

*Full Length Research Paper*

# **A novel filter compensation scheme for single phase-self-excited induction generator micro wind generation system**

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**The paper presents a novel flexible alternating current transmission system (FACTS) based stabilization scheme developed by the second author for use in small scale residential/commercial micro grid (wind-induction generator) utilization schemes in the range 5 to 50 kVA, for stabilized efficient renewable wind utilization. The novel FACTS stabilization scheme is fully validated using Matlab/Simulink for small scale residential and commercial electric loads. The use of three-phase induction generator ensures both efficient utilization, improved power factor operation of the single phase-self excited operation of the three phase induction generator equipped with FACTS based switched filter compensation scheme (SFC) used to ensure Dynamic Voltage Regulation (DVR), and efficient energy utilization of micro grid wind schemes for residential/commercial applications.**

**Key words:** Flexible alternating current transmission system - switched filter compensation, efficient utilization, micro-wind generation.

## **INTRODUCTION**

The growing demand for alternative/renewable energy utilization is motivated by global demand and rising environmental concerns. The expected excessive World demand for energy and rising cost of fossil fuel due to depleted resources worldwide is pushing the drive to harness viable solar and wind energy in large scale, as well as micro grid green energy applications and large scale energy-farming. Green energy resources such as photovoltaic, wind and geothermal are now real economic choices due to competitive cost of energy and emerging technologies in advanced materials, processing and large scale energy farming, now resulting in competitive energy cost per kW hour; which is now estimated to range between \$ 0.05 and 0.06 for wind, and 0.25 and 0.35 for new efficient thin film PV solar cells.

The need for energy in remote, arid, village and island electricity in communities not connected to the utility grid, add a new economic incentive to wind and PV micro grid applications in replacing diesel fuel transportation cost. Interface issues, power quality and voltage regulation need to be addressed is becoming a serious issue for distributed renewable energy generation (Teoderescu and Blaabjerg, 2004).

Wind energy is a clean and sustainable energy source converting part of the wind kinetic energy in the moving air into electricity without producing any type of air pollution (Elmoursi and Sharaf, 2006). While hydro-power is already well established, wind energy is a promising renewable energy source (Jafri et al., 2012). In many countries, the potential for wind energy production exceeds by far the local consumption of electricity. China became the leading producer of wind power with capacity of 44,733.0 MW in 2009 and 18,900.0 MW added capacity (WWEA, 2011).

Flexible AC Transmission Systems (FACTS) technology

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is a new emerging technology for control, stabilization and efficient energy utilization for sudden generator and load changes (Johnsen and Eliasson, 2004). Although wind energy generation is a clean energy source, it creates security, reliability and stability problems in electric grid systems (Szeidert, 2006).

In this paper, an efficient squirrel cage low cost three phase induction machine is converted into single phase-self-excited induction generator (SPIG) operation and equipped with a novel FACTS based voltage stabilization scheme to ensure robust interface and efficient wind energy utilization in residential/commercial small scale applications.

The novel FACTS scheme developed by the second author is utilized to ensure full stabilization and dynamic voltage regulation as well as prevent sudden loss of excitation due to wind velocity excursions and/or load changes (Sharaf et al., 2007).

The main objective of this study is the study is to validate a low cost micro wind generation system using single phase-self excited operation of the three phase induction generator (Slootweg et al., 2003). The system is controlled by a multi-loop error driven regulation scheme developed by the second author and validated using Matlab/Simulink/SimPower toolbox. The digital simulation results are presented in the paper for different operation conditions and excursions.

The paper presents a novel low cost efficient and robust micro wind-generation scheme using the three-phase-to-single phase self-excited induction generator operated as a single phase machine with special terminal capacitors (Belakehal et al., 2009). The proposed FACTS-DVR scheme is fully validated for voltage stabilization and efficient utilization.

**WIND TURBINE AND GENERATOR MODELLING**

The wind turbine model is based on the steady-state characteristics. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine must be combined with those of the generator coupled to turbine. The mechanical power captured by wind turbine depends on its power utilization coefficient  $C_p$  for a given velocity  $v$ , and can be represented by:

$$P_m = \frac{1}{2} C_p(\lambda, \beta) \rho A v^3 \tag{1}$$

where, ‘A’ is the area swept by rotor blades, ‘v’ is the wind velocity and ‘ $\rho$ ’ is wind air density. Equation 1 can be normalized in the per unit (pu) system given by:

$$P_{m\_pu} = k_p C_{p\_pu} v_{wind\_pu}^3 \tag{2}$$

where, ‘ $k_p$ ’ is power gain for  $C_{p\_pu} = 1 pu$  and  $V_{wind\_pu} = 1 pu$ .  $v_{wind\_pu} = 1 pu$ ,  $k_p$  is less than or equal to 1.

A general equation based on the modelling turbine characteristics, is given by:

$$C_p(\lambda, \beta) = C_1 \left[ \frac{C_2}{\lambda_1} - C_3 \beta - C_4 \right] e^{-\frac{C_5}{\lambda_1}} + C_6 \lambda \tag{3}$$

and with this equation and using coefficients are obtained characteristic curves (Siegfried, 1998).

$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

The coefficients  $C_1$  to  $C_6$  are:  $C_1 = 0.5176$ ,  $C_2 = 116$ ,  $C_3 = 0.4$ ,  $C_4 = 5$ ,  $C_5 = 21$ ,  $C_6 = 0.0068$ . The peach angle  $\beta$  is used a constant and value is assigned as 0.

The mechanical power,  $P_m$ , as a function of generator speed, for different wind speeds and for blade pitch angle  $\beta = 0$  degree, is illustrated in Figure 1 as a wind turbine power characteristics. This figure generated m-file is used in Matlab/Simulink application to defined wind power as per unit.

Mechanical Torque,  $T_m$ , using the turbine characteristics and wind speed is obtained from turbine model given in Figure 2.

Asynchronous generators are preferred to convert mechanical energy into electrical energy due to their operating characteristics and compatibility with variable wind speed ranges (Chen et al., 2009).

The induction generator is a self excited squirrel cage induction generator. This model includes the terminal compensating capacitors and a gear box which is between the turbine and the generator (Gagnon et al., 2005). This model is shown in Figure 3.

The micro wind-induction generator scheme is modelled using the dq reference frame (Equation 5). In the equations, the stator transients for the squirrel cage induction generator are neglected (Palvalia and Sing, 2008).

$$\begin{aligned} v_{ds} &= -R_s i_{ds} + w_s ((L_{\sigma s} + L_m) i_{qs} + L_m i_{qr}) \\ v_{qs} &= -R_s i_{qs} + w_s ((L_{\sigma s} + L_m) i_{ds} + L_m i_{dr}) \\ v_{dr} &= 0 = -R_r i_{dr} + s w_s ((L_{\sigma r} + L_m) i_{qr} + L_m i_{qs}) + \frac{d\psi_{dr}}{dt} \\ v_{qr} &= 0 = -R_r i_{qr} + s w_s ((L_{\sigma r} + L_m) i_{dr} + L_m i_{ds}) + \frac{d\psi_{qr}}{dt} \end{aligned} \tag{5}$$

where s is the slip, v is voltage, i is current, R, L respectively resistance and inductance, and  $\psi$  is flux

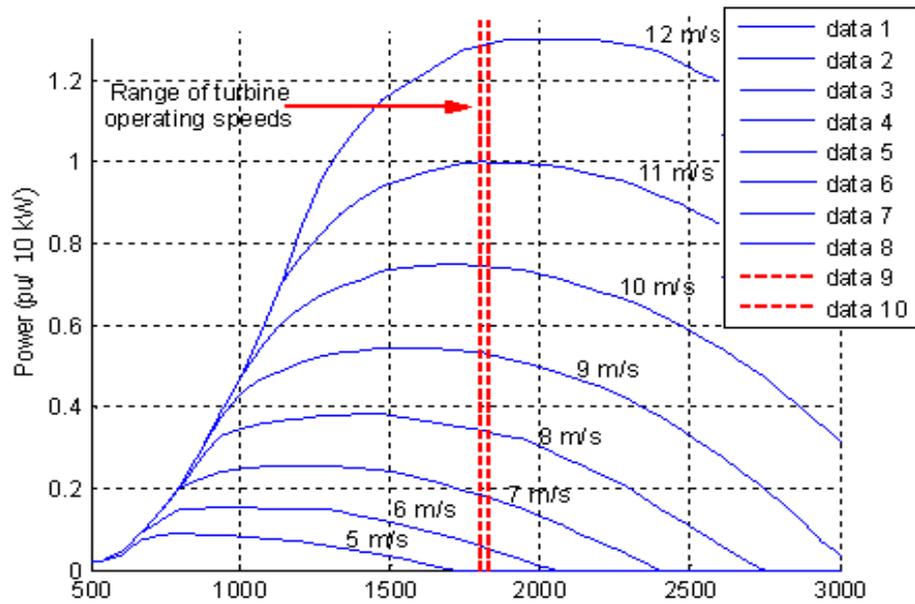


Figure 1. Power characteristics of the wind turbine.

