Performance of Single Phase PV Integrated DSTATCOM Operating in Polluted Utility Condition

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***Abstract*—In this paper, a control technique based on cascaded second order-generalized integrator (CSOGI) is presented for the control of single phase photovoltaic integrated distribution static compensator (PV-DSTATCOM). The system compensates for reactive power and harmonics in the load current along with injecting power from PV array. Two SOGI blocks are used to extract the fundamental component of grid voltage and load current which is then used in control of PV-DSTATCOM. Due to the cascaded structure, CSOGI can better filter the third and fifth harmonic voltage present in the grid and can extract the fundamental component. Maximum power point tracking (MPPT) algorithm is used to get the reference voltage for dc-link voltage control. System performance is evaluated by simulating it in MATLAB/Simulink environment under dynamic conditions like irradiation and load change.**

***Keywords*—Power quality, PV-DSTATCOM, CSOGI, MPPT.**

I. Introduction

Day by day, power generation through renewable sources is increasing due to environmental issues arising from fossil fuels. Grid connected systems are extensively used for distributed power generation. But grid connected renewable generation would create power quality issue in the grid. Renewable energy generation sources are intermittent and have high fluctuations due to time dependent nature of renewable energy. As renewable energy penetration increases over time, these high fluctuations would create serious challenges to the power quality in the grid. Different kinds of loads draw current according to their real and reactive power needs. Nonlinear loads like switch mode power supplies (SMPS), controlled and uncontrolled rectifiers draw harmonic power and thus create power quality problem in the utility grid. Power quality is one of the important parameters for efficient functioning and stability of the grid.

Static compensator with the help of fixed capacitor is traditionally used to improve power quality related problems.But it comes with many limitations like fixed system dependent performance, fixed compensation, and resonance with line reactance [1]. DSTATCOM has been introduced in the literature which helps in solving these power quality problems. It is a shunt compensator device which when connected in parallel with nonlinear load can fulfill the harmonic current demand of non-linear loads. DSTATCOM, with the help of control algorithm, draws only sinusoidal current from the grid when the load connected at the point of common coupling (PCC) is nonlinear. Control requires sensing of grid current, grid voltage, load current and voltage of dc link capacitor. In [2], control algorithms have been described for active power filtering and their comparison has also been given. In [3], control based on state feedback is described. Other types of control are also being presented in the literature. Different DSTATCOM topologies have been used and control algorithms are selected accordingly. But some researchers have changed the system for implementing control algorithm [4]–[7]. For single phase system, a different topology other than traditional converter has been proposed in [4]. Control technique model DSTATCOM and load collectively as a resistor. In [5], control is implemented with the help of power that makes it an intricated technique.

A major part of DSTATCOM is to extract fundamental component from the grid voltage. The success of DSTATCOM depends upon how well it can generate the reference signal [8]. Various Phase locked loop (PLL) and their control have been described to extract the fundamental component of grid voltage in the literature [9]. Some of the important PLL are E-PLL, SRF-PLL, SPLL, and power based PLL in [8], [10]–[12]. A digital adptive notch filter (DANF) based filter has been used for extracting fundamental component of load current and grid voltage [13]. Second order generalized Frequency locked loop (SOGI-FLL) has been proposed in [14] which gives good performance under distorted conditions. In [15], Cascaded SOGI-Band Pass Filter (CSOGI-BPF) has been used to extract the fundamental component of grid voltage for UPQC operating under polluted condition. But to extract active fundamental component of load current, series combination of CSOGI-BPF and diginal signal cancellation (DSC) has been employed. A CSOGI scheme has been reported in [16] which has dc-offset rejection capability. Every PLL has their own pros and cons. SOGI is a simple PLL which has a less computational burden. But accurate extraction of fundamental component is difficult when harmonics closer to fundamental frequency are sufficiently present in the signal.

