Wind Energy System Using Self Excited Induction Generator with Hybrid FACTS Device for Load Voltage Control

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Abstract. The Modern Power systems are incorporated with renewable energy generation resources such as solar and wind power plants. The everlastingDemand for electrical power leadsto dynamic load variations on the electric grid subsequently results in frequency and voltages fluctuations.

This article engrossedon development of a Hybrid FACTS Device to control load voltages over wide range of load variations on wind power plant equipped with Hybrid FACTS device with Self Excited Induction Generator (SEIG). The distribution generationsystem is developed with Hybrid FACTS Device fed SEIG based wind power plant feeding an isolated load. The wind plant is subjected to speed variations as well as load perturbations leading to voltage fluctuations; hence SEIG is best suited generator for the wind plant.

The SEIG is equipped with shunt compensator or any Hybrid FACTS Device as used in the present case. This article deals with wind energy generation unit used to supply local loads.The terminal voltage has been maintained at constant nominal value for different load scenarios by the use of Hybrid FACTS Device and these results are presented in this article, which proves the effectiveness of the proposed device on maintaining constant voltage over wide range of load variations.

Keywords: Series compensation with DSTATCOM · SEIG · Wind energy generation · Voltage control in wind plant · Hybrid FACTS device · Voltage stabilization · Reactive power control · Series and shunt compensation

1 Introduction

The energy demand is rising day by day as the population is increasing at a very rapid rate. So to meet the energy needs we have to generate more electricity. In conventional methods to produce electricity the fossil fuels are used that pollute the environment and have a very negative impact on the environment. So to have sustainable growth

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we need to generate more electricity by the use of renewable energy. The renewable energy includes wind energy, solar energy, tidal energy etc. These types of energy are clean energy sources and produce no pollution and do not harm the environment. The power generated by the wind must be integrated into the grid. In recent years there has been extensive growth in the use of wind energy. The wind plant is subjected to speed variations as well as load perturbations leading to voltage fluctuations. The closed loop control of the DSTATCOM ensures the voltage stabilization of load for various load scenarios presented in this article.

DSTATCOM injects the reactive power into the system and hence voltage fluctuations have been reduced by the injection of reactive power. The flow of the reactive power is controlled by the control of the bus voltage, the magnitude of the bus voltage decides the direction of reactive power flow.

2 Wind Power Plant

Wind Energy in Generating Electrical Power through wind was started in the nineteenth century, due to consumption of fossil fuels at a high rate that led to innovation of new ideas related to wind energy.Wind generation with large commercial scale Advancements, wind energy systems become more cost efficient and it is widely used electrical source in modern age, which minimizes the greenhouse effect and subsequently global warming [1–6].

2.1 Wind Turbine

Wind Turbine is a device that converts the wind's kinetic energy into electrical energy. Wind turbines are manufactured in a wide range of sizes, with either horizontal or vertical axes as depicted in Fig. 1. The available range of power generation by the horizontal wind turbine is low and is 50 W to 4.5 KW, whereas vertical type is high power range is about 2.5 to 3 MW [1–6].

The wind power generation P_W is determined by the power coefficient C_P as specified in the following Eqs. (1) and (2) respectively. PW is the wind power, ρ is the air density, CP is the coefficient of performance, A if frontal area and v is the velocity of wind. The power coefficient is a nonlinear function of the blade pitch angle and the blade tip speed ratio λ and is the ratio of the angular rotor speed of the wind turbine to the linear wind speed at the tip of the blades given by the Eq. (4) and 1/x in terms of λ and β as depicted in the Eq. (3) [1–6].

$$P_W = \frac{1}{2}\Big(C_P(\lambda, \beta)\rho A V^3\Big) \tag{1}$$

$$C_P = 0.22\left(\frac{116}{x} - 0.4\beta - 5\right)e^{\frac{-12.5}{x}} \tag{2}$$

$$\frac{1}{x} = \frac{1}{(\lambda - 0.08\beta)} - \frac{0.035}{(1+\beta^3)} \tag{3}$$

$$\lambda = \frac{wR}{v} \tag{4}$$

The Wind Power Plant with Self Excited Induction Generator with DSTATCOM as illustrated in the Fig. 1 below. The wind turbine input parameters, which controls the wind power generation are wind speed (*v*) and pitch angle (β). These wind turbine characteristics have been illustrated in Fig. 2, which shows the power generation curves against per unit turbine speed with constant wind speed of 10 m/s, 12 m/s to maximum 24 m/s respectively. The wind turbine output is given to the SEIG excited and controlled with Hybrid FACTS Device [3, 4, 8].

