

Robust STATCOM Control Design Using P-Q theory for Wind Driven Induction Generator

R. M. Al-Bouthig, Ahmed A. A. Hafez and J. I. AL-Sadey
Department of Electrical Engineering
University of Assiut
Assiut, P.O. 715164, Egypt
elhafez@aun.edu.eg

Abstract - This article proposes a unified and robust control for Static Synchronous Compensator (STATCOM) for a wind driven self-excited induction generator. The criterion of the control was extracted from instantaneous P-Q theory. The proposed control has the merits of simplicity and reliability. An analytical expression was advised for dimensioning the DC-link capacitor. Comprehensive simulation results in Matlab environment were illustrated for corroborating the performance of the advised control under rigorous operating scenarios.

Index Terms - Wind energy, Self-excited induction generator, STATCOM, P-Q theory, DC-link capacitor.

I. INTRODUCTION

The escalating prices of fossil fuels along with their environmental and economical inconveniences directed the research into Renewable Energy Sources (RESs). Wind, particularly wind-generated electricity, is considered the strongest candidate within RESs to alleviate these deficiencies. Wind-generated electricity enjoys the features of sustainability, reliability and environmental compatibility [1]. Thus, a rapid growth in wind power plants was reported during the last two decades [1,2].

Induction Generator (IG) is the preferred option in a wind power system due to its advantages such as: robustness, maintenance free and absence of separate DC excitation system [2]. IG in these disciplines is either grid-connected or off-line; for the case of grid-connected, the reactive power requirements for the generator and the load are supplied principally by the grid. However, in isolated system an external source of reactive power is used for exciting the generator and fulfilling the load demands. A typical source is capacitor bank at the terminals of the generator. However, this configuration has the drawback of the difficulty to control voltage/frequency under variable load conditions. For example, a change of the load power may result in large voltage transients and even instability. To avoid this drawback, the capacitor self-excitation is replaced or augmented by power electronics based reactive power compensators [2-6].

STATCOM is normally a current controlled-voltage source inverter; thus, it could instantaneously deliver reasonable reactive power and hence maintain the voltage profile in the isolated system within the allowed range. Moreover, as STATCOM is usually parallel connected, it enjoys reduced

volumetric dimension and rating. STATCOM could also be deployed for harmonic cancellation, load balancing and improving power quality [6-9].

Several control algorithms were proposed for controlling STATCOM [9-19]. Among other, phase-shift, decoupled current control and regulation of AC and DC voltages are widely implemented. In phase shift control, the angle of the STATCOM generated AC voltage is regulated. However, an external DC source is required, due to the absence of self-supporting DC bus [9,10]. The application of phase locked loop in decoupled current control yields erroneous results particularly for distorted mains. Moreover, the excessive number of Proportional Integral (PI) controller reduces the response time significantly [9,11,13]. In DC and AC voltage regulation control scheme, two PI controllers are used for regulating AC and DC voltages. Thus, this method has albeit slow response time. Moreover, complete harmonic cancellation could not be achieved for nonlinear loads [9,14,16-19].

This article fundamentally advises a simple, unified and robust STATCOM control. The load currents and voltages are manipulated by the instantaneous P-Q theory to compute the compensated powers and thus the controlled signals. The STATCOM in this work fulfils load reactive power requirements. Accordingly, the proposed controller regulates the injected reactive power and the DC-link voltage. The proposed control has the merits of robustness and simplicity. The article also introduces a design procedure for STATCOM in a stand-alone wind power system, particularly the capacitor on the inverter DC-side. A simple analytical expression for dimensioning the DC-side capacitor was advised.

II. SYSTEM LAYOUT

The system under concern is composed of self-excited IG driven by wind turbine, Fig. 1. The generator operates in a stand-alone mode. Fixed excitation arrangements were used to ensure successful build up operation for no load/unity power factor load conditions. Three-phase STATCOM is attached near to the load. The sensed DC link voltage V_{DC} , load voltages, v_{Li} , and currents, i_{Li} are manipulated via proposed controller to generate reference currents i_{ri} . Then, the switching signals that drive the Voltage Source Inverter (VSI) are obtained from a hysteresis controller. A large DC capacitor C_{DC} is utilized for maintaining the voltage of

STATCOM DC side constant. To filter the high frequency switching ripples, a filter inductor is inserted between the STATCOM and the point of the common coupling. Occasionally, the STATCOM is coupled to the system through a transformer, which may eliminate the need for inductor filter. The parameters of the system under concern are given in Table 1.

