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*Research Article*

# DSTATCOM supported induction generator for improving power quality

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*Valluri Chandra Sekhar, Krishan Kant ✉, Bhim Singh*

*Department of Electrical Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110 016, India*
✉ *E-mail: krishankantbhalla@gmail.com*

**Abstract:** This paper presents an implementation of sliding mode controller (SMC) along with a proportional and integral (PI) controller for a DSTATCOM (Distribution STATic COMpensator) for improving current induced power quality issues and voltage regulation of three-phase self-excited induction generator (SEIG). The use of SMC for regulating the DC link voltage of DSTATCOM offers various advantages such as reduction in number of sensors for estimating reference currents and the stable DC link voltage during transient conditions. The use of PI controller for terminal voltage control gives the error free voltage regulation in steady state conditions. The voltage regulation feature of DSTATCOM offers the advantages of single point voltage operation at the generator terminals with the reactive power compensation which avoids the saturation in the generator. Other offered advantages are balanced generator currents under any loading condition, harmonic currents mitigation, stable DC link voltage and the reduced number of sensors. The SMC algorithm is successfully implemented on a DSTATCOM employed with a three-phase SEIG feeding single phase or three phase loads. The performance of the proposed control algorithm is found satisfactory for voltage regulation and mitigation of power quality problems like reactive power compensation, harmonics elimination, and load balancing under nonlinear/linear loads.

## 1 Introduction

The use of an induction machine for the power generation has increased in past two decades due to popularity of distributed renewable energy resources. The use of an induction machine is prominent in remote/isolated areas such as micro-hydro power and biomass power generation due to having its own advantages compared with conventional synchronous generator [1, 2]. The induction machine is economical for small power generation in the aspects of low maintenance, brush-less operation, ruggedness, free from field excitation etc. Apart from these advantages, the induction machine requires leading volt ampere reactive (VAR) at its terminals for building up of the voltage. The machine requires variable capacitance across terminals for maintaining the constant terminal voltage from no load to full load condition. In earlier days, the terminal voltage of the induction machine is controlled by switching on and off of passive components such as inductors and capacitors [3]. The drawback of discrete control in the above method is eliminated with the invention of self-commutating solid-state power conducting devices. The use of static VAR compensator with an induction generator [4, 5] has given better voltage control but the size of passive components such as capacitors and inductors has become the major issue. With the recent development of power electronic devices and micro-controller, attempts have been made to control the induction generator with the help of electronic load controller [6, 7]. Various techniques [1–9] have been reported for voltage regulation of induction generators. The use of single-phase induction generators for feeding the single-phase loads is not feasible because of low efficiency and large size for the given output when compared with a three-phase induction generator. The use of single-phase loads on three-phase induction generator causes the unbalance voltages and currents in the phases. Some phases with high amount of single-phase loads cause overheating of windings which results in under-utilisation of rated capacity of the machine. Along with this problem, the use of non-linear loads such as compact fluorescent lamps, television, computers, and battery chargers injects harmonics into the system [10] affects other connected loads and causes heating of generator windings. All these problems can be solved by using custom power device such as Distribution STATic COMpensator (DSTATCOM) for the induction machine [8, 9].

In this paper, the sliding mode control with proportional–integral (PI) control algorithm is used for control of the dynamic operation of the DSTATCOM in distributed generation which improves the power quality at the terminals of the induction machine with reduced number of sensors. Extensive research has been done on the analysis of self-excited induction generator (SEIG) feeding balanced/unbalanced loads. The control algorithms for the operation of DSTATCOM such as synchronous reference frame theory, instantaneous reactive power theory, Icos Ø algorithm, Adaline algorithm and notch filter-based algorithm use sensed load currents for estimating the reference supply currents [10–13]. The main advantage of using sliding mode controller (SMC) is that the reference supply currents are estimated from the DC-link voltage of voltage source converter (VSC) which gives the robust control during transient conditions [14]. The PI controller helps in terminal voltage regulation of the induction generator. The power quality at the SEIG terminal is improved within the limits of an Institute of Electrical and Electronics Engineers (IEEE)-519 standard [15].

In the present paper, the DC-link voltage of VSC used as DSTATCOM is regulated by the SMC which suppresses undershoots and overshoots in the DC-link voltage. A reduced rating of DC-link capacitor may be used owing to this feature. The terminal voltage of the SEIG is also regulated at a value which lies away from the saturation point of the SEIG (even below the knee voltage). The operation has to be single point voltage operation; therefore, a PI controller is used to attain the reference voltage without any steady-state error. The operation below the knee voltage reduces the magnetising current drawn by the generator and hence increases its capability and reduces the harmonic distortion caused by the magnetising current. Moreover, the power quality issues are also mitigated. The generator currents are always balanced and free from harmonics; therefore, the utilisation of the generator is further increased and the operation is observed noiseless. The present system can feed a single-phase load connected line–line at 220 V of SEIG and still maintains the SEIG three-phase currents balanced and sinusoidal.

## 2 Configuration of DSTATCOM supported induction generator

Fig. 1*a* shows the schematic diagram of an induction generator supported by VSC-based DSTATCOM in the distributed generating system. DSTATCOM is connected in parallel with the load and an induction generator at the point of common coupling (PCC) for improving the power quality. The system is developed in such a way that an induction generator can feed the single- or three-phase linear/non-linear loads of the consumers simultaneously. The rated voltage of the induction generator is 230 V line–line voltage. Excitation capacitors are connected at the terminal of the induction generator for initial voltage buildup. Once the voltage is built and it is feeding the load, DSTATCOM starts its operation. It regulates the voltage by supplying the total reactive power required by the load and the extra reactive power required for maintaining the terminal voltage of an induction generator. The DSTATCOM operation is achieved by a control algorithm which is implemented in digital signal processor (DSP) as shown in Fig. 1*a*. Its details are discussed in the next section. The control algorithm gives the reference currents and the current tracking is carried out by hysteresis controller which generates gate pulses for VSC of DSTATCOM.

