A New Voltage Control Strategy to Improve Performance of DSTATCOM in Electric Grid

Chandan Kumar, *Senior Member, IEEE*, Mahesh K. Mishra, *Senior Member, IEEE,* and Saad Mekhilef, *Senior Member, IEEE*

***Abstract*— A new voltage control strategy of distribution static compensator (DSTATCOM) has been proposed in this paper for electric grid applications. The proposed control scheme combines two methods of DSTATCOM operation to improve its performance. Considering power factor and voltage magnitude as degree of freedom, the DSTATCOM provides features such as mitigation of voltage and current harmonics, balancing of source currents, improvement of power factor, voltage regulation during voltage sag and swell, reduction in inverter losses, and control of load power to achieve energy conservation. The performance of proposed DSTATCOM control is better as compared to its conventional operation at any time of operation. PSCAD simulation and experimental results validate the performances.**

***Index Terms*— Reactive power, DSTATCOM, multifunctional.**

I. Introduction

WITH significant penetration of power electronics devices in electric distribution grid, maintenance of power quality (PQ) within grid codes is a challenging task [1], [2]. Current related PQ problems are distorted unbalanced load currents and nonzero neutral currents [3]–[5]. These increase grid current, losses in line and transformer, make voltages unbalanced and distorted. At the same time, increased renewable integration and faults create voltage related PQ issues such as voltage variations, voltage sag/swell, unbalance, flicker, etc. If these violate grid codes, performance of the sensitive loads will not be satisfactory [6], [7]. Various devices such as fixed capacitor (FC), static VAr compensator (SVC), distribution static compensator (DSTATCOM), dynamic voltage restorer (DVR), unified power quality conditioner (UPQC), etc., are proposed to improve PQ. In literature, due to flexibility in its control, DSTATCOM is one of the best solutions for mitigation of various PQ problems in electric distribution grid [8]–[10].

The DSTATCOM mitigates both current as well as voltage related PQ problems [11]–[14]. In current control mode (CCM) operation, the DSTATCOM supplies reactive, harmonics and unbalance of load currents. Moreover, the DSTATCOM maintains load terminal voltages balanced and sinusoidal in voltage control mode (VCM) operation, irrespective of disturbance in electric grid [15], [16]. However, as objectives of the two modes are different, the conventional operation of DSTATCOM solves only one type of PQ problems at any given time.

In CCM operation, the DSTATCOM normally maintains unity power factor (UPF) at the PCC [17]. However, consumers can draw limited reactive power without paying any penalty. This needs DSTATCOM to operate at a power factor other than unity in CCM. At the same time, a DSTATCOM cannot regulate voltage during voltage disturbances while operating at CCM.

Sensitive loads operate satisfactorily when operated within a range as specified by local grid code [18], [19]. Conventional DSTATCOM operating in VCM maintains PCC voltage at a constant value of 1.0 per unit (p.u.). Various power converter based loads are constant power load, and always draw rated power. However, there are several loads which draw power based on the terminal voltage. In this situation, special attention has been paid to conservation voltage reduction (CVR) method, where energy saving can be achieved by decreasing the voltage at the load terminal [20], [21]. However, loads draw rated power at rated voltage resulting in high electricity bills. Moreover, equipments will have more heating losses reducing their life. At the same time, the DSTATCOM compensates for feeder drop to maintain PCC voltage at 1.0 p.u. This needs higher filter current increasing rating requirement of DSTATCOM.

Recently, high efficient and reliable power electronics transformer also called smart transformer (ST) is proposed to improve performance of electric distribution grid [22]. The ST LV converter maintains a constant voltage at the LVAC terminal. Due to the capability to maintain any voltage at its LVAC terminal, the ST LV converter can also maintain suitable voltage to achieve benefits of conservation voltage reduction (CVR) [20]. However, the ST LV converter still supplies load reactive and harmonic power, and it cannot reduce the LVAC voltage considerably. Otherwise, the voltage at the end point of LVAC line will fall below the grid code.

From aforementioned benefits and limitations, it can be

Manuscript received September 19, 2020; revised October 25, 2020; accepted November 11, 2020. Date of publication December 25, 2020; Date of current version December 18, 2020.

This publication is an outcome of the research work supported by Central Power Research Institute (CPRI), India research project entitled “Design, operation, and control of distributed generation (DG) integrated unified power quality conditioner (UPQC) in electric grid”. *(Corresponding Author: Chandan, Kumar)*

Chandan Kumar is with Electronics and Electrical Engineering Department, Indian Institute of Technology Guwahati, India (e-mail: chandank@iitg.ac.in).

Mahesh K. Mishra is with Electrical Engineering Department, Indian Institute of Technology Madras, Chennai, India (e-mail: mahesh@ee.iitm.ac.in).

Saad Mekhilef is with Department of Electrical Engineering, University of Malaya, Malaysia (email: saad@um.edu.my). He is also with School of Software and Electrical Engineering, Swinburne, Victoria, Australia, and Center of Research Excellence in Renewable Energy and Power Systems, King Abdulaziz University, Jeddah 21589, Saudi Arabia.

Digital Object Identifier 10.30941/CESTEMS.2020.00036

considered that the power factor and voltage magnitude at the PCC are two degree of freedoms when operating DSTATCOM for PQ improvement. Recently, multifunctional DSTATCOM has been explored for achieving the advantages of both CCM and VCM operation [23]–[26]. An interesting concept of minimum power point tracking (mPPT) is proposed in [27]. However, these schemes do not consider DSTATCOM operation where it can influence the load power, energy conservation, and operation of power distribution system by effectively utilizing both degree of freedoms i.e., power factor (*pf*) and voltage magnitude at PCC.

This paper proposes a new voltage control strategy of DSTATCOM to improve its utilization in electric grid. The control flexibly selects power factor and reference PCC voltage such that grid codes are not violated. Instantaneous symmetrical component theory, which gives explicit option of choosing power factor, is used to compute reference source currents. The reference load voltages are computed such that the least allowable power factor is maintained at the PCC. Consequently, load power is appropriately controlled and advantages of energy conservation are also achieved. If reference load voltage at the predefined minimum *pf* comes less than the lowest allowable operating voltage, then *pf* is improved to get new reference load voltage. Therefore, proposed scheme ensures that conservation voltage reduction is achieved while drawing allowable reactive power from the source. Moreover, load voltage is maintained at the constant value during voltage disturbances to protect the sensitive loads.

