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An Improved Electronic Load Controller for Isolated Small Hydro Wind Hybrid system

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ABSTRACT
A standalone hydro wind hybrid grid feeding a common three phase four wire load is considered. There are three generators Synchronous and Induction Generator fed by a hydro-turbine and a variable Wind speed turbine driven Permanent Magnet Synchronous Generator (PMSG). An Electronic Load Controller (ELC) based on Statcom principle is connected in shunt with the system. Vector control scheme for reference current generation technique of Statcom is developed. The major objectives in a standalone system are regulation of frequency and voltage. A battery bank is used on the dc side of Statcom thus enabling it for active power control and thus regulating the frequency. The ELC also performs other functions such as voltage regulation, reactive power compensation, neutral current compensation and harmonic elimination. The output from PMSG is connected to dc link via three phase voltage source converter (VSC) which is used for maximum power point tracking (MPPT). All models are developed using Matlab, Simulink.

Keywords-**Battery Energy Storage, Voltage and Frequency regulator, MPPT, Standalone Hydro Wind system**

I. INTRODUCTION

Standalone generation with small hydro turbines is widely used in developing countries. On average it can feed as many as 600 houses which can be widely dispersed. However, only a single source makes these schemes far from reliable. Normally Synchronous Generators are preferred in small hydro plants due to their better voltage regulation capability. For a standalone Wind system, Permanent Magnet Synchronous Generators are preferred due to reduction in gear box and non-requirement for excitation capacitors. Thus a more reliable isolated grid can be developed if we can integrate these two sources.

The major challenge in an isolated grid is voltage and frequency regulation. The voltages are allowed +-5% variation and frequency +-2% variation from its nominal value.

An isolated grid can have an increase in load demand in future. Thus an additional generator is needed to meet the extra demand. Induction Generator will be more suitable for this purpose due to ruggedness and economic reasons.

Unlike SG they do not have Automatic Voltage Regulators(AVR) which results in poor voltage regulation capability. They also need capacitor banks for voltage buildup during no load condition. When the IG is loaded, extrareactive power is needed for its continuous operation.

Variable speed wind generators are very popular and are an ideal choice for standalone systems. PMSG based schemes allow much lower cost and thus can be considered for hybrid with the hydro schemes. However variable wind schemes suffer from intermittency and thus a battery based schemes will give more reliable operation.

Parallel operation of Synchronous and Induction Generator has been reported in literature[1]. A Power-Quality Improvement of a Stand-Alone Induction Generator Using a Statcom with Battery Energy Storage System is also suggested [2].A variable speed drive Permanent magnet Synchronous Generator in hybrid with a hydro driven squirrel cage Induction Generator along with a battery is also discussed [3].Analysis of voltage control for a self-excited induction generator using a current-controlled voltage source inverter (CC-VSl) which also performs functions of load balancing and harmonic elimination is also discussed [4]. A Permanent Magnet Synchronous Generator-Based Standalone Wind Energy Supply System has also been suggested [5].

In this work an attempt is made to use Statcom as both voltage and frequency controller which acts as an improved electronic load controller (IELC) for a standalone system feeding 3-phase 4-wire loads driven by uncontrolled micro hydroturbine and a variable wind speed turbine.

The proposed controller is a 4 Leg IGBTs based VSCs which are connected to the each phaseof the generator through interfacing inductors.The neutral point of the load is connected to neutral point of the fourth leg of the controller. A dc link capacitor and a battery are connected on the dc bus of the VSCs. The output from variable wind speed driven PMSG is connected to a three phase VSC which is then again connected to the common dc bus. Maximum power point tracking(MPPT) based on constant torque control is used.The proposed IELC is also found capable of reactive power compensation, harmonic elimination and neutral current compensation.

The schematic diagram of the proposed ELC is shown in Fig. 1. There are two generators namely Synchronous and Squirrel Cage Induction Generator fed by uncontrolled hydro turbines. These turbines always produce a rated power which is given to the generator. The exciter voltage is limited to 2pu which is just sufficient for it to produce rated voltage during full load condition.The Induction Generator is connected to an external capacitor bank which helps in voltage buildup at no load condition. When there is an increase in load demand, additional reactive power is needed for IG to supply real power. As the AVR output is limited, Statcom has to supply this additional reactive power to keep the voltage to its rated value. The Statcom is implemented using three phase VSC with an additional leg for neutral current compensation. On the dc side of the Statcom a capacitor to filter voltage ripple and a dc battery is connected. Thus, it can also provide or absorb real power whenever needed. The amount of real power it can provide depends on the capacity of the battery. It can also absorb excess power in case of lightly load condition and thus the Statcom acts both as a voltage and frequency controller.

The control structure for a Statcom is based on Vector Control principle where synchronously rotating reference frame is considered.This reference frame is chosen as it gives the transformed quantities in dc variables which are ideal for compensation and also filtering purpose.Besides functioning as voltage and frequency controller, it also performs other functions like harmonics eliminator and neutral current compensator. The third generator used is Permanent Magnet Synchronous Generator which is driven by a variable speed small wind turbine. As the scheme is a variable speed wind system, a maximum power point tracker (MPPT) must be employed for efficient power production. This is implemented using Vector Control technique based on constant torque angle control as shown in Fig. 4. Again a three phase VSC is used to track the reference speed based on optimum tip speed ratio at certain wind velocity.

