International Journal of Emerging Engineering Research and Technology
Volume 2, Issue 3, June 2014, PP 261-272

ISSN 2349-4395 (Print) & ISSN 2349-4409 (Online)

Fixed-Speed and Variable Speed (PMSG) Induction Generators Based Wind Farms with Statcom Control under Asymmetrical Grid Faults

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Abstract: *Recently, renewable wind energy is enjoying a rapid growth globally to become an important green electricity source to replace polluting and exhausting fossil fuel. The stability of fixed-speed induction generator (FSIG)-based wind turbines can be improved by a StatCom, which is well known and documented in the literature for balanced grid voltage dips and comparing with the variable speed permanent magnet synchronous machine. Under unbalanced grid voltage dips, the negative sequence voltage causes heavy generator torque oscillations that reduce the lifetime of the drive train. In my project, investigations on an FSIG-based wind farm in combination with a StatCom and variable speed permanent magnet synchronous machine under unbalanced grid voltage fault are carried out by means of theory, simulations. A StatCom control structure with the capability to coordinate the control between the positive and the negative sequence of the grid voltage is proposed. The results clarify the effect of the positive- and the negative-sequence voltage compensation by a StatCom on the operation of the FSIG-based wind farm and variable speed pmsg. With first priority, the StatCom ensures the maximum fault-ride-through enhancement of the wind farm by compensating the positive-sequence voltage. The remaining StatCom current capability of the StatCom is controlled to compensate the negative-sequence voltage, in order to reduce the torque oscillations. This total project is carried out in MATLAB SIMULINK software.*

Keywords: *Matlab/Simulink , wind energy, Induction generator, low-voltage ride through, StatCom*

1. Introduction

With the progress of industrial society and the increasing needs for energy and especially electrical energies and increasing environmental and economical concerns and Concerns about the ending of fossil energy resources in the world using of wind energy to generate electricity has been widely considered word-wide and wind generator in large scale has been installed. For optimal utilization and expecting outputs of such generators one of the fundamental topic is the system simulation and modeling error conditions.

WIND energy is playing a key role on the way toward a sustainable energy future. Among the generator types used for wind turbines, the technical development has moved from fixed-speed to variable-speed concepts [1]. Although a major part of the newly installed wind turbines are of the variable-speed type using either a doubly fed induction generator (DFIG) or permanent-magnet synchronous generator, a non negligible percentage of 15% of the operating wind turbines in Europe in 2010 [2] is still of the fixed-speed induction generator (FSIG)-type directly connected to the grid.

New industrial applications require variable speed drives with high dynamic performance. In recent years several techniques of control have been developed, allowing PMSM with variable speed to achieve these performances. It gives high dynamic performance for a wide range of applications. The complexity of the dynamic model of the permanent magnet synchronous variable speed and the presence of external disturbances and parametric variations limit the performance of the control law.

Because this generator type cannot provide reactive power control, it cannot fulfill the demanding grid code requirements [3] without additional devices. During voltage dips, the induc- tion generators may consume a large amount of reactive power as their speed deviates from the synchronous speed, which can lead to a voltage collapse and further fault propagation in the network.

Different methods have been investigated to enhance the fault-ride-through capability and to fulfill grid code require- ments. Besides using the pitch control of the turbine or installing additional equipment like a brake chopper or an energy storage system, the installation of a StatCom has been identified to provide the best dynamic stability enhancement capabilities [4]. The capability of a static var compensator compared to a StatCom to increase the stability of FSIG-based wind turbines is given in [9] and [10]. The StatCom can also perform an indirect torque control for the same kind of generators [11], [12] to decrease the mechanical stress during grid voltage dip.

Balanced grid faults were reffered above things, but the majority of grid faults are of the unbalanced nature. The unbalanced-voltage problem can cause unbalanced heating in the machine windings and a pulsating torque, leading to mechanical vibration and additional acoustic noise [13]. The StatCom control structure can be adapted to these unbalanced- voltage conditions [14], and the positive and the negative sequence of the voltage can be controlled independently. Different current injection methods based on symmetrical components can also be applied to the StatCom, resulting in different output-power distributions [11]–[14]. How these different current injection targets affect the operation of an FSIG-based wind farm and variable speed induction generator is investigated in [10] and in [17]. However, regarding the damping of the torque ripple of the generators, it is more effective to control the positive- and the negative-sequence voltage control of a StatCom at an FSIG based wind farm and variable speed PMSG.

