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Modeling, Simulation and Control of Photovoltaic Based DSTATCOM

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Abstract**—** Due to extensive use of automatic and power electronic based devices in an electric distribution system, power quality problems have substantially increased. The paper presents an effective solution to the said power quality problems via complete modeling; simulation and control of 3-phase 3-leg Distribution Static Compensator (DSTATCOM) is fed by PV module using different control algorithms. The DSTATCOM is a three wire/leg voltage source Converter (VSC) with a DC link capacitor. The PV module is used to regulate the DC link voltage. Power quality improvement is achieved in terms of power factor improvement, harmonic reduction and DC link voltage control. The performance evaluation of DSTATCOM in Unity Power Factor (UPF) and AC voltage control (ACVC) modes using different control theories is presented. The proposed power quality mitigation solution is demonstrated via simulation platform using MATLAB/Simulink software. The simulation results obtained in output waveforms of source voltage, source currents, load currents, DC voltage and point of common coupling (PCC) voltage justify the effectiveness of the proposed solution. The comparative performance is also presented of different controllers in terms of DC link voltage, PCC voltage and harmonic distortions.

Keywords**—** IRP, PCC, Power quality, SRF, Unit template.

NOMENCLATURE

v_{abc}	Source voltage
i_{abc}	Source current
i_L	Load current
$i^*_{sa}, i^*_{sb}, i^*_{sc}$	Refernce source current
R_s, L_s	Source resistance, source inductance
R_f, L_f	Interfacing Resistance, Inductance
PCC	Point of common coupling
V_{dc}	DC voltage
V^*_{dc}	Reference DC voltage
V_{dce}	DC voltage error
V_t	PCC voltage
V^*_t	Reference PCC voltage
K_p	Proportional gain controller
K_i	Integral gain controller

I. INTRODUCTION

Due to the wide requirement of electrical energy, a lot of research investigations are going in the field of Renewable Energy sources. Solar Photovoltaic is a widely used renewable energy source. Continuous efforts are going on for performance improvement of applications in the field of electrical energy. On the other hand, due to the use of nonlinear and sensitive loads in the distribution system, power quality becomes the major issue of concern as it injects harmonics and reactive power into the distribution system [1]-[5]. Poor power quality results in poor power factor, waveform distortion, and inclusion of harmonics [3]-[6]. All power quality mitigation controllers, which are used in distribution systems, are known as custom power devices (CPD's) [1], [3]-[6]. In this paper DSTATCOM is used as the solution of

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power quality problems [1], [2], [7]-[13]. DSTATCOM is shunt connected custom power device [1], [2], [7]-[13]; and it is widely used for power quality improvement. The control of DSTATCOM is mainly dependent upon the control theories [1], [2], [7]-[13], which are used to generate reference source current. A new area has come up as the application of solar photovoltaic for power quality improvement. This paper includes designing, modeling and simulation of photovoltaic system [14]-[16] along with its application as photovoltaic based DSTATCOM in distribution systems to meet power quality standards [17].In this paper, the recent developments are summed up and presented as photovoltaic based DSTATCOM [18]-[23]. To control the DSTATCOM Synchronous Reference Frame (SRF), Instantaneous Reactive Power (IRP) and unit template based algorithms [7]-[13] are used.
In the proposed system, the modeling of solar Photovoltaic is initially done using its basic equations [13]-[16]; simulation is performed on MATLAB. The DSTATCOM is modeled in the form of three phase three leg voltage source converter (VSC); and switching is controlled by different controllers. Reference currents are generated using controllers and compared with actual source currents. This error signal is used to feed the signals for PWM generators for generating switching signals for DSTATCOM [10]-[13]. Effectiveness of controllers is shown by the balanced source current, while unbalancing at the load side is present. Unbalanced condition in the phases is created using a circuit breaker tool within the specified time. Harmonic analysis is done using FFT analysis; and THD is calculated for source voltage, source currents and load currents. Simulation results demonstrate the effectiveness of controllers of DSTATCOM for power quality improvement in terms of harmonic reduction, power factor improvement and DC link voltage regulation under the unbalanced conditions.

II. SCHEMATIC REPRESENTATION

Fig. 1 shows the basic system configuration of PV based DSTATCOM. DSTATCOM is a three-phase three-leg voltage source inverter connected in shunt with load; and its DC side is fed through the PV array. Interfacing resistances and inductors are used to connect the DSTATCOM with the line. Modeling and simulation of PV array is done in MATLAB [13]-[16]. In this work, irradiation level is considered constant at 1000W/m^2 .Three types of controllers are used here to control the switching of DSTATCOM. All the design and control parameters of the proposed system are given in Appendix.

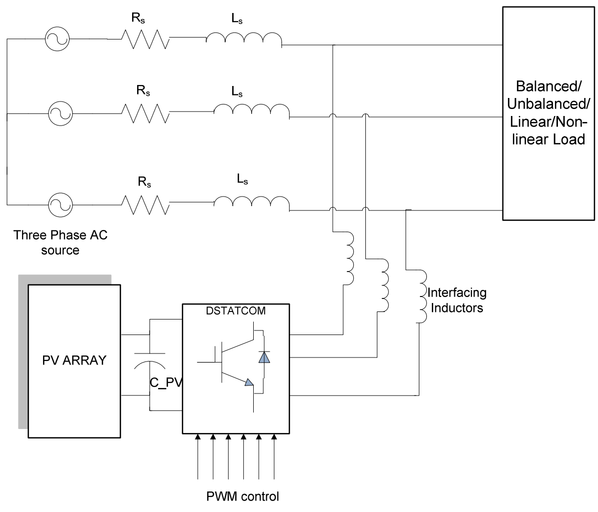


Fig. 1. Schematic representation

III. MODELING OF PV ARRAY

The electrical equivalent circuit of a solar PV cell [13]-[16] is shown in Fig. 2. Its *I-V* characteristics are given by the following relationship:

$$I = I_L - I_0 \left(e^{\frac{q(V - IR_S)}{AKT}} - 1 \right) - \frac{V - I\,R_S}{R_{SH}} \tag{1}$$

Where I is the solar cell output current; V is the solar cell output voltage; I_0 is the diode saturation current; q is the charge of an electron ($1.602\mathrm{x}10^{-19}$C); A is the diode quality factor; K is the Boltzmann constant ($1.381\mathrm{x}10^{-23}$J/K); T is the absolute temperature (K); R_s is the series resistances of the solar cell; and R_{SH} is the shunt resistances of the solar cell.
The *I-V* characteristic of a PV Array/module is given by the following equation, where n_s and n_p are the number of series and parallel solar cells respectively:

$$I \approx n_p I_L - n_p I_0 \left(e^{\frac{q(V - IR_S)}{n_S AKT}} - 1 \right) \tag{2}$$

With the help of these equations, a 100kW PV array has been modeled in MATLAB. *I-V* and *P-V* characteristics are shown in Fig. 3 for different irradiation levels.