II. DSTATCOM Configuration And Control

As shown in Fig. 1, a 3-phase, 4-wire distribution system with linear unbalanced and distorted load is considered. The DSTATCOM, connected in parallel with loads at the PCC, is realized by a two-level voltage source inverter (VSI) and an LC interfacing filter (L_f and C_f) [28]. In this system, v_{sj}, v_{tj}, i_{sj}, and i_{lj} are grid voltage, PCC voltage, source current, and load current, respectively where $j = a, b, c$ are three phases. Grid resistance and reactance are R_s and X_s, respectively. The dc link capacitors of VSI are represented by $C_{dc1} = C_{dc2} = C_{dc}$, whereas the voltages maintained across them are $V_{dc1} = V_{dc2} = V_{dc} = V_{dcref}$. Inverter side and grid side currents of DSTATCOM are i_{f1j} and i_{f2j}, respectively.

A. Modeling of DSTATCOM

A single phase equivalent circuit of the DSTATCOM in electric grid is shown in Fig. 2. In this work, ideal VSI switches are considered. Therefore, at any given instant, one switch of a leg will be ON and other will be OFF, i.e.,

$$u = 1 \textit{ if upper switch of a leg is ON}$$
$$u = -1 \textit{ if lower switch of a leg is ON} \quad (1)$$

The state equations for any phase are given as

$$\begin{aligned}\frac{dv_t}{dt} &= \frac{1}{C_f} i_{f1} - \frac{1}{C_f} i_{f2} \\ \frac{di_{f1}}{dt} &= -\frac{1}{L_f} v_t - \frac{R_f}{L_f} i_{f1} + \frac{V_{dc}}{L_f} u \\ \frac{di_s}{dt} &= -\frac{1}{L_s} v_t - \frac{R_s}{L_s} i_s + \frac{1}{L_s} v_s\end{aligned} \quad (2)$$

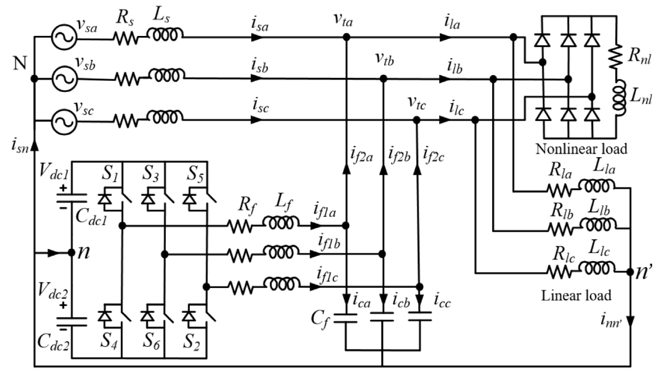

Fig. 1. DSTATCOM in electric distribution system.

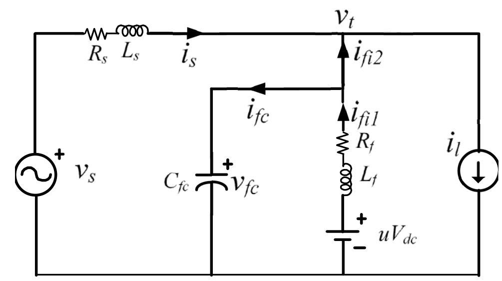

Fig. 2. Single phase equivalent circuit.

where uV_{dc} is voltage at the VSI leg. The eq. (2) is rewritten as follows:

$$\dot{x} = Ax + Bz \quad (3)$$

where

$$A = \begin{bmatrix} 0 & 1/C_f & 0 \\ -1/L_f & -R_f/L_f & 0 \\ -1/L_s & 0 & -R_s/L_s \end{bmatrix} B = \begin{bmatrix} 0 & -1/C_f & 0 \\ V_{dc}/L_f & 0 & 0 \\ 0 & 0 & 1/L_s \end{bmatrix},$$

$$x = \begin{bmatrix} v_t & i_{f1} & i_s \end{bmatrix}^T, z = \begin{bmatrix} u & i_{f2} & v_s \end{bmatrix}^T$$

For digital implementation of control algorithm, discrete state space form of (3) with a sampling time T_d is given as following [29]:

$$x(k+1) = G\,x(k) + H\,z(k) \quad (4)$$

where

$$G = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} = L^{-1}\left[sI - A\right]^{-1} \approx I + AT_d + \frac{A^2T_d^2}{2}$$

$$H = \begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{21} & H_{22} & H_{23} \\ H_{31} & H_{32} & H_{33} \end{bmatrix} = \int_0^{T_d} e^{A\lambda} B d\lambda \approx \int_0^{T_d} \left(I + A\lambda\right) B d\lambda$$

In above, the term k is sampling instant. Moreover, it is assumed that all the variables are constant between two consequent sampling instants. Also, the terms G_{13} and H_{13} are zero. Hence, discrete equation for ac capacitor voltage is given as follows:

$$v_t(k+1) = G_{11}v_t(k) + G_{12}i_{f1}(k) + H_{11}u(k) + H_{12}i_{f2}(k) \quad (5)$$

Here, the objective of DSTATCOM operation is to maintain a suitable voltage across the ac capacitor. Therefore, cost function minimization must eliminate the difference between reference and actual ac capacitor voltages [30]. Therefore, we have

$$v_t(k+1) = v_t^*(k+1) \quad (6)$$

Substituting $v_t(k+1)$ from (6) into (5), reference voltage control law is given as

$$u^*(k) = \frac{v_t^*(k+1) - G_{11}v_t(k) - G_{12}i_{f1}(k) - H_{12}i_{f2}(k)}{H_{11}} \quad (7)$$

In (7), $v_t(k+1)$ is not known and it is predicted as follows [31]:

$$v_t^*(k+1) = 3v_t^*(k) - 3v_t^*(k-1) + v_t^*(k-2) \quad (8)$$

B. Reference PCC Voltage and Switching Pulses Generation

The proposed scheme aims to maintain a balanced sinusoidal voltage at the PCC. Let V_t^* is reference rms voltage. After computing load angle (δ) for power balance, reference voltage will be

$$\begin{aligned} v_{refa} &= \sqrt{2}V_t^* \sin(2\pi ft - \delta) \\ v_{refb} &= \sqrt{2}V_t^* \sin(2\pi ft - 2\pi/3 - \delta) \\ v_{refc} &= \sqrt{2}V_t^* \sin(2\pi ft + 2\pi/3 - \delta) \end{aligned} \quad 9)$$

These voltages are replaced in (7), and then $u^*(k)$ is regulated around a hysteresis band to realize the desired voltages. The value of reference voltage V_t^* for different operating conditions is computed in the following section.