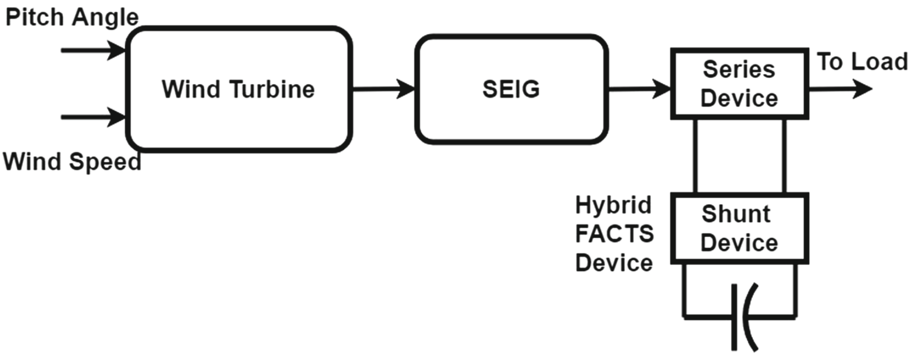

Fig. 1. Wind power plant with self excited induction generator with DSTATCOM

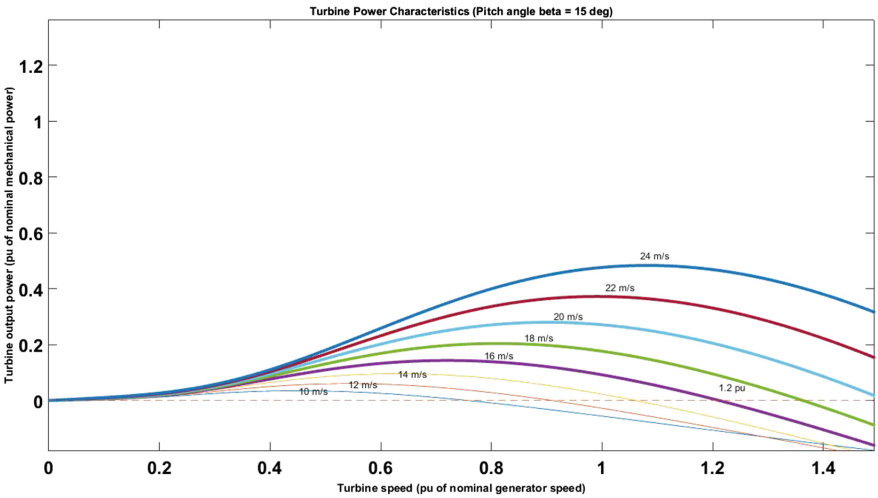

Fig. 2. Wind turbine characteristics

3 Self Excited Induction Generator

Induction Machines when run at more than synchronous speed, the slip is negative and power flow reversal will be the end result, which means it is running as Generator. It has three different modes of operation, one is grid connected: in which it consumes reactive power from the grid and supplies active power to grid and is not possible for isolated loads. The second is in self excited mode of operation in which capacitor bank or any shunt reactive power compensator is used to get the self excitation process with suitable amount of reactive power and is suitable for isolated loads. The third is Doubly Fed Induction Generator, it also involves the grid in its study, and hence for isolated loads we may not prefer it. Hence SEIG is chosen in this article to present the case study of different load scenarios in isolated mode without grid connection and have been presented the results. This article deals with the SEIG equipped with closed loop control of the DSTATCOM as depicted in the Fig. 3, which consists of SEIG, DSTATCOM and loads [7, 10].

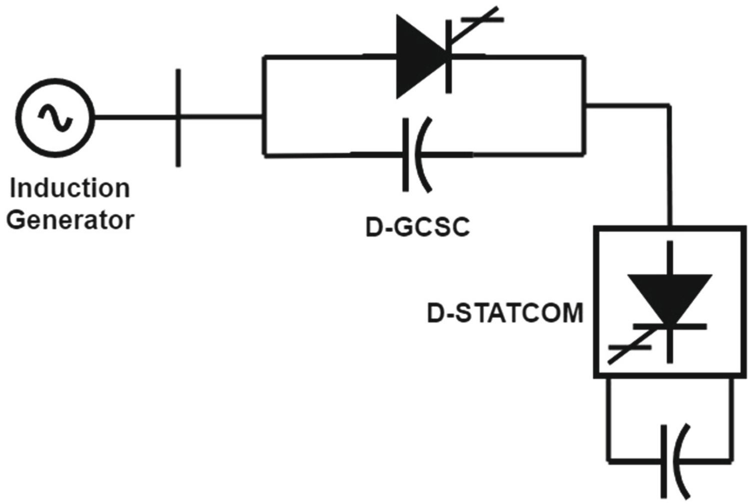

Fig. 3. Schematic diagram of 3-ph self excited induction generator with hybrid FACTS device

3.1 Mathematical Modelling of SEIG

The modelling is equations of Induction Machine as described by the stator and rotor side voltage and flux linkage equations as below, Eq. (5) shows the stator voltage equation, Eq. (6) describes the stator flux linkages and similarly Eq. (7) illustrates the rotor voltage equation and Eq. (8) shows the flux linkage equation of rotor. The machine will work as motor when the speed is less than synchronous speed i.e. the slip is positive and it is around less than +5%, whereas the machine will work as Generator when the speed is greater than synchronous speed i.e. the slip is negative and it is around less than −5%, corresponding torque slip characteristics as shown in Fig. 4 [5–10].