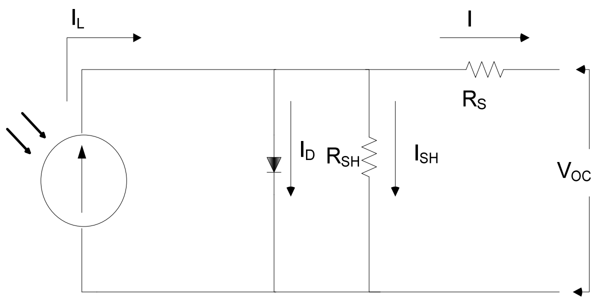


Fig. 2. Equivalent circuit of PV array

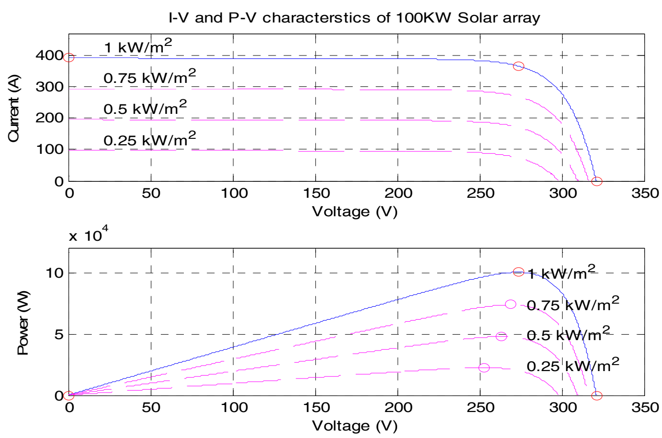


Fig. 3. *I-V* and *P-V* characteristics of 100kW solar array

IV. CONTROL ALGORITHMS

A. Synchronous Reference Frame (SRF) Based Control Theory

The SRF theory is also known as *dq* control algorithm because, in this theory, three-phase currents are converted into the synchronously rotating *dq* frame [2], [8], [10]-[13], [18]-[20],

[23]. This theory uses the following equations for a transformation known as Park's transformation [10]-[13]:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = 2/3 \begin{bmatrix} \sin\omega t & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos\omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{3}$$

The flow diagram of SRF based controller is shown in Fig. 4. In the given figure, the average values of i_d and i_q are estimated after passing these values from low pass filters. Two PI regulators are used: one is to maintain the DC link voltage as constant; and another is to regulate the PCC voltage as constant. These values are represented by i_{cd} and i_{cq}; and can be found out with the help of the following equations [2], [10]-[13], [18]-[20], [23]:

$$i_{cd} = K_{pd} V_{dce} + K_{id} \int V_{dce}\, dt \tag{4}$$

$$i_{cq} = K_{pq} V_e + K_{iq} \int V_e\, dt \tag{5}$$

Where V_{dce} is the error in DC voltage, which is the difference between reference DC link voltage and actual voltage of DC bus of DSTATCOM (PV array voltage); K_{pd} and K_{id} are the gains of Proportional and Integration controllers; and V_e is the error of the PCC voltage. Reference values in d_q frame (i^*_d and i^*_q) are obtained by adding the components i_{cd}, i_{cq} and the outputs of low pass filters. Finally, reference source currents (i^*_{sa}, i^*_{sb}, i^*_{sc}) are obtained with the help of Inverse Parks transformation as [10]-[12]:

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = 2/3 \begin{bmatrix} \sin\omega t & \cos\omega t \\ \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i^*_{sd} \\ i^*_{sq} \end{bmatrix} \tag{6}$$

The above obtained currents (i^*_{sa}, i^*_{sb}, i^*_{sc}) and actual source currents are compared; and error is generated. This error signal is used to generate the pulses for DSTATCOM.

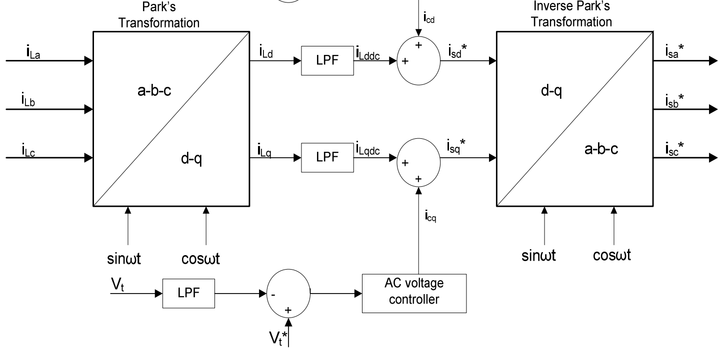


Fig. 4. SRF based control algorithm of DSTATCOM

B. Instantaneous Reactive Power (IRP) Control Theory

The block representation of IRP theory [7], [9], [10]-[13] is given in Fig. 5. In this theory, PCC voltage and currents are converted into α-β frame using the Clark's transformation [10]-[13], [23] with the use of the following equations:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{8}$$

With the help of PCC voltage and load current values in α-β frame, instantaneous values of active and reactive power are calculated. It has two components dc and ac. To extract the dc values of load power, low pass filters are used. Reference values of active (p^*) and reactive power (q^*) can be calculated with the help of the following equation [10]-[13]:

$$p^* = p_{dc} + p_{loss} \tag{9}$$

$$q^* = q_{VR} + q_{dc} \tag{10}$$

In UPF mode, q^* is kept zero to maintain the unity power factor. In ACVC mode, the extra reactive power and the load reactive power are supplied by the DSTATCOM to compensate the voltage drop in the source impedance. The active power is supplied by the source [21], [23]. Two *PI* regulators are used to maintain the DC link voltage and PCC voltage. The same regulators are used in SRF controller.

The estimated power is used to obtain the currents in α-β frame and extract reference source currents as [10]-[13], [23]:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v^2{}_\alpha + v^2{}_\beta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p^* \\ q^* \end{bmatrix} \tag{11}$$

Then, the source currents i_α and i_β are converted into three-phase source currents using inverse Clark’s transformation [10]-[13], [23] as:

$$\begin{bmatrix} i*_{sa} \\ i*_{sb} \\ i*_{sc} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i*_\alpha \\ i*_\beta \end{bmatrix} \tag{12}$$

Reference source currents and actual currents are compared; and an error signal is generated. This error signal is used to give a switching signal to the DSTATCOM.