The DC-link voltage and its capacitor of DSTATCOM are selected depending on the PCC voltage and rating of the load which is to be compensated for improving the power quality. The value of DC-link voltage should be selected in such a manner that the DSTATCOM should be able to inject the currents into the system during the overvoltage condition and worst load dynamics. The DC-link voltage should sustain during the transient conditions and its value should be selected at least twice the peak value of the system phase voltage [9]. The DC-link voltage is estimated as

$$v_{dc} = \frac{(2\sqrt{2}(V_L/\sqrt{3})}{m_a} = \frac{(2\sqrt{2}(220/\sqrt{3})}{1} = 360\,\text{V} \qquad (1)$$

where $V_L$ is the line voltage at PCC, $m_a$ is the modulation index and its maximum value is 1.

The minimum value estimated as 360 V for 220 V AC system where as the reference DC-link voltage is selected as 400 V.

The value of the capacitor should be selected in such a way that it should allow the energy exchange during transient conditions and computational delay of the control action.

From the name plate details of the induction generator, the value of full load reactive power required at the terminals can be computed as

active component of current,

$$I_{active} = \frac{P_{gen}}{\sqrt{3}\times V_L} = \frac{3700}{\sqrt{3}\times 230} = 9.28\,\text{A} \qquad (2)$$

reactive component of current,

$$I_{re} = \sqrt{I_{rated}^2 - I_{active}^2} = \sqrt{14.5^2 - 9.28^2} = 11.1\,\text{A} \qquad (3)$$

The kilo volt ampere reactive (kVAR) required by an induction generator for maintaining terminal voltage at full load condition is computed as

kVAR rating of induction generator,

$$Q_{IG} = \sqrt{3}\times V_L \times_{re} = \sqrt{3}\times 230\times 11.1 = 4.48\,\text{kVAR} \qquad (4)$$

For having self-excitation, 1.7 kVAR ($Q_{Cap}$), 230 V, three-phase delta connected capacitor bank is connected across the terminals of the induction generator.

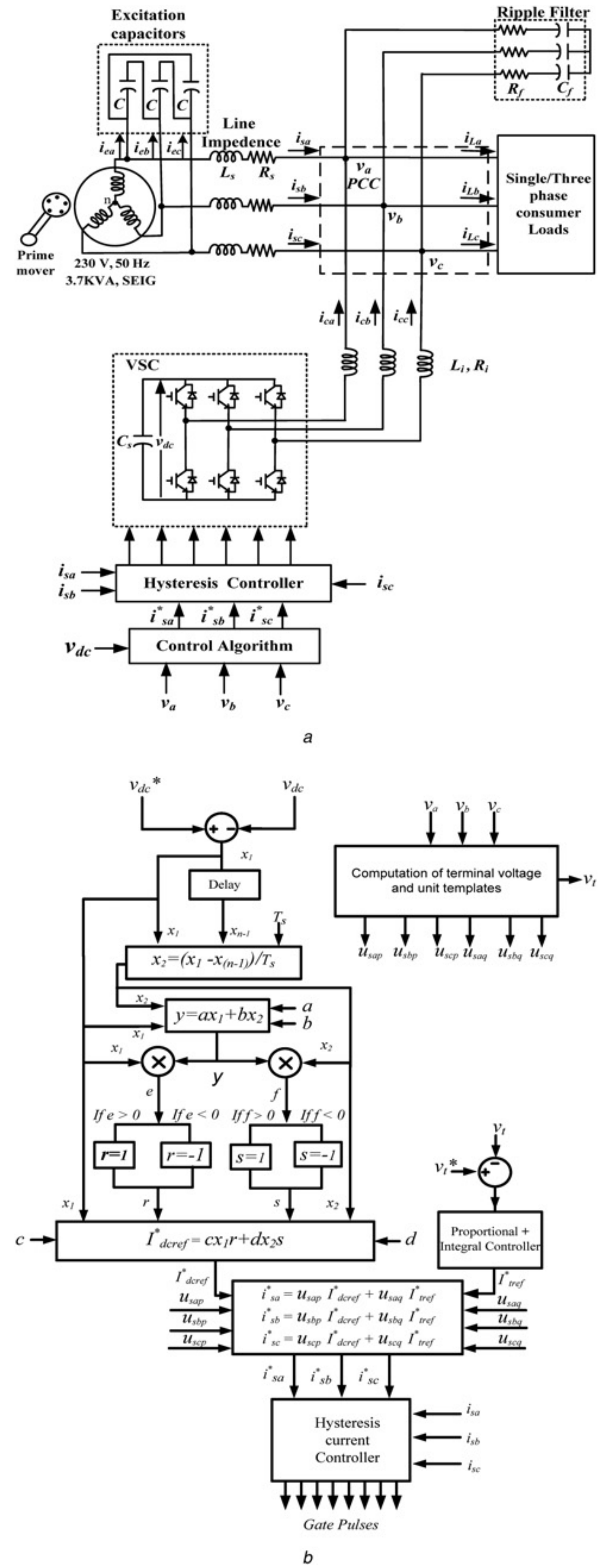



**Fig. 1** *Configuration of DSTATCOM supported induction generator*

*a* Schematic diagram of induction generator supported by VSC-based DSTATCOM
*b* Control algorithm of DSTATCOM for estimation of reference currents using SMC with PI controller

The load reactive power is considered as 2 kVAR ($Q_{\text{load}}$) and the total reactive power supplied by the DSTATCOM is calculated as

$$Q_{\text{DSTAT}} = \left\{ Q_{\text{load}} + (Q_{\text{IG}} - Q_{\text{Cap}}) \right\}$$
$$\text{kVAR} = \{2 + (4.48 - 1.7)\} = 4.78\,\text{kVAR} \tag{5}$$

The reactive component of compensating current is calculated as

$$I_{\text{com}} = \frac{Q_{\text{DSTAT}}}{\sqrt{3} \times V_{\text{L}}} = \frac{4780}{\sqrt{3} \times 220} = 12.54\,\text{A} \tag{6}$$

