Unified P-Q based STATCOM Control for Wind Driven Induction Generator

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Abstract: *This paper principally advises a simple and reliable control for Static Synchronous Compensator (STATCOM) in a stand-alone wind driven self-excited induction generator power system. The control was proposed based on instantaneous P-Q theory. The advised control enjoys the merits of robustness, reliability and simplicity. The paper also proposes a dimensioning procedure for the STATCOM that involves advising an annotative analytical expression for sizing the DC-link capacitor. This procedure has the advantages of applicability for different reactive power compensators that depend on a separate DC-link in its operation. Comprehensive simulation results in Matlab environment were illustrated for corroborating the performance of the advised control under rigorous operating scenarios. The results show the feasibility, reliability and practicability of the proposed controller.*

***Index Terms*—** **DC-Link Capacitor, P-Q theory, Self-Excited Induction Generator, STATCOM, Wind energy.**

I. Introduction

Wind-generated electricity is penetrating utility grids progressively. This electricity form is predicted to have a great share in the demand and thus releasing the dependency on fossil fuels with their environmental and economical inconveniences [1]. This steady growth of the electricity-based wind is attributed to the salient features of sustainability, reliability and environmental compatibility [1,2].

Induction Generator (IG) is the preferred option in a wind farm, due to its advantages such as: robustness, maintenance-free, and absence of separate DC excitation system [2,3]. IG in a wind power system operates either as 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 stand-alone operation 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 drawbacks of the difficulty to control voltage/frequency under variable load conditions. Thus, 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].

Recently, different power electronics based converters are emerged for providing capacitive reactive power to IG in grid-connected/stand-alone wind power systems. STATCOM is the preferred option, as it is normally a current controlled-voltage source inverter. Therefore, 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 [7,8].

Several control algorithms were advised [9-17] for controlling STATCOM. Phase-shift, decoupled current control and regulation of AC and DC voltages are the widely implemented STATCOM controlling technique. In phase shift control, the angle of the STATCOM generated AC voltage is modulated. However, an external DC source is required, due to the absence of self-supporting DC bus [14,16,18]. The application of phase locked loop in decoupled current control yields erroneous results particularly for distorted mains [15]. Moreover, the excessive number of PI controller reduces the response time significantly. 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 [16-18].

This paper presents a design procedure for STATCOM in a wind driven Self-Excited Induction Generator (SEIG) system. The STATCOM in this work fulfils the generator and load reactive power requirements. Thus, the proposed controller regulates the injected reactive power and the DC-link voltage. The article principally 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. The proposed control has the merits of robustness and simplicity. A simple analytical expression for dimensioning the DC-side capacitor was proposed also in this paper. This sizing procedure could be employed for different reactive power compensators as SSSC, which requires DC source for fulfilling reactive power requirements.

II. STAND-ALONE WIND POWER SYSTEM

The system under concern is composed of SEIG driven by a wind turbine, Fig. 1. The generator operates in stand-alone mode. Fixed excitation arrangements were used to ensure successful build up operation for full load unity power factor condition. 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. Commonly, the STATCOM is coupled to the system through a transformer, which may eliminate the need for the inductor filter. The parameters of the system under concern are given in Table 1.

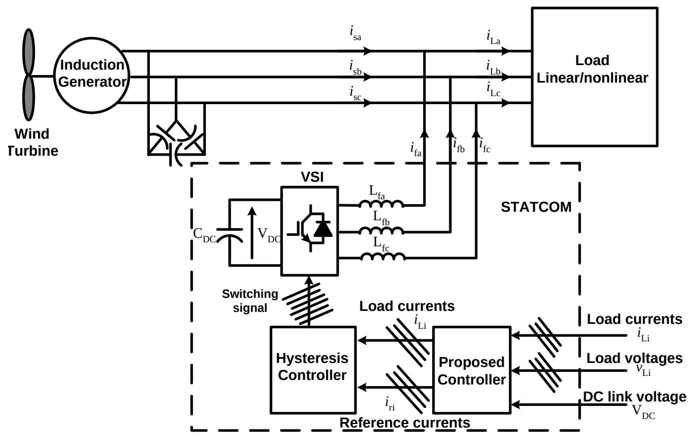

Fig. 1. Schematic of the system under concern

TABLE 1
SYSTEM PARAMTERS

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 bases values are the full output power, 3.5kW, line-to-line voltage, 400V, and synchronous speed of 1500rpm.