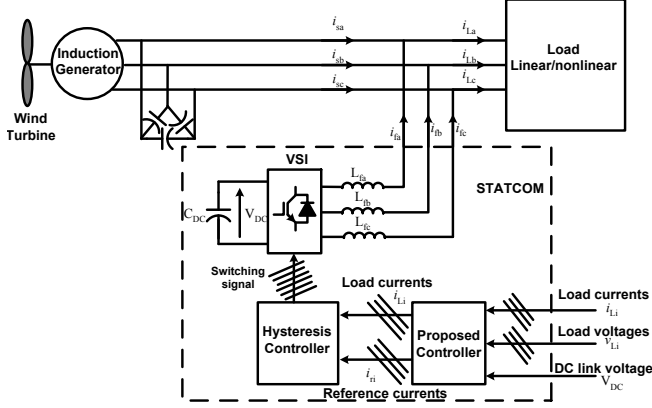


Fig. 1 Schematic of the system under concern

TABLE 1
SYSTEM PARAMETERS

Parameters of IG	4pole, 4kVA, Y, 400V, 50Hz.
Pu stator resistance and reactance respectively	0.0035, 0.045
Pu rotor resistance and reactance respectively	0.0084, 0.045
Pu mutual inductance	2.8
Pu Filter inductance	0.045

The parameters are given in pu, to generalize the analysis for different stand-alone wind power systems. The base values are the full output power, 3.5kW, line-to-line voltage, 400V, and synchrous speed of 1500rpm.

The characteristics of the turbine that drives SEIG under concern is shown in Fig. 2, at different wind speed. The wind speed of 10m/sec is taken as the base speed.

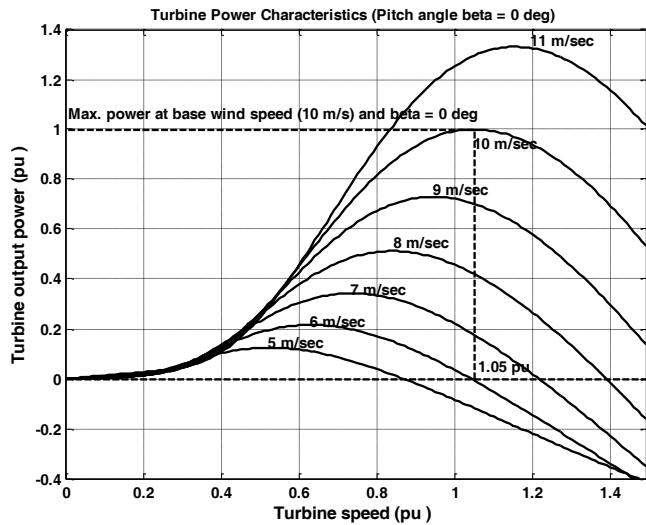


Fig. 2 Characteristics of the wind turbine at different wind speeds

Fig. 2 reveals that the turbine delivers the rated power at wind speed of 10m/sec and turbine speed of 1.05pu . The

maximum output power of the turbine is occurred at zero pitch angle, Fig. 2.

III. STATCOM DESIGN

The principles and fundamentals of the STATCOM are adequately highlighted in the literature [6-8]. The dynamic model of the STATCOM is well addressed in [7]; thus the focus here is on the design of the DC side capacitor and controller as given in the following sections.

a. Dimension of the DC-link capacitor

In grid-connected wind induction generator system, the prime target of the STATCOM is partially and or fully fulfilling the generator reactive power requirements, particularly under transient conditions. Moreover, it may contribute in supplying load reactive power demands. This has the advantages of loading the transmission lines to their maximum limits.