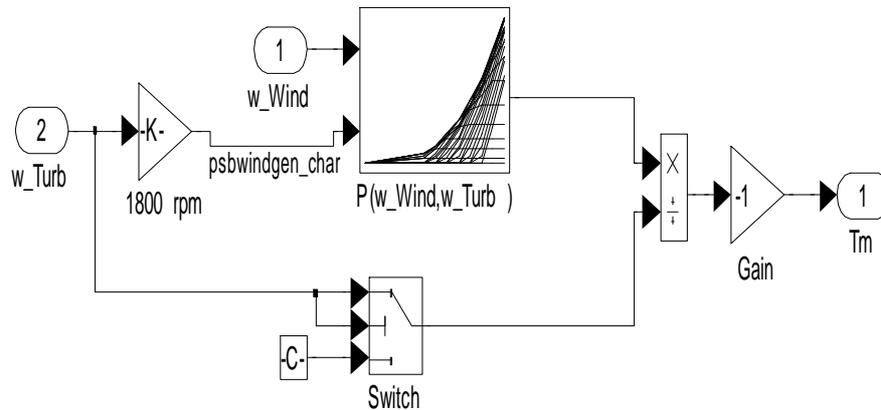


Figure 2. Wind turbine functional model in Matlab/Simulink.

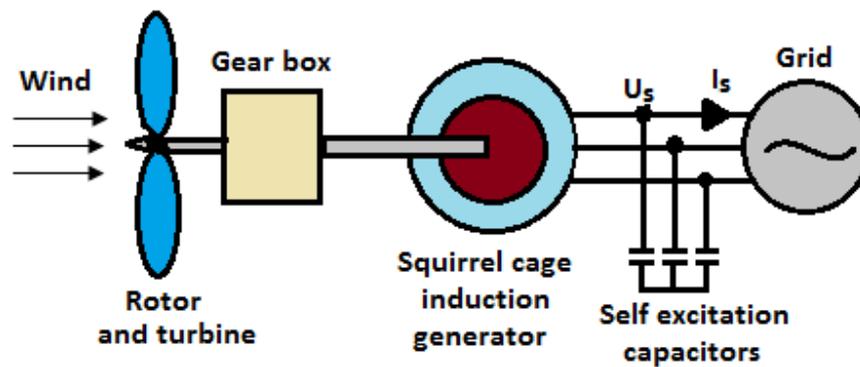
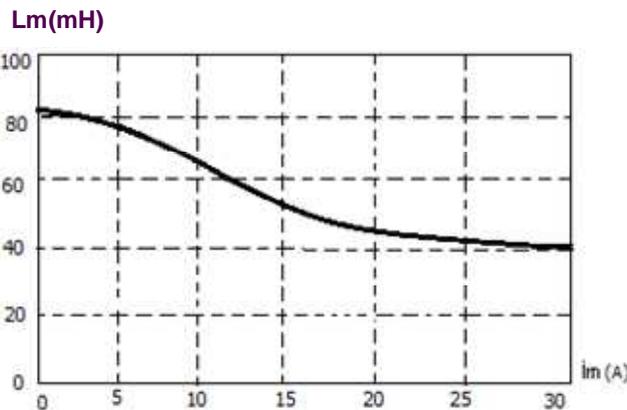


Figure 3. Wind turbine generating system.

**Table 1.** Study system parameters.

<b>Induction generator parameters</b>	
Power and phase	2.2 kW, 3 phase
Voltage and Frequency	415 V, 50 Hz
Generator Speed	1440 rpm
Stator resistance and inductance (r1, x1)	0.072 ohm, 0.083 H
Rotor resistance and inductance (r1', x1')	0.054 ohm, 0.083 H
Mutual inductance (Lm)	0.2 H
<b>Compensating and filtering capacitors</b>	
Cs	50 µF
Cn	45 µF
Cg	15 µF
Cf	150 µF
<b>Line and load parameters</b>	
Rs (line resistance)	0.1 ohm
Ls	1 Mh
Linear load	400 VA
NLL	200 VA (arc type model)
Motor (SPIM)	400 VA Driving $T_L = T_{L0} = T_{Rated}$



**Figure 4.** A non-linear magnetizing inductance characteristic  $L_m$  [ $L_m = f(i_m)$ ].

Linkage (Rahim et al, 2011). The indexes d and q stand for direct and quadrature component, the indexes s and r are for rotor and stator, m for mutual and  $\sigma$  for leakage (Sofiano et al, 2008).

The electrical torque is given by:

$$T_e = \psi_{qr} i_{qr} - \psi_{dr} i_{dr} \tag{6}$$

The generator parameters used in the system simulation are given in Table 1. The compensating capacitors depicted in Figure 3 are included in the grid model and are, therefore, not represented in the preceding equations

that describe the constant speed generating system (Mahato et al., 2007).

The three phase squirrel cage induction generator is operated as a single phase generator with terminal capacitors. The magnetizing inductance  $L_m$  is a nonlinear function of magnetizing current  $i_m$ :

$$L_m = f(i_m) = \frac{\phi_m}{i_m} \tag{7}$$

as shown in Figure 4, where  $L_m$  is the mutual inductance of the induction generator (Piegari and Rizzo, 2004).

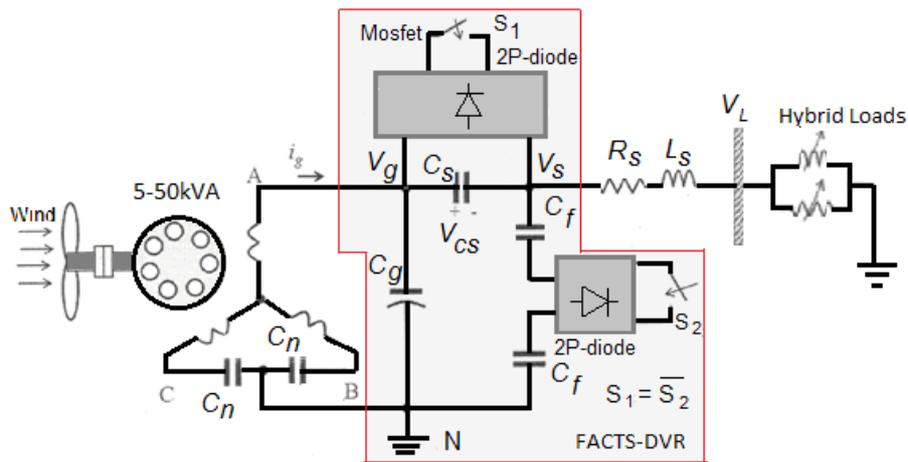


Figure 5. Single-line diagram of the proposed micro wind-generation system.

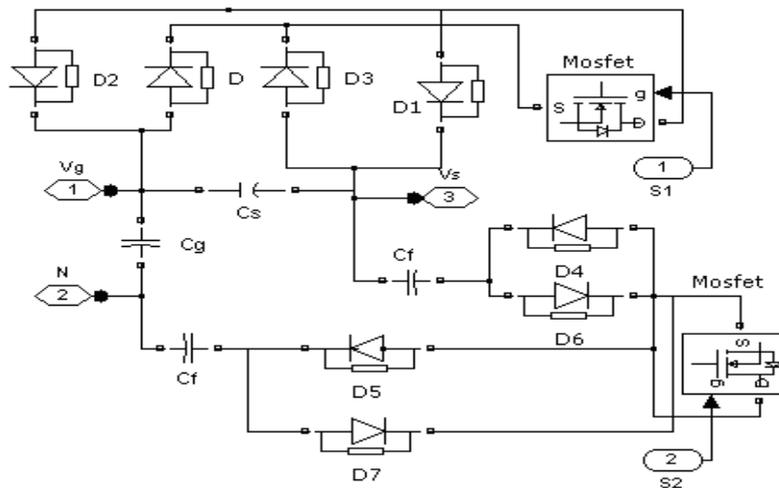


Figure 6. The Simulink model of the SPFC.