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

Fig. 2 reveals that the turbine delivers the rated power at wind speed of 10m/sec and turbine speed of 1.05 pu . The maximum output power of the turbine is occurred at zero pitch angle, Fig. 2.

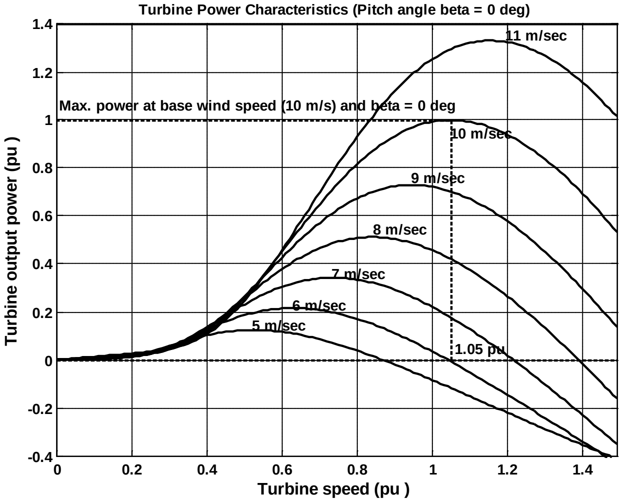

Fig. 2 characteristics of the wind turbine at different wind speeds

III. STATCOM DESIGN

The principles and fundamentals of the STATCOM are adequately highlighted in the literature [7,8]. 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. Sizing 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 wind induction generator power system, according to generator and load reactive power requirements considering the reactive power supplied by self-excitation arrangements.

In the system under consideration, 3.75kW SEIG is assumed to operate at 0.85pf. Thus, this generator requires around 2.4kVAR at full load conditions. It is worth to mention that the fixed excitation facilities are designed for fulfilling only the generator reactive power at full load operation at unity power factor (pf) and rated speed, as they supplies under such conditions around 2kVAR.

The voltage of the DC-link voltage, V_{DC}, generally fluctuates during transient conditions in the range of (0.6-1.4) times the reference value.

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. The DC-link C_{DC} is given by,

$$C_{DC} = \frac{Q_{rated\_Statcom} nT}{V^2_{DCmax} - V^2_{DCmin}} \qquad (1)$$

where $Q_{rated\_STATCOM}$, T and n are rating of STATCOM, time of AC voltage cycle and ratio of response time to supply periodic time respectively.

The rated reactive power of the STATCOM, $Q_{rated\_STATCOM}$ is 2kVAR; this value is selected according to full load conditions of 3.5kW at 0.85pf lag. The DC-link capacitor C_{DC} for system under concern is nearly 6mF, where the DC-link voltage V_{DC} is assumed to fluctuate from 0.6 to 1.4 times the reference value.

b. Control Design

The control is advised based on P-Q theory. This theory is comprehensively analyzed in [18,19]. The schematic of the proposed control technique is shown in Fig.3 . Load voltages and currents are transformed from abc to αβ coordinates; then load power are computed to define 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 DC-link voltage V_{DC}.

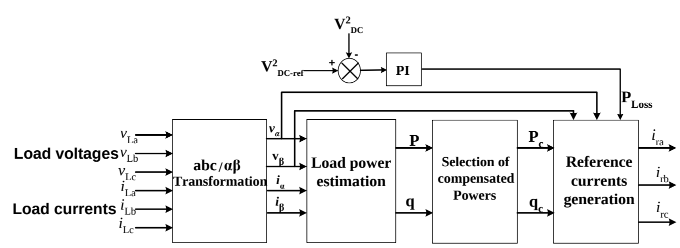

Fig. 3 Proposed control scheme

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 [19],

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

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,

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

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

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 $V^2_{DC\_ref}$ and V^2_{DC}. 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),

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

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

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

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 $\Delta V^2_{DC} / \Delta V^2_{DC\_ref}$ is shown in Fig. 4.