STATCOM is dimensioned in a stand-alone IG based system, according to the generator and the load reactive power requirements, considering the reactive power supplied by self-excitation arrangements. In the system under consideration, 3.75kW self-excited IG is assumed to operate at 0.85 power factor (pf) lag. Thus, this generator requires around 2.4kVAR at full load conditions. It is worth to mention that the fixed excitation facilities are dimensioned for fulfilling only the generator reactive power at unity power factor full load operation at rated speed, as they supply under such conditions around 2kVAR. Thus, an additional reactive power source has to be employed for securing load requirements. Moreover, the capacitance bank excitation as mentioned suffers from the inability to cope with abrupt load change in terms of maintaining system voltage and frequency.

The voltage of the DC-link voltage, V_{DC} , generally fluctuates during transient conditions in the range of (1.4-1.8) times the peak voltage of the AC voltage, V_{peak} .

The value of the DC-link C_{DC} could be estimated from the energy balance during a disturbance, at which the STATCOM injects rated reactive power. Accordingly, the DC-link C_{DC} is given by,

$$C_{DC} = \frac{Q_{rated_STATCOM} n T}{V_{DCmax}^2 - V_{DCmin}^2} \quad (1)$$

where $Q_{rated_STATCOM}$, T and n are rating of STATCOM, periodic time of AC voltage cycle and ratio of response time to supply periodic time respectively. V_{DCmax} and V_{DCmin} are the maximum and minimum allowed limits of the DC voltage during a disturbance.

The rated reactive power of the STATCOM, $Q_{rated_STATCOM}$ is 2kVAR; this value is selected according to a load of 3.5kW at 0.85pf lag, which resembles rated load of the generator. The DC-link capacitor C_{DC} for system under concern is nearly 6mF, where the DC-link

voltage V_{DC} is assumed to fluctuate between 1.8 V_{peak} to 1.4 V_{peak} of the AC voltage.

b. Control Design

The control is advised based on P-Q theory. This theory is comprehensively analyzed in [20,21]. The schematic of the proposed control technique is shown in Fig. 3. Load voltages and currents are transformed from abc to $\alpha\beta$ coordinates; then load power are computed to defines the compensated power components. Finally, the reference currents are expressed in abc coordinates and compared with the actual currents through hysteresis band controller. A PI controller is used for regulating the DC-link voltage V_{DC} .

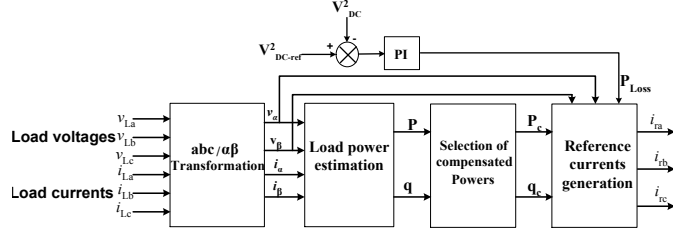


Fig. 3 Proposed control scheme

Transforming load voltages, v_{La} , v_{Lb} and v_{Lc} , and currents, i_{La} , i_{Lb} and i_{Lc} , from (a-b-c) to (α - β -0) coordinates through Clarke formula as,

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} f_{La} \\ f_{Lb} \\ f_{Lc} \end{bmatrix} \quad (2)$$

where f stands for voltage and current. The instantaneous active and reactive powers are given by,

$$p = v_\alpha i_\alpha + v_\beta i_\beta = \bar{p} + \tilde{p} \quad (3)$$

$$q = -i_\alpha v_\beta + i_\beta v_\alpha = \bar{q} + \tilde{q} \quad (4)$$

The active power p is considered to have two components: average \bar{p} and oscillating \tilde{p} . The average component \bar{p} represents the value of the instantaneous real power, which is transferred from the power supply to the load. \tilde{p} represents the oscillating energy flow per time unity, which naturally produces a zero average value; it represents an amount of additional power flow in the system without effective contribution to the energy transfer. Likewise, the load reactive power q could be separated into an average \bar{q} and oscillating \tilde{q} components. \bar{q} corresponds to the conventional three-phase reactive power, while \tilde{q} corresponds to a power that is being exchanged among the three phases, without transferring any energy between source and load. A Butterworth high pass filter is used for separating average and oscillating components of the active and reactive powers.