In this paper, CSOGI is used to extract the fundamental component of load current and grid voltage which are used to calculate the active fundamental component of load current. This scheme is particularly useful when the load current contains dc-offset current. The PV array is directly connected to PV-DSTATCOM. The reference PV voltage (dc-link voltage) is calculated with the help of MPPT algorithm. Gate pulses are generated through the hysteresis controller. The complete system is tested under changing load and irradiation conditions. The CSOGI algorithm is tested under distorted grid conditions.

II. PV-DSTATCOM and System Configuration

PV-DSTATCOM is a voltage source converter (VSC) with integrated PV array. It consists of power semiconductor switches (S_1,S_2,S_3,S_4), filter component (L_f), ripple filter (R_f,C_f) and a dc link capacitor (C_{pv}). This device is connected at PCC between grid and PV-DSTATCOM through inductors (L_{L1},L_{L1}).

Schematic diagram of PV-DSATCOM is shown in Fig. 1. Full bridge converter has been used to implement PV-DSTATCOM. The switches are controlled with the help of gate pulses generated from the CSOGI based control algorithm. PV array is connected to the dc link capacitor via reverse blocking diode which prevents the power flowing into the PV array. Sizing of DC link capacitor, filter component, and ripple filter can be done after PV array power, approximate load to be compensated for and the dc link voltage is decided. Full bridge converter draws maximum power from the PV array with the help of MPPT algorithm.

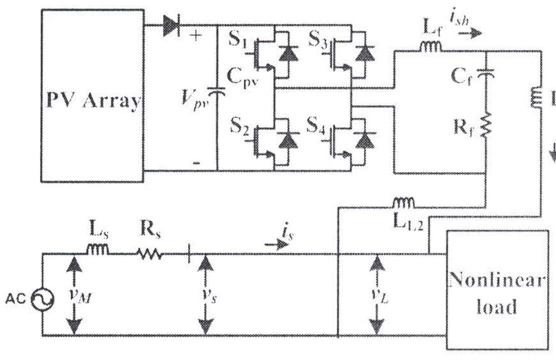


Fig. 1. Schematic diagram of PV-DSTATCOM.

III. Control Sturcture of PV-DSTATCOM

The complete control structure is shown in Fig. 2. Nonlinear loads require active and reactive power of which the active component partly comes from the grid and partly from the PV array while the reactive power is wholly supported by PV-DSTATCOM. So, the reference current i_s^* should have active as well as reactive component which is calculated by adding three components: a) PV array component (I_{PVg}) b) Active load current component (I_{FLa}) and c) Loss component (I_{loss}).

These three components of magnitude of reference current I_s^* are calculated as follows:

A. Estimation of PV array components (I_{PVg})

The PV component of current is calculated with the help of V_{pv},I_{pv} and V_s by eq. 1

$$I_{pvg} = 2\frac{V_{pv}I_{pv}}{V_s} \tag{1}$$

B. Estimation of Loss components (I_{loss})

Estimation of the loss component (I_{loss}) of reference current (i_s^*) is based upon a PI controller. The dc-link voltage (V_{dc}) is sensed and low passed and is compared with dc-link reference voltage (V_{dc}^*) which is obtained with the help of MPPT algorithm. The generated error signal of these two signals is given to a PI controller which ultimately generates the loss component (I_{loss}).

C. Estimation of Active load current components (I_{FLa})

Active component of fundamental of load current (I_{FLa}) is calculated with the help of eq. 2.

$$\begin{aligned} I_{FLa} &= I_{FL}\cos(\phi_{i_L} - \phi_{v_s}) \\ &= I_{FL}(\cos\phi_{i_L}\cos\phi_{v_s} + \sin\phi_{i_L}\sin\phi_{v_s}) \end{aligned} \tag{2}$$

where I_{FL}, $\cos(\phi_{v_s})$, $\sin(\phi_{v_s})$, $\cos(\phi_{i_L})$ and $\sin(\phi_{i_L})$ have been estimated from the CSOGI algorithm.