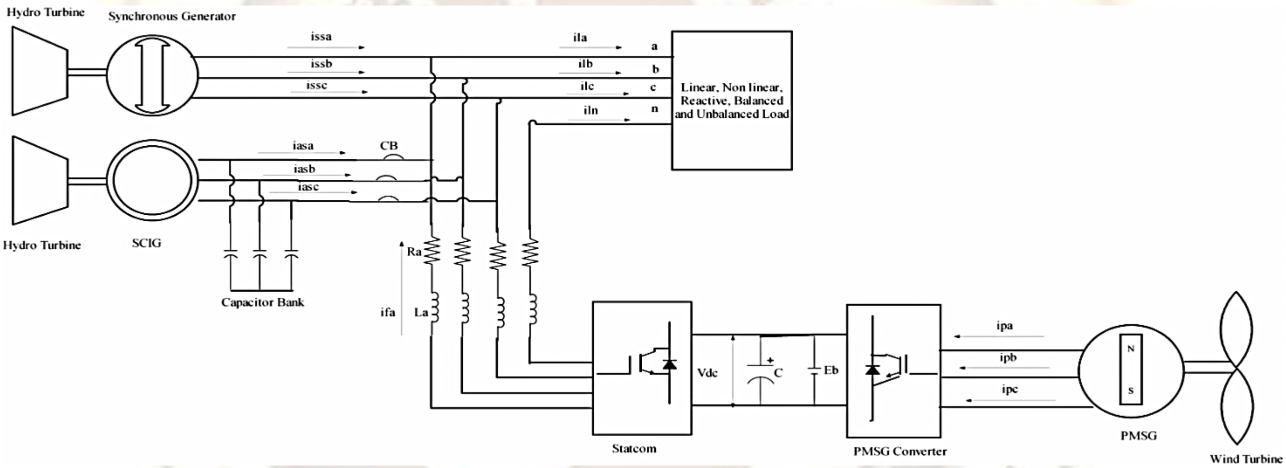

Fig.1. Schematic diagram of Hydro-Wind Hybrid system

II. MODELING OF THE SYSTEM

2.1 StatcomReference Current Generation

The control structure for Statcom is based on synchronously rotating reference frame theory as shown in Fig. 3.When the three phase voltages are transformed in dq quantities, based on given direction of q axis leading d,peak voltage isobserved on the d axis only.A three phase PLL is used to synchronize and thus calculate the position of transformation angle Θ_s.

Real power and reactive power in dq co-ordinates can be written as

$$P = \frac{3}{2} * \left(V_d I_d + V_q I_q\right) (1)$$

$$Q = \frac{3}{2} * \left(V_q I_q - V_d I_d\right) (2)$$

As V_q=0 thus

$$P = V_d I_d (3)$$

$$Q = -V_d I_q (4)$$

where, V_d, I_d, V_q, I_q are d-axis and q-axis voltage and current respectively.

Equation (3) and (4) shows the decoupling of active and reactive power. Thus by controlling I_d we can control the real power and by controlling I_q we can control the reactive power.

Since the battery cannot produce reactive power and the dc link voltage is held constant by the battery unlike in other schemes where it is held constant by capacitor, I_d directly relates to the current that should be produced or absorbed by the battery to keep the frequency constant. This current is kept within a safe value given by the battery rating using a limiter.

d-axis reference current generation

When the speed of the machine is at rated value and thus frequency is at its nominal value, there is no absorption or production. The load current is decomposed into its direct and quadrature component. When harmonic loads are present, there will also be an oscillating component in which is added to frequency regulating component.

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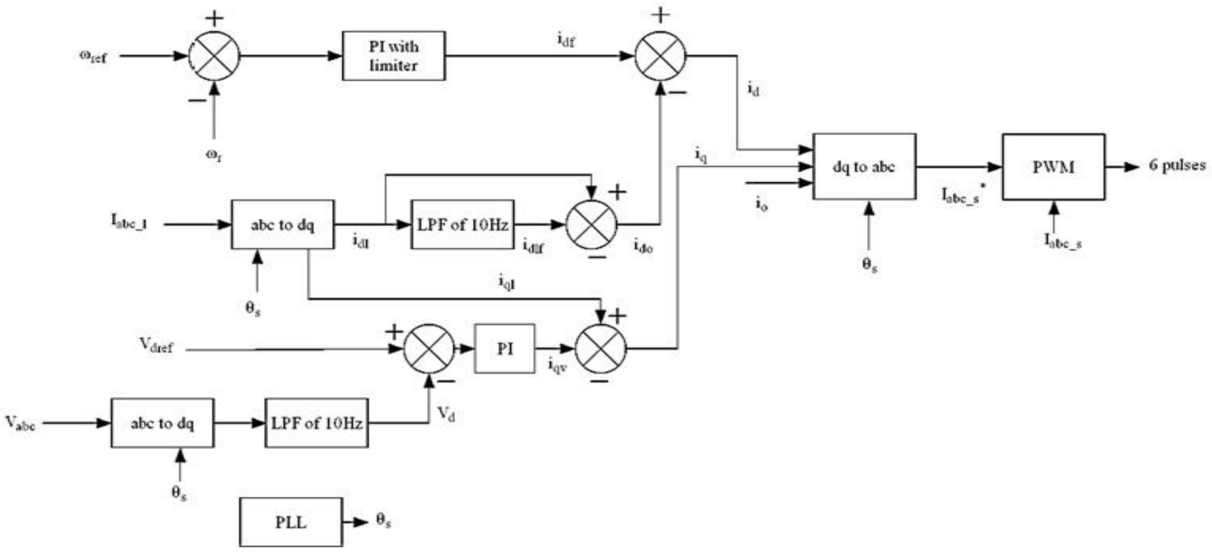

Fig. 2. Block diagram of Statcom reference generation

$\omega_{err} = \omega_{ref\,(n)} - \omega_r$ (5)

$I_{df} = I_{df}(n-1) + K_{pf}\left(\omega_{err} - \omega_{err}(n-1)\right) + K_{if}\,\omega_{err}(\text{n})$ (6)

$I_{do} = I_{dl} - I_{dlf}$ (7)

$I_d = I_{do} + I_{df}$ (8)

ω_{ref} is the reference speed,$\omega$is the actual rotor speed, K_{pf}&$K_{if}$are PI controller gains respectively, I_{do} is the oscillating component of load current, I_{dl} is the total d axis load current, I_{dlf} is the filtered d axis load current.

q-axis reference generation

For voltage regulation, peak voltage of three phase system (325 in this case) is compared with the direct axiscomponent of the voltage which is obtained after passing through a low pass filter of 10Hz. The error is passed through a PI controller and subtracted from total load quadrature component

$V_{err} = V_{dref}(n) - V_d$ (9)

$I_{qv} = I_{qv}(n-1) + K_{pv}\left(V_d(n) - V_d(n-1)\right) + K_{iv}V_{err}(n)$(10)

$I_q = I_{ql} - I_{qv}$(11)

WhereV_{dref} is the rated d axis voltage, K_{pv} and K_{iv} are PI controller values respectively. I_{ql} is the q-axis load current.

After obtaining reference currents from dq to abc conversion, these are compared with the actual Statcom currents and given to a PWM generator.A similar method of reference current generation technique can also be seen in [6].