III. Proposed Control of DSTATCOM

The control strategy aims to improve DSTATCOM performance with reduced rating and losses in VSI. The algorithm also controls load power to realize energy conservation. In normal operating conditions, the DSTATCOM is operated to maintain the least allowable power factor at the PCC without violating the grid code. During the voltage disturbances, a flat voltage is maintained at the PCC for continuous operation of the load. Fig. 5 shows control block.

In normal operation, source currents are maintained balanced sinusoidal while maintaining PCC voltage within grid specified limits. For achieving the balanced sinusoidal currents, instantaneous symmetrical component theory (ISCT) is used to generate reference currents and given as follows.

$$\begin{aligned} i_{sa} &= \frac{v_{ta} + \beta(v_{tb} - v_{tc})}{\sum_{j=a,b,c} v_{tj}^2}(P_{lavg} + P_{loss}) \\ i_{sb} &= \frac{v_{tb} + \beta(v_{tc} - v_{ta})}{\sum_{j=a,b,c} v_{tj}^2}(P_{lavg} + P_{loss}) \\ i_{sc} &= \frac{v_{tc} + \beta(v_{ta} - v_{tb})}{\sum_{j=a,b,c} v_{tj}^2}(P_{lavg} + P_{loss}) \end{aligned} \quad (10)$$

where $\beta = tan\phi_{vi+}/\sqrt{3}$ Angle (ϕ_{vi+}) is power factor angle of positive sequence component of voltage and current. Average load power (P_{lavg}) and VSI losses (P_{loss}) are computed as follows.

$$\begin{aligned} P_{lavg} &= \frac{1}{T}\int_{t_1-T}^{t_1}(v_{ta}i_{la} + v_{tb}i_{lb} + v_{tc}i_{lc})dt \\ P_{loss} &= \frac{1}{T}\int_{t_1-T}^{t_1}(v_{ta}i_{f2a} + v_{tb}i_{f2b} + v_{tc}i_{f2c})dt \end{aligned} \quad (11)$$

Consider a single-phase equivalent circuit as given in Fig. 4, the voltage at the PCC is computed as follows:

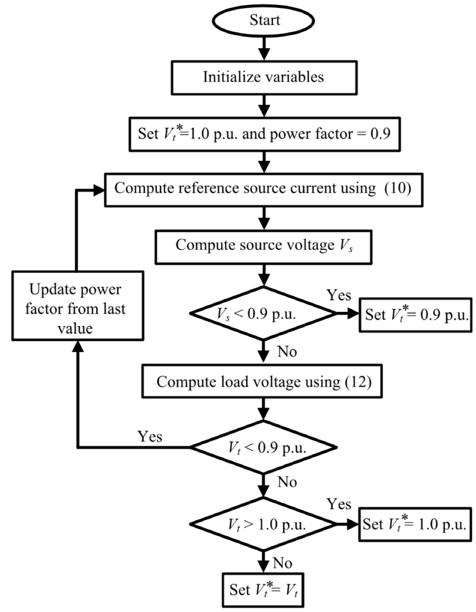

Fig. 3. Proposed control of DSTATCOM to compute reference PCC voltage.

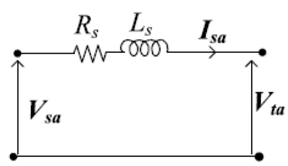

Fig. 4. Single phase equivalent circuit.

$$V_{ta} = \sqrt{V_{sa}^2 + (I_{sa}Z_s)^2 - 2V_{sa}I_{sa}Z_s\cos(\phi_{vi+} + \delta - \theta_z)} \quad (12)$$

Based on this voltage V_t, appropriate reference PCC voltage for various operating conditions is computed as shown in Fig. 3 and explained as follows.

A. *Source* Voltage is Less Than 0.9 p.u.

Voltage sag occurs when PCC voltage lies between 0.9 p.u. to 0.1 p.u. of rated voltage for half cycle to one minute [32]. In this case, the conventional DSTATCOM operation maintains load voltage at 1.0 p.u. At this reference voltage, it draws high currents from VSI resulting in more losses. The load draws rated power in this case. In the proposed algorithm, reference PCC voltage is chosen as 0.9 p.u. during voltage sag. This provides advantages such as i) satisfactory operation of load, ii) reduction in load power consumption as compared to rated power in conventional VCM operation, and iii) reduced VSI losses as compared to conventional VCM operation.

B. Source Voltage is Greater Than 0.9 p.u.

In CCM, the DSTATCOM maintains unity power factor at PCC. However, the customers are allowed to draw some amount of reactive power without any penalty (this paper considers 0.9 power factor lagging). At this power factor, PCC voltage is computed using (12). At this voltage, following conditions are possible:

1) V_t < 0.9 p.u.: In this case, the power factor at the PCC is improved in steps of 0.005 from the lowest value of 0.9 lagging. Based on the new power factor, reference source currents and PCC voltages are again computed. If the reference PCC voltage

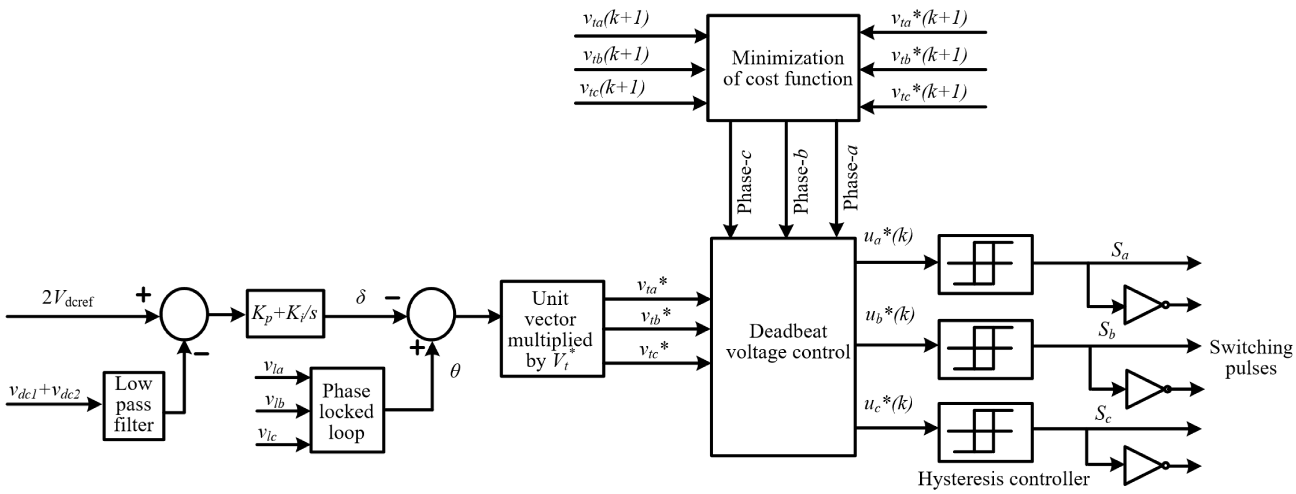

Fig. 5. Block diagram of control of DSTATCOM.