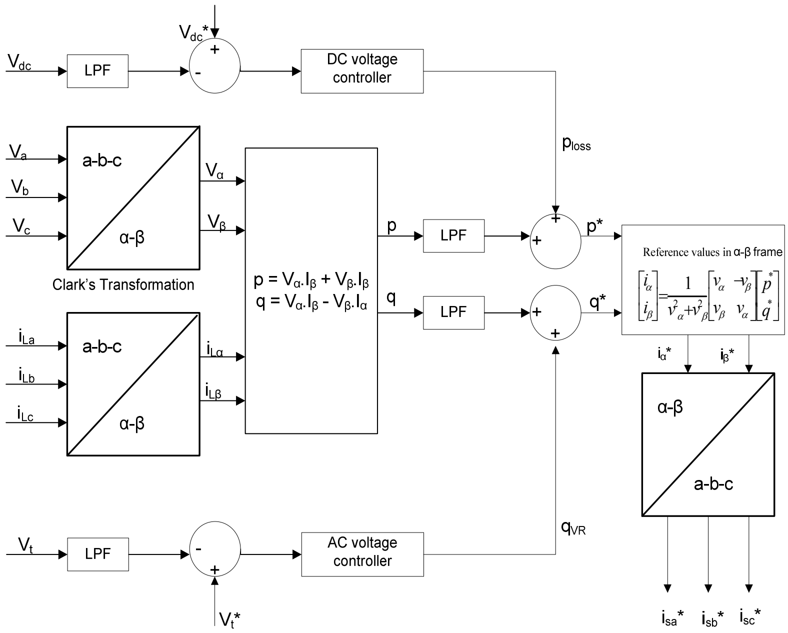


Fig. 5. IRP based control algorithm of DSTATCOM

C. Unit Template Based Control Theory

The basic block diagram of unit template based control theory is shown in Fig. 6. In this control algorithm, the reference source current is divided into two components [10], one in phase (I^*_{sm}) of the PCC voltage and the other in quadrature (I^*_{sn}) with PCC voltage. To generate reference source currents, unit templates are derived from PCC voltages.

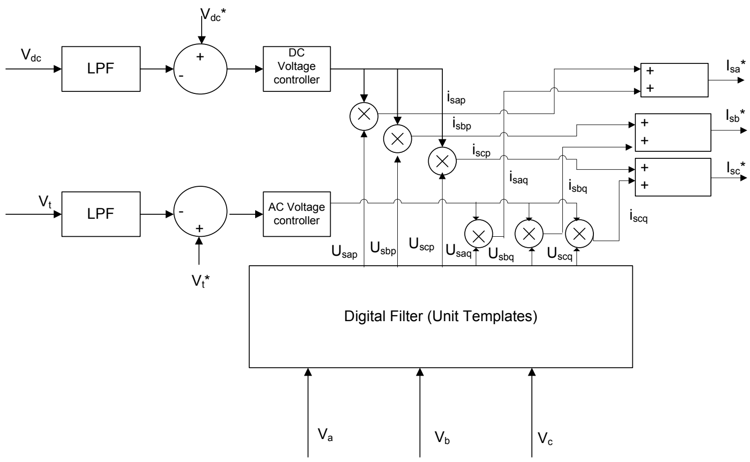


Fig. 6. Unit template based control algorithm of DSTATCOM

In phase unit templates with PCC voltage are obtained as [10]:

$$u_{sap} = v_a / V_t ; u_{sbp} = v_b / V_t ; u_{scp} = v_c / V_t \tag{13}$$

Where V_t is the amplitude of PCC voltage.
The unit template that is in quadrature with PCC voltage is obtained as [10]:

$$u_{saq} = \left(-u_{sbp} + u_{scp} \right) / \sqrt{3} \; ;$$
$$u_{sbq} = \left(u_{sap}\sqrt{3} + u_{sbp} - u_{scp} \right) / 2\sqrt{3} \; ; \tag{14}$$
$$u_{scq} = \left(-u_{sap}\sqrt{3} + u_{sbp} - u_{scp} \right) / 2\sqrt{3} \; ;$$

The amplitude of in-phase component of the reference source current (I^{*}_{m}) is computed based on the following equation:

$$I^{*}_{sm}(n) = I^{*}_{sm}(n-1) + K_p \{V_{de}(n) - V_{de}(n-1)\} + K_i . V_{de}(n) \tag{15}$$

Where $V_{de}(n) = V^{*}_{dc} - V_{dc}(n)$ is the error in DC bus voltage; and K_p and K_i are the gains of proportional and integral controller. The amplitude of in-phase component of the reference source current is calculated based on the output of this PI controller. Three-phase in-phase components of reference source currents (i^{*}_{sap}, i^{*}_{sbp}, i^{*}_{scp}) are computed using unit templates as:

$$i^{*}_{sap} = I^{*}_{sm}\, u_{sap};\; i^{*}_{sbp} = I^{*}_{sm}\, u_{sbp};\; i^{*}_{scp} = I^{*}_{sm}\, u_{scp} \tag{16}$$

The amplitude of quadrature component of reference source currents is calculated according to the following equation:

$$I^{*}_{sn}(n) = I^{*}_{sn}(n-1) + K_{pa} \{V_{e}(n) - V_{e}(n-1)\} + K_{ia}\, V_{e}(n) \tag{17}$$

Where $V_e(n) = V^{*}_{t} - V_t(n)$ is the error in amplitude of ac bus voltage. K_{pa} and K_{ia} are the gains of PI controller of proportional and integral controller respectively.
The quadrature components of reference source currents (i^{*}_{saq}, i^{*}_{sbq}, i^{*}_{scq}) are computed using unit templates as:

$$i^{*}_{saq} = I^{*}_{sn}\, u_{saq};\; i^{*}_{sbq} = I^{*}_{sn}\, u_{sbq};\; i^{*}_{scq} = I^{*}_{sn}\, u_{scq} \tag{18}$$

Total reference source current is calculated with the help of in-phase and quadrature components (16) and (18). Reference source currents can be calculated as:

$$i^{*}_{sa} = i^{*}_{sap} + i^{*}_{saq};\; i^{*}_{sb} = i^{*}_{sbp} + i^{*}_{sbq};\; i^{*}_{sc} = i^{*}_{scp} + i^{*}_{scq} \tag{19}$$

These extracted reference source currents (i^{*}_{sa}, i^{*}_{sb}, i^{*}_{sc}) are compared to the actual source currents (i_{sa}, i_{sb}, i_{sc}) and sent to the PWM generator for switching of DSTATCOM.

V. MATLAB MODEL OF PV BASED DSTATCOM

Fig. 7 shows the MATLAB model of the complete PV based DSTATCOM. In this model, three-phase source of 415V, 50Hz is used. Solar irradiation is considered as 1000W/m^2. Three controllers are used in the complete simulation model: The first is DC controller which controls the DC voltage; the second is AC voltage controller which regulates the PCC voltage; and the third is saturation based current controller. If DSTATCOM is working in UPF mode, only DC voltage controller and current controller are used as power factor is maintained at unity. If DSTATCOM is functioning in AC voltage control mode, AC voltage regulator is also used to maintain the constancy of the PCC voltage.