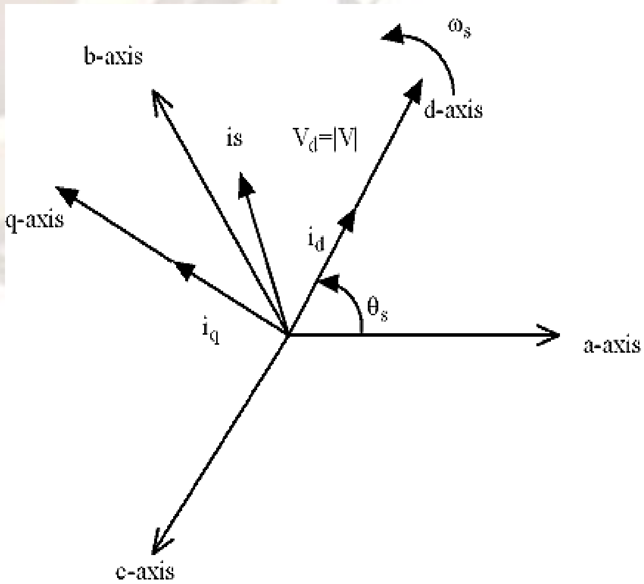

Fig.3. Vector control of Statcom

2.2Vector control of PMSG

The stator flux linkage equations can be written as [7]

$V_{qs}^{r} = R_q i_{qs}^{r} + p\lambda_{qs}^{r} + \omega_r \lambda_{ds}^{r}$ (12)

$V_{ds}^{r} = R_d i_{ds}^{r} + p\lambda_{ds}^{r} - \omega_r \lambda_{qs}^{r}$(13)

$\lambda_{qs}^{r} = L_s i_{qs}^{c} + L_m i_{qr}^{c}$ (14)

$\lambda_{ds}^{r} = L_s i_{ds}^{c} + L_m i_{dr}^{c}$ (15)

$\lambda_{qs}^{r} = L_q i_{qs}^{r}$ (16)

$Te = \frac{3}{2}\ \frac{P}{2}\left(i_{qs}^{r}\lambda_{ds}^{r} - i_{ds}^{r}\lambda_{qs}^{r}\right)$ (17)

$Te = \frac{3}{2}\ \frac{P}{2}\left(i_{qs}^{r}\lambda_{af}^{r} + (L_d - L_q) i_{ds}^{r} i_{qs}^{r}\right)$(18)

$Te = \frac{3}{2}\ \frac{P}{2}\left(i_{qs}^{r}\lambda_{af}^{r}\right)$ (19)

where V_{qs}^{r}, I_{qs}^{r} are rotor q axis voltage and current λ_{qs}^{r}andλ_{ds}^{r} are stator q and d axis flux linkages, L_d, L_q, L_m are d, q axis inductance and mutual inductance respectively, P is number of poles, T_e is electromagnetic torque .
This vector control scheme is based on constant torque angle control, where torque angle δ is maintained at 90 degrees as shown in Fig. 4 hence, the field or direct axis current is made to be zero, leaving only the torque or quadrature axis current in place.
Reference speed can be found by

$\omega_{opt} = \frac{\lambda * V}{r}$ (20)

$\omega_{err} = \omega_{ref\,(n)} - \omega_r$ (21)

$I_q = I_q(n-1) + K_{pg}\left(\omega_{err} - \omega_{err}(n-1)\right) + K_{ig}\,\omega_{err}(\mathrm{n})$ (22)

This speed is compared with the actual speed and passed through a PI controller with limiter to produce the reference torque.

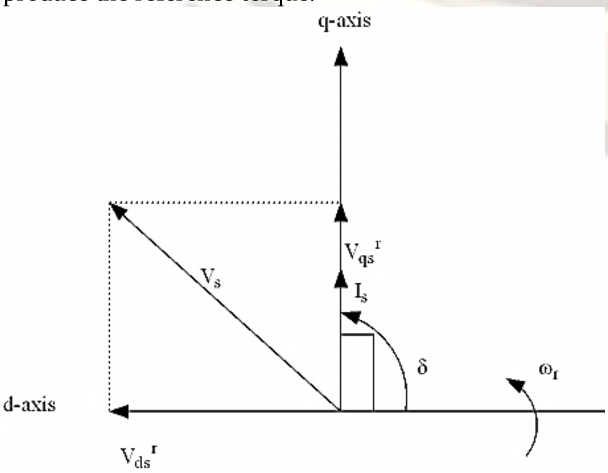

Fig. 4.Vector control of PMSG

As, I_d=0

$I_q = \frac{4*Te}{3*P*\lambda af}$ (23)

$\Theta_m = \frac{P}{2} * \Theta_e$ (24)

$i_{pae} = i_{pa}^{*} - i_{pa}$ (25)

$i_{pbe} = i_{pb}^{*} - i_{pb}$ (26)

$i_{pce} = i_{pc}^{*} - i_{pc}$ (27)

Where, ω_{opt} is the optimal speed, λ is the tip speed ratio, V is the free wind velocity, r is the radius of the turbine, ω_{ref} is the reference speed,ω_r is the actual rotor speed, I_q is quadrature current component, K_{pg}&$K_{ig}$are PI controller gains respectively, i^{*}_{pa}, i^{*}_{pb}, i^{*}_{pc} are reference PMSG a, b and c currents respectively, i_{pa}, i_{pb} and i_{pc} are actual PMSG a ,b, c currents respectively, Θ_m and Θ_e are mechanical and electrical angles respectively.
These currents are transformed into abc domain and compared with the actual currents and given to the PWM generator and to the three phase VSC.

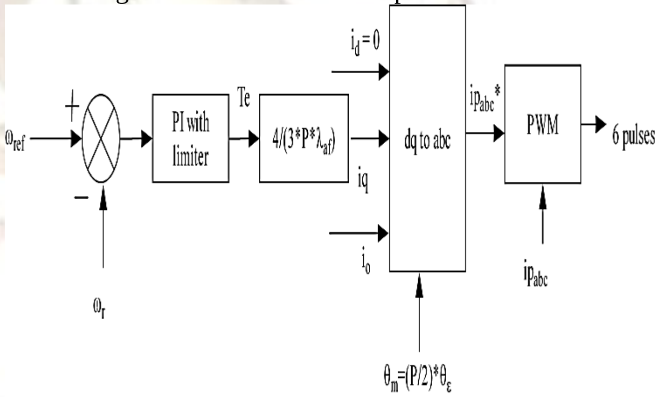

Fig. 5. Control scheme of PMSG converter

III. DESIGN OF COMPONENTS

3.1DC link design

For proper PWM operation,

$Vdc > 2\frac{\sqrt{2}}{\sqrt{3}} * V_l * m_a$ (28)

Taking line voltageV_l as 400V and modulation index, m_a as 1, V_{dc} is chosen as 700V which is also the battery dc voltage.

C >= $\frac{m_a * I_s}{4*2\pi f * \Delta V}$ (29)

C is the dc link capacitance, ΔV is the allowed voltage ripple (5% in this case), $I_s$is the Statcom current, f is the supply frequency.
The battery is chosen of 700V, 150Ah and C as 8000μF.

