And $\tau_{w_{ra}}(k)$ represents the varying step-size component, where $m$ corresponds to phases, a, b, & c, and is derived by,

$$\tau_{w_{ra}}(k) = \tau_{w_{ra}}(k-1) - \beta \nabla J(k)$$

(24)

where the objective function $J(k)$ is represented as,

$$J_{ra}(k) = \frac{1}{2} e_{ra}^2(k) + \frac{1}{2} \alpha \tau_{w_{ra}}^2(k-1)$$

(25)

$\alpha$ and $\beta$ being constants, ranging (0,1).

The equivalent value of reactive quadrature-of-phase weight component ($w_{L_{ra}}$) is given as,

$$w_{L_{ra}} = \frac{w_{ra} + w_{rb} + w_{rc}}{3}$$

(26)
Fig. 2. Control algorithm

The error between the terminal voltage $V_t(k)$ and the reference terminal voltage $V_t^*(k)$, is fed to a PI regulator, whose output is taken to be $w_Rt$ and is expressed as,

$$w_Rt(k) + K_p \{e(k) - e(k-1)\} + K_i e(k-1)$$  \hspace{1cm} (27)

where $e(k) = V_t^*(k) - V_t(k)$  \hspace{1cm} (28)

The total reactive quadrature-of-phase weight component ($w_Rs$) is evaluated as,

$$w_Rs = w_Rt - w_Lsa$$  \hspace{1cm} (29)

The reactive quadrature-of-phase reference currents are evaluated as,

$$i_{Ra}^* = w_{Ra} u_{Ra}$$

$$i_{Rs}^* = w_{Rs} u_{Rs}$$

$$i_{Re}^* = w_{Re} u_{Re}$$

$$i_{Rs}^* = w_{Rs} u_{Rs}$$

$$i_{Re}^* = w_{Re} u_{Re}$$

$$i_{Rb}^* = w_{Rb} u_{Rb}$$

$$i_{Rc}^* = w_{Rc} u_{Rc}$$

$$i_{Rb}^* = w_{Rb} u_{Rb}$$

$$i_{Rc}^* = w_{Rc} u_{Rc}$$

$$i_{Rc}^* = w_{Rc} u_{Rc}$$

The total reference currents are evaluated as,

$$i_{Ra}^* + i_{Rb}^* + i_{Rc}^* = i_{Ra}^* + i_{Rb}^* + i_{Rc}^* = i_{Ra}^* + i_{Rb}^* + i_{Rc}^*$$

And the neutral reference current is taken as,

$$i_{gn}^* = 0$$  \hspace{1cm} (30)

The hysteresis current controller is used to generate the required gating pulses of the VSC, by comparing the reference grid currents ($i_{Ra}^*$, $i_{Rb}^*$, $i_{Rc}^*$, $i_{gn}^*$) and sensed supply currents ($i_{Ra}$, $i_{Rb}$, $i_{Rc}$, $i_{gn}$).

III. RESULTS AND DISCUSSION

A model of a three-phase 4-wire grid-tied SPV system constituted of VSC, SPV and three single-phase non-linear loads is developed in MATLAB/Simulink. The behavior under PFC and ZVR modes is studied in detail. The obtained responses under steady and dynamic conditions are studied in detail by analyzing the waveforms of grid voltages ($v_{gabc}$), grid currents ($i_{gabc}$), grid active power ($P_g$), grid reactive power ($Q_g$), load currents ($i_{labcn}$), reference grid currents ($i_{gabcn}^*$), DC-link voltage ($V_{dc}$), currents of the four legs of VSC ($i_{abcm}$), SPV current ($I_{pv}$), SPV voltage ($V_{pv}$), SPV power ($P_{pv}$), terminal voltage ($V_t$) and solar insolation ($G_{pv}$). The parameters taken for the system are reported in Appendix.

A) Steady State Response of SPV Grid Tied System under Nonlinear Load

Figs. 3 (a-b) show the response of the system when a nonlinear load is connected across it. Fig. 3 (a) shows at under steady condition, the $P_{pv}$ remains constant, and $Q_{g}$ is also zero implying no reactive power is drawn or given to the grid. Fig. 3 (b) shows the non-sinusoidal load current ($i_{la}$), while the reference grid currents ($i_{la}^*$) generated are sinusoidal. Moreover, the sum of neutral current flowing in loads is equal to that generated by the VSC, thus, no neutral current flows in the grid.
Figs. 3 (a-b) Response of SPV grid tied system to non-linear load in steady state.