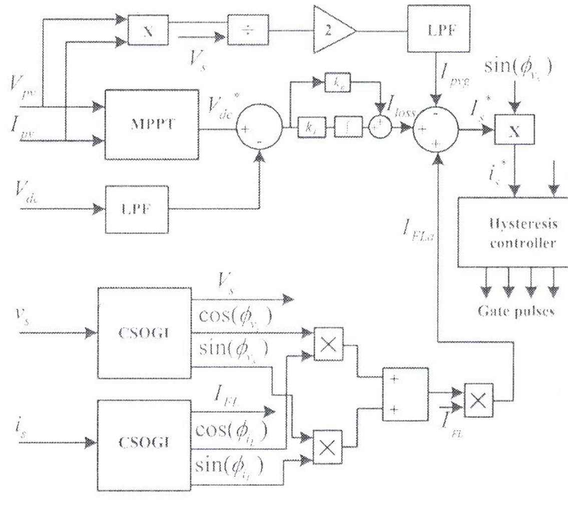


Fig. 2. Complete control structure of PV-DSTATCOM.

After calculating the magnitude of reference current (I_s^*), the reference current (i_s^*) is calculated by multiplying it with the grid voltage template ($\sin(\phi_{v_s})$) which has been obtained from the application of grid voltage to CSOGI algorithm. Finally, the reference current signal (i_s^*) and grid current (i_s) are applied to the hysteresis controller to obtain the gate pulses for PV-DSTATCOM.

The main component of PV-DSTATCOM is CSOGI which is used to extract the in phase, quadrature phase, and magnitude of fundamental grid voltage and load current. CSOGI is a phase locked loop where two SOGI blocks are used in cascade so that it can better extract the fundamental signal even when 3^{rd} and 5^{th} harmonics are present in the grid voltage and load current. The control structure of CSOGI is shown in Fig. 3. The value of gain K_1 and K_2 is adjusted to get the accurate fundamental signal.

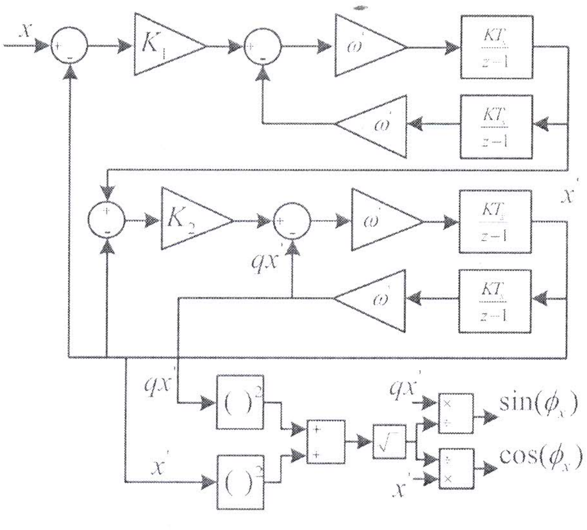


Fig. 3. Complete structure of CSOGI

IV. RESULTS AND DISCUSSION

The PV-DSTATCOM based on CSOGI is simulated in MATLAB/Simulink environment and its performance is evaluated. Two parallel string, each having thirteen series connected Soltech 1STH-FRL-4H-260-M60-BLK based solar panel has been used as PV array to obtain the required power. Specifications of the PV array has been provided in Table I. A diode bridge rectifier that is used as a nonlinear load is connected at the PCC with the help of two inductors. It draws reactive and active current but the grid current which is drawn from grid is active only. The reactive current comes from the PV-DSTATCOM. The harmonics drawn by the load are supplied by PV-DSTATCOM. The complete system is tested under changing radiation and changing load conditions. The CSOGI is tested when 3^{rd} and 5^{th} harmonics are present in the grid voltage.