3.2 Synchronous link reactor design

The synchronous link reactor is chosen as [8]

$$L = \frac{Van + 0.5*Vdc}{4*ft*\xi} \quad (30)$$

Where, V_{an} is the phase voltage, ft is the frequency of the carrier wave, ξ is the amplitude of carrier wave.
Taking, Van=230V, ft=20 KHz,
L=7.25mH

3.3. Selection of wind turbine

The wind turbine used for simulation purpose is taken from Simpower systems, Matlab Simulink which has maximum power coefficient cp=0.48 and tip speed ratio λ=8.1. Turbine rating is taken as 5kW and radius can be found using

$$P = \frac{1}{2} * Cp * \pi * R^2 * \rho * V^3 \quad (31)$$

Where R= radius of the turbine, ρ=air density, v is wind velocity.
R=2.3m

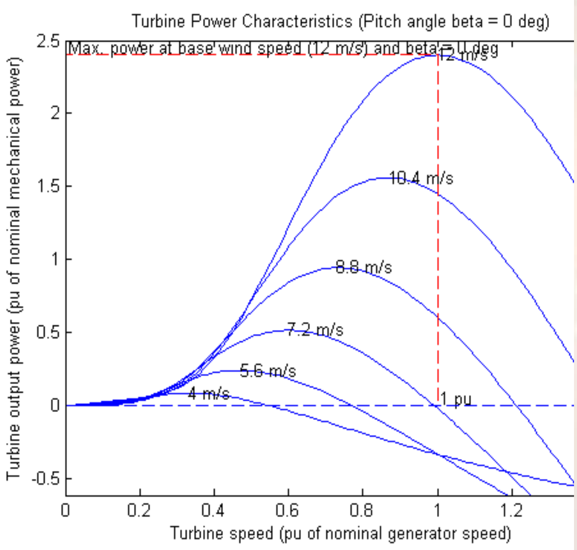

Fig. 6. Turbine output characteristics

3.4 Tuning of PMSG converter

The overall PMSG side with its controller can be can be modeled as [9]

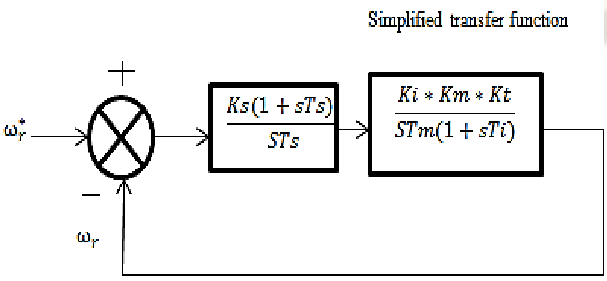

Fig. 7. Closed loop speed control of PMSG

$$Ks = \frac{4}{9*Kg*Twi} \quad (32)$$

$$Ts = 6*Twi \quad (33)$$

Root locus method is used to tune the PI controller where the design requirement taken are damping ratio, ξ=0.707, maximum overshoot, M_p = 2%, rise time, t_r= 0.005s and settling time, ts= 0.01s.

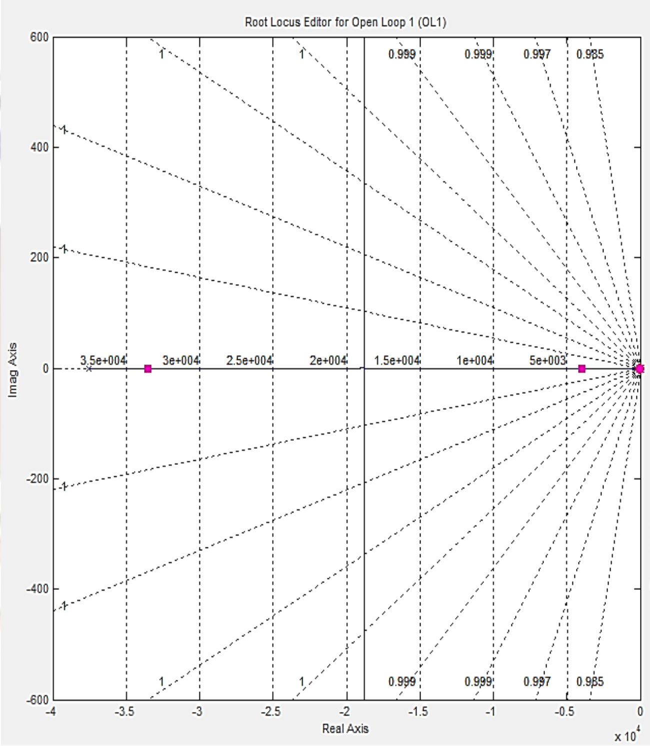

Fig. 8. Root locus plot of closed loop system

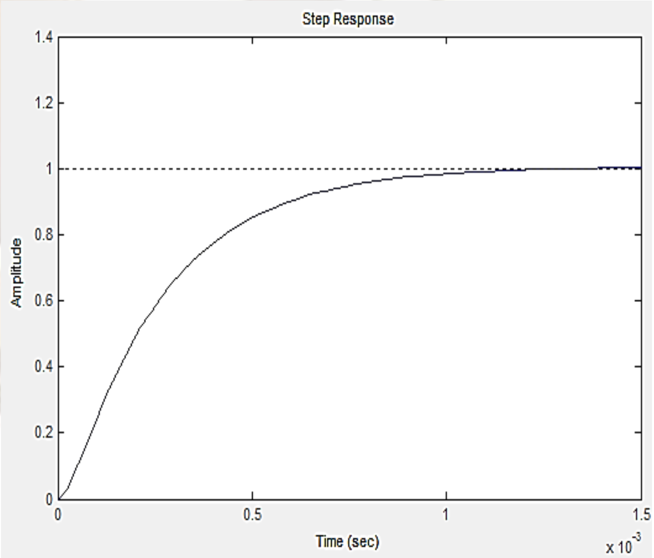

Fig. 9.Step input response for given system

IV. RESULTS

4.1 Statcom as voltage regulator

At 0.5s an IG is connectedthrough a circuit breakerin parallel with the Synchronous Generator as shown in Fig. 11.There is an injection of reactive power by the Statcom which quickly restores thedipping terminal voltage back to its rated value.

4.2 Statcom as frequency regulator

As in Fig. 10.Initally as the total connected load is 12kW and Synchronous Generator produces around 15.4kW, remaining 3.4kW is consumed by the Battery leading to its charging.
At 0.5s, Induction generator of 3.8kW is connected thus changing total generating power (SG and IG) to 19.2kW, thus causing a mismatch of 7.2kW. This power is again consumed by the battery.
At 1s, an extra load of 12kW and 8kVAR is connected. This causes deficiency in the generating power of around 4kW which is supplied by the Statcom. Thus we can see asStatcom keeps the total generated and consumed power equal and thus the system frequency is kept at nominal value (50Hz).

4.3 Statcom as reactive power compensator

In Fig. 11.at 1s, an extra load of 12kW and 9kVAR, considering power factor of 0.8 lagging is connected. Since the Statcom is designed to keep the supply side power factor as unity, its reactive power injection increases from 0 to 8kVAR.