After segregating the powers, the components need to be compensated are given by,

$$p_c^* = \bar{p} \quad (5)$$

$$q_c^* = (k\bar{q} + \tilde{q}) \quad (6)$$

The gain k is used for increasing the control applicability to generator type/system layout. For, example in case of induction generator k is nearly equal to 1.0; as the STATCOM has to partially/fully satisfy the generator and load reactive power requirements in case of stand-alone mode.

It is worth to mention here, that the oscillating components disappear in case of harmonic free loads; the reference currents in α - β are obtained from,

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p_c^* + p_{loss} \\ q_c^* \end{bmatrix} \quad (7)$$

The component p_{loss} , equation (7), is added to account for the system losses. The reference currents could be expressed in a-b-c coordinates by,

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \quad (8)$$

c. DC-link voltage Compensator

Commonly, a PI controller is used to suppress the fluctuation in the DC-link voltage of the STATCOM under non-constant load conditions. The error signal that drives the controller usually is obtained by comparing the reference V_{DC_ref} and the DC voltage V_{DC} . The response time of this scheme has the disadvantage of being slow. Thus, fast acting DC-link voltage controller is proposed. The compensator is driven by the difference between $V_{DC_ref}^2$ and V_{DC}^2 . The mathematical basis for this advised control is given in the following.

A certain amount of active power, P_{loss} , should be supplied to the STATCOM, to maintain the DC-link voltage V_{DC} at the reference value,. Equating P_{loss} by DC-link power yields,

$$P_{loss} = V_{DC} I_{DC} \quad (9)$$

STATCOM dynamics equation is,

$$\frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} \quad (10)$$

Substituting (10) into (9),

$$P_{loss} = C_{DC} V_{DC} \frac{dV_{DC}}{dt} = \frac{C_{DC}}{2} \frac{dV_{DC}^2}{dt} \quad (11)$$

Taking V_{DC}^2 as a state variable instead of V_{DC} , Substituting $x = V_{DC}^2$, averaging and extracting the transfer function $G(s)$, $x(s)/P_{loss}(s)$,

$$G(s) = \frac{2}{sC_{DC}} \quad (12)$$

A PI controller is deployed for maintaining the DC-link voltage V_{DC} at the reference value V_{DC_ref} . The parameters of this controller are given in Table 2. Frequency response of closed loop transfer function $\Delta V_{DC}^2 / \Delta V_{DC_ref}^2$ with the proposed PI controller is shown in Fig. 4.

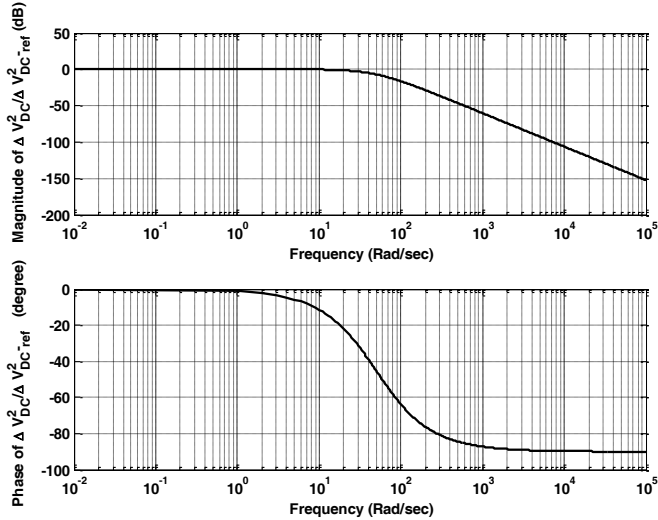


Fig. 4 Frequency response of closed loop transfer function $\Delta V_{DC}^2 / \Delta V_{DC_ref}^2$

TABLE 2
PARAMETERS OF PI CONTROLLER

Proportional gain	0.5
Integral gain	0.02

Fig. 4 shows that the controller in Table 1 resulted in bandwidth of around 68rad/sec. This bandwidth is considered a good compromise between the performance speed and the attenuation of the low frequency ripple in the feedback signals.