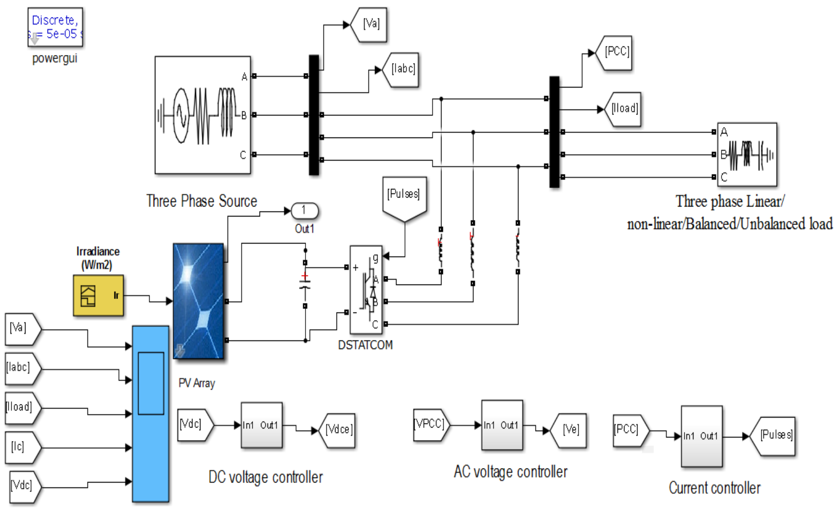
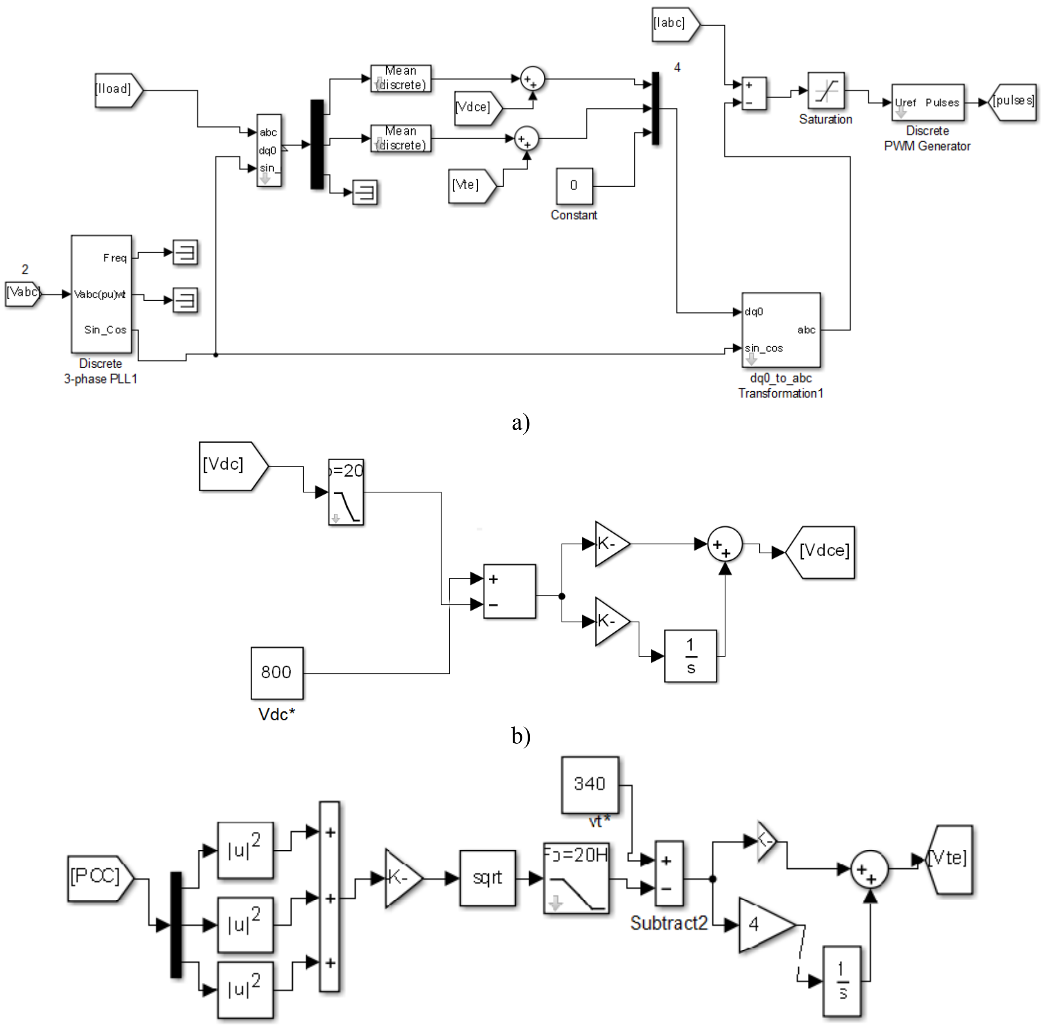


Fig. 7. MATLAB/Simulink model of PV based DSTATCOM

VI. MATLAB BASED CURRENT CONTROLLERS

Fig. 8a shows the MATLAB/Simulink model of current controller that is based on the flow diagram of SRF control theory.



c)

Fig. 8. SRF control a) current controller, b) DC voltage controller, c) AC voltage controller

Different blocks of Simulink library are used for the complete simulation. Two PI controllers are also used for DC controller and AC voltage controller with the help of Simulink as shown in Fig. 8b and 8c. Gains are set for maintaining the DC voltage and PCC voltage. Fig. 9 shows the simulation model of IRP control in accordance with the block diagram shown in Fig. 5. The simulation model of current controller of unit template based method is shown in Fig. 10. Flow diagram is shown in Fig. 6.