4.4 Statcom as neutral current compensator

At 1.5s, an unbalanced load of 6kW with two phase switched off is connected. Thus the load currents are highly unbalanced as shown in Fig. 11. However, the source currents are balanced as the Statcom provides a path for neutral current through its fourth leg.

4.5 Statcom as harmonic eliminator

Fig. 12 shows connection of only nonlinear load. The nonlinear here considered is a three phase diode bridge rectifier with 50 ohms resistor. As we can notice, the currents are highly distorted but the source currents are linear.
Fig. 13 and 14 shows the Total harmonic distortion (THD) values of load and source current.Load current have THD equal to 25% which is very high whereas source currents have their THD well within allowed level of 3%.

4.6 PMSG output

Initially, wind velocity is at 8m/s as shown in Fig. 17 which gives reference speed of 34.11 rad/s for maximum power extraction. The electromagnetic torque developed is 45Nm and the generator output is 2kW. At 0.5s, wind velocity increases to 12m/s which correspond to reference speed of 51 rad/s. The electromagnetic torque developed is around 102Nm and the Power output is 4.7kW.

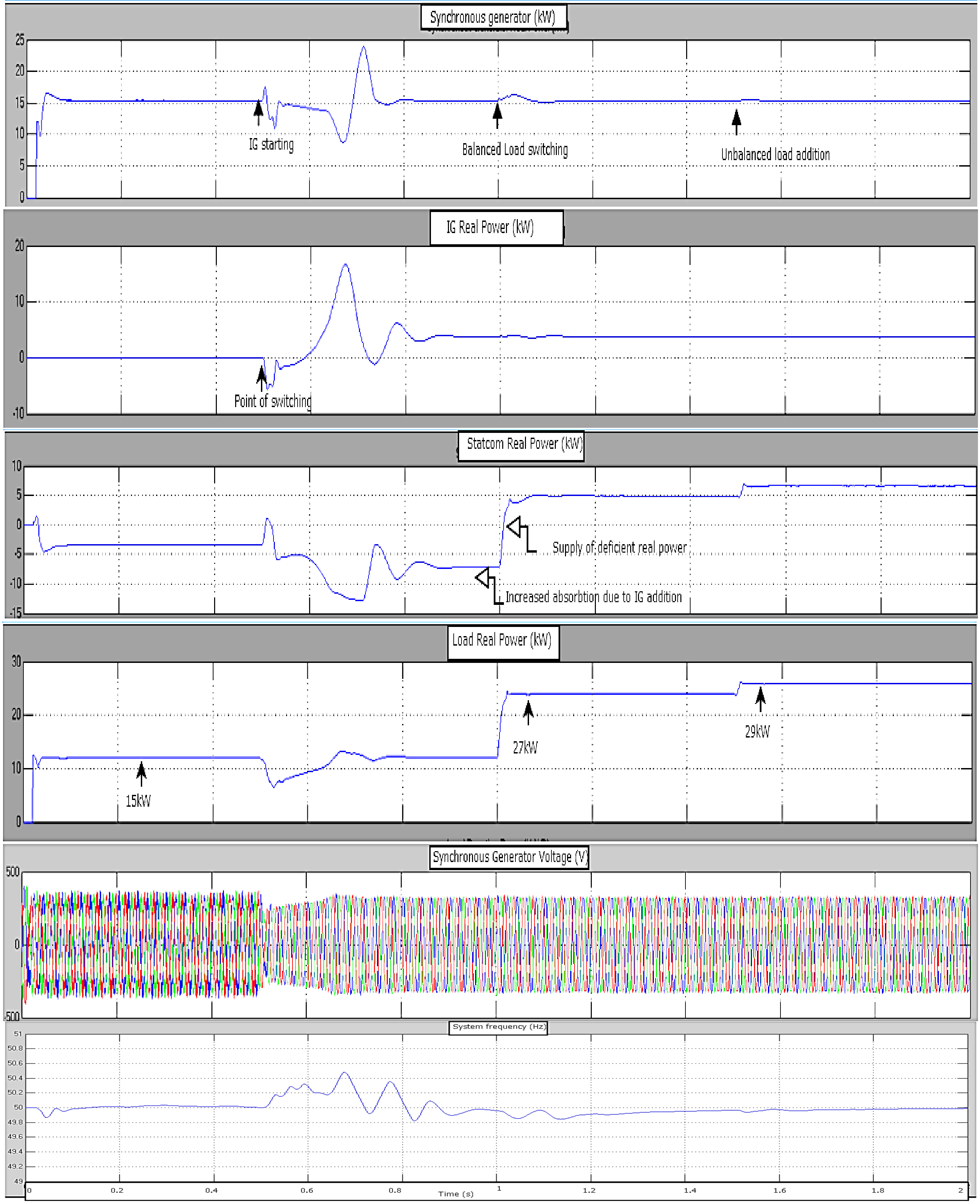

Fig. 10. Statcom as frequency regulator

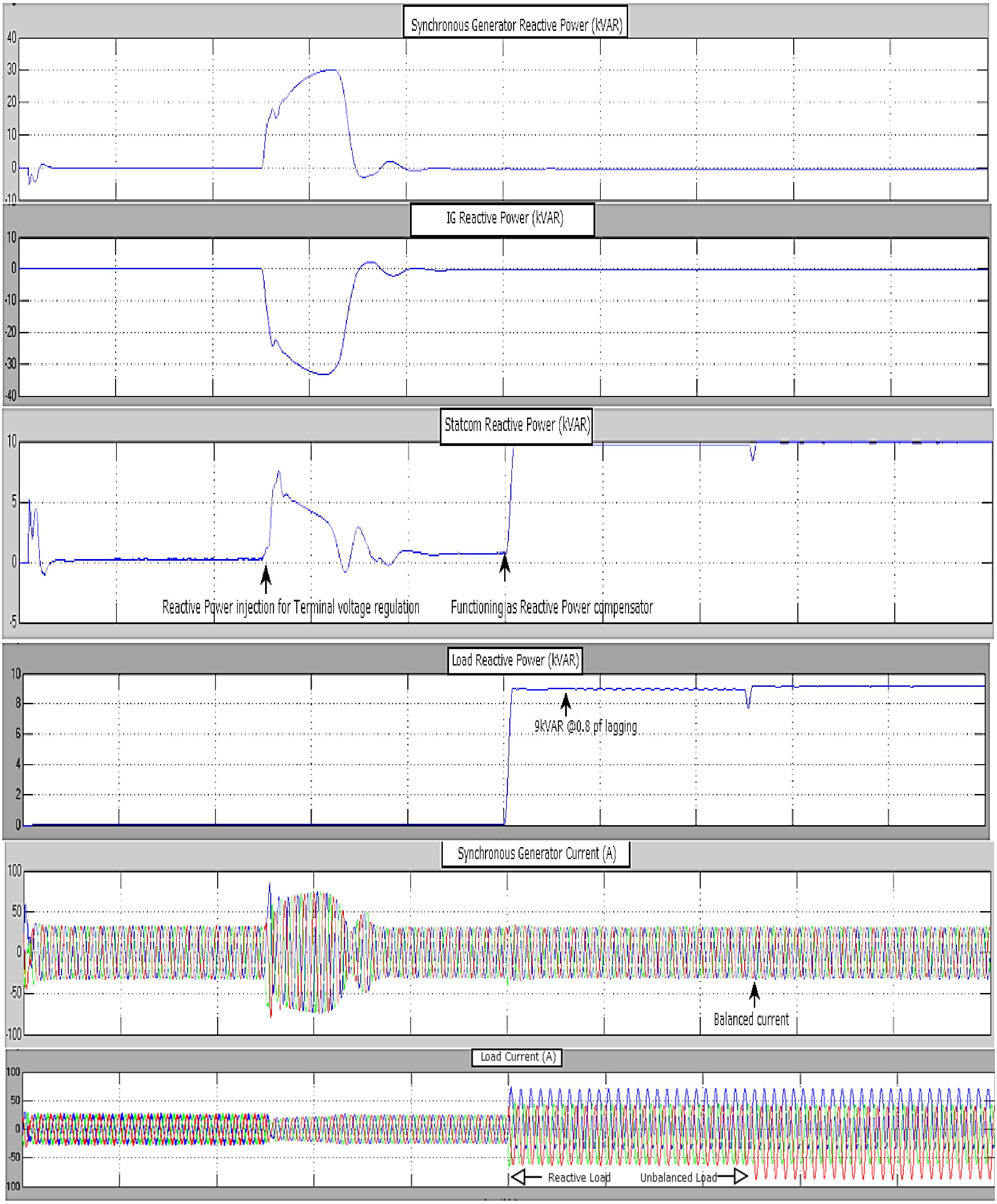

Fig. 11. Statcom as voltage regulator

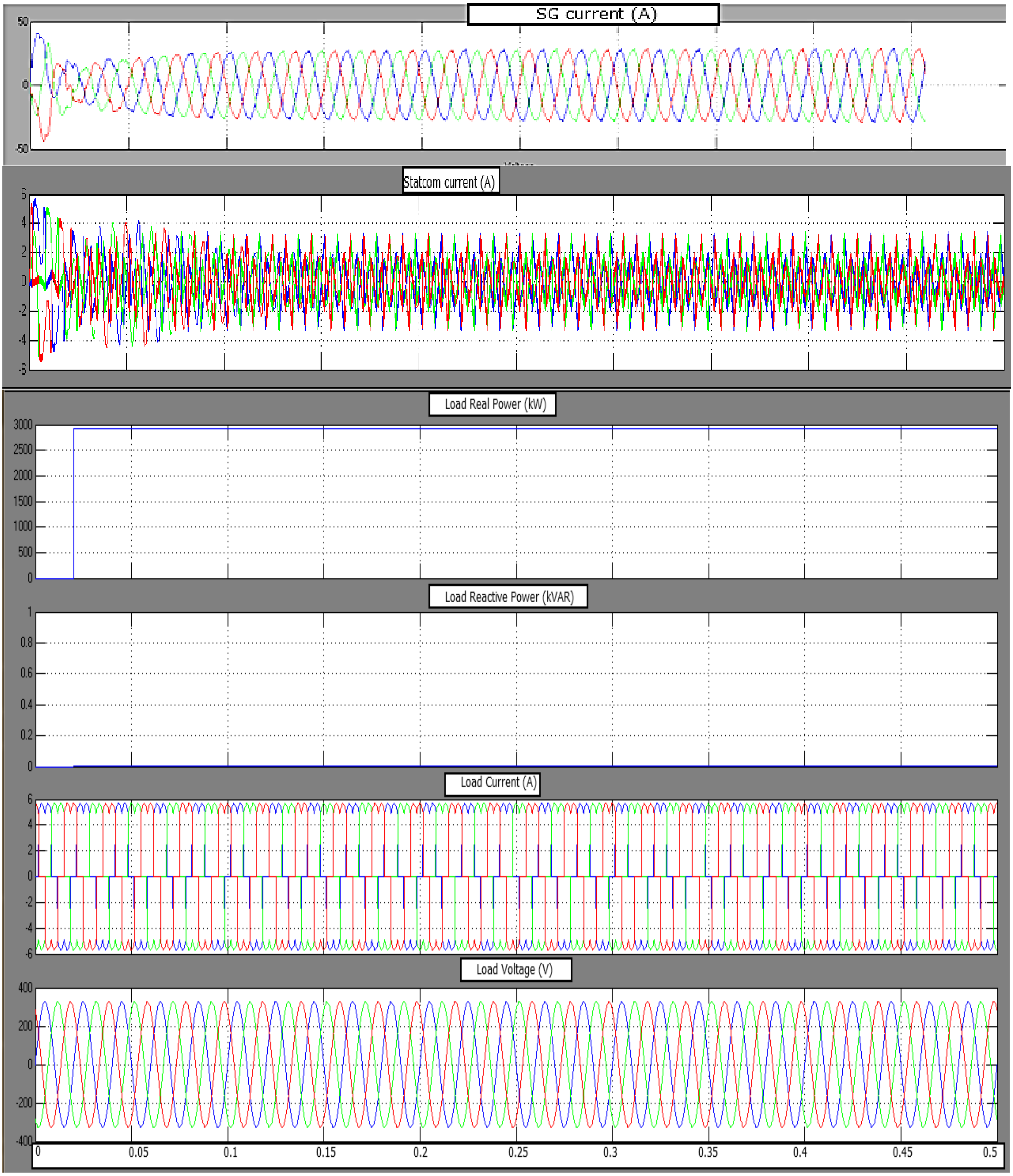

Fig. 12.Statcom as harmonic eliminator

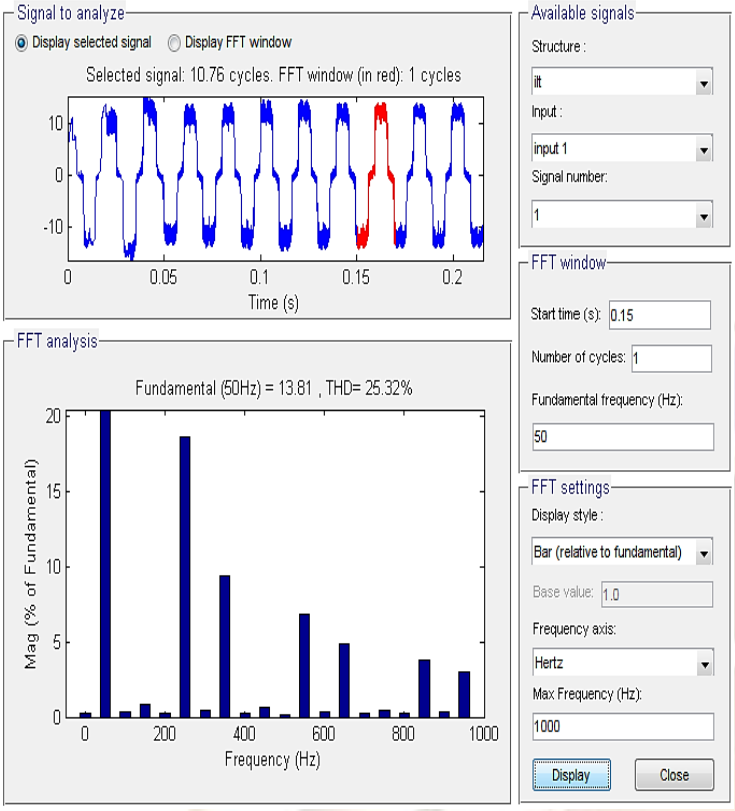

Fig. 13. THD of source current

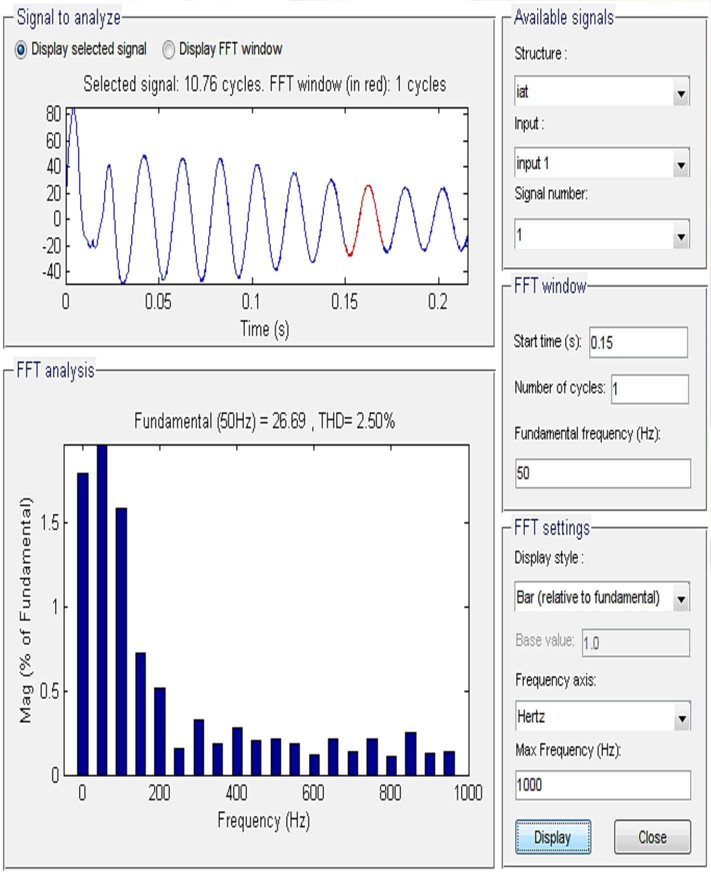

Fig. 14. THD of source current

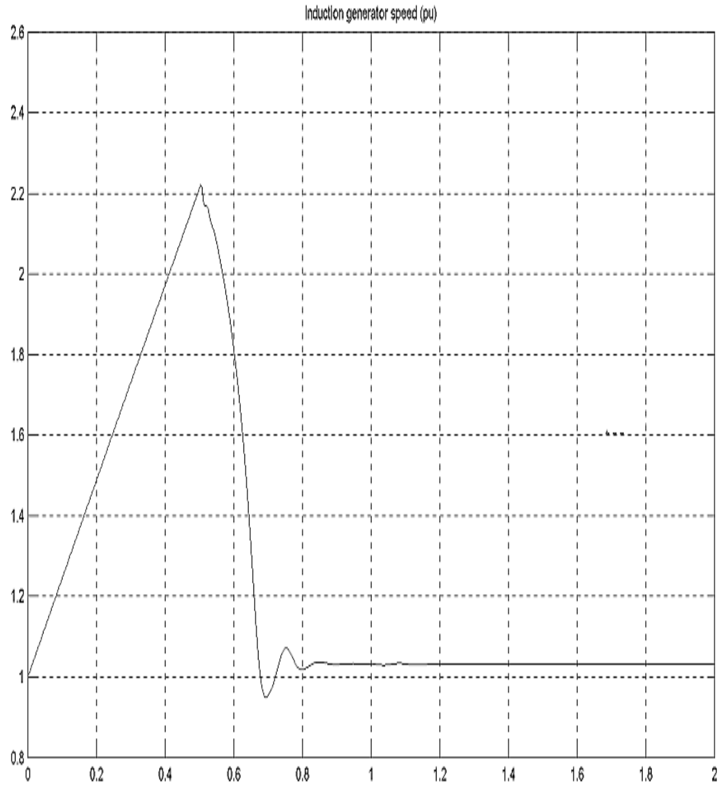

Fig. 15. Speed of Induction Generator (pu)

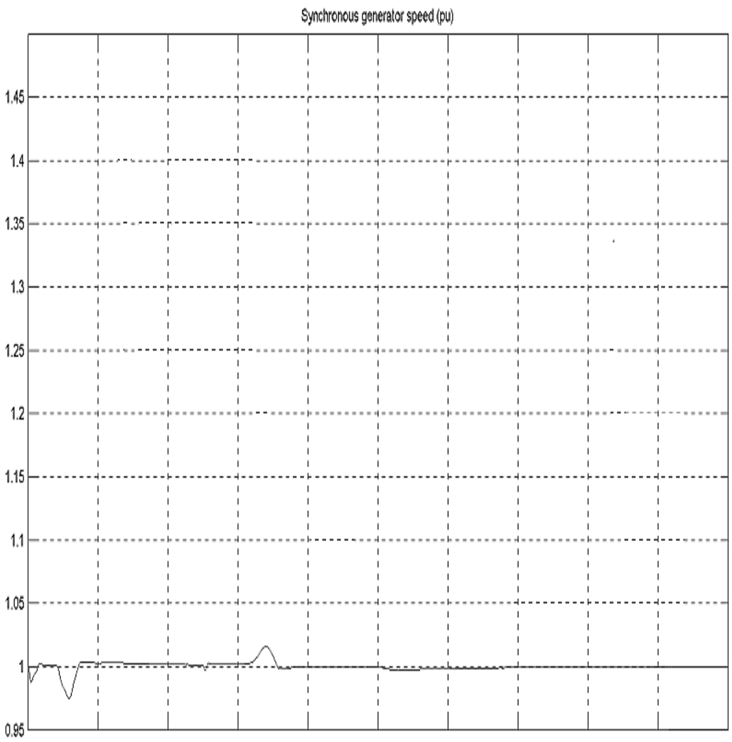

Fig. 16. Speed of Synchronous Generator (pu)