III. CASE STUDY

To test the control viability, the following scenario is implemented. The system under concern Fig.1 initially operates without STATCOM and is loaded with 1kW at unity pf. Then, at 0.2sec a 2.5kW, 0.75pf lag load is suddenly applied to the system. The STATCOM is coupled to the system at 0.4sec.

The load, supply and compensating currents are illustrated. Also, DC-link voltage, injected reactive power, and the generator torque and speed are drawn.

Fig. 5 shows increase in load power above the designated value prior to injection of the inductive load, 0.75 lag pf. This is attributed to self-excitation arrangements, as they are designed to satisfy generator requirement at unity pf full load, and the system was only loaded by a pure resistive load of nearly 25% from its rated.

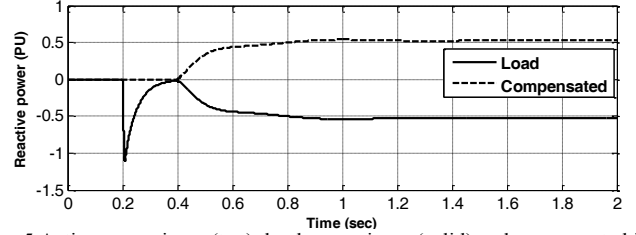
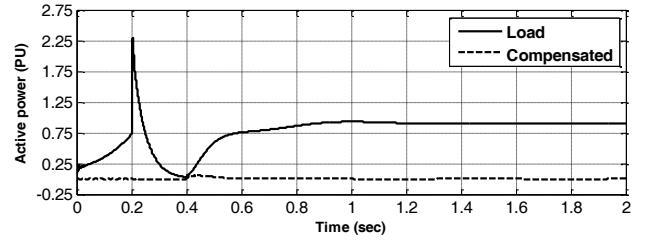


Fig. 5 Active power in pu (top): load power in pu (solid) and compensated in pu (dashed), reactive power in pu (bottom): load power in pu (solid) and compensated in pu (dashed); for load step from 1kW unity pf, to 3.5kW 0.85 lag pf at 0.2sec; STATCOM connected at 0.4sec.

After STATCOM deployment the load power increases until settling at 3.5kW, which is the rated value. It was found that without the STATCOM, the system could not tolerate any sudden load injection even for resistive loads. Moreover, the size of static excitation could be reduced in the presence of the STATCOM.

Fig. 5 shows the load reactive power was nearly zero before 0.2sec, then it suddenly rises to 4kVAR; which is beyond the capacity of generator excitation. Thus, the system voltage decreases and hence active and reactive power. However, after 0.4sec, the powers increase again. The reactive power requirements, 2kVAR, of the load after 0.4sec are nearly supported by the STATCOM; while capacitor banks at the generator terminals secure its reactive power demand.

Fig. 5 depicts the merit of STATCOM in maintaining the generator/load voltage and power after sudden load injection. The generated power was about to diminish before connecting the STATCOM.

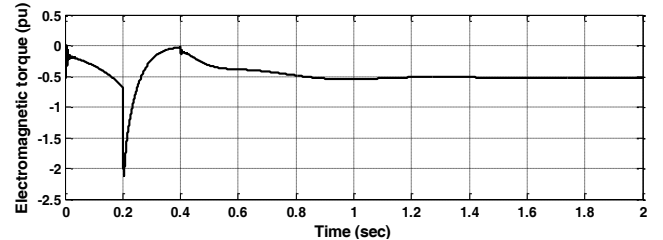
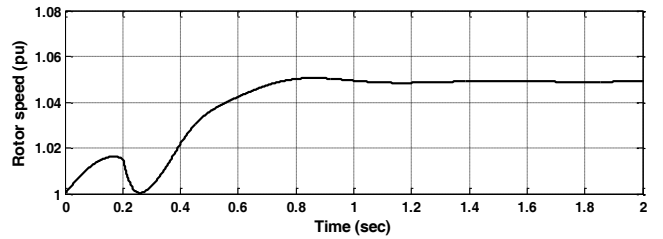


Fig. 6 Rotor speed in pu (top), electromagnetic torque in pu (bottom); for load step from 1kW unity pf, to 3.5kW 0.85 lag pf at 0.2sec; STATCOM connected at 0.4sec.