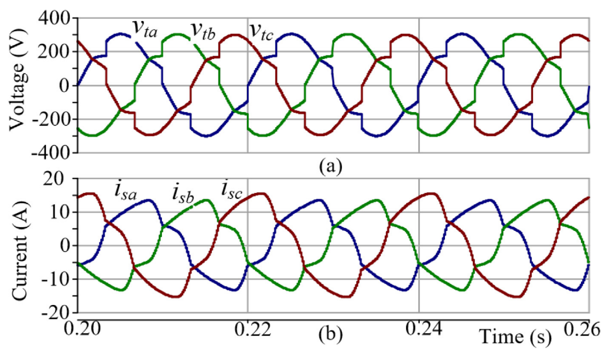

Fig. 6. Simulation results without compensation.

becomes more than 0.9 p.u. then same voltage is used as reference PCC voltage.

2) 0.9 ⩽ V_t ⩽ 1.0 p.u.: In this case, reference PCC voltage is computed using (12) at 0.9 power factor lagging at the PCC. In case the PCC voltage is not more than 0.9 p.u., power factor is improved to make PCC voltage becomes more than 0.9 p.u. In this paper, the power factor is limited to unity. If load voltage does not become greater than 0.9 p.u. at unity power factor, then 0.9 p.u. is set as reference voltage.

3) V_t > 1.0 p.u.: In this case, the PCC voltage is computed at 0.9 lagging power factor. If load voltage does not become less than 1.0 p.u. even for 0.9 power factor, a flat voltage of 1.0 p.u. is maintained.

IV. Simulation Results

Simulations are carried out for a 230 V per phase rms, 50 Hz system as shown in Fig. 1. The results for various cases are explained as follows.

A. Performance Comparison of Proposed Control with Conventional CCM

Conventional CCM performance during normal operation is shown in Fig. 7. The source currents are balanced, sinusoidal, and in phase with the PCC voltages as the harmonic and reactive components of load currents are supplied by the DSTATCOM. For this operation, various parameters are given in Table I. Since the conventional CCM operation of

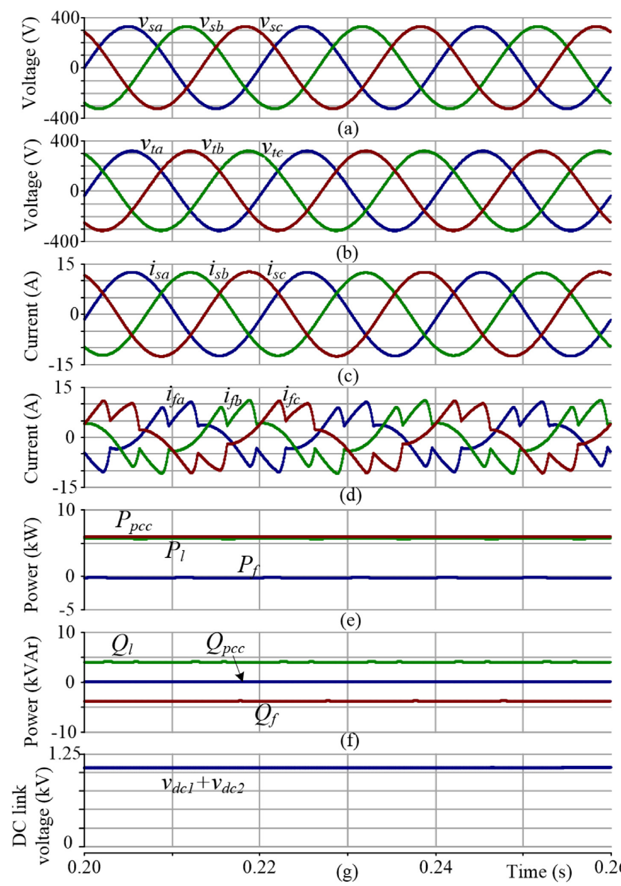

Fig. 7. Simulation results for conventional CCM.

DSTATCOM only mitigates current related power quality problems, this can not improve PCC voltage during the voltage disturbance. Therefore, conventional CCM operation is not useful during the voltage disturbances.

Performance of proposed control of DSTATCOM during normal operation is shown in Fig. 8. The power factor is set to 0.9 lagging. At this value, value of load voltage is computed using (12) and found to be between 0.9 to 1.0 p.u. Therefore, this voltage is set as reference load voltage. For this voltage, the source currents are balanced, sinusoidal, and have 0.9 power

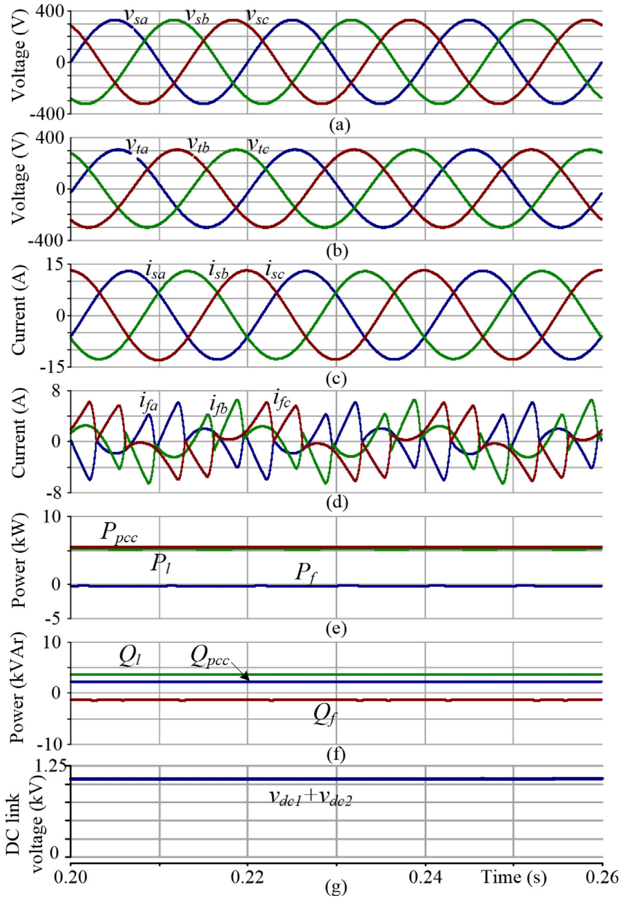

Fig. 8. Simulation results for proposed scheme in steady state.

