Improvement of power quality using DSTATCOM supported by induction generator

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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 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 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.

KEYWORDS: DSTATCOM, SMC, SEIG, REACTIVE POWER.

I. 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-utilization 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, I cosØ 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) 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 magnetizing current drawn by the generator and hence increases its capability and reduces the harmonic distortion caused by the magnetizing current. Moreover, the power quality issues are also mitigated. The generator currents are always balanced and free from harmonics; therefore, the utilization 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 sinusoida.

II.CONFIGURATION OF DSTATCOM SUPPORTED INDUCTION GENERATOR

Fig. 1a 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. 1a. 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

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

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,

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

Reactive component of current,

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

$I_{re} = \quad I^2 \qquad\qquad - I^2$

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,

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

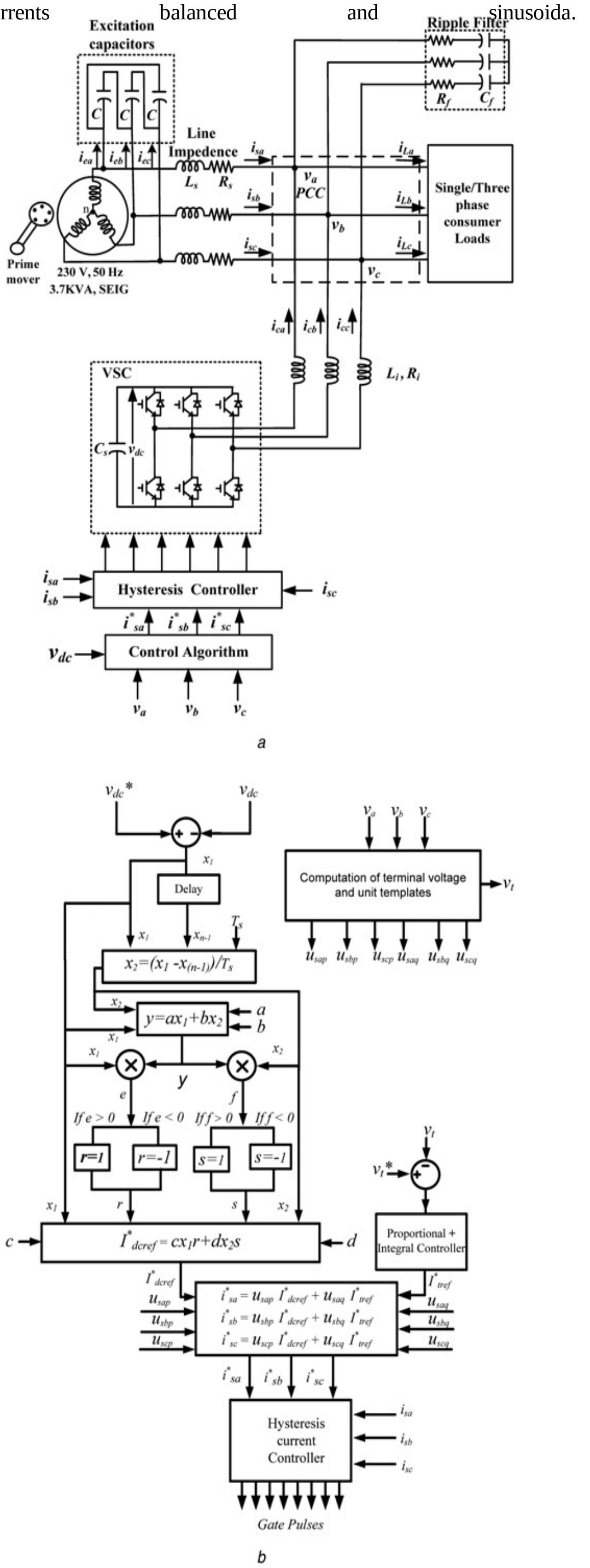


Fig. 1 Configuration of DSTATCOM supported induction generator

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

delta connected capacitor bank is connected across the terminals of active component of current, the induction generator.

For having self-excitation, 1.7 kVAR (Q_{Cap}), 230 V, three-phase

III. 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:

$$r = +1 \quad \text{if} \quad yx_1 - 0 = -1 \quad \text{if} \quad yx_1 < 0 \qquad (5)$$

$$s = +1 \quad \text{if} \; yx_2 - 0 = -1 \quad \text{if} \quad yx_2 < 0$$

Where ‘y’ is the switching hyper plane function, $y = ax_1 + bx_2$. The amplitudes of reference active source currents are found as

$$I_{dcref} = cx_1 r + dx_2 s \qquad (6)$$

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

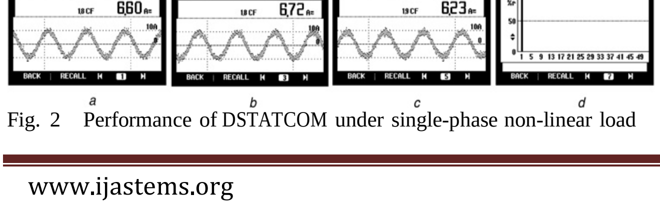
VI.RESULTSAND DISCUSSION

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 current (i_{Lab}). Figs. 2b and c show load power ($P_{L\ and}$ Q_L) and source power (P_S and Q_S). The load reactive power 1.03 kVAR asshown in Fig. 2b is compensated by the DSTATCOM and the source currents in Fig. 2c are relieved from the reactive power burden with an improved power factor. Fig. 2d gives information about the nature of the reactive power that is injected at the PCC through compensating currents. Figs. 2a–d shows DSTATCOM compensating currents (i_{ca}, i_{cb}, and i_{cc}) and DC-link voltage v_{dc} with i_{sab}. Figs. 2a–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.