Generally, 10% of the total available energy is sufficient to make the energy exchange during transient conditions

$$\Delta e_{\text{dc}} = 0.1 \times 3 \times V_{\text{ph}} \times (a \times I_{\text{com}}) \times t = \frac{1}{2} C_{\text{dc}} (v_{\text{dcsteady}}^2 - v_{\text{dc}}^2) \tag{7}$$

where $V_{\text{ph}}$ is the phase voltage of the system, $a$ is the overloading factor, $I$ is the phase current, $t$ is the time allowed for DC-link voltage to recover during transient conditions, $C_{\text{dc}}$ is the capacitance value of the capacitor in Farads, $v_{\text{dcsteady}}$ and $v_{\text{dc}}$ are the steady-state voltages of DC-link and undershoot of DC voltage, respectively. As the SMC having inherent characteristics of small steady-state error is discussed in Section 3, the DC-link steady-state voltage is considered as 385 V. Substituting the system parameters in (7) gives

$$\Delta e_{\text{dc}} = 0.1 \times 3 \times (220/\sqrt{3}) \times (1.2 \times 12.5) \times 30 \times 10^{-3}$$
$$= \frac{1}{2} C_{\text{dc}} (385^2 - 375^2) \tag{8}$$

From the above expression, the estimated capacitor value is 1508 μF, whereas selected value in hardware implementation is considered as 1650 μF.

The interfacing inductors help to mitigate the ripples in the compensating currents. The selection of interface inductor depends on the switching frequency of the pulse-width modulation and the allowable percentage ripple current through it. Its value is selected as 10%. The value of inductor can be computed as

$$L_{\text{f}} = \frac{(\sqrt{3}/2) m_a v_{\text{dc}}}{6 a f_{\text{s}} I_{\text{cr,pp}}} = \frac{(\sqrt{3}/2) \times 1 \times 385}{6 \times 1.2 \times 8 \times 10^3 \times (0.1 \times 12.54)} = 4.63\,\text{mH} \tag{9}$$

where $v_{\text{dc}}$ is the DC bus voltage, $m_a$ is the modulation index, $f_{\text{s}}$ is switching frequency, $I_{\text{cr,pp}}$ is the allowable ripple current through inductor, '$a$' is a overloading factor. From the calculation the estimated inductor value is 4.63 mH, whereas its selected value is 5 mH.

A ripple filter is made with the resistors and capacitors for filtering the switching noise at PCC due to switching of insulated gate bipolar transistors (IGBTs) of VSC. A three-phase three-wire VSC consists of six IGBTs along with the anti-parallel diodes. In the proposed control algorithm, the dynamic operation of DSTATCOM depends on the small variation in DC-link voltage and terminal voltage under sudden change in load conditions.

## 3 Control of DSTATCOM

This SMC with PI controller-based algorithm used for control of three-phase VSC-based DSTATCOM is explained in the following section.

The advantages offered by the SMC with PI controller are as follows:

1. For hardware implementation, the use of SMC in the control of DC-link voltage can eliminate the load current sensors which make the DSTATCOM cost effective.
2. SMC gives the robust control during transient conditions and the fast dynamic response in terms of overshoot and undershoot of DC-link voltage of VSC during load variation/transient condition.
3. The use of PI controller in terminal voltage regulation gives the zero-voltage regulation during steady-state condition.

For some cases, the SMC offers a disadvantage also, which is the steady-state error. SMC tracks the reference very robustly but with a small steady-state error. This is not a problem in the present case as the DC link has to be maintained at a certain minimum level and remains within a specified range, not at a given level.

Fig. 1*b* shows the step-by-step procedure to estimate the reference supply currents using SMC and PI controller-based algorithm. The SMC gives in-phase component current for meeting the load active power, losses in the DSTATCOM, and PI controller gives the quadrature component current for regulating the terminal voltage. In sliding mode control, the DSTATCOM compensating currents are controlled to track or slide along the reference or trajectory. The SMC control algorithm [16–21] detects the deviation from the reference trajectory and promptly changes the switching control strategy to follow the reference trajectory. The SMC control gives the robust performance under parameter variations.

The in-phase components of unit vectors are estimated from the PCC voltages ($v_a$, $v_b$, and $v_c$).

The instantaneous amplitude of PCC is estimated as

$$V_t = \sqrt{2\left(v_a^2 + v_b^2 + v_c^2\right)/3} \tag{10}$$

The in-phase components of unit templates are computed as

$$u_{sap} = v_a/V_t; \quad u_{sbp} = v_b/V_t; \quad u_{scp} = v_c/V_t \tag{11}$$

The quadrature components of unit templates are computed as

$$u_{saq} = \left(-u_{sbp} + u_{scp}\right)\Big/\sqrt{3}$$
$$u_{sbq} = \left(u_{sap}\sqrt{3} + u_{sbp} - u_{scp}\right)\Big/2 \tag{12}$$
$$u_{scq} = \left(-u_{sap}\sqrt{3} + u_{sbp} - u_{scp}\right)\Big/2$$

In SMC algorithm, the amplitudes of in-phase reference currents are estimated from DC-link voltage. The sensed DC voltage ($v_{\text{dc}}$) is filtered using a low-pass filter and it is compared with the reference voltage ($v_{\text{dc}}^*$) to generate the error signal, $x_1$ as

$$x_1 = v_{\text{dc}}^* - v_{\text{dc}} \tag{13}$$

Moreover, the derivative of above equation gives

$$x_2 = \dot{x}_1 = \frac{1}{T}\left\{x_1 - x_{(n-1)}\right\} \tag{14}$$

where $x_1$, $x_2$ are the state variables, $x_{(n-1)}$ is the previous sample value, and $T$ is the sampling time.

According to the slope of the DC-link voltage error, the switching parameters $r$ and $s$ are selected.

The values of $r$ and $s$ are found from the logic decisions as follows

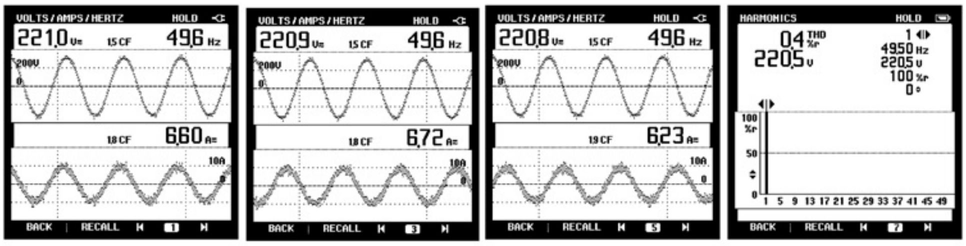
$$r = +1 \quad \text{if} \quad yx_1 > 0 = -1 \quad \text{if} \quad yx_1 < 0$$
$$s = +1 \quad \text{if } yx_2 > 0 = -1 \quad \text{if} \quad yx_2 < 0 \tag{15}$$

where '$y$' is the switching hyper plane function, $y = ax_1 + bx_2$.