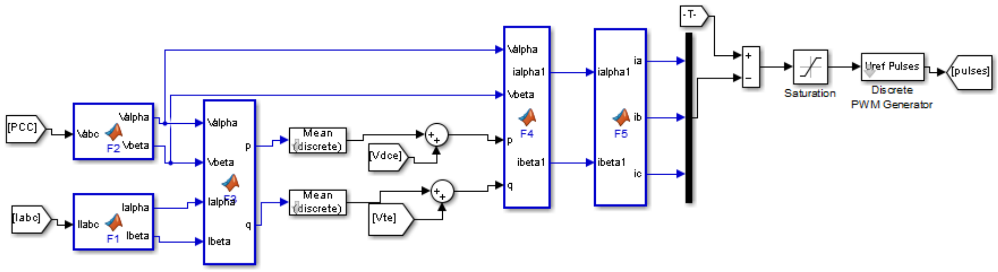


Fig. 9. Current controller for IRP control

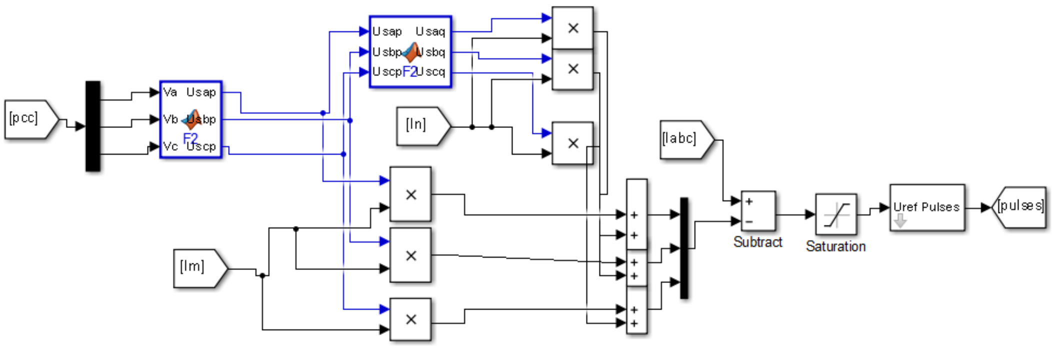


Fig. 10. Current controller for unit template based control theory

VII. Results and Discussions

A. SRF Based Control Theory

In Fig. 11, simulation results are shown for SRF controller with non-linear load while DSTATCOM is working in UPF mode. Irradiation of PV system is considered as $1000 W/m^2$. The effectiveness of DSTATCOM's performance is analyzed for UPF and ACVC modes. Fig. 12 shows the simulation results for ACVC mode. In both modes, one phase (phase *c*) is opened from 0.4s to 0.5s to create unbalanced load. In UPF mode, source currents and voltages during the unbalanced condition are in the same phase that shows unity power factor operation. DC voltage is also maintained constant to verify the effectiveness of the whole system. In ACVC mode, magnitude of PCC voltage is maintained constant at 340V during the unbalanced condition as well.

B. IRP Based Control Theory

Fig. 13 and 14 show the simulation results for IRP control theory in UPF and ACVC modes respectively. Phase *c* is opened from 0.4s to 0.5s to create unbalanced load. Its dynamic performance clearly shows the effectiveness of the PV based DSTATCOM system as it maintains the DC voltage constant. Unity power factor is achieved in UPF mode of operation. PCC voltage is also maintained constant in ACVC mode of operation of DSTATCOM.

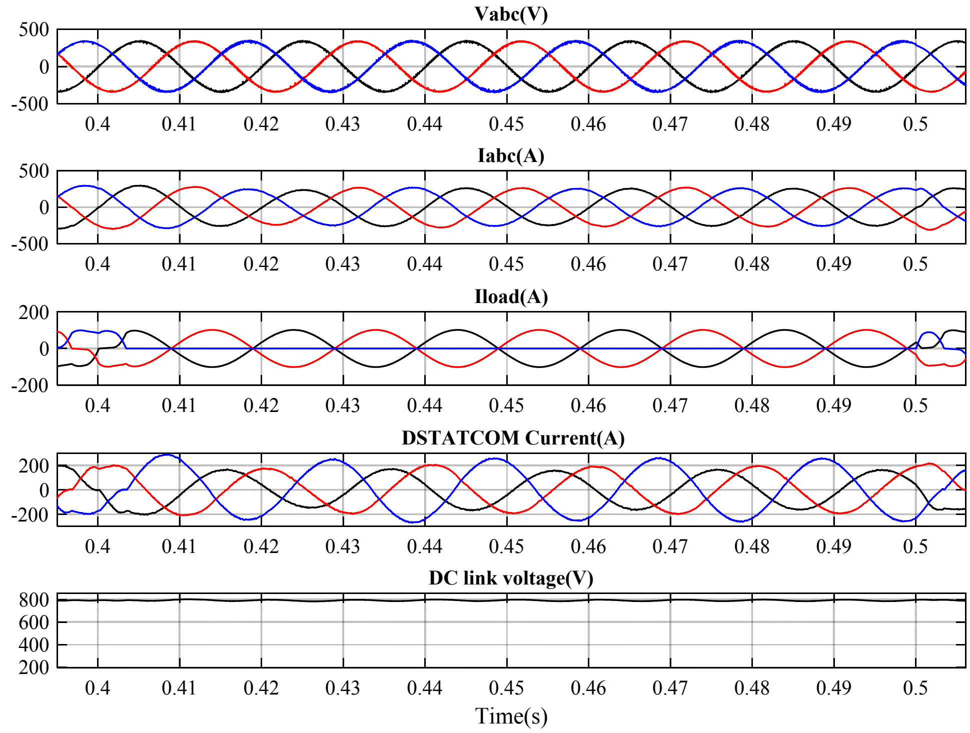


Fig. 11. Performance analysis of SRF control theory in UPF mode

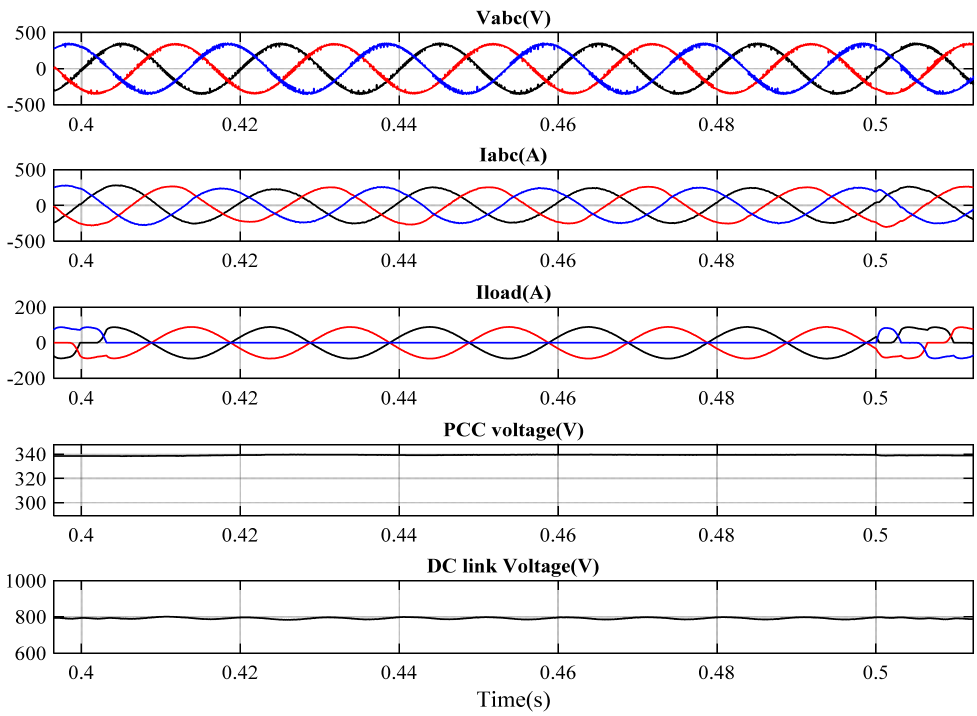


Fig. 12. Performance analysis of SRF control theory in ACVC mode

C. Unit Template Based Control Theory

The dynamic performance of DSTATCOM in UPF and ACVC modes is shown in Fig. 15, 16a and 16b respectively using unit template method. The load is considered as non-linear load of 26kW. One phase is opened from 0.4s to 0.5s for creating the load unbalancing condition. The output waveforms show that the load current in phase *c* is zero for this duration but source currents are balanced and in-phase with source voltage. The current injected from the DSTATCOM is also shown in the simulation output waveforms. In ACVC mode of operation, PCC voltage is maintained constant at 340V.