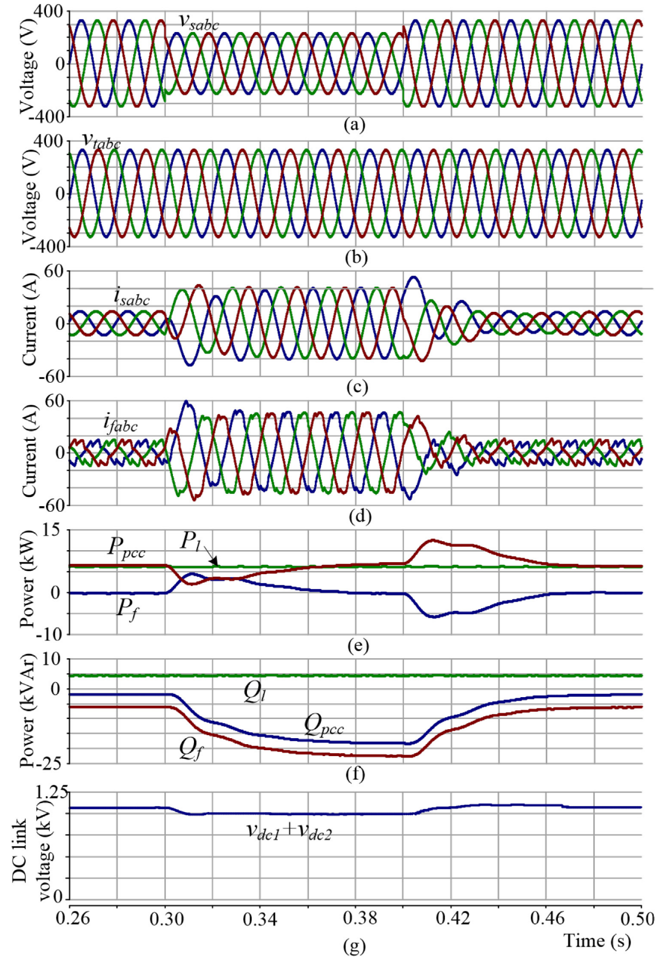

Fig. 9. Simulation results for conventional VCM during sag..

factor lagging to the respective PCC voltages. For this operation, various parameters are given in Table I. Since reactive power drawn by load is reduced, filter also supplies reduced power resulting in its reduced current injection.

B. Performance Comparison of Proposed Control with Conventional VCM

In conventional VCM operation, the DSTATCOM maintains PCC voltage at 1.0 p.u. and the corresponding waveforms are given in Fig. 9. At this PCC voltage, load always draws rated power resulting in more electricity bills. Moreover, VSI supplies additional reactive power to support the rated voltage.

Fig. 10 shows performance of proposed control of DSTATCOM, where performance during normal conditions is same as that of Fig. 8. Moreover, if comparison is made with conventional VCM during normal conditions, the proposed scheme provides various advantages and are listed in Table I During the voltage sag of 30%, PCC voltage is maintained at 0.9 p.u. This allows load to operate satisfactorily and at the same time load demand decreases. This further requires filter to supply reduced reactive power. Therefore, a reduced rated VSI provides same capability to mitigate sag.

Fig. 11 shows performance of proposed control of DSTATCOM during voltage swell. As long as the computed load voltage is greater than 1.0 p.u., a voltage of 1.0 p.u. is maintained.

V. EXPERIMENTAL RESULTS

The experimental studies are carried out at a reduced rating experimental set up to test the validity of the proposed operational scheme of the DSTATCOM. The source voltage of 50 V rms per phase-to-neutral has been used. Voltage source inverter is realized by the SEMIKRON made IGBT module. The inverter is controlled by digital signal processor (DSP) TMS320F2812. The experimental setup is shown in Fig. 12. Firstly, all high power feedbacks are converted into low voltage

TABLE I
DSTATCOM PERFORMANCE COMPARISON

Mode of Operation	System conditions	P_l (kW)	P_f (kW)	P_s (kW)	Q_l (kVAr)	Q_f (kVAr)	Q_s (kVAr)	I_{fta} (A)	I_{ftb} (A)	I_{ftc} (A)
Conventional CCM	Normal	5.7	0.2	5.9	4	4	0	6	6.3	6.7
	Sag	-	-	-	-	-	-	-	-	-
Conventional VCM	Normal	6.1	0.3	6.4	4.25	6.2	2.05	8.9	9.15	9.6
	Sag	6.1	0.7	6.8	4.25	22.6	18.35	32.6	32.8	33.3
Proposed scheme	Normal	5.2	0.1	5.3	3.6	1.4	2.2	2.6	2.9	3.1
	Sag	4.9	0.5	5.4	3.4	14.8	11.4	23.6	23.8	24.2

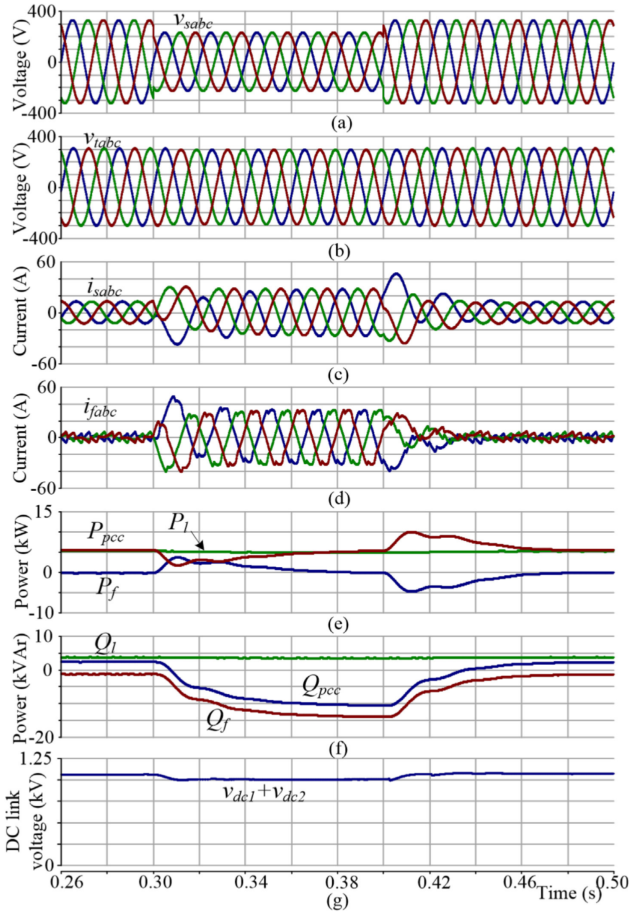

Fig. 10. Simulation results for proposed scheme during sag.