A. *Performance under changing irradiation condition*

The system is simulated under varying irradiation conditions as shown in Fig. 4. The grid voltage and current (v_s and i_s), load current (i_L), PV-DSTATCOM current (i_{sh}), PV array voltage and current (v_{pv} and i_{pv}) and irradiation (G) have been shown in Fig. 4. Irradiation (G) is changed from 1000 W/m^2 to 500 W/m^2 in 0.05 sec from 4.1 sec to 4.15 sec. Upto 4.1 sec, sufficient power is available from the PV array so nonlinear load draws less current from grid but after 4.1 sec, PV array power starts gradually dropping, it begins to draw more current from the grid.

TABLE I
SPECIFICATIONS OF SOLAR PV ARRAY

Parameter	Value
Open circuit voltage(V_{oc})	501.8 (V)
Short circuit current(I_{sc})	17.86 (A)
Voltage at Maximum power point(V_{mp})	410.8 (V)
Current at maximu power point(I_{mp})	16.42 (A)
Maximum power(P_{mp})	6.75 (kW)

The harmonic analysis of grid current (i_s) and load current (i_L) at 1000 W/m^2 solar irradiation is presented in Fig. 5. The grid current total harmonic distortion (THD) is 2.63 % while load current THD is 35.55 %.

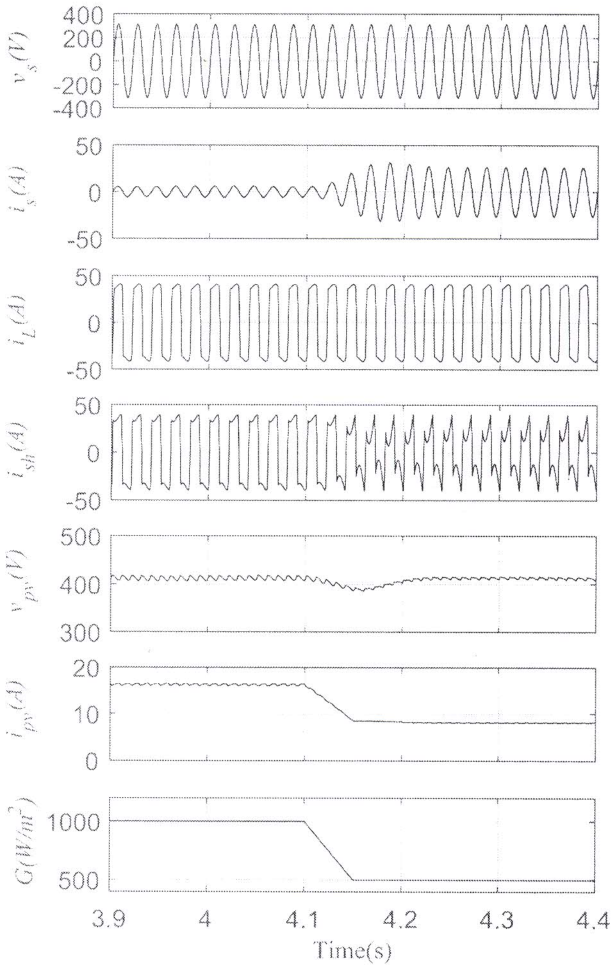
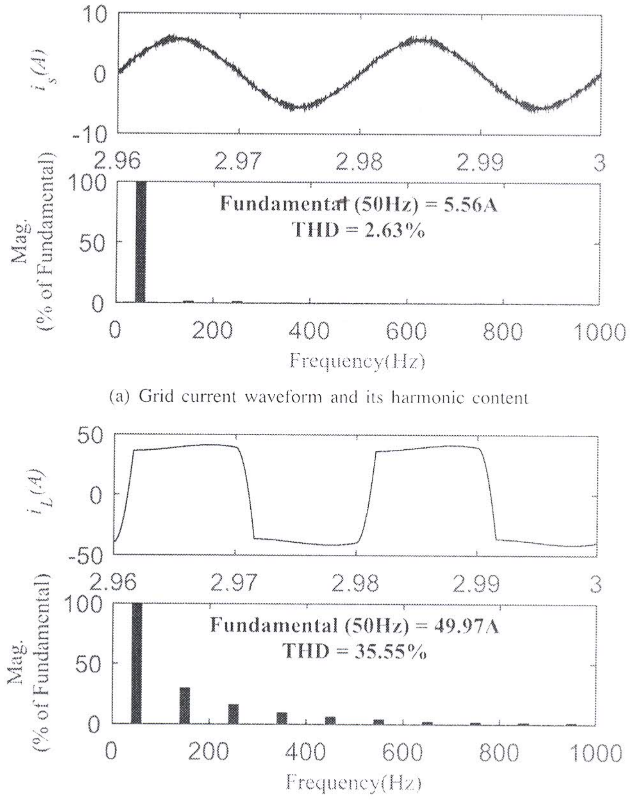