Fig. 4 (a) shows the THD (Total Harmonic Distortion) of ila, which is 32.43% because of non-sinusoidal nature of current. All odd harmonics are present in this current. Fig. 4 (b) shows the FFT analysis of iga. Here, the THD of grid current is 0.85%, which is in the limit of IEEE-519 standard [10].

B) Effect of Load Disconnection of Phase ‘a’ on SPV Grid Tied System in PFC Mode

Fig. 5 (a) depicts the output waveforms when the load is disconnected from phase ‘a’ at 0.4 sec. The current in phase ‘a’ (iₐ) becomes zero while currents in phases ‘b’, ‘c’ and in the load neutral conductor are increased. The neutral current of the grid (iₙ) remains zero even after the load disconnection.

Fig. 5 (b) shows the variation of $e_{As}$, $e_{As}^3$, $u_{As}$, $\tau$, and various weights of the system. $w_{As}$ decreases as $w_{LAs}$ decreases on the disconnection of load in phase ‘a’. The variation in $\tau$ with time can be seen from this figure. Here, $\tau$ keeps on varying depending on its previous value and value of ‘e’ at a given instant of time.
C) Effect of Load Disconnection of Phase ‘a’ on SPV Grid Tied System in ZVR mode

Figs. 6 (a-b) show the impact of disconnection of load of phase ‘a’. As it can be seen that, \( V_t \) is maintained constant and equal to nominal terminal voltage \( (V_t^* = 340 \text{ V}) \) irrespective of load variations. The current in phase ‘a’ \( (i_{la}) \) becomes zero and the currents in phases ‘b’, ‘c’ remain same as that of their previous values while the current in the load neutral conductor increases. The neutral current of the grid \( (i_{ln}) \) remains zero even after the disconnection. From here, it can be easily seen that ZVR and PFC modes can’t occur at the same time, either of the two is possible at a particular time.

D) Impact of Varying the Solar Insolation Level on SPV Grid Tied System

Figs. 7 (a-b) depict the effect of variable solar insolation on the system. The \( G_{pv} \) is increased from 600 W/m² to 1000 W/m². As a result, \( I_{pv} \) also increases, and so it does in \( P_{pv} \). The grid currents in the phases \( (i_{gabc}) \) are increased, while the grid neutral current \( (i_{gn}) \) remains zero.
IV. CONCLUSION

The behavior of a three-phase four-wire distribution system interfaced to a SPV and VSC has been studied under a nonlinear load and its performance has been found satisfactory. An adaptive control algorithm has provided the fast convergence. The impact of load disconnection in PFC and ZVR modes has also been analyzed. The effect of connecting a fourth leg in the VSC to decrease the harmonics in the grid currents has been thoroughly investigated. The maximum power has been extracted from the system under various operating conditions. The impact of varying the solar insolation level on the system has also been studied in detail.

APPENDICES

SPV Array: Current of individual module, \( I_{mp} = 7.61 \) A; Voltage of individual module, \( V_{mp} = 26.3 \) V; Power of SPV array, \( P_{mp} = 54 \) kW; \( N_s = 27; N_p = 10 \); AC Supply: 3-phase, 4-wire, 415 V at 50 Hz; Ripple Filter: \( R_f = 5 \) \( \Omega \), \( C_f = 10 \mu F \); Load: Three single-phase non-linear loads, \( R = 20 \) \( \Omega \), \( L = 100 \) mH; \( L_f = 3 \) mH; Rating of VSC = 60 kVA; \( C_{dc} = 12 \) mF; \( V_{dc} = 710 \) V; \( V_{r} = 340 \) V; \( Kp1 = 4 \) and \( K_i1 = 0.75 \); \( Kp2 = 4 \) and \( K_i2 = 0.75 \); \( \alpha = 0.0001 \), \( \beta = 0.001 \); sampling time, \( T_s = 10 \) \( \mu s \).

ACKNOWLEDGMENT

The authors are highly thankful to DST, Govt. of India, for supporting this project under Grant Number: RP02583.

REFERENCES