TABLE 2
PARAMTERS OF PI CONTROLLER

Proportional gain	0.5
Integral gain	0.02

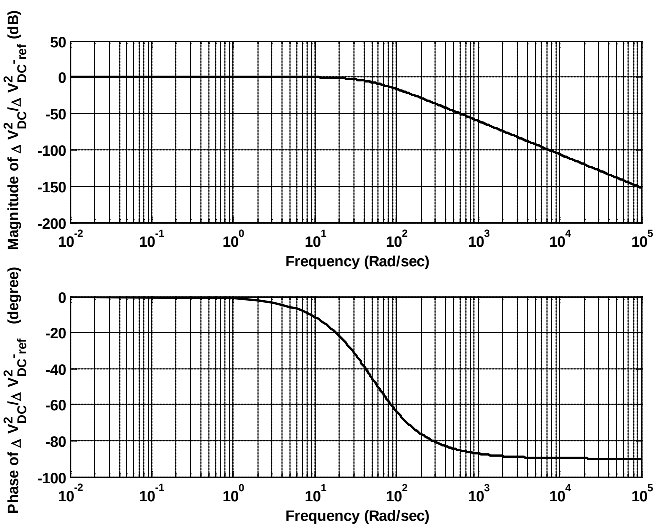

Fig. 4 Frequency response of closed loop transfer function $\Delta V^2_{DC} / \Delta V^2_{DC\_ref}$

Fig. 4 shows that the controller in Table 1 yields a bandwidth of around 85rad/sec. This bandwidth is considered a good comprise between the performance speed and the attenuation of the low frequency ripple in the feedback signals.

III. CASE STUDY

To validate the advised control, the following scenario is implemented in Matlab environment. The system under concern, Fig.1, initially operates with 1kW at unity pf load. Then, at 0.05sec a 2.5kW, 0.75pf load is suddenly applied to the system. The STATCOM operates since the start of the simulation.
The load, supply and compensating currents are illustrated. Also, DC-link voltage, injected reactive power, and the generator torque and speed are drawn.

Prior to injection of 2.5kw, 0.75pf lag load, the load power had increased even more than the designated value, Fig. 5. This may be attributed to self-excitation arrangements, as they are designed to satisfy generator requirement at full load, and the system was only loaded by a pure resistive load of nearly 25% from its rated.
Following load injection, the load power decreases significantly. Then it increases again 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.

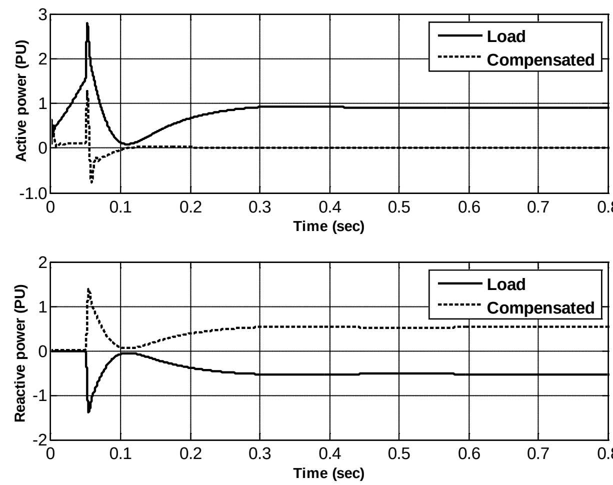

Fig. 5 Active power in pu (top) load power in pu (solid) and compensated in pu (dashed), reactive power in pu (bottom) for load step from 1kW unity pf, to 3.5kW 0.85 lag pf at 0.05sec

Fig. 5 shows that compensated active power is zero under steady-state conditions, while it is not during transient. Also, during load transient, STATCOM pumps active power to the load. Thus, the STATCOM DC voltage may suffer from significant dip.
Fig. 5 shows the load reactive power was nearly zero before 0.2sec, then it suddenly rises to 5kVAR; which is beyond the capacity of generator excitation. Thus, the system voltage decreases and hence active and reactive power. However, after 0.1sec, the powers increase again. The reactive power requirements, 2kVAR, of the load 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 restoring the generator/load voltage and power after sudden large load injection.