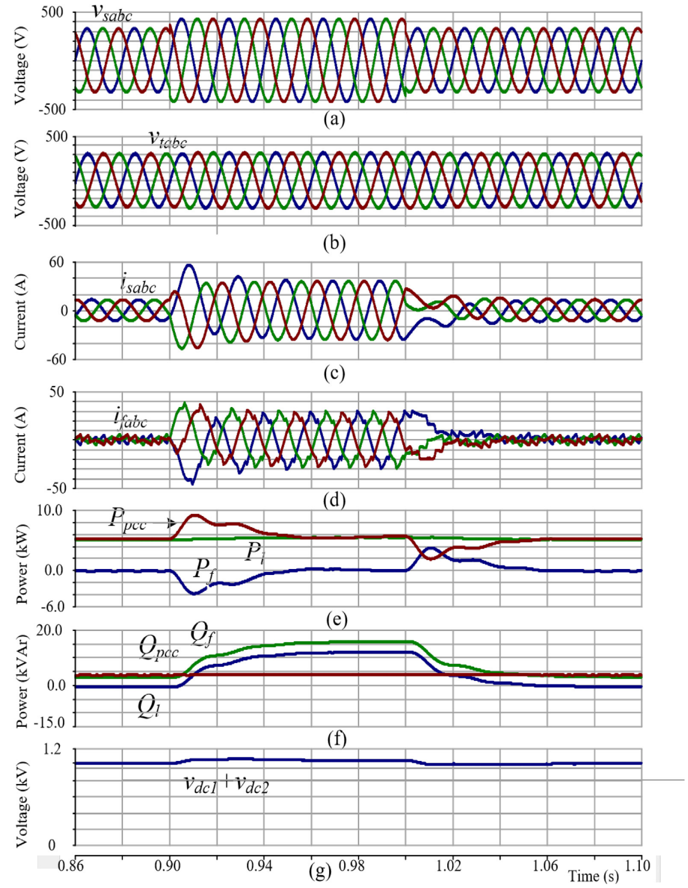

Fig. 11. Simulation results for proposed scheme during swell.

signals using Hall effect transducers. The signal conditioning circuit brings this signal in the range of 0-3 V which is suitable for processing by unidirectional analog to digital channel (ADC). Once the control algorithm is executed, switching pulses are taken from DAC of processor, which are in the range of 0-3 V. A booster circuit is used to bring these pulses in the range of 0-15 V, which is necessary to operate the IGBT switches of the VSI. Voltage source is realized using programmable ac power sources. This is used to create various disturbances as well.

A. Compensation Performance of Conventional VCM Operation of DSTATCOM

The performance under normal operating conditions is shown in Fig. 13. It shows the waveforms of load voltage (v_{ta}), source current (i_{sa}), load current (i_{la}), and DSTATCOM current (i_{f2a}). The reference load voltage is set to 1.0 p.u. and is maintained by the DSTATCOM. Hence, filter supplies more reactive current at the PCC. Moreover, load is forced to draw rated power for the entire operation with PCC voltage maintained at 1.0 p.u.

B. Compensation Performance of Proposed Scheme

The reference PCC voltage is generated based on the proposed algorithm given in Fig. 3. The steady state performance is illustrated in Fig. 14. The filter supplies reactive current such that the appropriate power factor is maintained at the PCC. Therefore, filter will supply only a part of the reactive

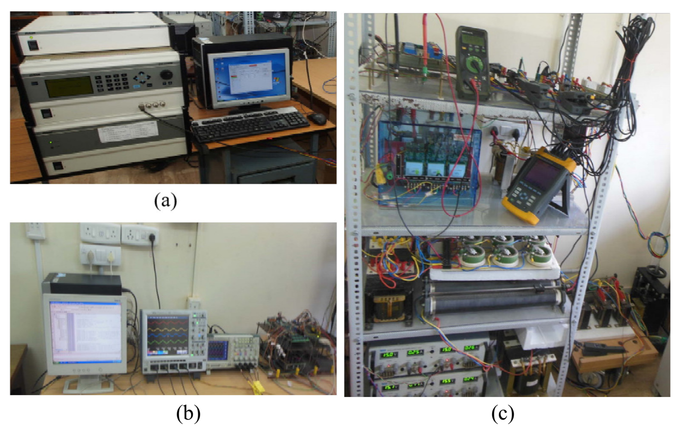

Fig. 12. Experimental setup photograph.

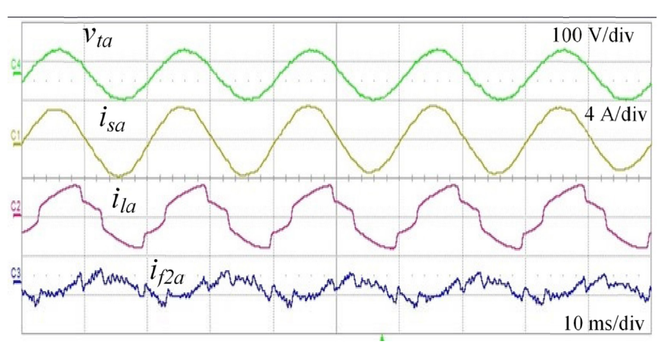

Fig. 13. Steady state experimental results of conventional VCM.

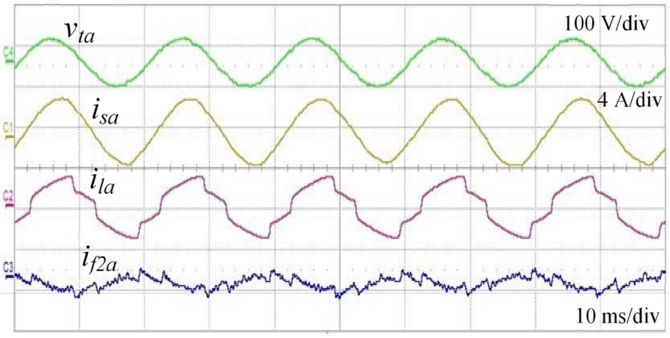

Fig. 14. Steady state experimental results of proposed scheme.