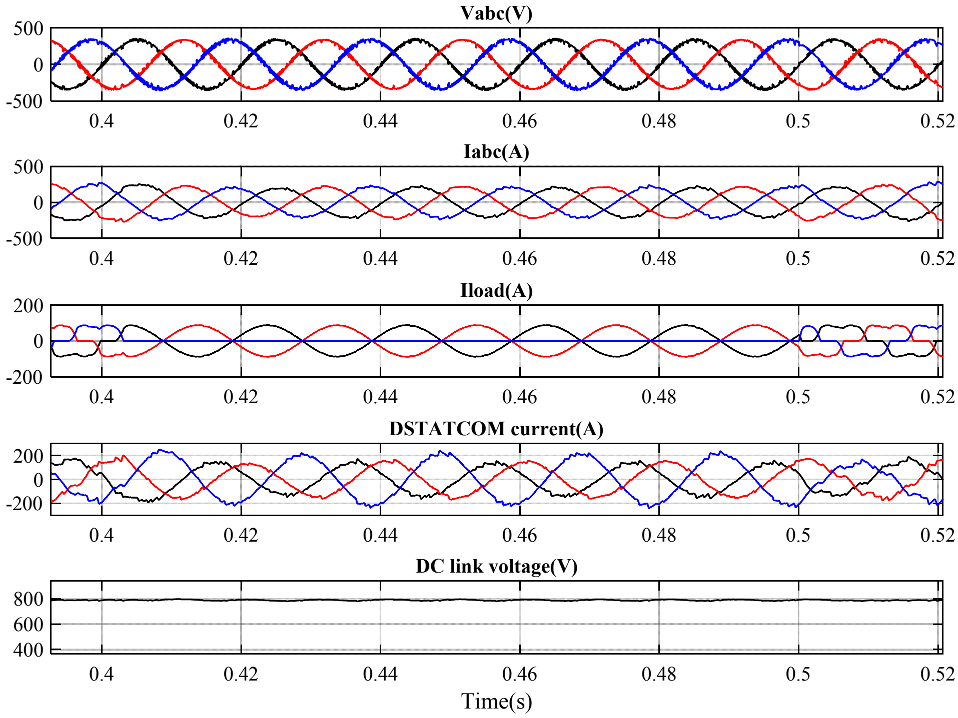


Fig. 13. Performance analysis of IRP control theory in UPF mode

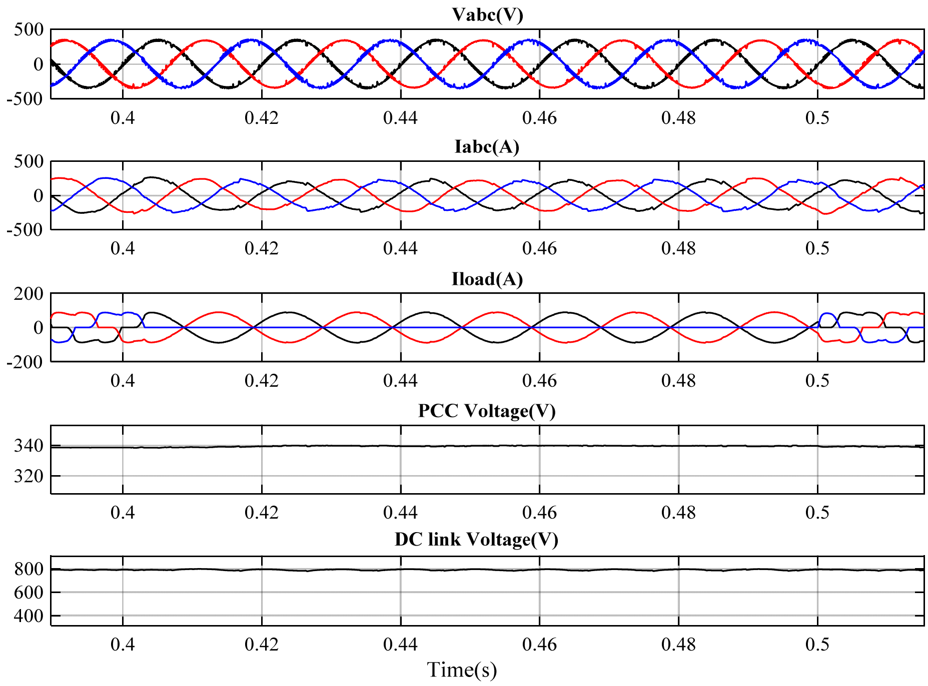


Fig. 14. Performance analysis of IRP control theory in ACVC mode

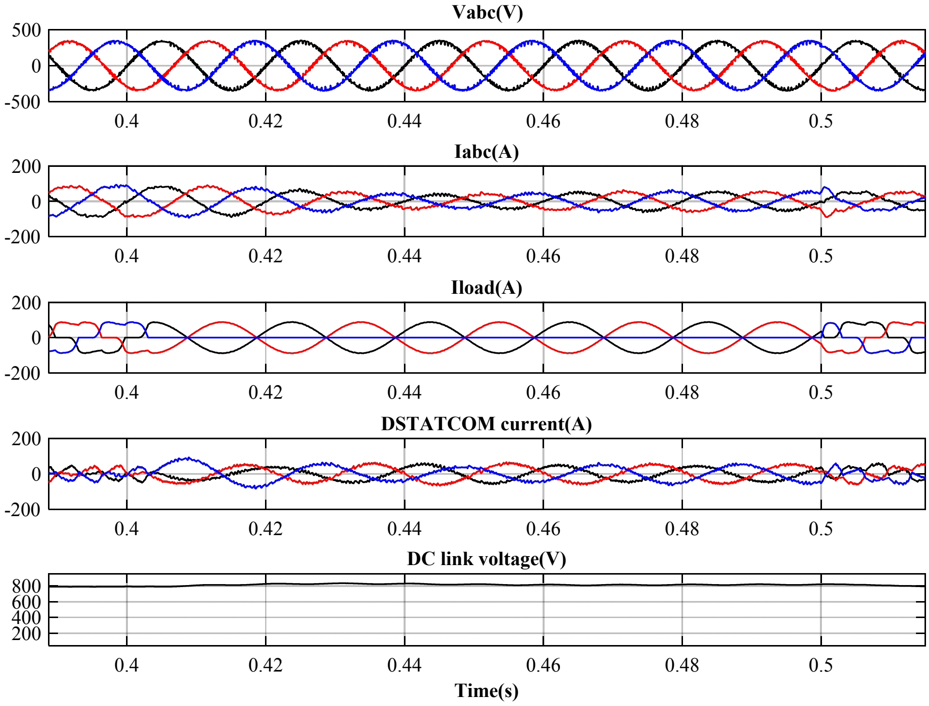


Fig. 15. Performance analysis of unit template based control theory in UPF mode

D. Comparative Analysis of Controllers

Fig. 17 shows the comparative performance analysis of all three controllers which are reported here on the basis of DC link voltage regulation in UPF mode of operation. Unit template based controller has poor voltage regulation compared to the SRF and IRP controllers as it is more sensitive to load variations. Regulation is under the 5%, and satisfies the IEEE limits. Fig. 18 shows the performance comparison of DC link voltage in ACVC mode. The PCC voltage profile is presented in Fig. 19.