Deployment of the STATCOM at 0.4sec, Fig. 6, restores the system voltage and hence power balance; thus the rotor speed/ electromagnetic torque settles at operating points corresponding to the new load state. The electromegntic torque changes abruptly to around twice the full load power, which may stress the machine significantly, Fig. 6. For system operation without STATCOM, it was found that rotor speed accelerates until the protection disengages the turbine and generator, as the electromagnetic torque remain at zero.

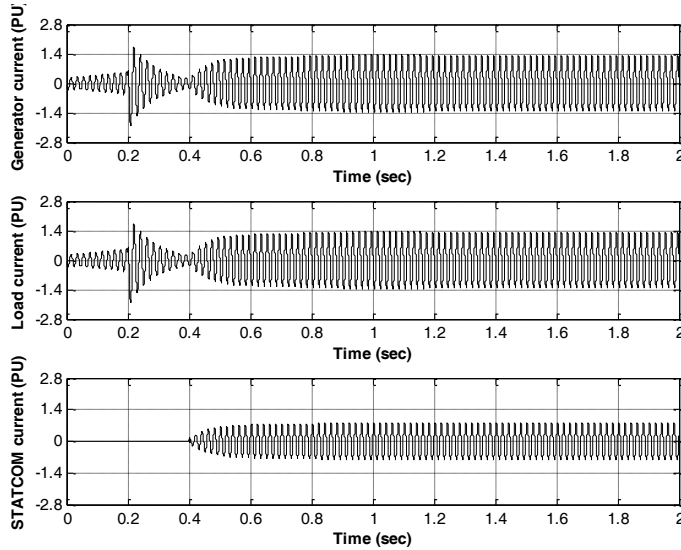


Fig. 7 Generator current in in pu (top), load current in in pu (middle), STATCOM current in in pu (bottom) got load step from 1kW unity pf, to 3.5kW 0.85 lag pf at 0.2sec; STATCOM connected at 0.4sec.

Fig. 7 shows the load, generator and STATCOM currents of phase A during the simulated time span. The load and generator currents increase before inductive load injection. This as mentioned before was attributed to improvement in load/generator voltage. However, after load connection and prior to the deployment of STATCOM the currents drop nearly to zero. After, STATCOM connection, the currents increase until they settle at their new values.

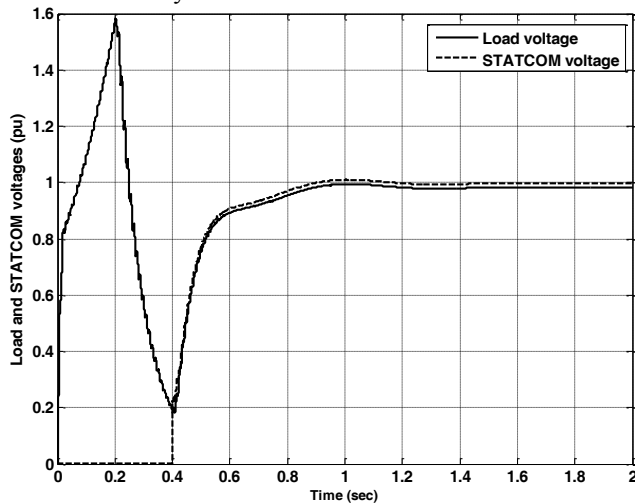


Fig. 8 pu load voltage pu (solid), pu STATCOM terminal voltage (dashed); for load step from 1kW unity pf, to 3.5kW 0.85 lag pf at 0.2sec; STATCOM connected at 0.4sec.

Fig. 8 illustrates the STATCOM and load voltages. The load voltage experiences increase before inductive load connection, which, as mentioned before, was attributed to generator self-excitation facilities. In the period of 0.2-0.4sec the load voltage suffers from a significant voltage dip, as it reaches around 0.2 pu. This level may not be acceptable, particularly for sensitive loads. STATCOM successfully restores the load voltage nearly at 1pu, Fig. 8. This is achieved by injecting around 2kVAR reactive power, Fig. 8. The voltage at STATCOM terminals is higher than that of the load. Thus, the STATCOM resembles over excited synchronous condenser.