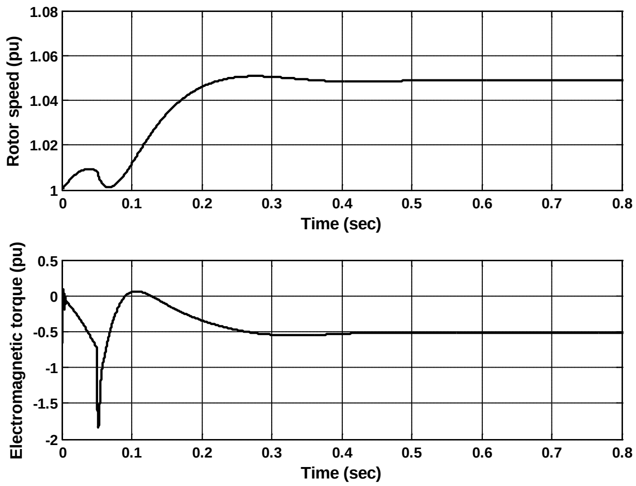

Fig. 6 Rotor speed in pu (top), electromagnetic torque in pu (bottom) for load step from 1kW unity pf, to 3.5kW 0.85 lag pf at 0.05sec

Fig. 6 shows that the rotor speed drops following load injection. Then, it increases until settles at an operating point corresponding to the new load state. Also, the torque changes abruptly and reduces until zero level. Then, it increases to its new steady-state level. This was attributed to voltage dip created from sudden load injection.

STATCOM successfully restores system voltage/power post abrupt load change scenario. However, it could be concluded that wind driven induction generator power system under concern is vulnerable. As, the system could not tolerate abrupt load change without be augmented with rapid reactive power compensation. Moreover, during the severe transient, the system may develop power/voltage instability. Thus, effective measures have to be considered to maintain system operation during/post load change or fault conditions.

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.

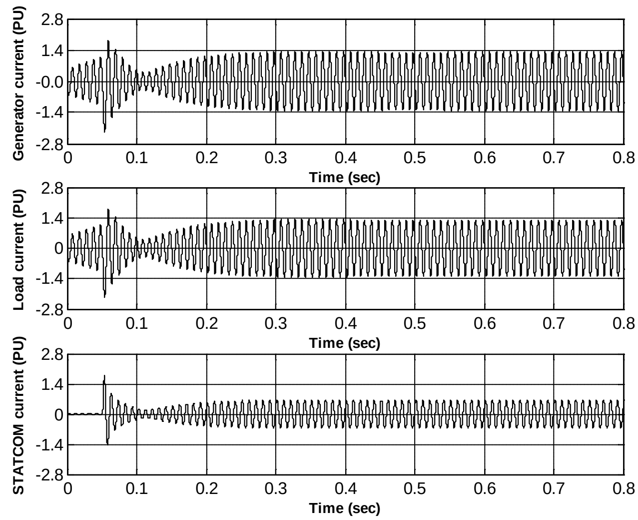

Fig. 7 Generator current (top), load current (middle), STATCOM current (bottom) for load step from 1kW unity pf, to 3.5kW 0.85 lag pf at 0.05sec

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 the currents drop.

The STATCOM is controlled primary to compensate load reactive power. Thus, the STATCOM current is zero before injection of 0.75 pf lag load, as the system was loaded by 1kW unity pf.

Fig. 8 illustrates the STATCOM and load voltages. The load voltage experiences increase before inductive load connection. The voltage increases 60% more than the rated value; which may not acceptable for sensitive loads. However, as mentioned before that the STATCOM was designed for compensating load reactive power; thus it was idle as the system during this period was loaded by pure resistive load. Following load injection, the system voltage suffers from a significant voltage dip, as it reaches around 0.3 pu. This level again may not acceptable, particularly for sensitive loads.