The amplitudes of reference active source currents are found as

$$I_{\text{dcref}}^* = cx_1 r + dx_2 s \tag{16}$$

where $a$, $b$, $c$, and $d$ are the constants of the SMC.




*a* *b* *c* *d*

**Fig. 2** *Performance of DSTATCOM under single-phase non-linear load*
*a–c* $v_{sab}$ with $i_{sa}$, $i_{sb}$, and $i_{sc}$
*d* $v_{sab}$ harmonic spectra

The estimated amplitude of the reference source current is multiplied with the in-phase unit templates to generate the active power component of reference source currents as

$$i^*_{sap} = I^*_{\text{dcref}} u_{sap}, \quad i^*_{sbp} = I^*_{\text{dcref}} u_{sbp}, \quad i^*_{scp} = I^*_{\text{dcref}} u_{scp} \tag{17}$$

The amplitude of quadrature component ($I^*_{\text{acref}}$) is computed using PI controller, taking the difference of reference AC voltage ($V^*_t$) and the calculated amplitude of PCC voltage ($V_t$) as

$$v_{\text{ace}} = V^*_t - V_t \tag{18}$$

The output of PI controller for maintaining terminal voltage at reference value is given as

$$I^*_{\text{acref}}(k) = I^*_{\text{acref}}(k-1) + K_{\text{pa}}\{v_{\text{ace}}(k) + v_{\text{ace}}(k-1)\} + K_{\text{ia}} v_{\text{ace}}(k) \tag{19}$$

where $K_{\text{pa}}$, $K_{\text{ia}}$ are the PI gains of the PI controller, respectively.

$v_{\text{ace}}(k)$ and $v_{\text{ace}}\,(k-1)$ are the voltage errors at the $k$th and $(k-1)$th instants, respectively.

The output of PI controller ($I^*_{\text{acref}}$) is multiplied with the quadrature unit templates to generate the reference quadrature source currents for regulating terminal voltage

$$i^*_{saq} = I^*_{\text{acref}} u_{saq}, \quad i^*_{sbq} = I^*_{\text{acref}} u_{sbq}, \quad i^*_{scq} = I^*_{\text{acref}} u_{scq} \tag{20}$$

The total reference source currents can be calculated by adding both quadrature reference currents ($i^*_{saq}$, $i^*_{sbq}$, $i^*_{scq}$) and the in-phase reference currents ($i^*_{spa}$, $i^*_{spb}$, $i^*_{spc}$)

$$i^*_{sa} = i^*_{sap} + i^*_{saq}, \quad i^*_{sb} = i^*_{sbp} + i^*_{sbq}, \quad i^*_{sc} = i^*_{scp} + i^*_{scq} \tag{21}$$

The sensed source currents ($i_{sa}$, $i_{sb}$, $i_{sc}$) are compared with these estimated reference source currents ($i^*_{sa}$, $i^*_{sb}$, $i^*_{sc}$) and the current error signals are given to the hysteresis current controller and the gating pulses are generated for the three legs of VSC used as DSTATCOM.

## 4 Results and discussion

The SMC with PI controller-based algorithm is validated experimentally and by simulation on a DSTATCOM supported induction generator. The system specifications are given in the Appendix.

### 4.1 Experimental results

The phase voltages and DC-link voltage are sensed by using voltage sensors (LEM CV3-1500). The source currents are sensed using Hall Effect current sensors (LEM CT100S). Since the system is balanced three-phase, three-wire, two current sensors are sufficient for sensing the three source currents. The SMC with PI controller-based algorithm is implemented on a DSTATCOM to control the power quality at the terminal of an induction generator using DSP (dSPACE-1104) for generating the switching signals for IGBT's of VSC of DSTATCOM. A three-leg IGBT's based VSC is used and it is connected to the PCC through interfacing inductors to eliminate the switching ripples. Extensive tests are conducted on a three-phase, 3.7 kW SEIG controlled by DSTATCOM and its DC-link voltage is regulated at 400 V. The value of DC-link capacitor used is 1650 µF. The steady-state and dynamic responses of SMC with PI controller-based algorithm are validated under different kinds of loads such as single-phase loads and three-phase non-linear/linear loads.

(1) *Steady-state performance of DSTATCOM under single-phase non-linear load:* A single-phase non-linear load is connected in between two terminals of the induction generator which causes unbalanced currents in the winding of the induction generator as the third phase is not loaded. An *R–L* load with a diode rectifier serves as a non-linear load which causes power quality problems such as injection of harmonics into the system. However, with the support of the DSTATCOM, these power quality problems such as unbalanced load, harmonics, and reactive power requirement are mitigated. Figs. 2*a–c* show the waveforms of PCC voltages ($v_{ab}$, $v_{bc}$, and $v_{ca}$) with three-phase source currents ($i_{sa}$, $i_{sb}$, and $i_{sc}$) which are balanced irrespective of the type of the load connected. Figs. 2*d* and 3*a–d* show harmonic spectra of PCC voltage ($v_{ab}$), source currents ($i_{sa}$, $i_{sb}$, and $i_{sc}$) and load current ($i_{\text{La}}$), out of which source current and PCC voltage total harmonic distortion's (THD's) are under limits of IEEE-519 standard. The operation of DSTATCOM helps in harmonics mitigation and source currents are relieved from harmonics content. In Figs. 3*a* and *d*, the THD of '*a*' phase source current and load current are observed as 3.6 and 27.4%, respectively. Fig. 4*a* shows $v_{ab}$ with non-linear load current ($i_{\text{L}ab}$). Figs. 4*b* and *c* show load power ($P_{\text{L}}$ and $Q_{\text{L}}$) and source power ($P_{\text{S}}$ and $Q_{\text{S}}$). The load reactive power 1.03 kVAR as shown in Fig. 4*b* is compensated by the DSTATCOM and the source currents in Fig. 4*c* are relieved from the reactive power burden with an improved power factor. Fig. 4*d* gives information about the nature of the reactive power that is injected at the PCC through compensating currents. Figs. 5*a–d* show DSTATCOM compensating currents ($i_{\text{ca}}$, $i_{\text{cb}}$, and $i_{\text{cc}}$) and DC-link voltage $v_{\text{dc}}$ with $i_{sab}$. Figs. 5*a–c* demonstrate the shapes of the compensator currents to make the source currents balanced and sinusoidal. From Figs. 2–5, it can be inferred that DSTATCOM controlled induction generator is able to feed the single-phase loads without any derating of the generator, instead increasing the active power capability of the generator.