**SYSTEM CONFIGURATION**

**Sample study system**

A three phase induction machine is converted for operation as a single phase machine using the terminal capacitors  $C_g$  and  $C_n$  as shown in Figure 5. The induction machine generates power when enough magnetic excitation is provided and its rotor is driven at a rotational speed higher than the synchronous speed of the stator rotating magnetic field. The required excitation current for the generator is obtained by self excitation capacitors across the three terminals (Szeidert, 2006).

The self-excited single phase induction generator operation has a major disadvantage of loss of excitation and dynamic voltage stabilization problems. The generator-terminal voltage depends upon the rotor speed,

terminal capacitance, load current and the power factor of the load. In order to keep a steady output power the novel proposed FACTS-DVR, compensator is utilized and is dynamically controlled by the pulse width modulated (PWM) switching of  $S_1$ ,  $S_2$  complementary MOSFET switches as shown in Figure 5.

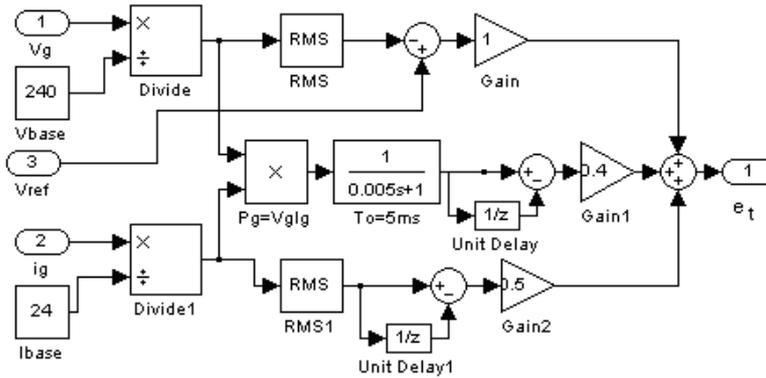
The unified AC system parameters for the induction generator, FACTS compensator, filter, and AC loads are given in Table 1.

**FACTS-DVR operation of the SFC - scheme**

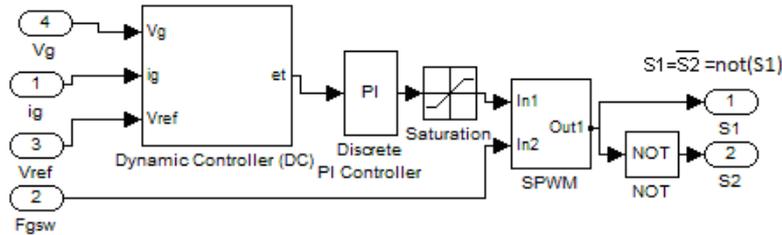
The unified micro wind generation scheme is modelled using the Matlab/Simulink including compensators FACTS-DVR as shown in Figure 6. In the proposed scheme,  $S_1$  and  $S_2$  are either MOSFET or IGBT

**Table 2.** Parameters of dynamic error generator.

RMS voltage loop gain	1.0
RMS current loop gain	0.5
RMS power loop gain	0.4
Loops time delay	0.005 s
Vref Signal	1.0 pu



**Figure 7.** Tri-loop dynamic error driven PID controller.



**Figure 8.** Sinusoidal pulse width modulation switching signal generator with dynamic tri-loop controller.

switches. The switching signals of the two MOSFET switches are generated by error driven controller. Both switches are complementary and turned on or off at the same time.

**Control scheme**

A novel tri-loop error driven regulator developed by the second author uses the actual measured per unit values voltage, power, and current variables. The parameters of the tri-loop dynamic error generation model are given in Table 2.

The tri-loop error driven PID controller is a modified version of the conventional one given in references to ensure fast dynamic response (Elmoursi and Sharaf,

2006). The Matlab/Simulink functional model is shown in Figure 7.

**Sinusoidal pulse width modulation switching**

The total error signal ( $e_t$ ) applied to the PI controller is utilized to adjust the Sinusoidal Pulse modulation index (M) for optimal switching of the two complementary switches ( $S_1 = \bar{S}_2$ ).

SPWM switching signals are generated by using either generator or load bus signals ( $V, I$ ). The measurements are evaluated by the proposed dynamic controller to generate the gating two complementary switching signals  $S_1$  and  $S_2$ .

The SPWM switching signal generator and the dynamic controller is fully depicted in Figure 8.

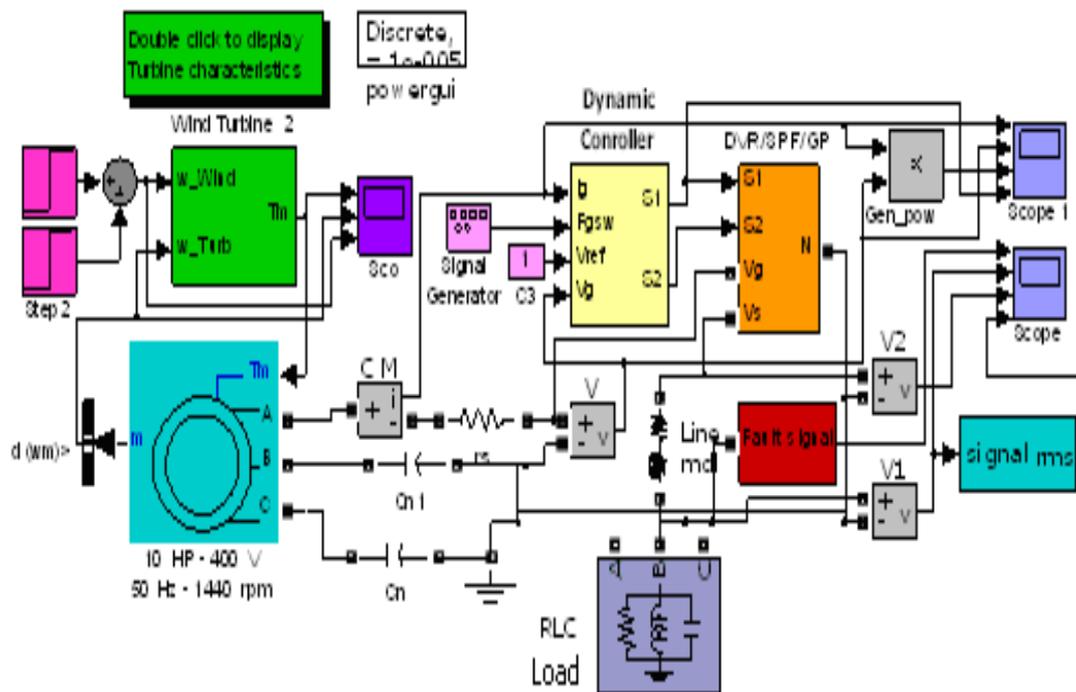


Figure 9. Micro wind-generation unified scheme functional model.

### SAMPLE STUDY SYSTEM

The micro wind-generator study system consists of a wind-turbine, single phase induction generator, FACTS-DVR error driven dynamic controller, SPWM switching signal generator and the terminal load bank. An efficient three-phase wind turbine-generator is converted to a single phase operation. Figure 9 shows the Matlab/Simulink functional model of the unified micro wind-induction generator scheme.

### DIGITAL SIMULATION RESULTS

The Matlab/Simulink digital simulation results of micro wind-generator scheme with FACTS-DVR switched filter compensator were obtained by using Matlab/Simulink software environment. The study system simulation results without and with FACTS-DVR compensation are compared to assess the stabilizing effect DVR device. System parameters are shown in Table 1. The simulation is carried out for 15 s with and without the controller to show its performance in voltage stabilization, harmonic reduction and reactive power compensating.

The first set of the digital simulation results depict the variation of generator speed according to wind speed, depending on turbine characteristics. The simulation results are given in Figure 10. The generator power varies with wind, and generator speeds depend on wind-turbine characteristics. The rotor speed is also decreased due to the nonlinear  $L_m$  saturation action.