Stator side equations

$$V^{a}{}_{abcs} = r_s\left(i^{a}{}_{abcs}\right) + \frac{d\lambda^{a}{}_{abcs}}{dt} \tag{5}$$

$$\lambda^{a}{}_{abcs} = (L_s + M)\left(i^{a}{}_{abcs}\right) + L_{sr}\left(i^{a}{}_{abcr}\right) \tag{6}$$

Rotor side equations

$$0 = r_r\left(i^{a}{}_{abcr}\right) + \frac{d\lambda^{a}{}_{abcr}}{dt} \tag{7}$$

$$\lambda^{a}{}_{abcr} = (L_r + M)\left(i^{a}{}_{abcs}\right) + L_{sr}\left(i^{a}{}_{abcs}\right) \tag{8}$$

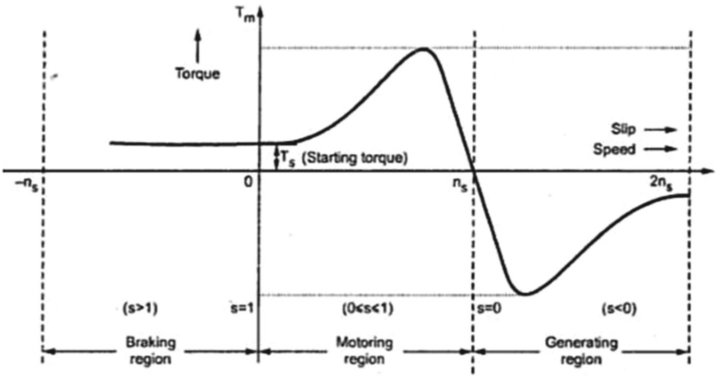

Fig. 4. Torque slip characteristics of induction machine

4 Hybrid Compensator

The Hybrid D-FACTS Controller is composed of a series compensator of Distributed GTO Controlled Series Capacitor (D-GCSC) and Distributed Static Synchronous Compensator (D-STATCOM). This device is used to get the superior performance of Wind Energy System (WES) against the load disturbances.

4.1 DSTATCOM

The DSTATCOM schematic is connected to the receiving end bus as shown in Fig. 4, it utilizes the GTOs as switching devices and d.c. link capacitance, which is used to enhance the performance of the wind plant as illustrated in Fig. 5 below [3–6].

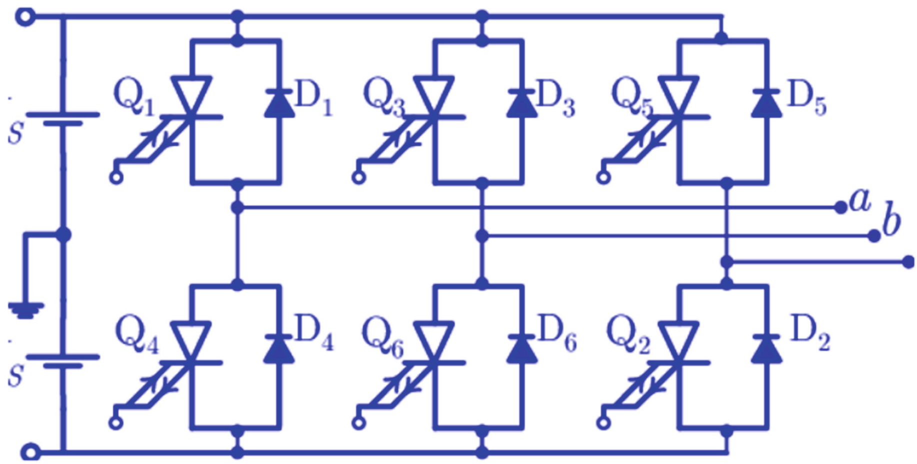

Fig. 5. Distribution system with D-STATCOM

4.1.1 Operation of Distributed Static Synchronous Compensator (DSTATCOM)

Flexible AC Transmission System (FACTS) devices have been emerged for enhancement in power system stability. The conditions like voltage stability, transient stability, reactive power flow control, power quality etc. are enhanced with power electronic based FACTS devices.

STATCOM is a shunt connected device which employs power electronic devices such as IGBT, GTO, MOSFET etc. as depicted in Fig. 4, which are basically fast acting switching devices in order to improve stability of power system and control of reactive power flow i.e. by absorbing reactive power from the system or by generation of reactive power meeting the demand to maintain the voltage at specific limits [3–5].