(2) *Dynamic performance of DSTATCOM under induction motor starting and non-linear load:* The dynamic response of the DSTATCOM is recorded during the starting of a three-phase induction motor along with the pre-existing non-linear load. Figs. 6*a* and *b* show variation of various indices of DSTATCOM such as PCC voltage ($v_{sab}$), source currents ($i_{sa}$, $i_{sb}$, and $i_{sc}$), compensating current ($i_{ca}$), and DC-link voltage ($v_{\text{dc}}$) during the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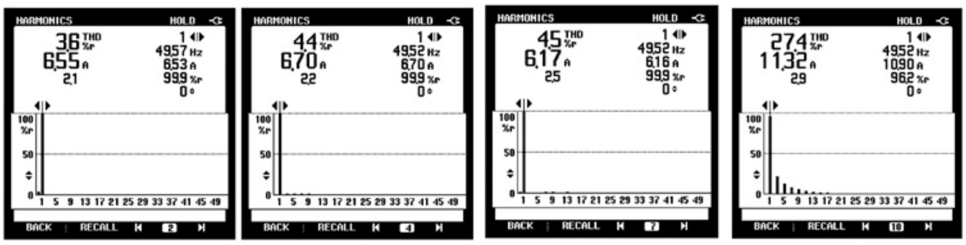
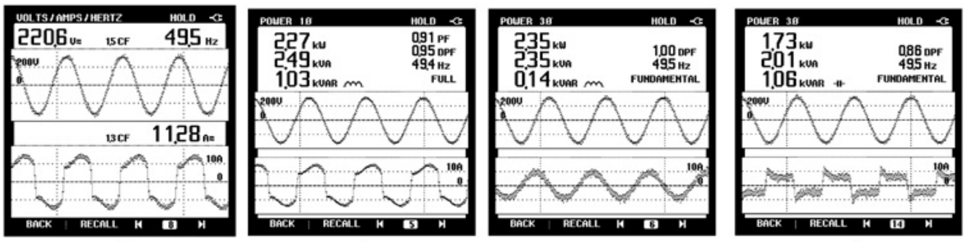



a b c d

**Fig. 3** *Performance of DSTATCOM under single-phase non-linear load*

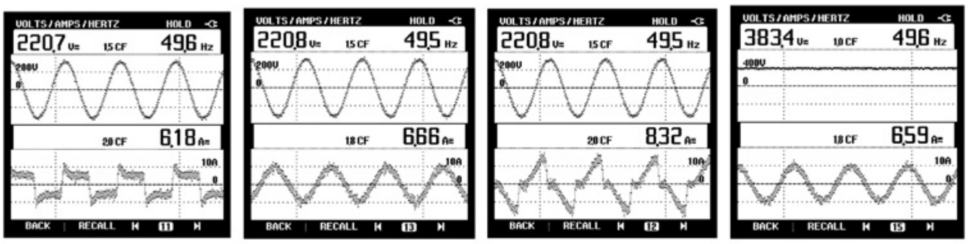
*a–d* $i_{sa}$, $i_{sb}$, $i_{sc}$, and $i_{Lab}$ harmonic spectra




a b c d

**Fig. 4** *Performance of DSTATCOM under single-phase non-linear load*

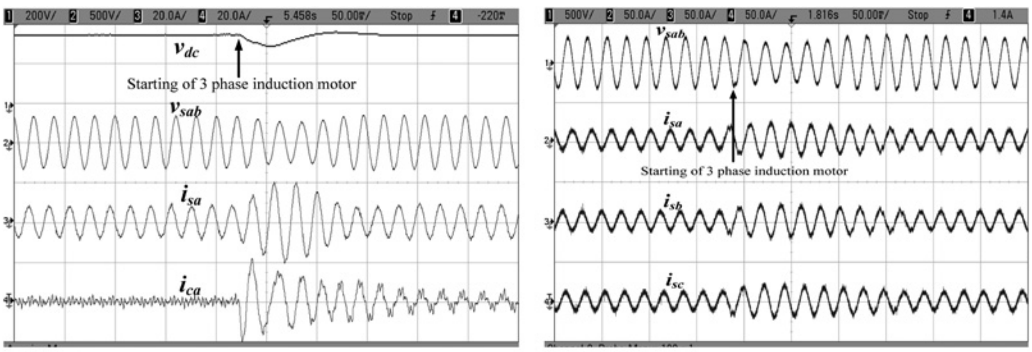
*a* $v_{sab}$ with $i_{Lab}$
*b* $P_L$ and $Q_L$
*c* $P_S$ and $Q_S$
*d* $P_C$ and $Q_C$




a b c d

**Fig. 5** *Performance of DSTATCOM under single-phase non-linear load*

*a–c* $v_{sabc}$ with $i_{ca}$, $i_{cb}$, and $i_{cc}$
*d* $v_{dc}$ with $i_{sab}$




a b

**Fig. 6** *Dynamic response of DSTATCOM under induction motor starting along with non-linear loads*

*a*, *b* Variation of parameters such as $v_{dc}$, $v_{sab}$, $i_{sa}$, $i_{sb}$, $i_{sc}$, and $i_{ca}$ during starting of one horse power three-phase induction motor

starting of the induction motor. An induction motor draws many times (4–6) of its rated current at starting to overcome the inertia. At starting of the induction motor, there is a dip in DC-link voltage ($v_{dc}$) and terminal voltage ($v_{sab}$) momentarily, and the compensating currents are quite high for supporting both active and reactive powers required for starting of the induction motor. Since of the dynamic