Fig. 4. Simulation results under changing irradiation conditions.



(a) Grid current waveform and its harmonic content

(b) Load current waveform and its harmonic content

Fig. 5. Harmonic analysis of grid and load current

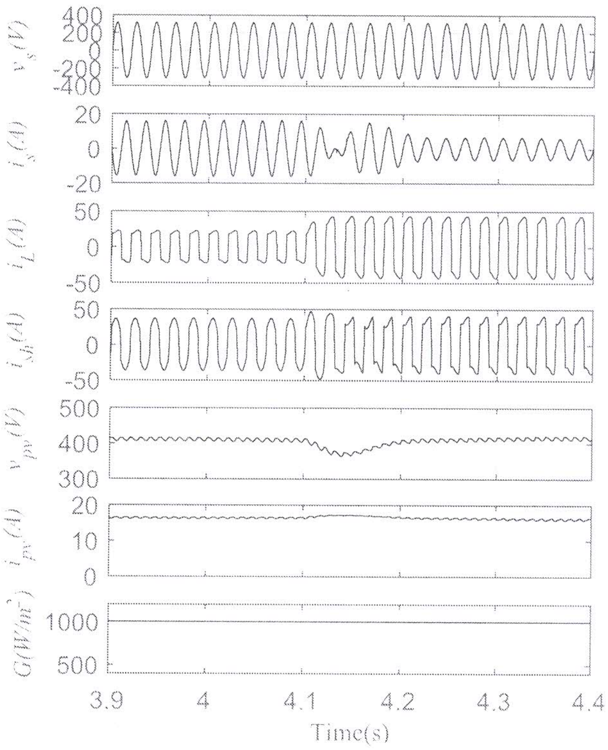


Fig. 6. Simulation results under load change conditions.

B. *Performance under changing load condition*

The system is simulated while the load is changed from 50 % to 100 %. Fig.6 shows the response of PV-DSTATCOM under step load change.The grid voltage and current (v_s and i_s), load current (i_L), PV-DSTATCOM current (i_{sh}), PV array voltage and current (v_{pv} and i_{pv}) and irradiation (G) have been shown in Fig. 6. At 4.1 sec, the load is changed from 50 % to 100 %. The grid current settles within 0.12 sec. The PV current is maintained at 16.42 A because the PV array operates at maximum power point. The load current has increased which results in less current being pumped into the grid by PV-DSTATCOM.

C. *Performance of CSOGI under distorted grid condition*

The system is simulated when grid voltage is polluted with 3^{rd} and 5^{th} harmonics. Performance of CSOGI is presented in Fig. 7. It is to be observed that the extracted in-phase grid voltage ($\cos\phi_{v_s}$) and in-phase load current ($\cos\phi_{i_L}$) have less than 5 % of harmonic content while grid voltage harmonic is 5.39 % and load current harmonic is 35.55 %.