The working principle of DSTATCOM, consider Inverter output voltage as V1 and system output voltage as V2. The exchange of reactive power in between the DSTATCOM and system is based on the voltages V1 and V2 i.e. if the demand in reactive power in the system increases, then the output voltage of the DSTATCOM gets increases and vice versa with no flow of active power in between the system and DSTATCOM by keeping the angle zero [4]. DSTATCOM comprises mainly Voltage Source Converter (VSC), is generally GTO type and IGBT based converters which converts DC voltage into AC voltage. In GTO type converter, AC output voltage can be varied by DC capacitor input voltage and similarly in IGBT based converter, Pulse Width Modulation (PWM) technique is used to generate a sinusoidal wave form with frequency of kHz from DC voltage. DC capacitor supply constant voltage to VSC and a transformer is coupled in between power system and DSTATCOM and also reduces the harmonics in square wave generated by VSC [1–10].

4.1.2 Mathematical Modelling of DSTATCOM

The equations for active power, reactive power of STATCOM are as follows;

Consider $V_t =$ system terminal voltage
$V_{st} =$ STATCOM output voltage
$X_L =$ Inductive reactance
$V_C =$ DC capacitor voltage

$$P = \frac{V_t V_C}{X_L} \sin\alpha \tag{9}$$

$$Q = \frac{V_t V_t}{X_L} - \frac{V_t V_C}{X_L} \cos\alpha \tag{10}$$

The equation of DSTATCOM DC side can be given as;
The mathematical equations of DSTATCOM can be expressed as;

$L =$ series inductance
$R =$ series resistance
i_{ac}, i_{bc}, i_{cc} are output currents of DSTATCOM
V_{ac}, V_{bc}, V_{cc} are output voltages of DSTATCOM
V_{ta}, V_{tb}, V_{tc} are terminal voltages

$$L\frac{di_{ac}}{dt} = Ri_{ac} + V_{ac} - V_{at} \tag{11}$$

$$L\frac{di_{bc}}{dt} = Ri_{bc} + V_{bc} - V_{bt} \tag{12}$$

$$L\frac{di_{cc}}{dt} = Ri_{cc} + V_{cc} - V_{ct} \tag{13}$$

4.2 D-GCSC

Distributed system to carry out the simulation study of our interest is designed with a feeder connected in series with D-GCSC used to feed both resistive and RL loads as shown in the Fig. 6 below. The same system with DSTATCOM for mitigating current harmonics subsequently voltage harmonics in the distributed system [6–8].

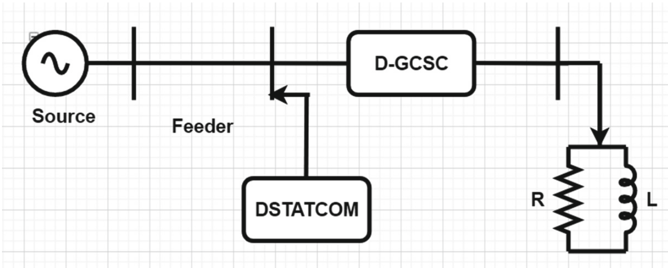

Fig. 6. Single line diagram of D-GCSC and DSTATCOM

The distribution feeder with feeder impedance connected in series with the D-GCSC feeding both resistive and RL loads as shown in Fig. 7. The D-GCSC schematic is described with the antiparallel combination of GTO Thyristors used to control the series injected voltage with the feeder as depicted in the below figure. The reactance and voltage variation of D-GCSC with the variation of the conduction angle as depicted by the following Eqs. (1) and (2) respectively. The harmonics injected by the device is illustrated in the Eq. (3) and the voltage wave form of complete control of the device is illustrated in Fig. 8 comprising of parts a, b and c as (a) D-GCSC Schematic circuit, (b) One complete cycle, (c) total current of D-GCSC. The total current shown in the waveform comprises of harmonics since the conduction angle is rapidly adjusted for controlling series voltage of the system [4–10].

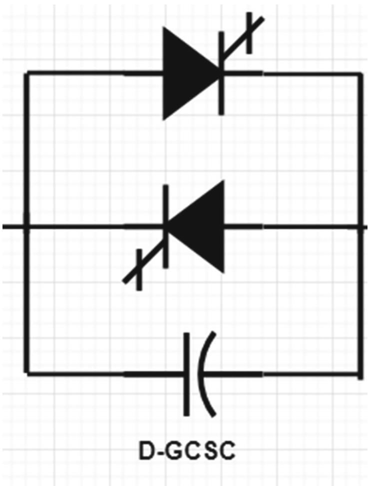

Fig. 7. Schematic diagram of D-GCSC

$$\mathrm{Xc}(\gamma) = \frac{1}{wC}\left(1 - \frac{2\gamma}{\pi} - \frac{\sin(2\gamma)}{\pi}\right) \tag{14}$$

$$V_{CF}(\gamma) = \frac{I}{wC}\left(1 - \frac{2\gamma}{\pi} - \frac{\sin(2\gamma)}{\pi}\right) \tag{15}$$

$$V_{Cn}(\gamma) = \frac{I}{wC}\frac{4}{\pi}\left(\left(\frac{\sin(\gamma)\cos(n\gamma) - \mathrm{n}\sin(n\gamma)\cos(\gamma)}{n(n^2-1)}\right) - \frac{\sin(2\gamma)}{\pi}\right) \tag{16}$$