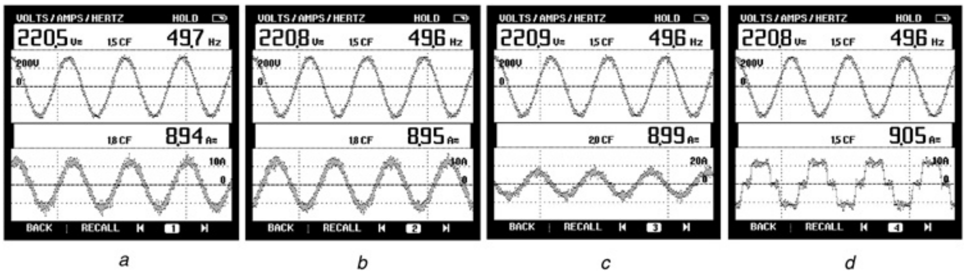



**Fig. 7** *Performance of DSTATCOM under three-phase non-linear load*
*a–d* $v_{sab}$ with $i_{sa}$, $i_{sb}$, $i_{sc}$, and $i_{La}$

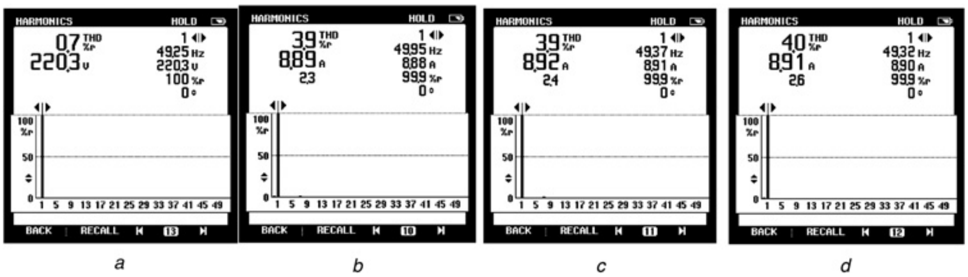



**Fig. 8** *Performance of DSTATCOM under three-phase non-linear load*
*a–d* $v_{sa}$, $i_{sa}$, $i_{sb}$, and $i_{sc}$ harmonic spectra

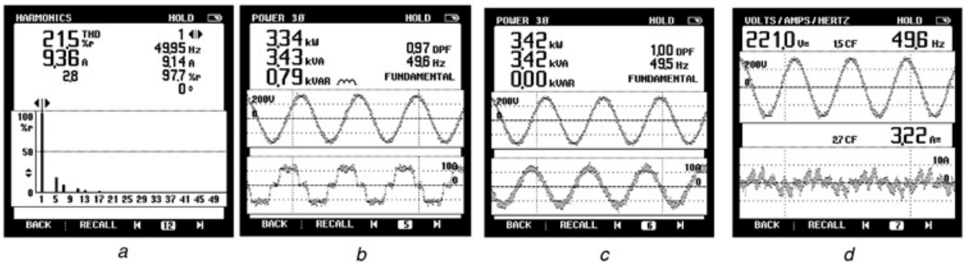



**Fig. 9** *Performance of DSTATCOM under non-linear load*
*a* $i_{La}$ harmonic spectra
*b* $P_L$ and $Q_L$
*c* $P_S$ and $Q_S$
*d* $v_{sab}$ and $i_{ca}$

operation of the DSTATCOM, the terminal voltage of the induction generator is not collapsed and the DC-link voltage and terminal voltage are quickly recovered from the dips. Fig. 6*b* shows the variation of source currents ($i_{sa}$, $i_{sb}$, and $i_{sc}$) and PCC voltage ($v_{sab}$) at the time of starting of the induction motor. From Fig. 6, it can be inferred that DSTATCOM-based induction generator is able to feed an induction motor load without collapsing the voltage of an induction generator during starting of the motor.

(3) *Steady-state and dynamic performances of DSTATCOM under three-phase non-linear load:* The dynamic performance is evaluated under three-phase non-linear load condition. A three diode rectifier with *R–L* load is used as the non-linear load. Figs. 7*a–c* show the waveforms of PCC voltage ($v_{ab}$) with three balanced phase source currents ($i_{sa}$, $i_{sb}$, and $i_{sc}$). Fig. 7*d* shows the PCC voltage ($v_{ab}$) and non-linear natured load current ($i_{La}$). Figs. 8*a–d* show harmonic spectra of PCC voltage ($v_{ab}$) and source currents ($i_{sa}$, $i_{sb}$, and $i_{sc}$). Fig. 9*a* shows the load current ($i_{La}$) harmonic spectra of phase '*a*', out of which source currents ($i_{sa}$, $i_{sb}$, and $i_{sc}$) and PCC voltage ($v_{ab}$), THD's are under the limits of IEEE-519 standard which are compensated with the operation of DSTATCOM. Figs. 9*b* and *c* show load power ($P_L$ and $Q_L$) and source power ($P_S$ and $Q_S$). The load reactive power 0.79 kVAR as shown in Fig. 9*b* is compensated by the DSTATCOM and the source in Fig. 9*c* are relieved from the reactive power burden. Fig. 9*d* shows the DSTATCOM compensating current ($i_{Ca}$). In Figs. 8*b* and 9*a*, the THD's of '*a*' phase source current and load current are observed as 3.9 and 21.5%, respectively. The dynamic response of the DSTATCOM is seen under unbalanced conditions to validate the basic functions of current balancing, mitigating harmonics and voltage regulation. The satisfactory dynamic performance of DSTATCOM can be seen from Figs. 10*a–d* which give the information about various indices of DSTATCOM such as waveforms of PCC voltage ($v_{ab}$), source currents ($i_{sa}$, $i_{sb}$, and $i_{sc}$), DC-link voltage ($v_{dc}$), compensating currents ($i_{ca}$, $i_{cb}$, and $i_{cc}$) and load current ($i_{La}$). Figs. 10*a* and *b* show the dynamic response of DSTATCOM during insertion of load on phase '*a*'. Fig. 10*a* shows that source currents ($i_{sa}$, $i_{sb}$, and $i_{sc}$) which still remain balanced when the load on phase '*a*' is reinserted. Fig. 10*b* shows the dynamics of compensating currents ($i_{ca}$, $i_{cb}$, and $i_{cc}$) when load on phase '*a*' is reinserted. The phase '*a*' compensating current is turned from sinusoidal to non-sinusoidal with the reinsertion of the load on phase '*a*'. Figs. 10*c* shows the dynamic response of DSTATCOM during phase '*a*' load removal. Fig. 10*d* shows the variation of various indices $v_{dc}$, $i_{sa}$, $i_{ca}$, and $i_{la}$ with respect to change in the load. It shows that with sudden change in load magnitude and shape, the compensator current is responding immediately to keep the source current sinusoidal. Moreover, during all this dynamics, there is a little dip in DC-link voltage