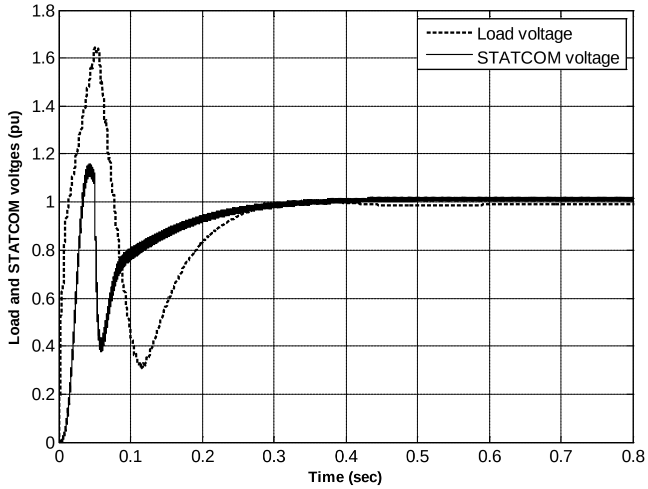

Fig. 8 pu load voltage pu (solid), pu STATCOM terminal voltage (dashed); for load step from 1kW unity pf, to 3.5kW 0.85 lag pf at 0.2sec; STATCOM connected at 0.4sec.

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.

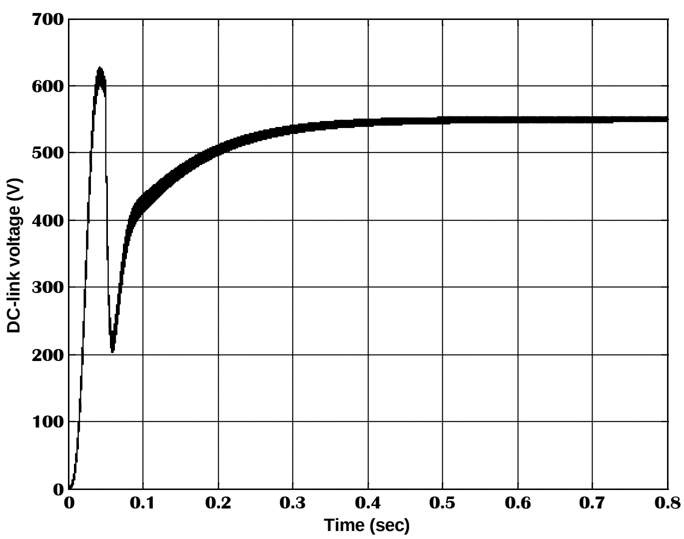

Fig. 9 DC-link voltage of the STATCOM for load step from 1kW unity pf, to 3.5kW 0.85 lag pf at 0.2sec; STATCOM connected at 0.4sec.

Fig. 9 shows that the proposed controller successfully maintains the DC-link voltage at the reference value under steady-state conditions. To cope with large load injection at 0.05sec, the STATCOM DC voltage experience significant drop around 40%. The ripples on the voltage are attributed to switching, Fig. 9.

VI. CONCLUSION

Simple and robust controller for STATCOM in stand-alone induction generator wind power system was advised. The mathematical basis for the advised control was comprehensively analyzed. The reference currents were derived based instantaneous P-Q theory. Also, a fast acting regulator for DC-link voltage was proposed. Abrupt load change was used to validate the proposed controls. Moreover, adequate simulation results were illustrated to collaborate the proposed control schemes. The following conclusion could be drawn:

1. In stand-alone wind power system, static excitation for induction generator suffers from the inability of fulfilling the generator/load reactive power demands under non-constant loads, particularly during load transient.
2. Deployment of STATCOM in off-line induction generator wind power system has the advantage of maintaining the voltage at the terminals of the generator and the load within allowed limits.
3. The advised control has the advantage of restoring system voltage/power during/after sever 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. Moreover, a dip/overshoot may occur during load increase/reduction.

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