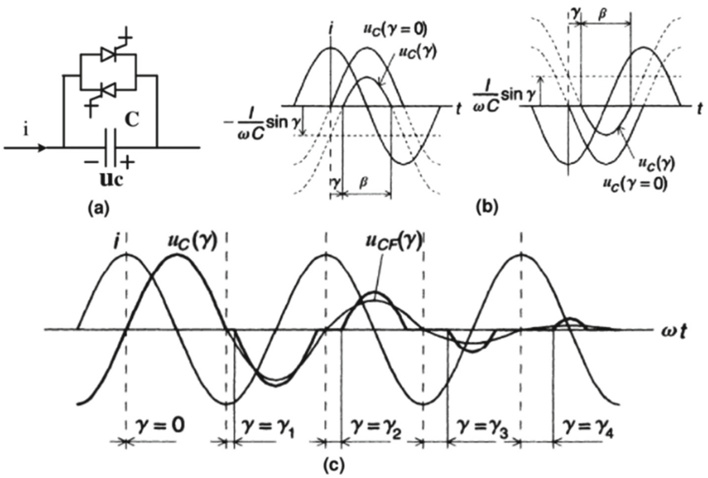

Fig. 8. (a) D-GCSC Schematic circuit, (b) One complete cycle, (c) total current of D-GCSC

5 Case Study and Conclusions

The Simulink diagram of the wind energy generation plant furnished with the SEIG controlled with the Hybrid D-FACTS device built with D-GCSC and DSTATCOM along with the different loads in isolated mode of operation as illustrated in Fig. 9. The wind speed is taken as 15 m/s and pitch angle as 30° as shown in the Fig. 9 below. The simulation is carried out with widely variable loadsincluding Hybrid Compensator and results have been presented in this article. Figure 10 depicts the DSTATCOM Simulink and Fig. 11 shows the wind energy generation including D-GCSCand Fig. 9 illustrates the Wind Energy Generation with Hybrid Compensator and SEIG.

Figure 12 SEIG shows the currents, voltages and torque waveforms with small loads, Fig. 13 depicts the SEIG currents, voltages and torque waveforms with small loads and voltage is at nominal value of 400V and per unit voltage of 1 p.u. as illustrated by the both the waveforms.

Figure 14 SEIG shows the currents, voltages and torque waveforms with medium loads, Fig. 15 depicts the SEIG currents, voltages and torque waveforms with medium loads and voltage is at nominal value of 400V and per unit voltage of 1 p.u. as illustrated by the both the waveforms.

Figure 16 SEIG shows the currents, voltages and torque waveforms with heavy loads, Fig. 17 depicts the SEIG currents, voltages and torque waveforms with heavy loads and voltage is at nominal value of 400V and per unit voltage of 1 p.u. as illustrated by the both the waveforms. In all load scenarios, the terminal voltage is maintained at strictly its nominal value of 400V and in per unit it is 1p.u, which is possible with the Hybrid Compensator.