V. Conclusion

A control technique based on CSOGI for PV-DSTATCOM has been implemented for reactive power and harmonic compensation. It has been simulated in MATLAB/Simulink environment and its performance is evaluated under distorted grid conditions, changing irradition and load conditions. PV-DSTATCOM and its control based on CSOGI perform satisfactorily when lower order harmonics like 3^{rd} and 5^{th} are present in the grid. The grid current THD has been found to be within the standard limit of 5 % set by IEEE 519-1992 under all testing conditions.

VI. Acknowledgement

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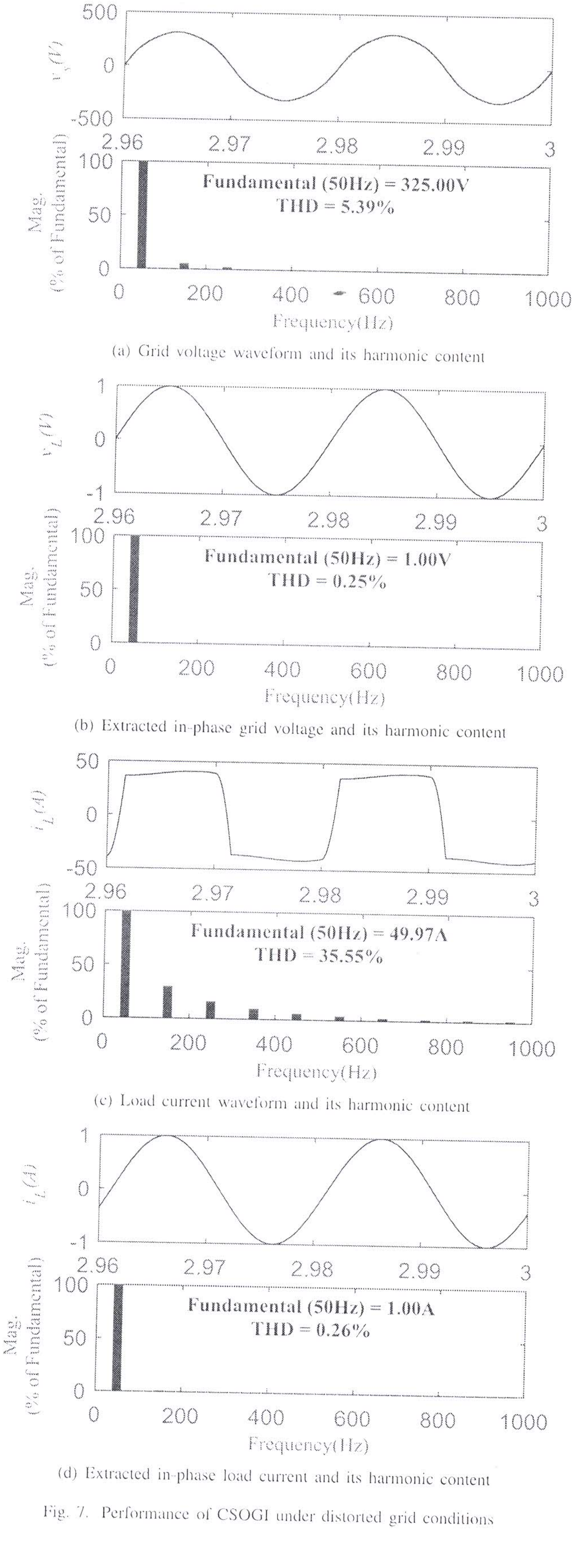
Appendix

System Parameter: Line voltage: Fundamental($V_{1,h}$) = 230V (50 Hz-ac), 3^{rd} Harmonic ($V_{3,h}$) = 5 % of $V_{1,h}$, 5^{th} Harmonic ($V_{5,h}$) = 2 % of $V_{1,h}$; Load: Uncontrolled Rectifier based on full bridge topology with R-L load: R = 5 Ω, L = 100 mH, DClink voltage(PV voltage) = 410V; DC-link Capacitor:4 mF, CSOGI for load current: $K1$ = 0.1, $K2$ = 1; CSOGI for grid voltage: $K1$ = 0.5, $K2$ = 1; PI-controller gains of DC-link controller: K_p = 0.5, K_i = 0.1

References

[1] S. Ostroznik, P. Bajec, and P. Zajec, "A study of a hybrid filter," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 3, pp. 935-942, March 2010.