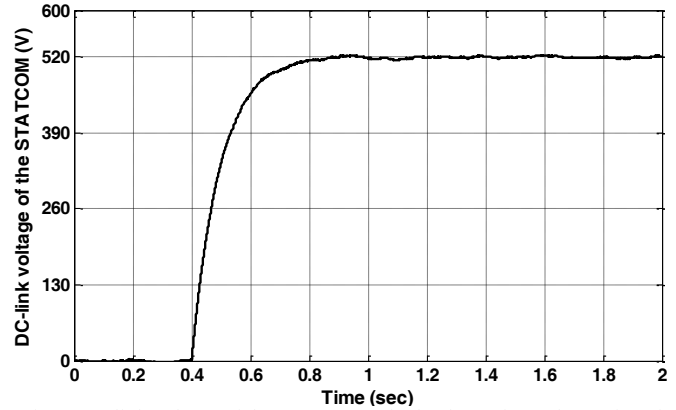


Fig. 9 DC-link voltage of the STATCOM for load step from 1kW unity pf, 5kW 0.85 lag pf at 0.2sec; STATCOM connected at 0.4sec.

Fig. 9, illustrates the advantage of the proposed controller in maintaining DC-link voltage at the reference value. The ripples on the voltage are attributed to switching.

VI. CONCLUSION

Simple and robust controller for STATCOM in off-line IG wind power system was proposed. The mathematical basis for the advised control was comprehensively analyzed. The reference currents were derived based on $\alpha\beta$ reference frame. Also, a fast acting regulator for DC-link voltage was proposed. Diverse load scenarios were used to validate the proposed controls. Moreover, adequate simulation results were illustrated to collaborate these schemes. The following conclusion could be drawn:

1. Static excitation for induction generator in stand-alone wind power system suffers from the inability of fulfilling the generator/load reactive power demands under non-constant loads.
2. To maintain the voltage at the terminals of the generator and the load within allowed limits under such condition, STATCOM has to be incorporated in the system.
3. The advised control has the advantage of restoring system voltage/power during/after severe drop/dip, as shown in Fig. 8.
4. The requirement for sensing phase voltages in the proposed control may limit applicability and viability.

5. The absences of the compensators in the proposed control yields in albeit slow response and distorted waveform particularly for non-linear loads.