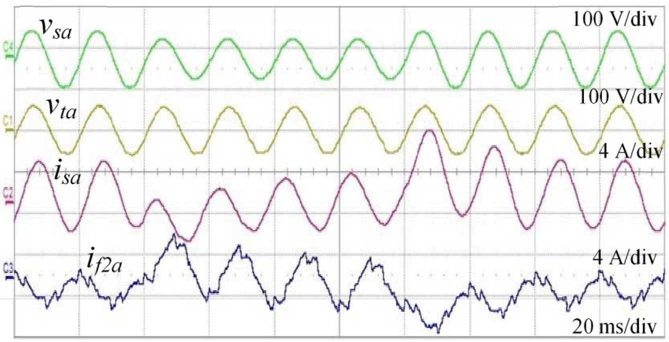

Fig. 15. Experimental results of proposed scheme during voltage sag.

component of load current. The rest of the load reactive power is supplied by source. Hence, filter current is reduced as compared to conventional VCM operation. Also, a reduced voltage is maintained at the PCC which will reduce the load power demand. Moreover, it is ensured that the PCC voltage and power factor remain within the limits.

Fig. 15 shows results with voltage sag of 30%. The load voltage is set at 0.9 p.u. during the voltage sag, which is sufficient for the satisfactory performance of a load. Therefore, load draws minimum required power for satisfactory performance. During the sag, the source current leads the PCC voltage as the reactive current is supplied by the filter. However, filter current will be reduced in proposed scheme in comparison to conventional VCM operation where PCC voltage is set at 1.0 p.u. Due to the nature of voltage disturbance, source current will have dc component during transients. Depending upon the network parameters, it decays with time and becomes zero once steady state has reached. As seen in waveform, the dc component in source current decays with time. But, it does not seem to be zero as disturbance is removed before it reaches the steady state. It will become zero if disturbance persists for more time. However, during voltage disturbances the aim is to maintain voltage.

Finally, the three phase load voltages before, during, and after voltage sag are shown in Fig. 16. A fast voltage regulation is achieved.

VI. CONCLUSIONS

The proposed control of DSTATCOM provides several operational features considering power factor and the PCC voltage as degree of freedom, which are not possible in conventional DSTATCOM operation. Least allowable power

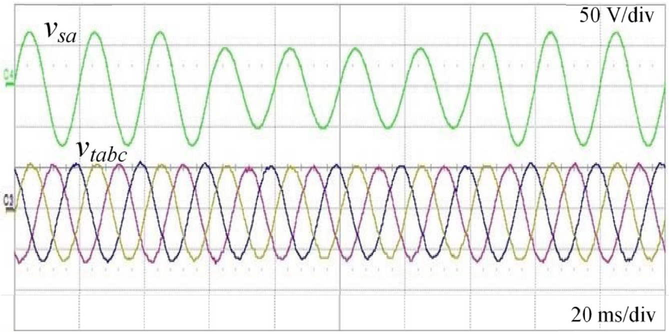

Fig. 16. Experimental results of proposed scheme during voltage sag.

factor is maintained at the PCC in normal operating conditions. Moreover, minimum voltage at which loads operate satisfactorily is maintained at the PCC during voltage sag. This voltage at the PCC also ensures that the loads draw reduced power from the grid, reducing electricity bills. These benefits are achieved with a reduced rating power converter. Also, the control scheme proposed in this paper can be used in some other applications such as hybrid-transformer or solid state transformer.

REFERENCES

[1] B. Singh, A. Chandra, and K. Al-Haddad, *Power quality: problems and mitigation techniques*. John Wiley & Sons, 2014.

[2] S. Devassy and B. Singh, "Implementation of solar photovoltaic system with universal active filtering capability," *IEEE Trans. on Industry Appl*. vol. 55, no. 4, pp. 3926–3934, 2019.

[3] C. Kumar, Mahesh K. Mishra, and M. Liserre, "Design of external inductor for improving performance of voltage-controlled dstatcom," *IEEE Trans. Ind. Electron.,* vol. 63, no. 8, pp. 4674–4682, Aug 2016.

[4] B. Singh, P. Jayaprakash, and D. P. Kothari, "A t-connected transformer and three-leg vsc based dstatcom for power quality improvement," *IEEE Trans. Power Electron*., vol. 23, no. 6, pp. 2710–2718, Nov 2008.

[5] S. Rahmani, A. Hamadi, K. Al-Haddad, and L. Dessaint, "A combination of shunt hybrid power filter and thyristor-controlled reactor for power quality," *IEEE Trans. Ind. Electron*., vol. 61, no. 5, pp. 2152–2164, May 2014.

[6] J. Barros and J. Silva, "Multilevel optimal predictive dynamic voltage restorer," *IEEE Trans. Ind. Electron.,* vol. 57, no. 8, pp. 2747–2760, Aug. 2010.

[7] M. Slepchenkov, K. Smedley, and J. Wen, "Hexagram-converter-based STATCOM for voltage support in fixed-speed wind turbine generation systems," *IEEE Trans. Ind. Electron*., vol. 58, no. 4, pp. 1120–1131, Apr. 2011.

[8] A. Ghosh and G. Ledwich, *Power quality enhancement using custom power devices*. Springer Science & Business Media, 2012.

[9] L. F. N. Loureno, M. B. de Camargo Salles, R. M. Monaro, and L. Quval "Technical cost of operating a photovoltaic installation as a statcom at nighttime," *IEEE Trans. Sustain. Energy*, vol. 10, no. 1, pp. 75–81, Jan 2019.

[10] E. Hossain, M. R. Tr, S. Padmanaban, S. Ay, and I. Khan, "Analysis and mitigation of power quality issues in distributed generation systems using custom power devices," *IEEE Access*, vol. 6, pp. 16 816–16 833, 2018.

[11] B. Singh and J. Solanki, "An implementation of an adaptive control algorithm for a three-phase shunt active filter," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 2811–2820, Aug 2009.

[12] B. Singh and S. Arya, "Back-propagation control algorithm for power quality improvement using DSTATCOM," *IEEE Trans. Ind. Electron*., vol. 61, no. 3, pp. 1204–1212, Mar. 2014.

[13] Mahesh K. Mishra, A. Ghosh, and A. Joshi, "Operation of a DSTATCOM in voltage control mode," *IEEE Trans. Power Del.,* vol. 18, no. 1, pp. 258–264, Jan. 2003.

[14] G. Modi, S. Kumar, and B. Singh, "Improved widrowhoff based adaptive

control of multiobjective pv-dstatcom system," *IEEE Trans. on Ind. Appl*., vol. 56, no. 2, pp. 1930–1939, 2020.

[15] Y. Hong and M. Liu, "Optimized interval type-ii fuzzy controller-based statcom for voltage regulation in power systems with photovoltaic farm," *IEEE Access*, vol. 6, pp. 78 731–78 739, 2018.