Figure 11 showed the dynamic voltage response at

generator and load busses, and RMS voltage variation at load bus. As it can be seen from the figure, the generator voltage amplitude carries the same value as obtained from the load bus. The RMS terminal load voltage value is stabilized.

Figure 11, is enlarged as in Figure 12. A sinusoidal generator voltage with max value of 300 V and an effective RMS value is 220 V as clearly shown.

The generator voltage, line current and the output power from the generator are also depicted in Figures 13 and 14 are shown.

For a short circuit condition for 1 s duration at load bus, dynamic simulation results are shown in Figures 15 to 17. The generator voltages, current and power for a single line temporary short circuit disturbance time are shown in Figure 16. In the figure, the change in the voltage amplitude varies with those of current at the same time. Current and power changes take the shape of a square wave. But as the value changes, there occurred big switching losses. The RMS values of this change are shown in Figure 17.

Finally, a disturbance of load is created at load bus by switching off for 9 s and switching on for 1 s. Simulation results are shown in Figures 17 to 19. And, the compared error signal after dynamic controller and the error signal after PI controller are compared in Figure 20.

At the end, the results are drawn at the same graphic to compare simulation results with and without novel controller as shown in Figures 21 and 22.

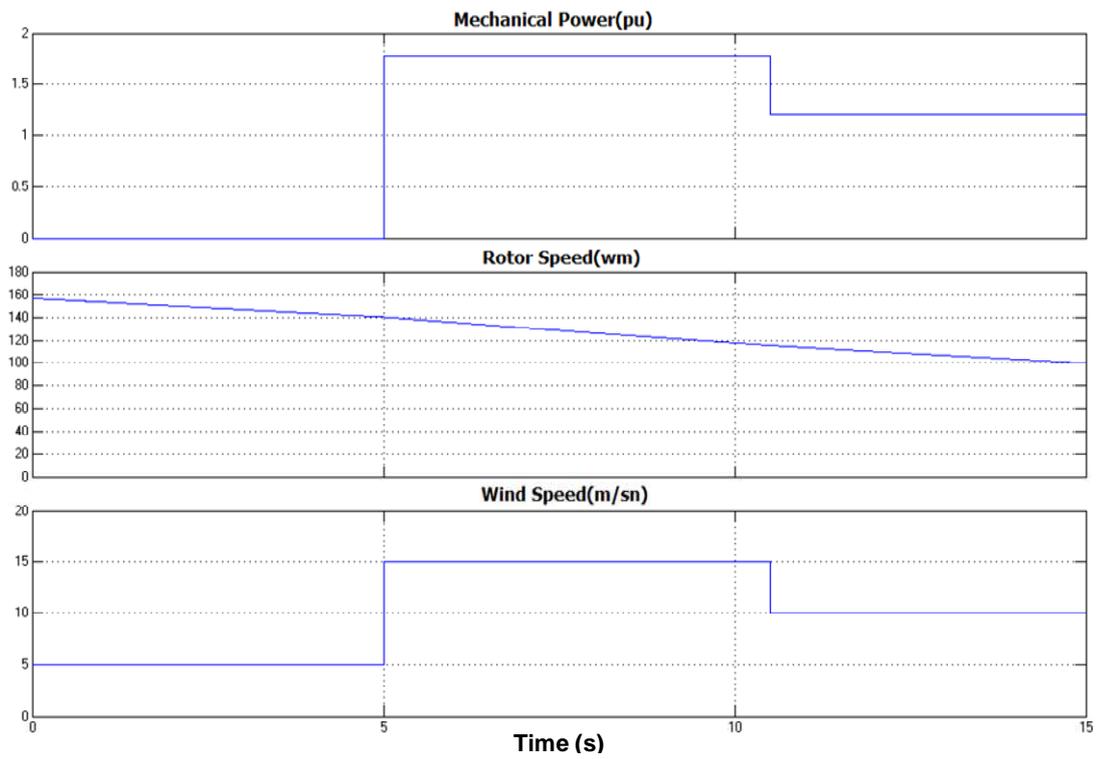


Figure 10. Mechanical power constant, generator rotor speed, and wind speed.

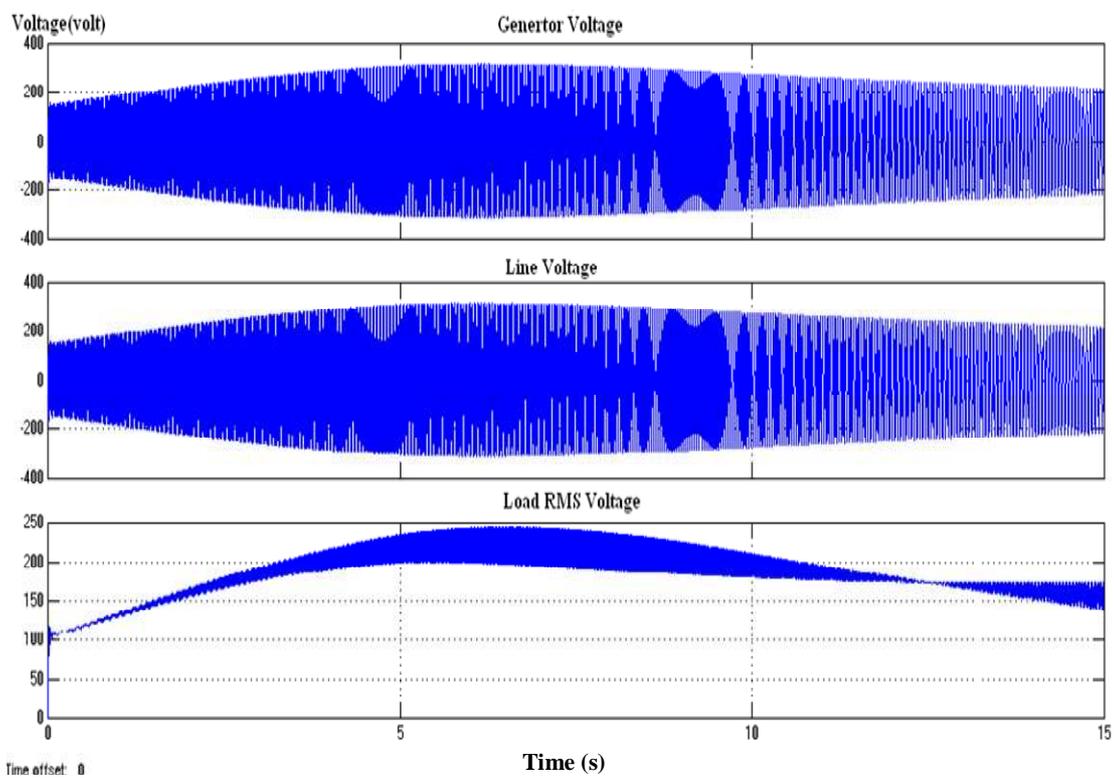


Figure 11. Generator voltage, line voltage and RMS value of the load voltage.