REFERENCES

- [1] Z., Chen and F., Blaabjerg "Wind farm—A power source in future power systems" *Renewable and Sustainable Energy Reviews*, vol. 13, no 6, pp. 1288-1300, 2008.
- [2] R. C., Bansal; T. S., Bhatti, and D. P. Kothari, "A bibliographical survey on induction generators for application of nonconventional energy systems", *IEEE Transaction on Energy Conversion*, vol. 18, no. 3, pp. 433-439, Sep. 2003.
- [3] M. H., Haque, " A Novel Method of Evaluating Performance Characteristics of a Self-Excited Induction Generator" , *IEEE Transaction on Energy Conversion*, Vol.24, pp.358-365, 2009.
- [4] V., Spitsa; A., Kuperman and G., Weiss" Design of a Robust Voltage Controller for an Induction Generator in an Autonomous Power System Using a Genetic Algorithm" *Proceedings of the 2006 American Control Conference*, pp. 3475-3481, June 14-16, 2006.
- [5] H.T., Jadhav and R., Ranjit " A Comprehensive Review on the Grid Integration of Doubly Fed Induction Generator" *International Journal of Electrical Power and Energy Systems*, vol. 2, pp. 243-250, 2012.
- [6] J. A., Barrado; R., Grino and H., Valderrama-Blavi" Power-Quality Improvement of a Stand-Alone Induction Generator Using a STATCOM With Battery Energy Storage System" *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2734-2741, Oct. 2010.
- [7] You Jie Ma, Yi Li, Xue Song Zhou" A Review of Static Synchronous Compensators (STATCOM)" *Applied Mechanics and Materials Journal*, vol. 270, pp. 1389-1392, 2013.
- [8] J. Soltani ; Y. Hassani and N. R., Abjadi, "A Novel Isolated Three-Phase Induction Generator with Constant Frequency and Adjustable Output Voltage Using a Three-Phase STATCOM" *ICPE 2011-ECCE Asia*, pp. 102-108, 2011.
- [9] A. Kanchana; M. A. Kumar and R. Goud" A COMPARATIVE STUDY OF CONTROL ALGORITHMS FOR DSTATCOM FOR POWER QUALITY ENHANCEMENT" *International Journal of Emerging trends in Engineering and Development*, vol. 4, no. 2, pp.380-388, 2012.
- [10] N. Mithulananthan; C. A.Canizares; J. Reeve and G. J. Rogers, " Comparison of PSS, SVC, and STATCOM controllers for damping power system oscillations" *IEEE Transactions on Power Systems*, vol.18, no. 2, pp. 786-792, 2003.
- [11] Y., Pal; A. Swarup and B., Singh " Control Strategy for Selective Compensation of Power Quality Problems through Three-Phase Four-Wire UPQC" *Journal of Power Electronics*, vol. 11, no. 4, pp.576-582, 2011.
- [12] S., Pawan; T. S., Bhatti and K. S. S, Ramakrishna; "Performance of statcom in an isolated wind-diesel hybrid power system" *International Journal of Green Energy*, vol. 8, no. 2, pp. 163-172, 2011.
- [13] P. Giroux; G. Sybille and H. Le-Huy" Modeling and simulation of a distribution STATCOM using Simulink's Power System Blockset " . The 27th Annual Conference of the IEEE Industrial Electronics Society, 2001. IECON '01, vol. 2, pp. 990-994, 2001.
- [14] K. Jain; K. Joshi; A. Behal and N. Mohan, "Modeling and Nonlinear Control of STATCOMs for Fast Voltage Regulation", *American Control Conference*. Portland, USA. pp. 1295- 1300, June 8-10, 2005.
- [15] N., Sumathy and S., Lenin prakash "A novel STATCOM control scheme for grid connected wind driven Induction Generator for power quality improvement" *International Conference on Advances in Power Conversion & Energy Technologies (APCET) 2012*, pp. 1-6, 2012.
- [16] W., Qiao; G. K., Venayagamoorthy and R. G., Harley "Real-time implementation of a STATCOM on a wind farm equipped with doubly fed induction generators" *IEEE Transactions on Industry Applications*, vol. 45, no. 1, pp. 98-107, 2009.
- [17] D., Ramirez; S., Martinez; F., Blazquez and C., Carrero" Use of STATCOM in wind farms with fixed-speed generators for grid code compliance" *Renewable Energy Journal*, vol. 37, no. 1, pp. 202-212, 2012.
- [18] M. Arun Bhaskar; S.S. Dash; R. Magdal; Joe Jerry; A. Mohammed Tamheed; S. Lakshman and S. Aravindan," Application of Integrated Wind Energy Conversion System (WECS) and Photovoltaic (PV) Solar Farm as STATCOM to Regulate Grid Voltage During Night Time Detail" In 2011 2nd International Conference on Advances in Energy Engineering (ICAEE), vol. 14, pp. 1536-1541, 2012.
- [19] P. Estonia; R. Cimbals; O. Krievis and L. Ribickis, "A Static Synchronous Compensator for Reactive Power Compensation under Distorted Mains Voltage Conditions", 10th International Symposium Topical Problems in the Field of Electrical and Power Engineering, pp151-155, Jan.10-15, 2011.
- [20] K. K. Pinapartuni and K. Mohan, " DQ based Control of DSTATCOM for Power Quality Improvement", *VSRD International Journal of Electrical, Electronics & Communication Engineering*, vol. 2, no. 5, pp. 207-227, 2012.
- [21] S. C., Leszek. "Instantaneous reactive power p-q theory and power properties of three-phase systems" *IEEE on Power Delivery Transactions* , vol. 21, no. 1, pp. 362-367, 2006.