*IET Renew. Power Gener.*, pp. 1–9

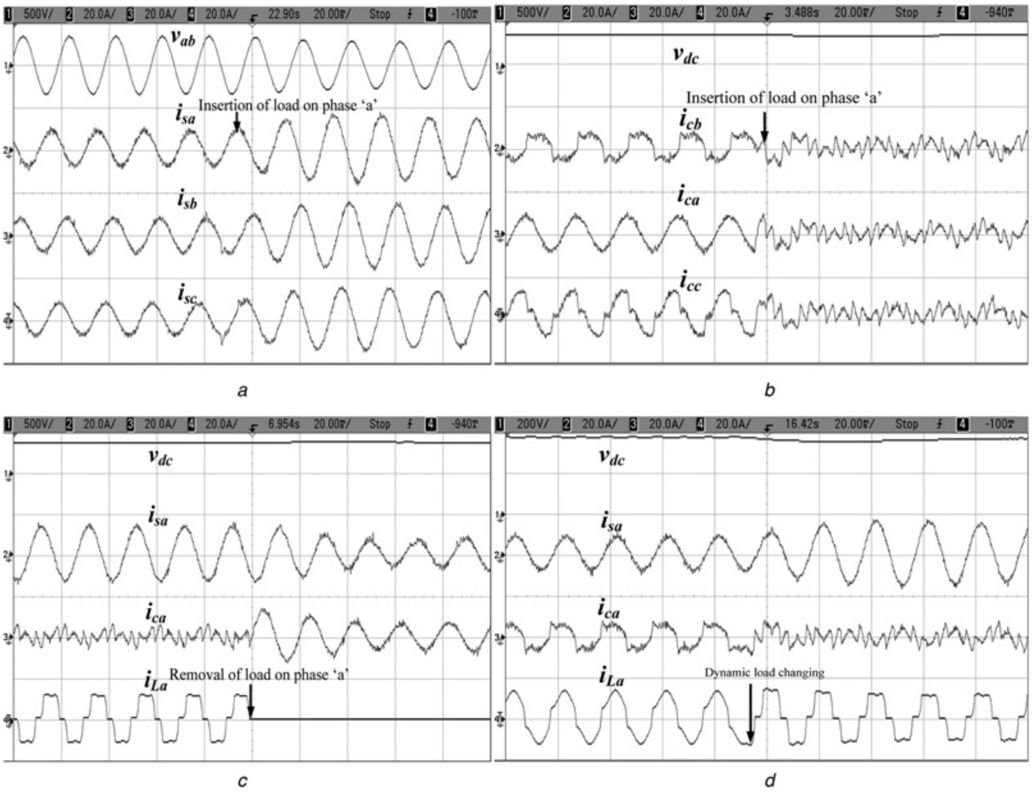



**Fig. 10** *Dynamic response of DSTATCOM*

*a* Removal of load on phase '*a*'
*b*, *c* Insertion of load on phase '*a*'
*d* Sudden load change

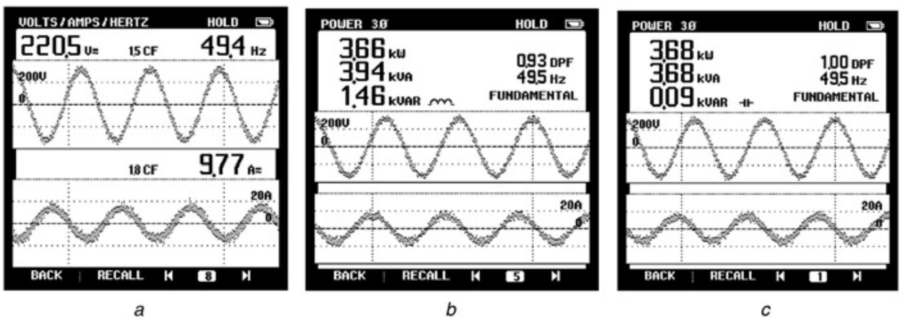



**Fig. 11** *Performance of DSTATCOM under linear load*

*a* Waveforms of $v_{sa}$ and $i_{sa}$
*b* $P_L$ and $Q_L$
*c* $P_S$ and $Q_S$

and it is regulated back. From Figs. 7–10, it can be inferred that DSTATCOM-based induction generator is able to feed the three-phase unbalanced/balanced non-linear loads without affecting the power quality standards.

(4) *Steady-state performance of DSTATCOM under linear load:* The dynamic response of DSTATCOM is validated by connecting three-phase unbalanced linear load (*R*–*L* load) at the PCC. The power factor at the source side is improved and maintained at unity power factor using DSTATCOM. Fig. 11*a* shows the PCC voltage ($v_{ab}$) with source current ($i_{sa}$). Figs. 11*b* and *c* show power consumed by the load ($P_L$ and $Q_L$) and source ($P_S$ and $Q_S$).