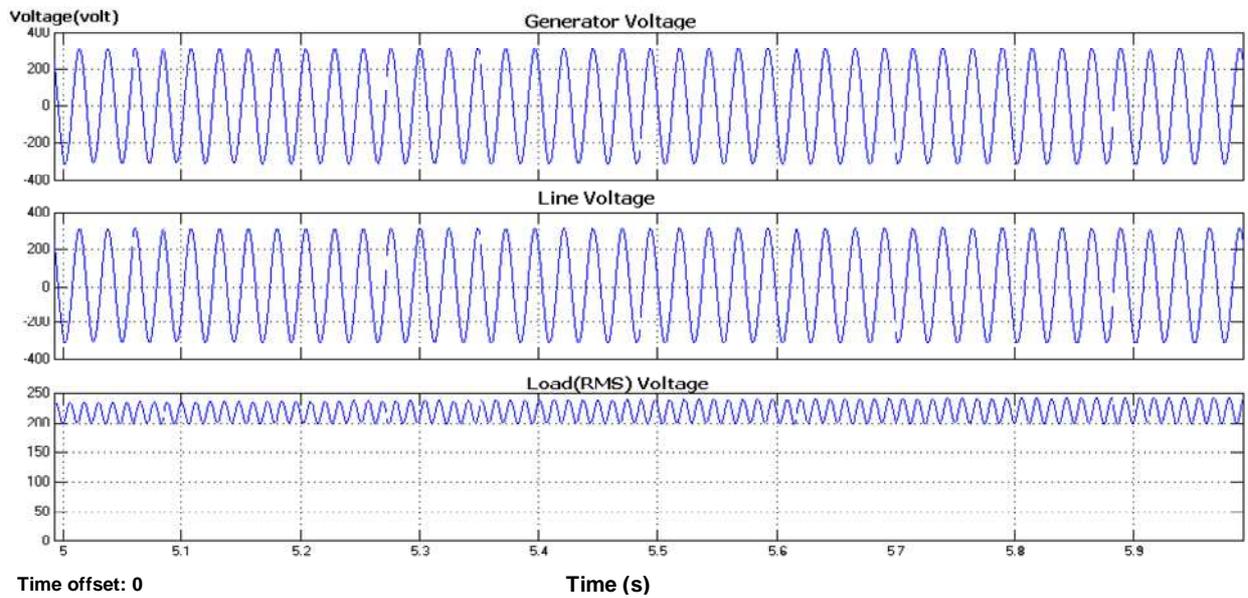


Figure 12. Generator, load and line voltages with enlarged Figure 11.

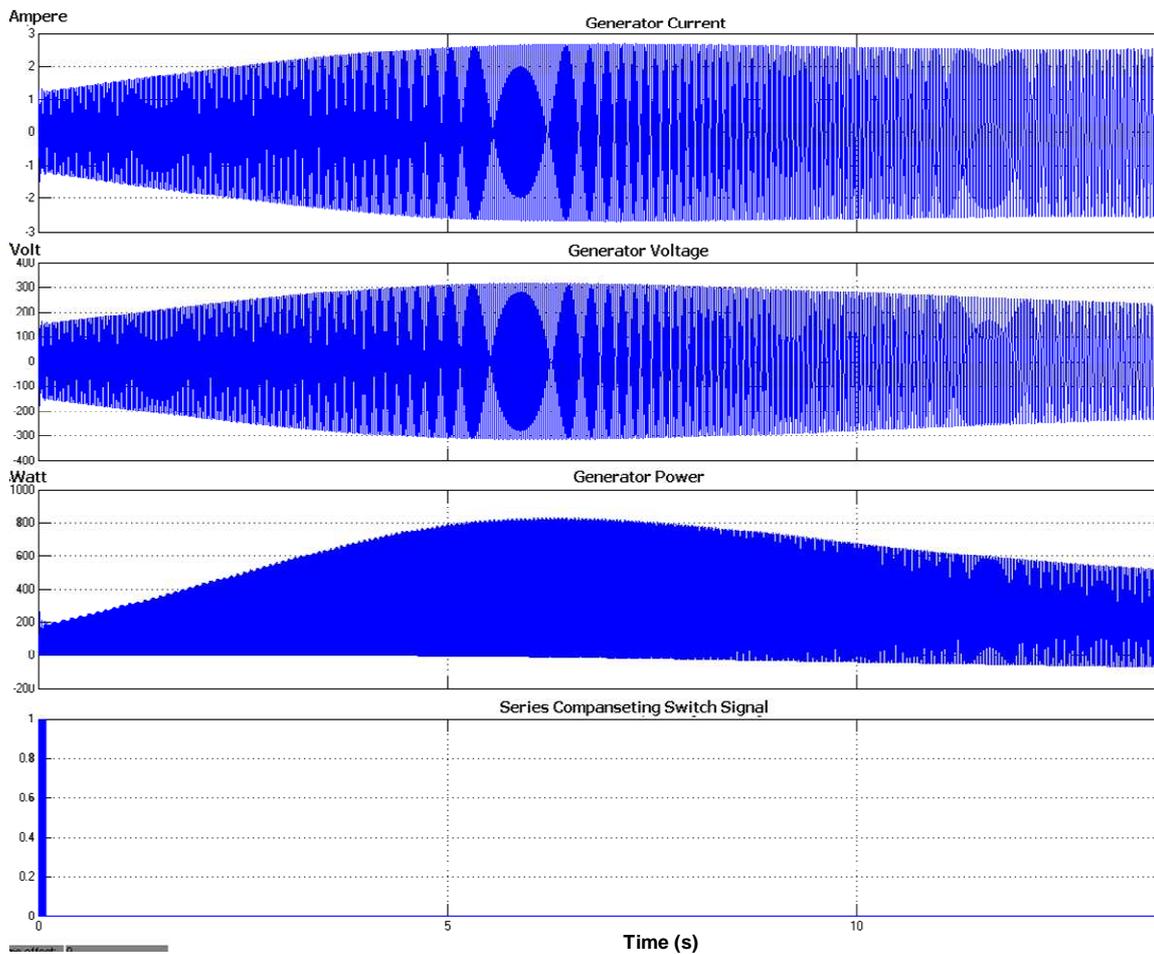


Figure 13. Single line transient voltage, current, power and series compensating switching signal.

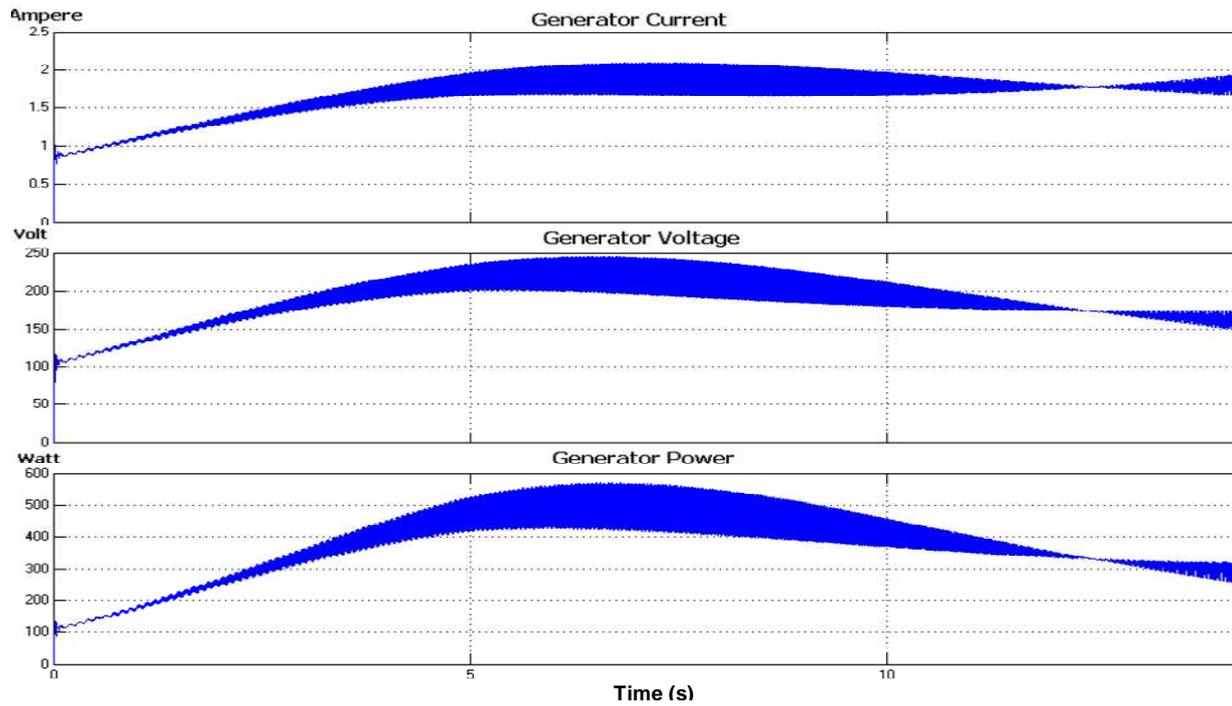


Figure 14. Single line RMS voltage, current and power.