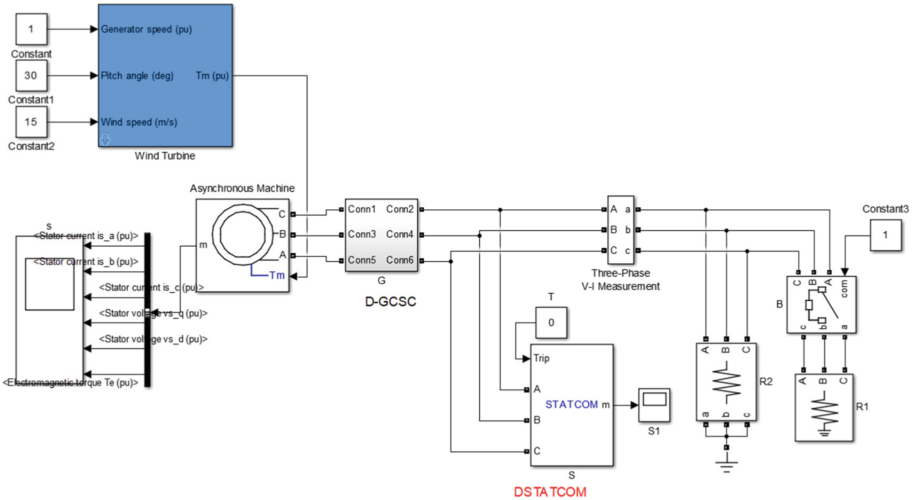

Fig. 9. Wind energy generation with hybrid compensator and SEIG

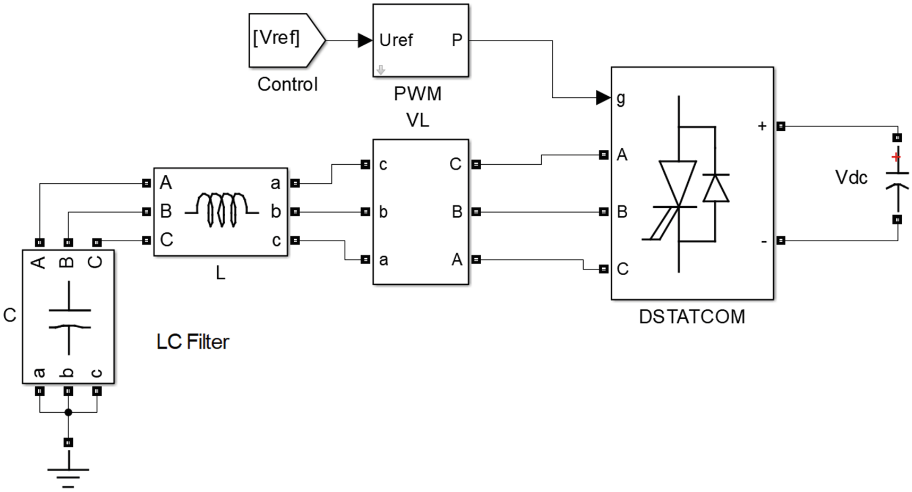

Fig. 10. DSTATCOM simulink power circuit

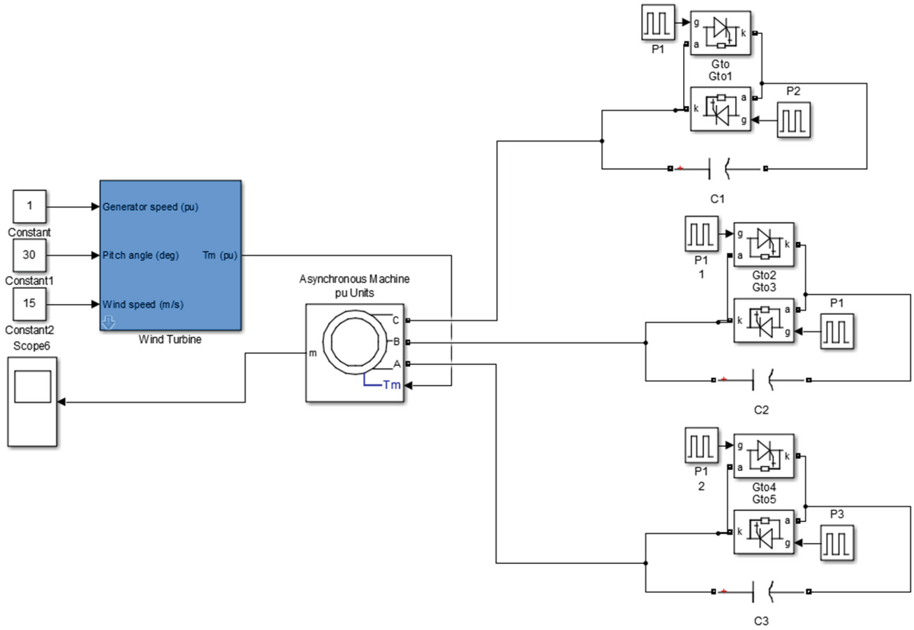

Fig. 11. DSTATCOM simulink closed loop control circuit

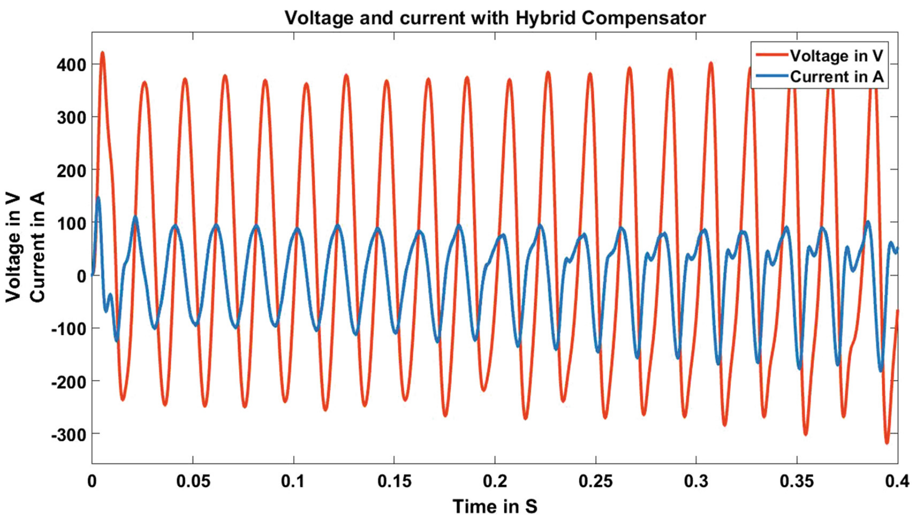

Fig. 12. Load voltage and current waveforms with small loads

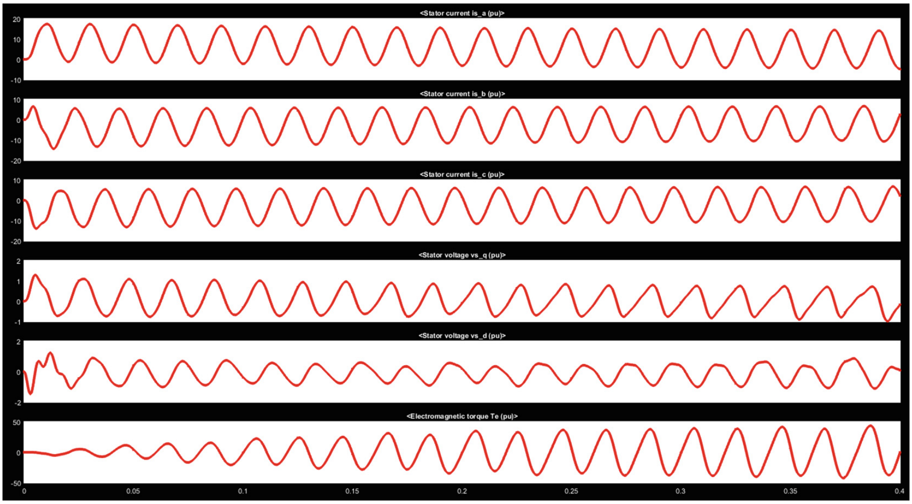

Fig. 13. SEIG currents, voltages and torque waveforms with small loads

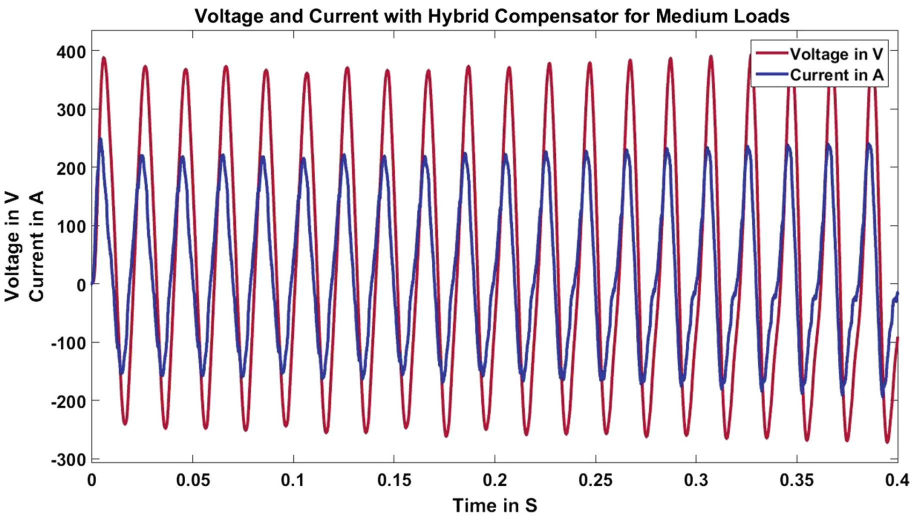

Fig. 14. SEIG currents, voltages and torque waveforms with medium loads

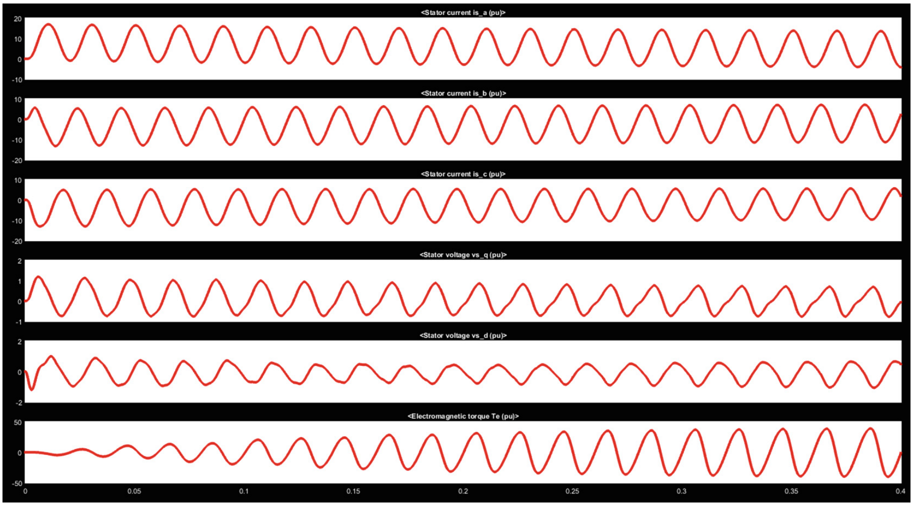

Fig. 15. SEIG currents, voltages and torque waveforms with medium loads

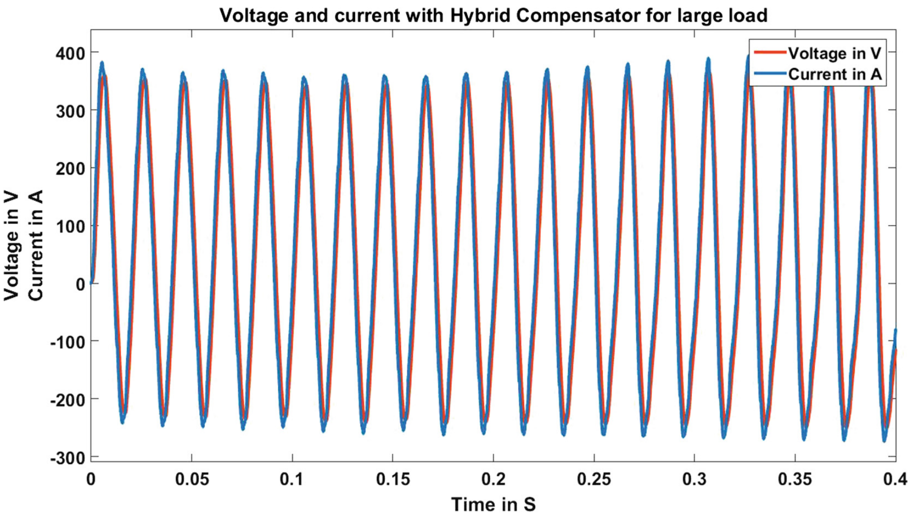