E. Harmonic Analysis

%THD in source voltage and currents are calculated using FFT tool of MATLAB. Fig. 20 shows the harmonic spectrum of source voltage in SRF control theory. Similarly, %THD is calculated for all control theories, UPF and ACVC modes as shown in Table 1. Harmonic distortion of load current is 20-30%, and DSTATCOM is able to reduce it within the IEEE limit [17] of 4-5% using different controllers. Table 1 also shows the effectiveness of the proposed system.

TABLE 1
%THD VALUES FOR CONTROLLERS OF DSTATCOM

Operating Mode of DSTATCOM and Control Algorithms	%THD		
	i_L	v_{abc}	i_{abc}
SRF (UPF mode)	19.62	1.01	1.06
SRF (ACVC mode)	23.81	4.2	1.72
IRP (UPF mode)	23.89	4.9	4.58
IRP (ACVC mode)	23.72	4.7	4.38
Unit Template method (UPF mode)	23.89	5.04	4.82
Unit Template method (ACVC mode)	23.80	5.37	5.13

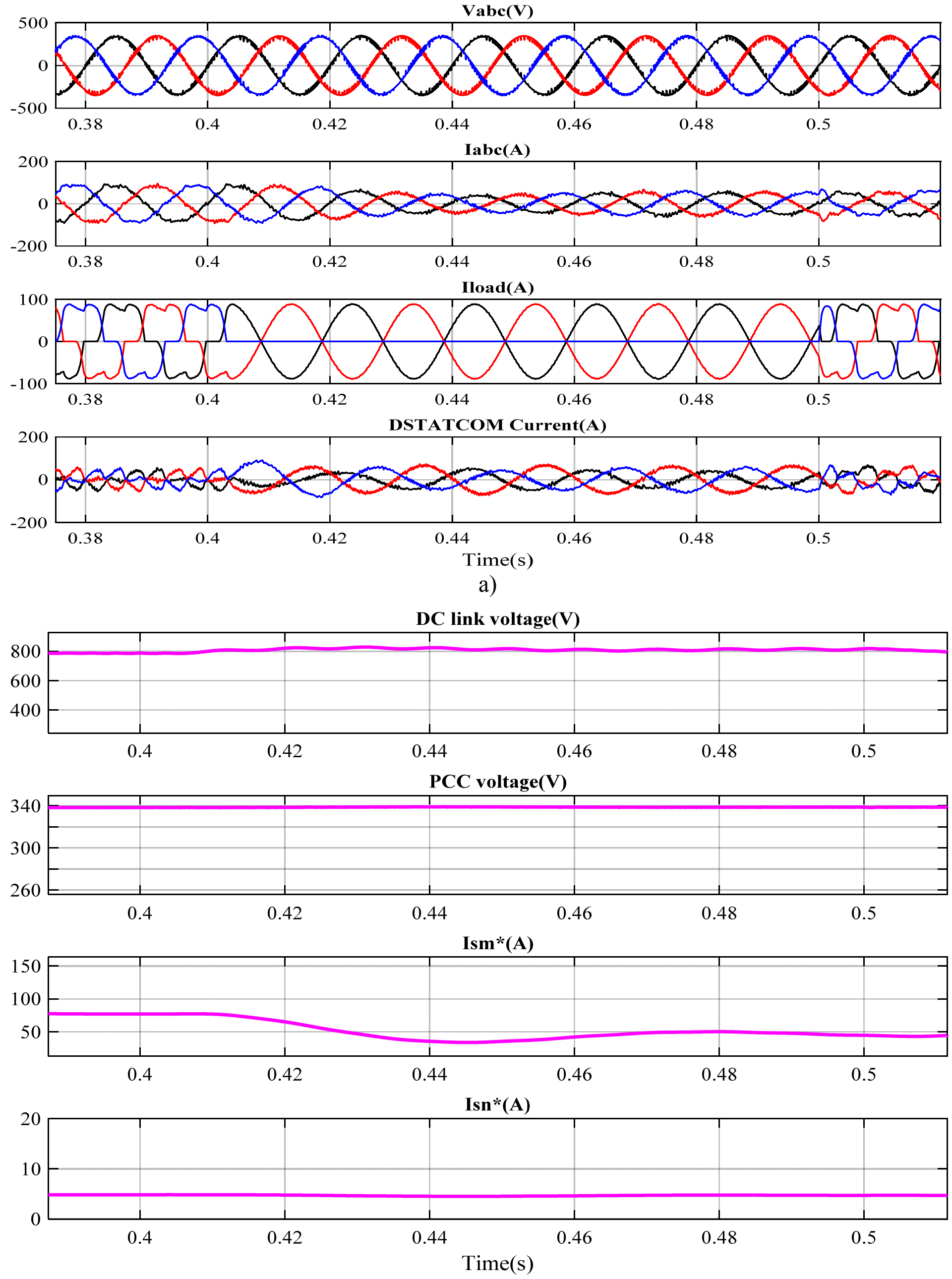


Fig. 16. Performance analysis of unit template based control theory in ACVC mode

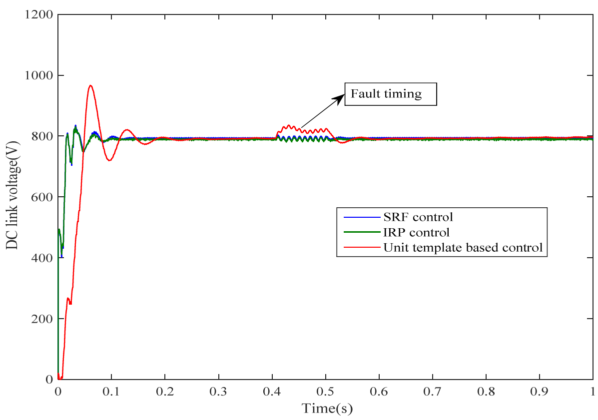


Fig. 17. Comparison of DC link voltage in SRF, IRP and unit template based controllers in UPF mode