(a) Grid voltage waveform and its harmonic content

(b) Extracted in-phase grid voltage and its harmonic content

(c) Load current waveform and its harmonic content

(d) Extracted in-phase load current and its harmonic content

Fig. 7. Performance of CSOGI under distorted grid conditions

[2] G. W. Chang and T.-C. Shee, "A comparative study of active power filter reference compensation approaches," in *IEEE Power Engineering Society Summer Meeting,*, vol. 2, July 2002, pp. 1017–1021 vol.2.

[3] A. Ghosh and G. Ledwich, "Load compensating dstatcom in weak ac systems," *IEEE Transactions on Power Delivery*, vol. 18, no. 4, pp. 1302–1309, Oct 2003.

[4] M. Angulo, D. A. Ruiz-Caballero, J. Lago, M. L. Heldwein, and S. A. Mussa, "Active power filter control strategy with implicit closed-loop current control and resonant controller," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 7, pp. 2721–2730, July 2013.

[5] M. Routimo, M. Salo, and H. Tuusa, "Current sensorless control of a voltage-source active power filter," in *Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, 2005. APEC 2005.*, vol. 3, March 2005, pp. 1696–1702 Vol. 3.

[6] K. Kant, S. R. Arya, and B. Singh, "Voltage sensorless control algorithm for power quality improvement in distribution network," in *2014 Eighteenth National Power Systems Conference (NPSC)*, Dec 2014, pp. 1–6.

[7] M. Salo, "Ac current sensorless control of the current-source active power filter," in *2005 IEEE 36th Power Electronics Specialists Conference*, June 2005, pp. 2603–2608.

[8] B. Singh and J. Solanki, "A comparison of control algorithms for dstatcom," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 7, pp. 2738–2745, July 2009.

[9] G.-C. Hsieh and J. C. Hung, "Phase-locked loop techniques. a survey," *IEEE Transactions on Industrial Electronics*, vol. 43, no. 6, pp. 609–615, Dec 1996.

[10] F. Gonzalez-Espin, E. Figueres, and G. Garcera, "An adaptive synchronous-reference-frame phase-locked loop for power quality improvement in a polluted utility grid," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 6, pp. 2718–2731, June 2012.

[11] F. Liccardo, P. Marino, and G. Raimondo, "Robust and fast three-phase pll tracking system," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 221–231, Jan 2011.

[12] Q. Zhang, X. D. Sun, Y. R. Zhong, M. Matsui, and B. Y. Ren, "Analysis and design of a digital phase-locked loop for single-phase grid-connected power conversion systems," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 8, pp. 3581–3592, Aug 2011.

[13] S. Devassy and B. Singh, "Discrete adaptive notch filter based single phase solar pv integrated upqc," in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, July 2016, pp. 1–5.

[14] Z. Xin, R. Zhao, P. Mattavelli, P. C. Loh, and F. Blaabjerg, "Re-investigation of generalized integrator based filters from a first-order-system perspective," *IEEE Access*, vol. 4, pp. 7131–7144, 2016.

[15] S. Devassy and B. Singh, "Control of solar photovoltaic integrated upqc operating in polluted utility conditions," *IET Power Electronics*, vol. 10, no. 12, pp. 1413–1421, 2017.

[16] A. Kulkarni and V. John, "Design of a fast response time single-phase pll with dc offset rejection capability," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, March 2016, pp. 2200–2206.