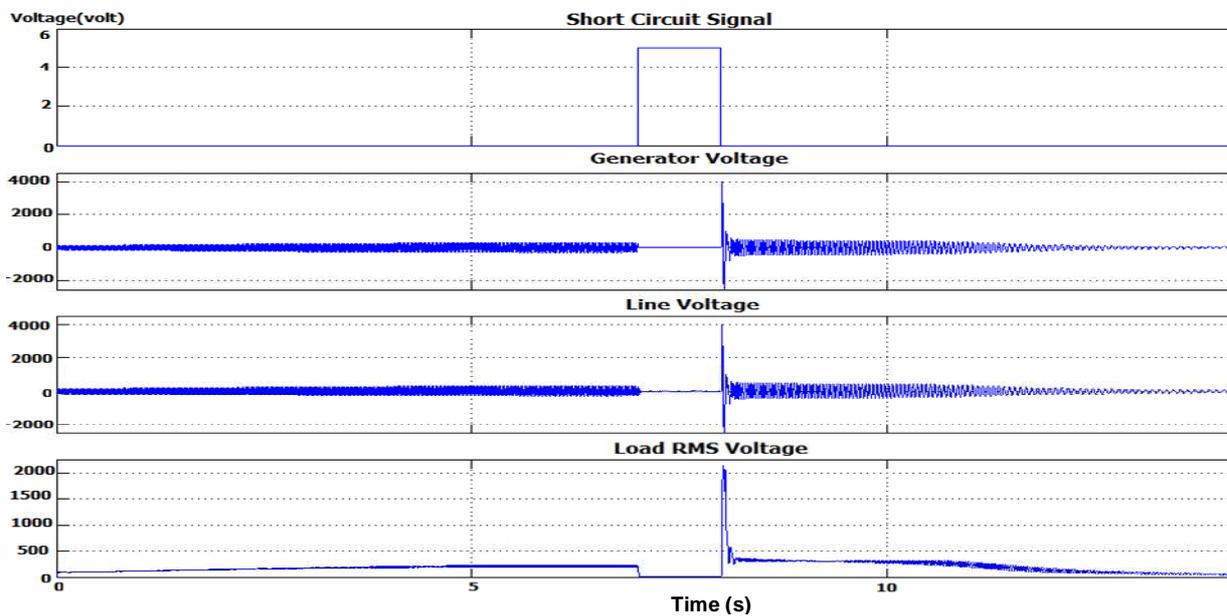


Figure 15. Digital simulation result for temporary short circuit disturbance at load bus.

**DISCUSSION**

This paper presents a novel FACTS based switched Filter-Compensation scheme for efficient and robust interface to a single phase self-excited micro wind

utilization scheme for use in small residential/commercial applications (5 to 50 kVA). However, the novel FACTS-DVR Switched Filter Compensation Scheme with the error driven dynamic multi loop regulation scheme developed by the second author is fully validated using

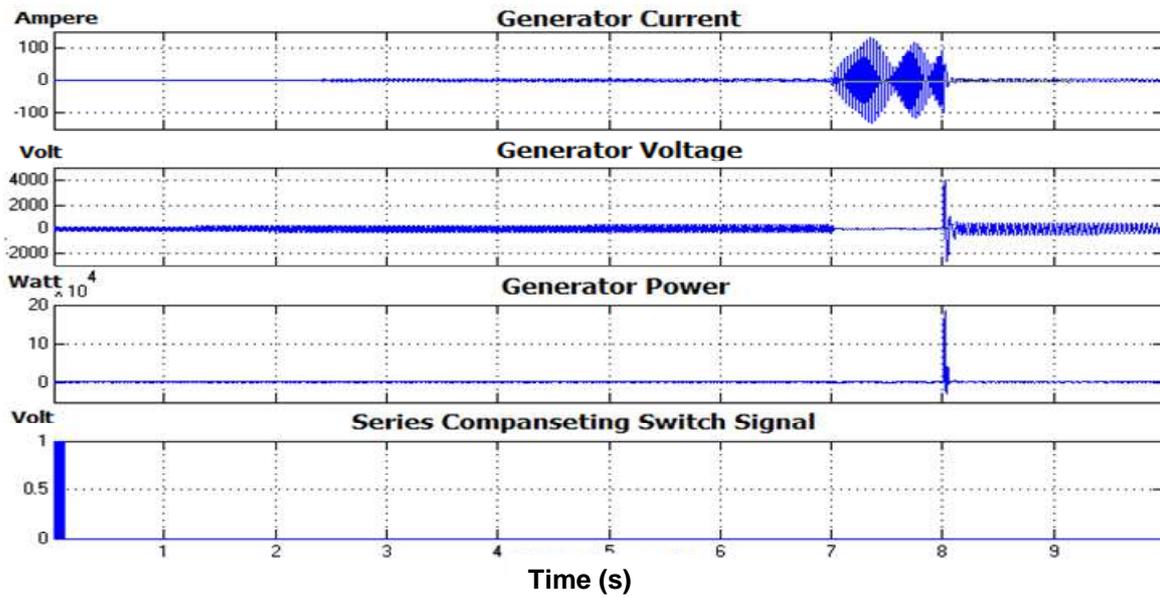


Figure 16. Short circuit disturbance effect on the generator voltage, current and power.

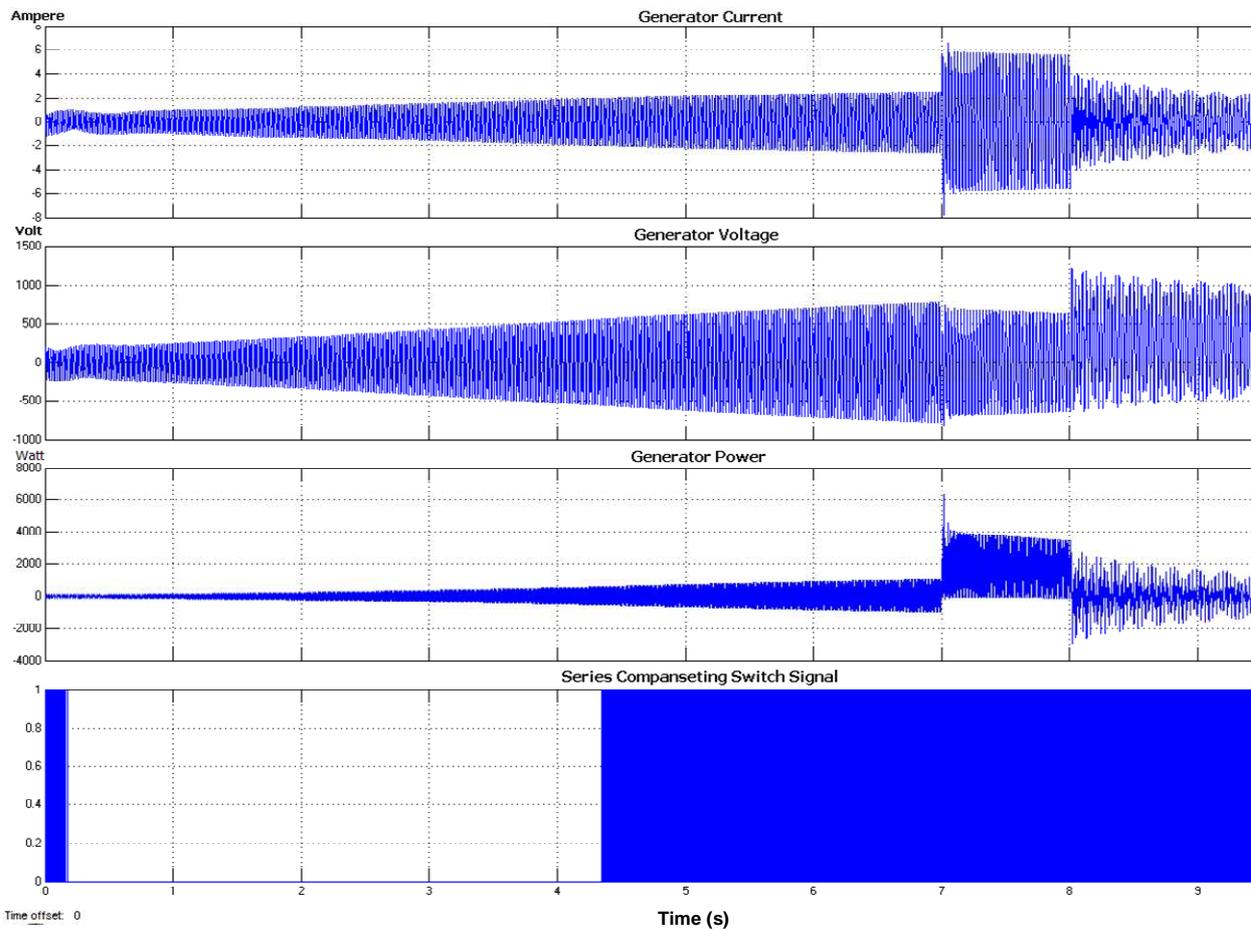


Figure 17. The generator voltage, current and power for overload disturbance.