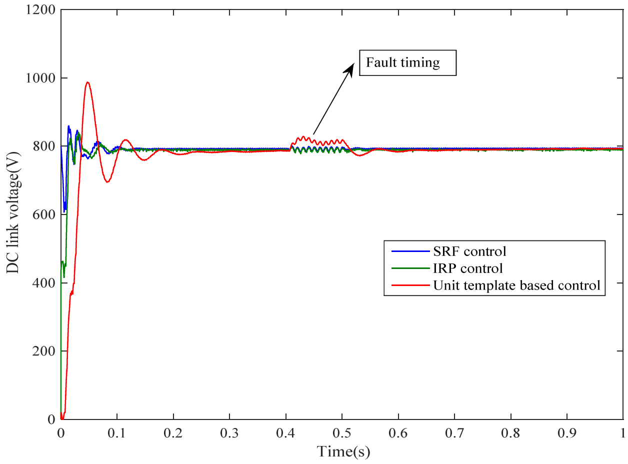


Fig. 18. Comparison of DC link voltage in SRF, IRP and unit template based controllers in ACVC mode

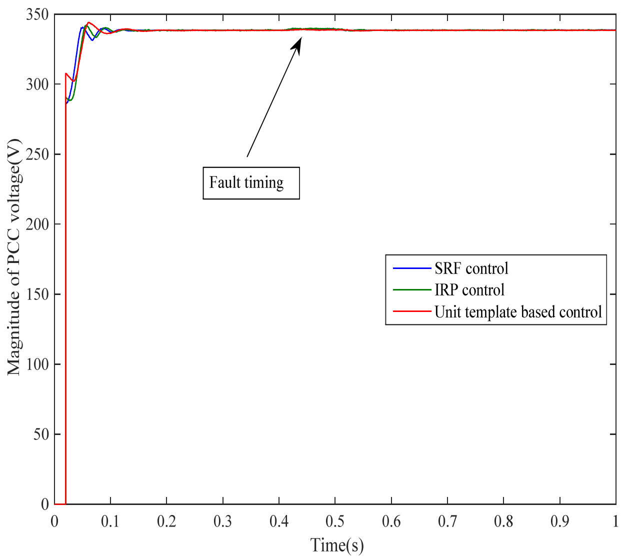


Fig. 19. Comparison of PCC voltage in SRF, IRP and unit template based controllers in ACVC mode

VIII. CONCLUSION

In this paper, complete simulation has been carried out of Photo voltaic based DSTATCOM using MATAB/Simulink software. The whole performance of the proposed system has been analyzed using Synchronous Reference Frame, Instantaneous Reactive power and Unit template based control algorithms. PCC voltage has been also regulated in ACVC mode of operation of DSTATCOM along with DC link voltage. A comparative analysis a DC link voltage, PCC voltage and %THD has been also presented for all control theories. Therefore, it has been observed that the results obtained from SRF and IRP control theories are better than unit template based control. In all the controllers, power quality has improved in terms of power factor improvement, harmonic reduction, PCC voltage regulation and DC link voltage control. Solar irradiation is considered constant in the current research work. This work can be extended for variable irradiation and temperature.

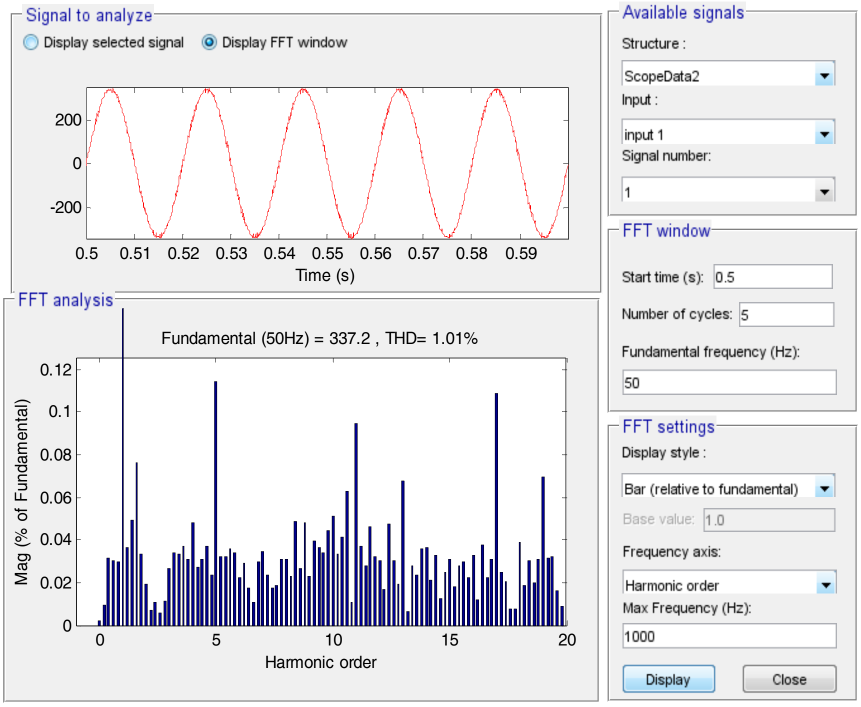


Fig. 20. FFT analysis of SRF control theory in UPF mode

APPENDIX

System Parameters:

TABLE A1
DESIGN PARAMETERS OF SOLAR PV

Solar PV module	Sun Power SPR-305-WHT
Solar PV specifications	100kW
No. of cells per module	96
No. of series connected modules per string	5
No. of parallel connected strings	66
V_{OC} of the PV module	64.2V
I_{SC} of the PV module	5.96A
V_{mp} of the PV module	54.7
I_{mp} of the PV module	5.58

TABLE A2
DESIGN PARAMETERS OF DISTRIBUTION SYSTEM AND DSTATCOM

Source voltage	415V
Source impedance	L_s=0.2mH, R_s=0.01Ω
Frequency	50Hz
Nonlinear load	Three-phase rectifier with 26kW DC resistive load
Switching frequency	10kHz
DC link capacitor	10000µF
DC bus voltage	800V
Interfacing inductor	3.5mH

TABLE A3
GAIN VALUES FOR CONTROLLERS

Gain values	SRF Control	IPR Control	Unit Template Based Control
Proportional gain (K_p)	15	6000	1.2
Integral gain (K_i)	5	500	2.1

Design of DSTATCOM:
DC link voltage can be calculated by [12], [13], [18], [22]:

$$V_{dc} = 2\sqrt{\frac{2}{3}}mV_l$$

For an overshoot of 10% in DC bus voltage and energy transfer lJ/l00W, C_{dc} can be calculated by [18], [22]:

$$\Delta e_{dc} = \frac{1}{2}C_{dc}\,(V_{dc}^{*2} - V_{dc}^2)$$

The value of interfacing inductor can be calculated according to [22]:

$$L_f = \frac{\left(\sqrt{3}/_2\right) m_a\, V_{dc}}{6af_s i_{cr(p-p)}}$$

Where m_a is modulation index, f_s is switching frequency and the allowed current ripple (i_{cr} (p-p)) through the AC inductor is 5%.
The magnitude of PCC voltage can be calculated by [12], [13], [18], [22]:

$$V_t = \sqrt{\left(\frac{2}{3}\right)(v_a^2 + v_b^2 + v_c^2)}$$

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