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. 3a 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_{dc}) during 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 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. 3b 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. 3, 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.



a b c d

Fig. 2 Performance of DSTATCOM under single-phase non-linear load

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.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

a–c v_{sab} with i_{sa}, i_{sb}, and i_{sc}

d v_{sab} harmonic spectra

(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. 3a–c show the waveforms of PCC voltage (v_{ab}) with three balanced phase source currents (i_{sa}, i_{sb}, and i_{sc}). Fig. 3d shows the PCC voltage (v_{ab}) and non-linear natured load current (i_{La}). Figs. 3a–d show harmonic spectra of PCC voltage (v_{ab}) and source currents (i_{sa}, i_{sb}, and i_{sc}). Fig. 3 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. 8b 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. 3 b is compensated by the DSTATCOM and the source in Fig. 3c are relieved from the reactive power burden. Fig. 3d shows the DSTATCOM compensating current (i_{Ca}). In Figs. 3b and 3a, 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. 3a–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. 3a and b show the dynamic response of DSTATCOM during insertion of load on phase ‘a’. Fig. 3a shows that source currents (i_{sa}, i_{sb}, and i_{sc}) which still remain balanced when the load on phase ‘a’ is reinserted. Fig. 3b shows the dynamics of compensating currents (i_{ca}, i_{cb}, and i_{cc}) when load on phase ‘a’ is reinserted.

Fig. 3 Dynamic response of DSTATCOM

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

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 The phase 'a' compensating current is turned from sinusoidal to non-sinusoidal with the reinsertion of the load on phase 'a'. Figs. 3c show the dynamic response of DSTATCOM during phase 'a' load removal. Fig. 3d 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 and it is regulated back. From Figs. 2–3, 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.

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. 3ashows the PCC voltage (v_{ab}) with source current (i_{sa}). Figs. 3b and c show power consumed by the load (P_L and Q_L) and source (P_S and Q_S).

Fig. 3b 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. 3c. 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.

V.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. 4a shows the performance of DSTATCOM fewer than 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. 4b 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.

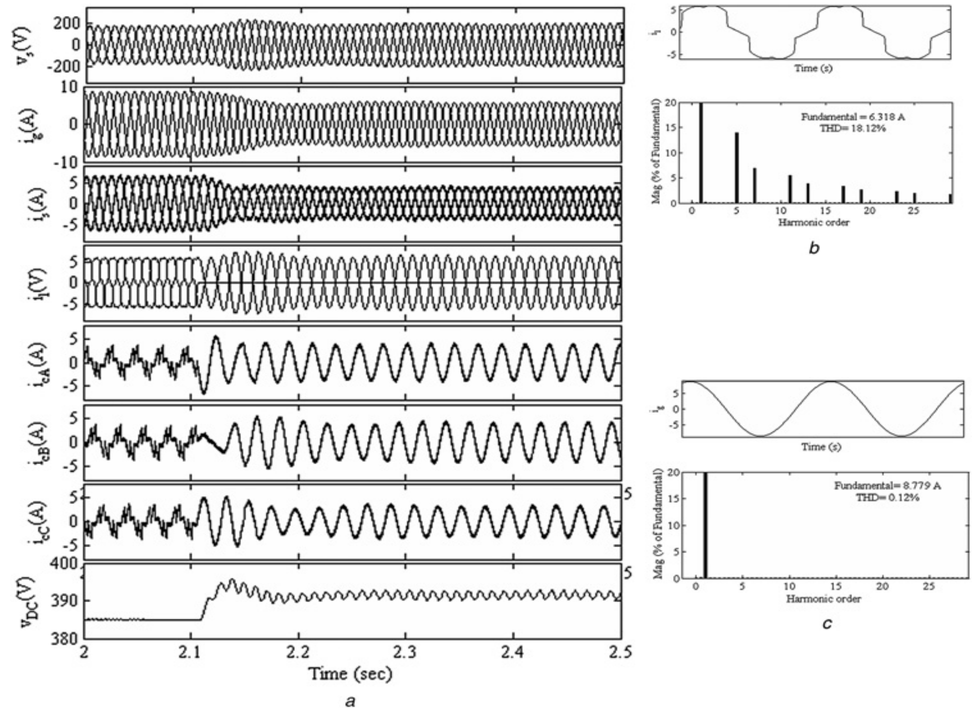


Fig. 4 Simulation results of DSTATCOM

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

VI.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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