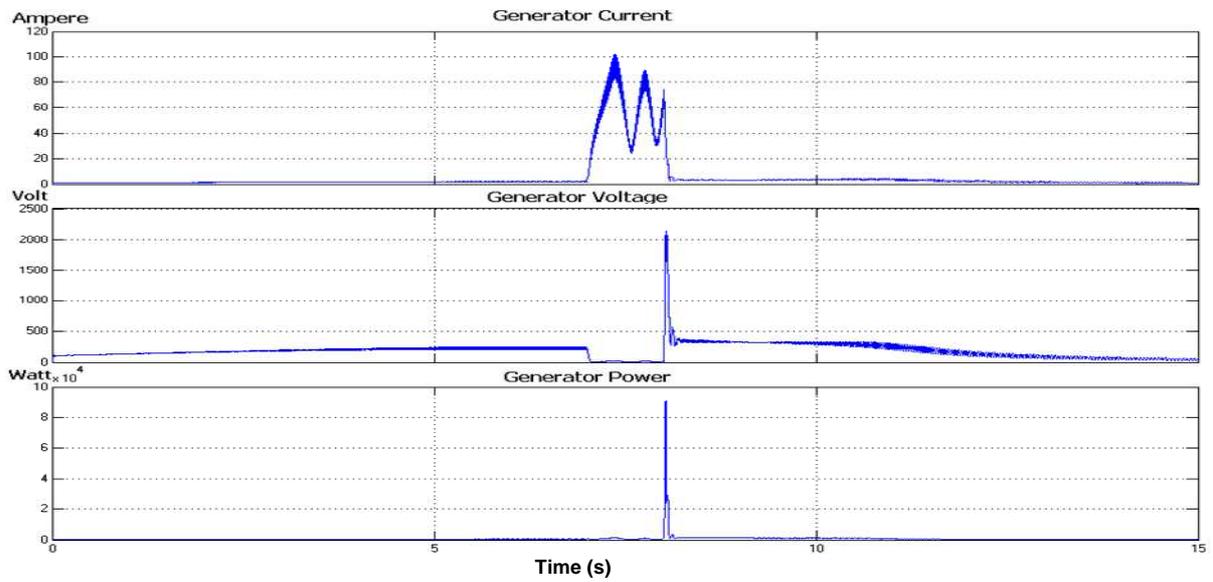


Figure 18. RMS value of generator voltage, current and power for overload disturbance.

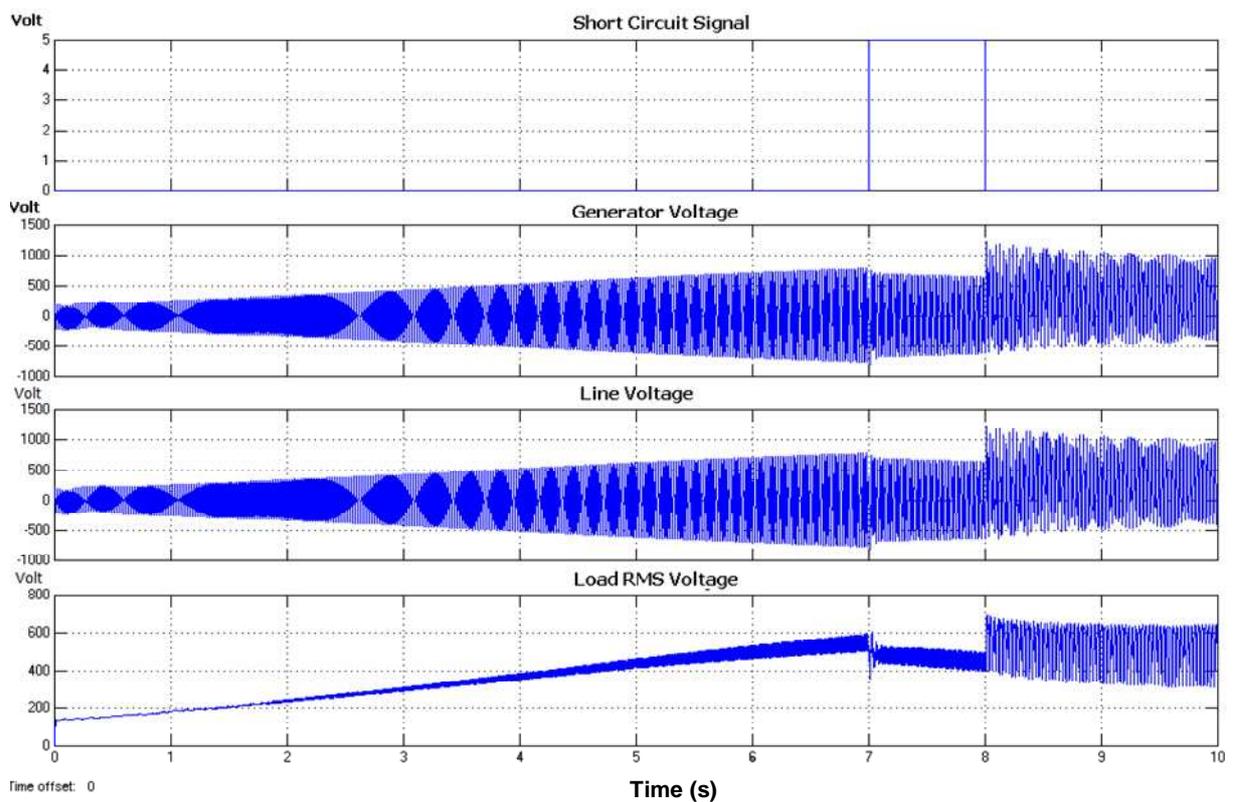
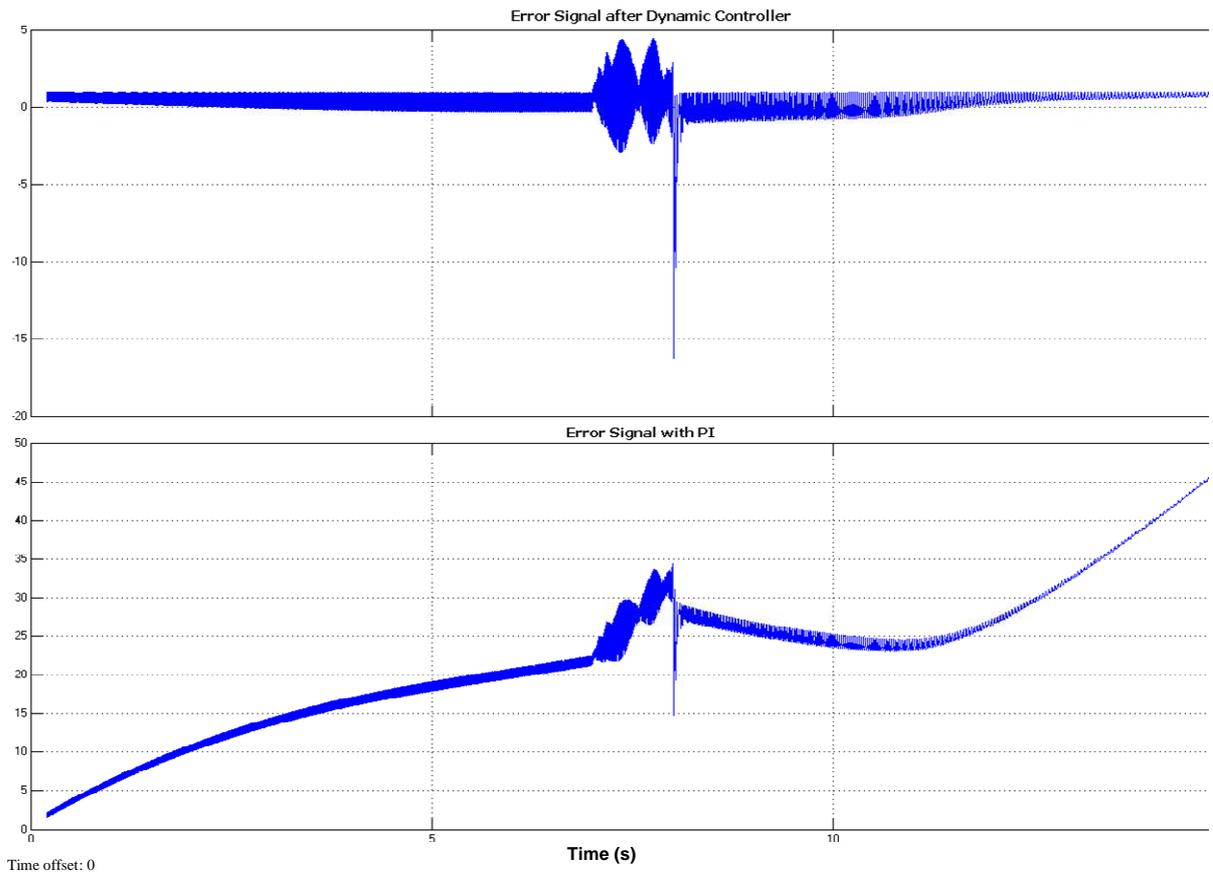