Fig. 11*b* shows that the load has needed 1460 VAR of reactive power but at PCC the reactive power drawn is almost zero and maintaining at unity power factor as shown in Fig. 11*c*. With the dynamic operation of DSTATCOM, all the reactive power required by the load is compensated and made the kVA rating of source power is less than the load kilo volt ampere (kVA) rating. The experimental results have shown that an induction generator supported by DSTATCOM using SMC with PI controller is able to perform the basic operation of DSTATCOM such as voltage regulation with reactive power compensation, harmonics mitigation, and source currents balancing.

### 4.2 Simulation results

The complete system with control algorithm is also verified using simulation. The performance is verified under non-linear load. An induction generator and DSTATCOM are modelled in MATLAB Simulink using the components parameters as described in the Appendix.

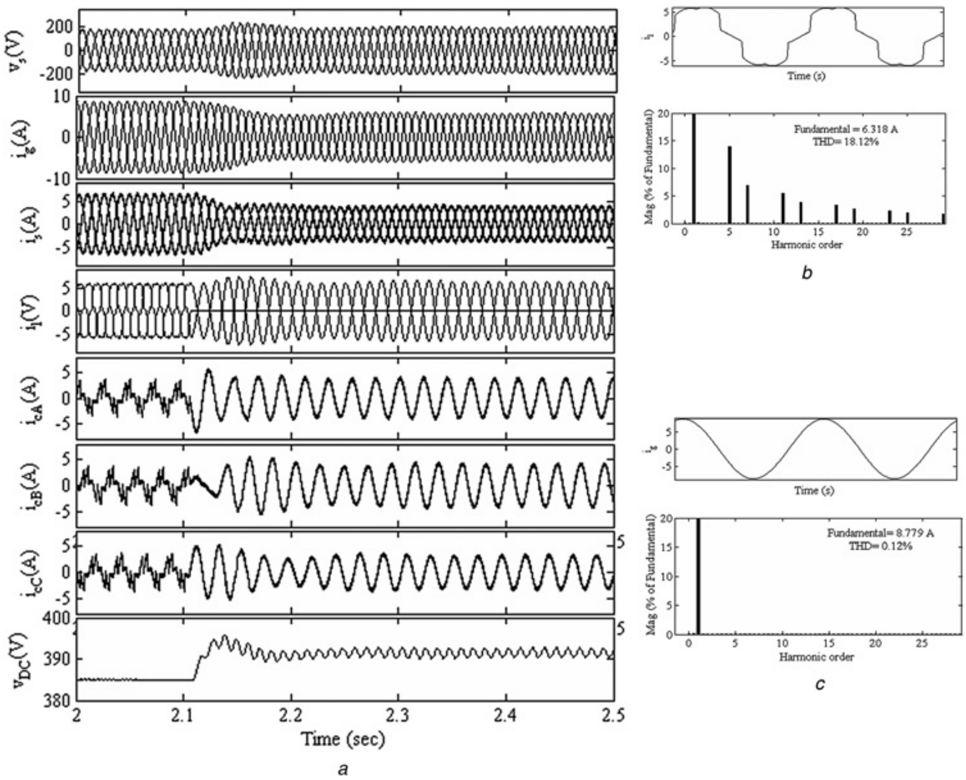



**Fig. 12** *Simulation results of DSTATCOM*

*a* Performance of DSTATCOM under three-phase and single-phase non-linear load
*b*, *c* Harmonic content of load current $i_{la}$ and generator current

Fig. 12*a* shows the performance of DSTATCOM under three-phase and single-phase loading conditions, also the dynamic performance during load switching. It can be seen that the overshoot is of order of 1% with the SMC. Moreover, the terminal voltage is also regulated and maintained at the reference value.

The induction generator with 230 V line voltage can be used to feed a single-phase load connected line–line without any compromise with the generator loading and derating. Regardless of the load, the generator currents are balanced and sinusoidal. Whether a three phase, single phase, or during dynamics, the terminal voltage is regulated, the generator currents are balanced and sinusoidal, and the DC-link voltage is also regulated in a very small range.

Figs. 12*b* and *c* show the harmonic spectra and THDs of load current and generator current. It shows that the harmonic content of the generator current is within acceptable range. This has reduced the unwanted heating, noise, and derating of the generator.

The simulation results are further supported with the concept and the feasibility. The power quality problem mitigation, DC-link voltage regulation, and terminal voltage regulation are working satisfactorily and further have agreement with the experimental results.

## 5 Conclusion

A DSTATCOM supported induction generator has been implemented with the SMC with PI control algorithm for mitigating the power quality problems and it has enhanced the active power capability of the generator. The SMC has been verified for the dynamics in the DC-link voltage and found robust and acceptably fast to avoid large variations in DC-link voltage. Moreover, from the experimental results it has been inferred that the sliding mode control with PI controller algorithm has been found capable of meeting various functionalities of DSTATCOM such as voltage regulation, source currents balancing, harmonics mitigation, and reactive power compensation.

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## 7 Appendix

See Table 1.

**Table 1** System and control parameters

| | | |
|---|---|---|
| generator parameters | 3.7 kW, 230 V, 14.5 A, 50 Hz, Y-connected, four pole | |
| load parameters | single-phase non-linear load: single-phase uncontrolled bridge rectifier feeding *R–L* load. $R = 14\ \Omega$ and $L = 250$ mH<br>motor load: three-phase 230 V, one horse power rating induction motor<br>non-linear load: three-phase full bridge uncontrolled rectifier with $R = 15\ \Omega$ and $L = 120$ mH<br>linear loads: 3.94 kVA 0.93 pf displacement power factor (DPF) lagging | |
| DSTATCOM parameters | DC-link capacitance | 1650 μF |
| | reference DC-link voltage ($v_{dc}$) | 400 V |
| | interfacing inductor ($L_f$) | 5 mH |
| | ripple filter ($R_f$, $C_f$) | 5 Ω, 10 μF |
| controller sampling time | 60 μs | |
| SMC controller gains | $a$ | 8 |
| | $b$ | 0.1 |
| | $c$ | 1 |
| | $d$ | 0.001 |
| PI controller gains | $K_{pa}$ | 0.4 |
| | $K_{ia}$ | 0.1 |
| simulation parameters | solver | Runge–Kutta fourth order |
| | sampling time | 10 μs |