Fig. 16. SEIG currents, voltages and torque waveforms with heavy loads

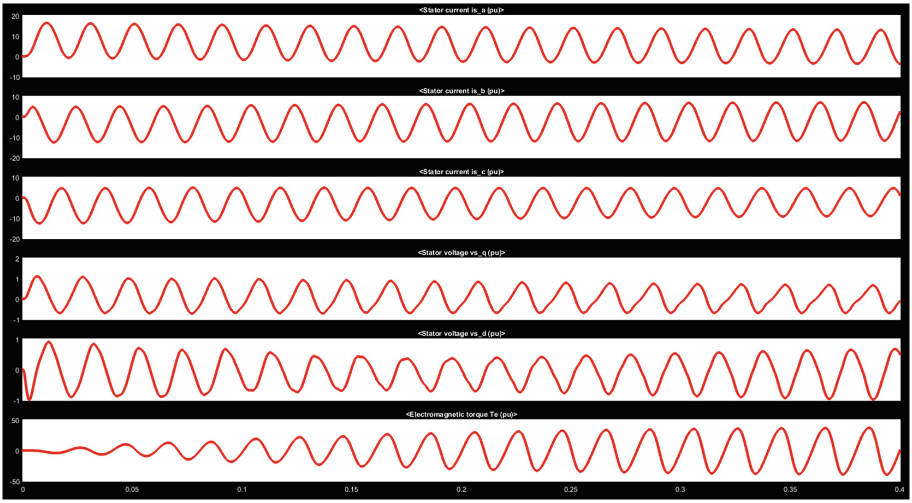

Fig. 17. SEIG currents, voltages and torque waveforms with heavy loads

6 Conclusions

This article engrossedon development of a Hybrid FACTS Device to control load voltages over wide range of load variations on wind power plant equipped with Hybrid FACTS device with Self Excited Induction Generator (SEIG). The distribution generation system is developed with Hybrid FACTS Device fed SEIG based wind power plant feeding an isolated load. The SEIG is equipped with shunt compensator or any Hybrid FACTS Device as used in the present case. This article deals with wind energy generation unit used to supply local loads. The terminal voltage has been maintained at constant nominal value for different load scenarios by the use of Hybrid FACTS Device and these results are presented in this article. The Simulink diagram of the wind energy generation plant furnished with the SEIG controlled with the Hybrid D-FACTS device built with D-GCSC and DSTATCOM along with the different loads in isolated mode of operation. The simulation is carried out with widely variable loads including Hybrid Compensator and results have been presented herewith. The load on the wind energy generating system is varied from small load to heavy loads with Compensator, the results are illustrating the robust performance of the compensator against wide variations of loads and terminal voltage is maintained at rated voltage at all loads.

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