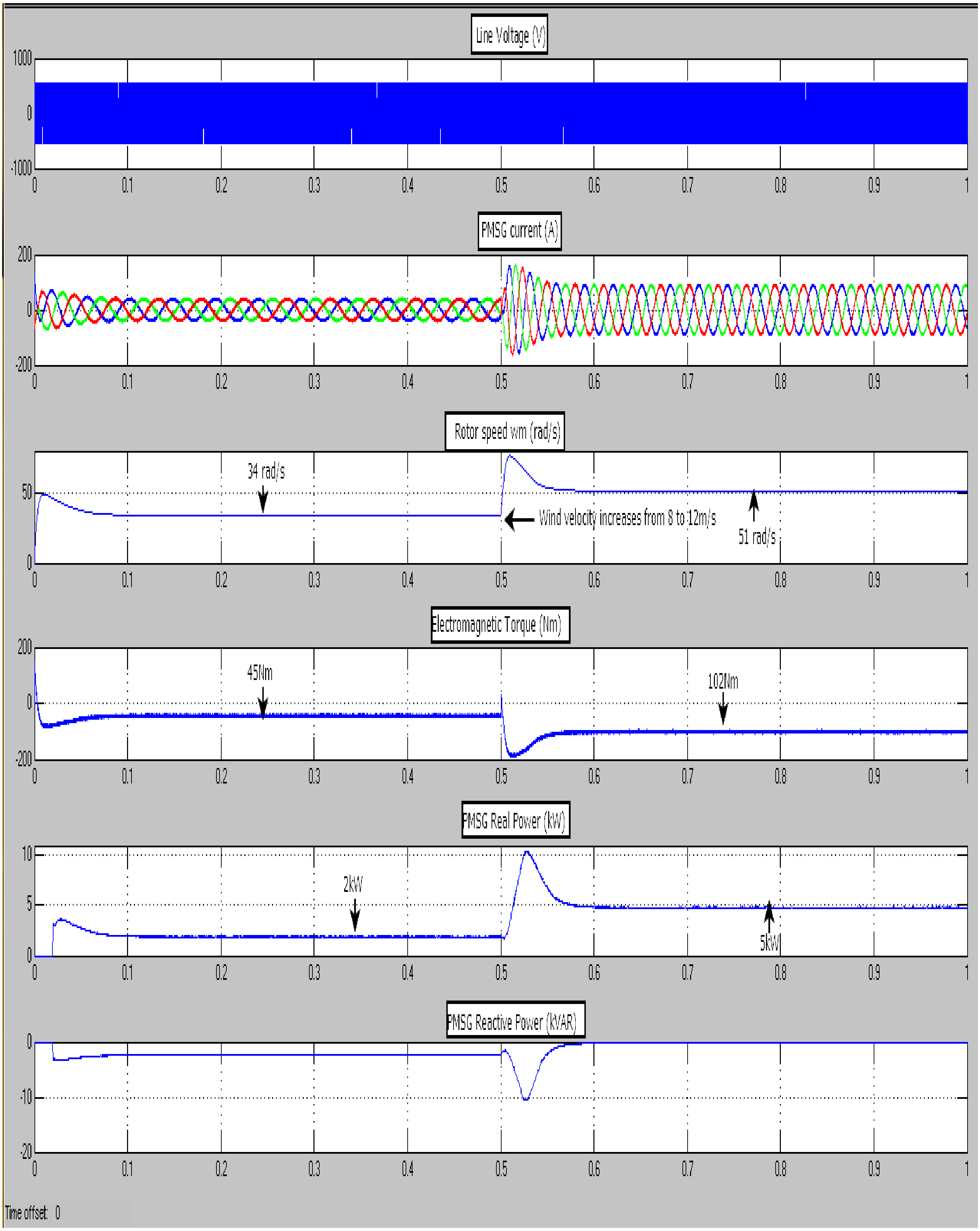

Fig. 17. Performance of PMSG converter

V. CONCLUSION

The paper has divided its focus on mainly two renewable sources, uncontrolled Hydro turbine and variable Wind turbine. An Electronic load controller or a Statcom is used interchangeably because it functions both as voltage and frequency control. It is based on vector control scheme based on synchronously rotating dq referenceframe.

A battery is connected on the dc side which is charged and discharged by the bidirectional activity of Statcom. This action helps to keep the frequency constant. Similarly, the battery is also charged from the output of PMSG converter. The Statcom also performs other functions like voltage regulation, harmonic elimination and neutral current compensation.

The PMSG machine converter is employed for MPPT tracking. Thus an overall hydro and wind hybrid has been developed which can perform satisfactorily even in an isolated case. All these models are developed using Matlab,Simulink.This paper can be extended to more detailedBattery Energy Management system. It can also be extended by using Multi level Inverter for higher power ratings and lesser harmonic output.

APPENDIX

Synchronous Generator

16kVA, 400V, 1500rpm, Xd=1.734pu, Xd'=0.177puXd'' = 0.111pu, Xq = 0.861pu ,

Xq''=0.199pu,Xl=0.07pu,Td=0.018s,Td''=0.0045s,Tq''=0.0045,Rs=0.02pu,H=0.5s,P=2

InductionGenerator

4kVA,400V,50Hz,Rs=0.03513pu,Lls=0.04586pu,Rr' =0.03488pu,Llr'=0.04586pu,Lm=2.8pu,H=0.2s, Excitation capacitor=1.5kVAR

Permanent Magnet Synchronous Generator

Rs=0.085Ω,Ld=0.95mH,Lq=0.95mH, Flux linkage=0.192Vs, J=0.008kgm^2,F=0.11Nms,P=8

Synchronous link reactor

Rf=0.44Ω,Lf=7.25mH

Statcom 40kVA

Vdc=700V,Cdc=8000μF,Battery=700V,150AH

PI controller

Frequency controller, K_{pf}=9000,K_{if}=30000

Ac voltage controller, K_{pv}=0.02,K_{iv}=0.02

PMSG converter, K_{pg}=5, K_{ig}=80

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