[16] R. K. Varma and E. M. Siavashi, "Pv-statcom: A new smart inverter for voltage control in distribution systems," *IEEE Trans. Sustain. Energy*, vol. 9, no. 4, pp. 1681–1691, Oct 2018.

[17] A. Bhattacharya, C. Chakraborty, and S. Bhattacharya, "Parallel connected shunt hybrid active power filters operating at different switching frequencies for improved performance," *IEEE Trans. Ind. Electron*., vol. 59, no. 11, pp. 4007–4019, Nov. 2012.

[18] M. H. Bollen, *Understanding power quality problems*. vol. 3, IEEE press New York, 2000.

[19] C. Kumar, R. Zhu, G. Buticchi, and M. Liserre, "Sizing and soc management of a smart-transformer-based energy storage system," *IEEE Trans. Ind. Electron*, vol. 65, no. 8, pp. 6709–6718, Aug 2018.

[20] G. De Carne, G. Buticchi, M. Liserre, and C. Vournas, "Load control using sensitivity identification by means of smart transformer," *IEEE Trans. on Smart Grid*, vol. 9, no. 4, pp. 2606–2615, 2018.

[21] Z. Wang and J. Wang, "Review on implementation and assessment of conservation voltage reduction," *IEEE Trans. on Power Sys*., vol. 29, no. 3, pp. 1306–1315, 2014.

[22] M. Liserre, G. Buticchi, M. Andresen, G. De Carne, L. F. Costa, and Z. Zou, "The smart transformer: Impact on the electric grid and technology challenges," *IEEE Ind. Electron. Mag*., vol. 10, no. 2, pp. 46–58, 2016.

[23] P. Shah, I. Hussain, and B. Singh, "Fuzzy logic based fogi-fll algorithm for optimal operation of single-stage three-phase grid interfaced multifunctional secs," *IEEE Trans. on Ind. Informat*., vol. 14, no. 8, pp. 3334–3346, Aug 2018.

[24] Chandan Kumar and Mahesh K. Mishra, "A multifunctional DSTATCOM operating under stiff source," *IEEE Trans. Ind. Electron*., vol. 61, no. 7, pp. 3131–3136, Jul. 2014.

[25] Kumar, C，Mishra, M.K "A voltage-controlled DSTATCOM for power-quality improvement," *IEEE Trans. Power Del*., vol. 29, no. 3, pp. 1499–1507, Jun. 2014.

[26] C. Kumar, M. V. M. Kumar, and M. K. Mishra, "A control scheme to enhance dstatcom operation in power distribution system," *in 2015 IEEE 6th International Symposium on Power Electronics for Distributed Generation Systems (PEDG),* 2015, pp. 1–6.

[27] R. T. Hock, Y. R. de Novaes, and A. L. Batschauer, "A voltage regulator for power quality improvement in low-voltage distribution grids," *IEEE Trans. Power Electron.*, vol. 33, no. 3, pp. 2050–2060, March 2018.

[28] Mahesh K. Mishra and K. Karthikeyan, "An investigation on design and switching dynamics of a voltage source inverter to compensate unbalanced and nonlinear loads," *IEEE Trans. Ind. Electron*., vol. 56, no. 8, pp. 2802–2810, Aug. 2009.

[29] I. Nagrath and M. Gopal, *Control systems engineering*. New York, Halsted Press, 1982.

[30] S. Kouro, P. Cortes, R. Vargas, U. Ammann, and J. Rodriguez, "Model predictive control-a simple and powerful method to control power converters," *IEEE Trans. Ind. Electron*., vol. 56, no. 6, pp. 1826–1838, Jun. 2009.

[31] J. Rodriguez, J. Pontt, C. Silva, P. Correa, P. Lezana, P. Cortes, and U. Ammann, "Predictive current control of a voltage source inverter," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 495–503, Feb 2007.

[32] H. Fujita and H. Akagi, "Voltage-regulation performance of a shunt active filter intended for installation on a power distribution system," *IEEE Trans. Power Electron*., vol. 22, no. 3, pp. 1046–1053, May 2007.

Chandan Kumarr (Senior Member, IEEE) received the B.Sc. degree from Muzaffarpur Institute of Technology, Muzaffarpur, India, in 2009; the M.Tech. degree from the National Institute of Technology, Trichy, India, in 2011; and the Ph.D. degree from the Indian Institute of Technology Madras, Chennai, India, in 2014, all in electrical engineering.

Since 2015, he is working as assistant professor in electronics and electrical engineering department at Indian Institute of Technology Guwahati, India. In 2016-17, he worked as Alexander von Humboldt research fellow at Chair of Power Electronics, University of Kiel, Kiel, Germany. He serves as an Associate Editor of the IEEE Access. His research interests include power electronics application in power system, power quality, and renewable energy.

Mahesh K. Mishra (Senior Member, IEEE) received the B.Tech. degree from the College of Technology, Pantnagar, India, in 1991, the M.E. degree from the Indian Institute of Technology Roorkee, Roorkee, India, in 1993, and the Ph.D. degree from the Indian Institute of Technology Kanpur, Kanpur, India, in 2002, all in electrical engineering.

He has about 29 years of teaching and research experience. For about ten years, he was with the Department of Electrical Engineering, Visvesvaraya National Institute of Technology Nagpur, India. He is currently a Professor with the Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai, India. His current research interests include power distribution systems, power electronics, microgrids, and renewable energy systems. Dr. Mahesh was the recipient of the IETE Prof. Bimal Bose Award in 2015 for his outstanding contributions to power electronics applications in power systems. He is a Life Member of the Indian Society of Technical Education. In 2017, he was elected as a Fellow of the Indian National Academy of Engineering. He served as an Editor for the IEEE Transactions on Sustainable Energy.

Saad Mekhilef (Senior Member, IEEE) received the B.Eng. degree in electrical engineering from the University of Setif, Setif, Algeria, in 1995, and the master degree in engineering science and the Ph.D. degree in electrical engineering from the University of Malaya, Kuala Lumpur, Malaysia, in 1998 and 2003, respectively.

He is currently a Professor and the Director of the Power Electronics and Renewable Energy Research Laboratory, Department of Electrical Engineering, University of Malaya. He is also the Dean of the Faculty of Engineering, University of Malaya. He is also a Distinguished Adjunct Professor with the School of Software and Electrical Engineering, Faculty of Science, Engineering, and Technology, Swinburne University of Technology, Melbourne, Australia. He has authored or coauthored more than 450 publications in international journals and conference proceedings. His current research interests include power converter topologies, the control of power converters, renewable energy, and energy efficiency.