Figure 19. Overload disturbance, generator voltage, line voltage and load RMS voltage.

Matlab-Simulink software environment. It is effective in voltage regulation, efficient utilization and prevention of

sudden loss of excitation due to wind and load sudden changes and excursions.



Time offset: 0

Figure 20. The total error ( $e_t$ ) signal generated from tri-loop error signal.

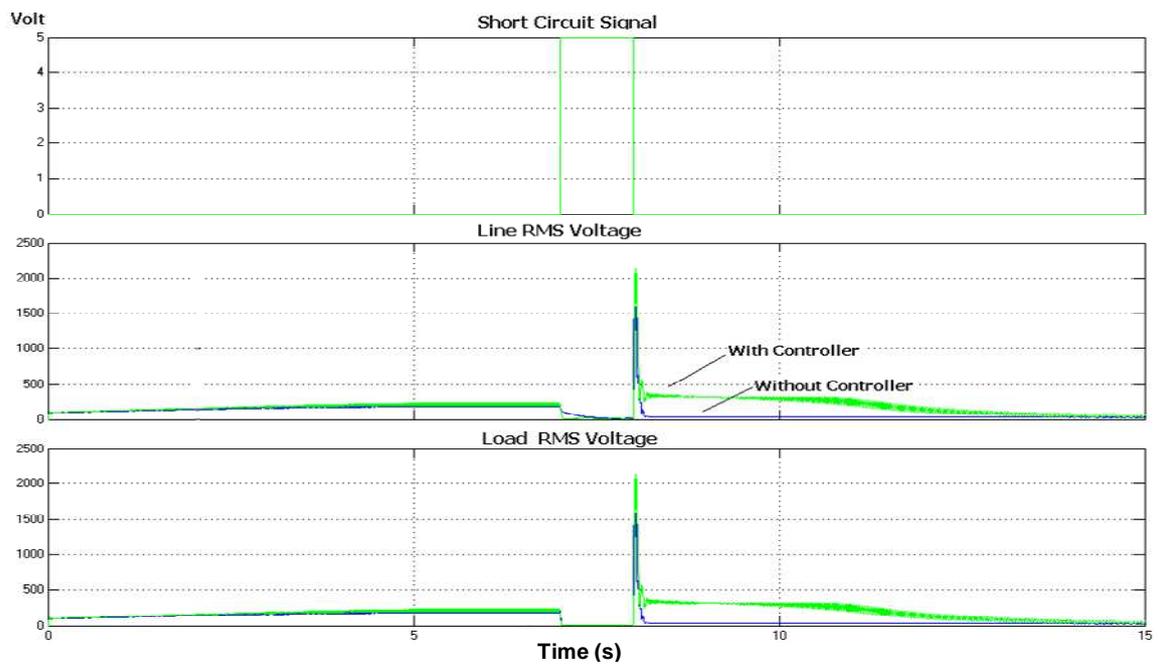
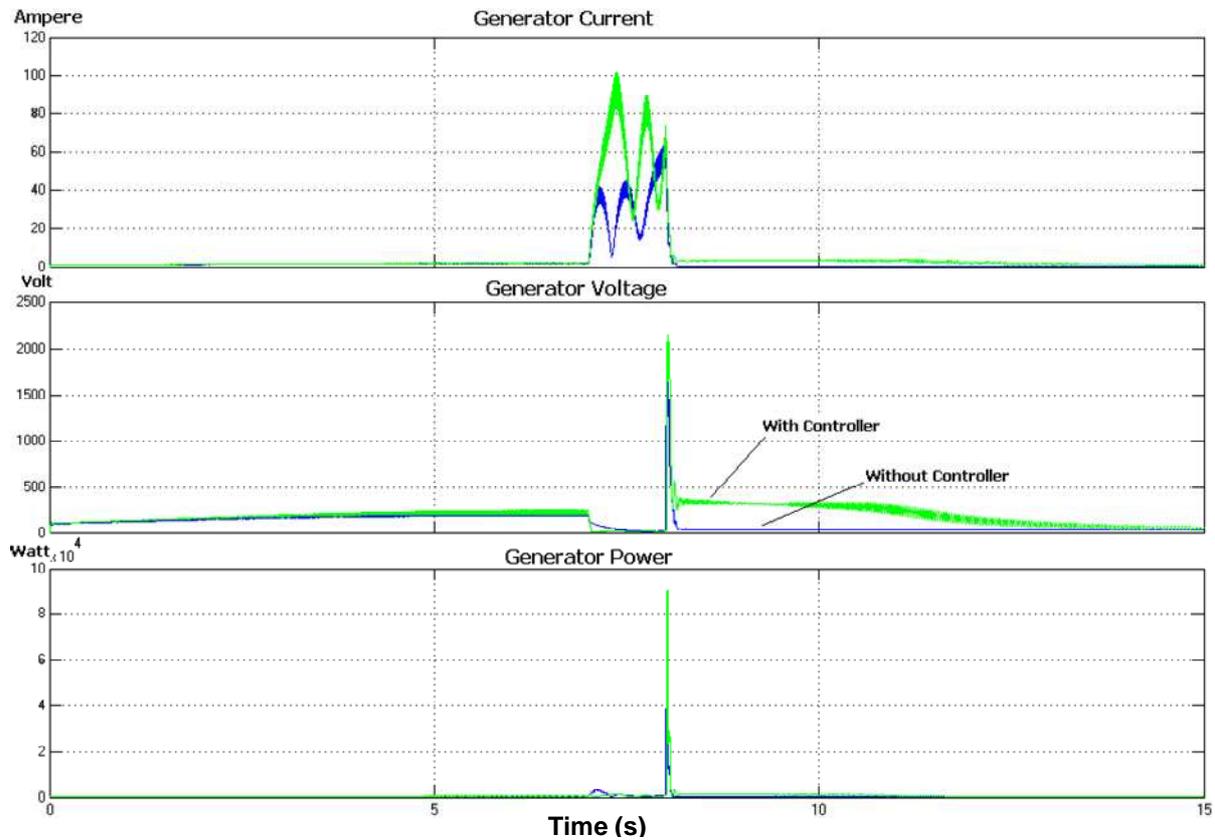


Figure 21. Short circuit signal, line and load RMS voltage with and without controller.



**Figure 22.** Induction generator RMS current, voltage and power with dynamic controller and without controller.

The squirrel cage low cost, low maintenance and efficient three phase induction machine is converted into a self-excited single phase generator operation and stabilized using a novel FACTS Modulated/Switched Filter Compensator which is fully controlled using a multi loop error driven dynamic regulation scheme to ensure efficient operation with enhanced efficiency and power factor. Digital simulation results using the Matlab/Simulink software environment validated the efficiency and stabilization effectiveness of FACTS-DVR device.

The same FACTS scheme with modified topologies is now extended to hybrid AC-DC distributed generation for use in smart grid applications using hybrid Wind-PV-Micro gas turbine green energy utilization schemes.

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