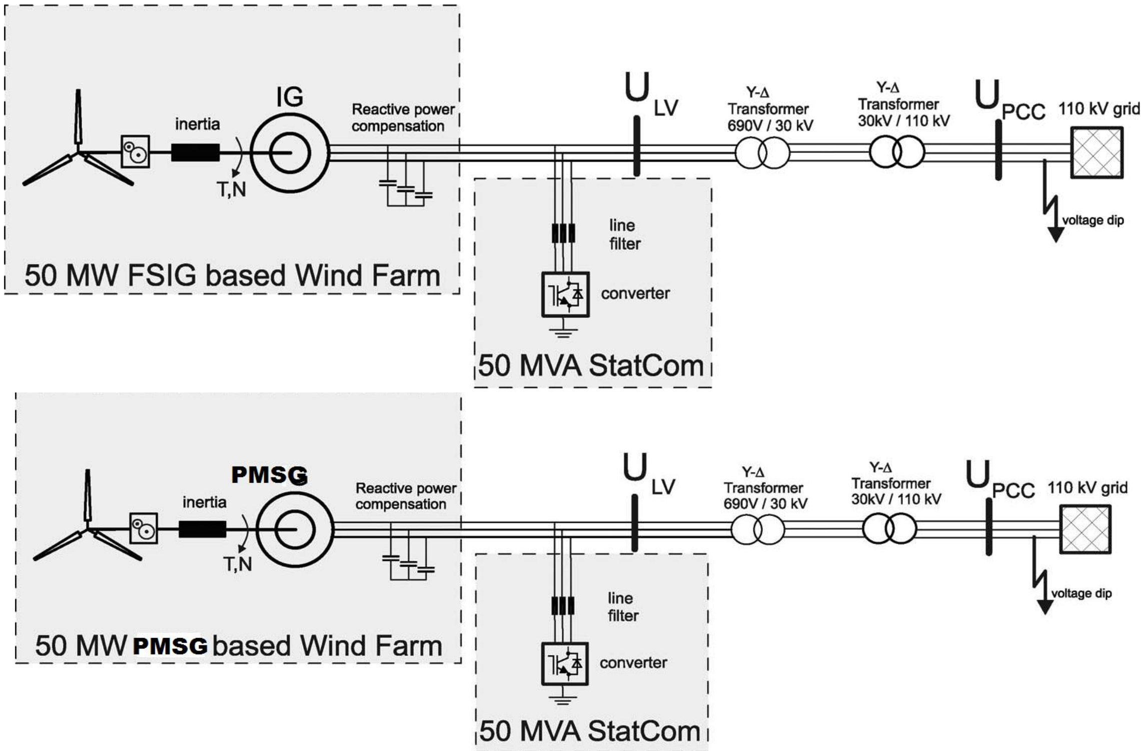


Fig.1. *Structure of the investigated system: FSIG and variable speed induction generator based wind farm and StatCom connected to the grid.*

In this analysis StatCom that is connected to an FSIG-based wind farm and Variable speed PMSG used to control the positive- and the negative-sequence voltage during grid faults. The novel contribution of this paper lies in the coordination of the positive- and the negative-sequence voltage control by the StatCom and the related effect on the wind turbine behavior. While the positive-sequence voltage compensation leads to an increased voltage stability of the wind farm, the negative- sequence voltage compensation leads to a reduction of torque ripple, increasing the lifetime of the generator drive train..

Table I. *Wind Farm Induction Generator and StatCom Parameters*

Wind Farm Induction Generator	Simu.	Lab.
Base apparent power	57, 5 MW	-
Rated active power	50 MW	22 kW
Rated voltage (line to line)	690 V	400 V
Stator resistance (R_S)	0,0108 pu	0,0155 pu
Stator stray impedance ($X_{S\sigma}$)	0,107 pu	0,056 pu
Mutual impedance (X_h)	4,4 pu	1,61 pu
Rotor resistance (R'_R)	0,01214 pu	0,374 pu
Rotor stray impedance ($X'_{R\sigma}$)	0,1407 pu	0,0187 pu
Compensation capacitors	0,17 F	-
Mechanical time constant H	3 s	-
StatCom		
Rated Power	50 Mvar	22 kVA
Rated voltage	690 V	400 V
Line filter L_{filter}	0,15 pu	2, 5 mH
L_{Netz}	-	2, 5 mH
DC voltage U_{DC}	1200 V	700 V
Current capability	1 pu	50 A

This paper is structured as follows. The investigated power system is described in Section II. An analysis of the induction generators behavior under grid faults in Section III is followed by the presentation of the proposed StatCom control structure in Section IV. Simulation results are given in Section V. Under the unbalanced grid voltage condition, the StatCom is con- trolled here to either compensate the positive- or the negative- sequence voltage. A coordinated control scheme is presented in Section VI. A conclusion closes this paper.

2. POWER SYSTEM STRUCTURE

The investigated power system is shown in Fig. 1 and con- sists of a 50-MW wind farm with squirrel cage induction gen- erators directly connected to the grid and a 50-MVA StatCom.

An aggregate model of the wind farm is used as usual here, which means that the sum of the turbines is modeled as one generator using the standard T-equivalent circuit Both devices are connected to the same low voltage bus and then

Table 2. *Grid and Transformer Parameters Used iN THe SimulatIons*

	Grid	HV transf.	MV transf.
Base apparent power	1000 MW	100 MW	100 MW
Rated voltage	110 kV	30 kV	690 V
Stray impedance (X_g)	0,98 pu	0,05 pu	0,1 pu
Resistance (R_g)	0,02 pu	0,01 pu	0,02 pu

connected to the medium voltage bus by a transformer. The medium voltage level is connected to the high voltage level by a second transformer. Both transformers are rated for the sum of the wind farm and StatCom power and have a series impedance of 5% and 10% per unit. The grid fault is assumed at the high voltage level of the grid, which is modeled by its Thevenin equivalent. All power system parameters are given in Tables I and electric circuit toolbox PLECS. [4]

3. INDUCTION GENERATOR

An induction generator or asynchronous generator is a type of AC electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotor in generator mode, giving negative slip. In most cases, a regular AC asynchronous motor is used as a generator, without any internal modifications

The torque of the induction generator T^+ shows a quadratic dependence of the positive-sequence stator voltage magnitude Vs^+ [15]. It can be calculated using

$$T^{+}(s) = 3 \cdot \frac{p}{2} \cdot \frac{R_r}{s\omega_s} \cdot \frac{(V_s^{+})^2}{(R_s + R_r/s)^2 + j(X_s + X_r)^2}$$

where Rs, Rr, Xs, and Xr are the typical stator and rotor (subscripts s and r) resistance and impedance parameters parameters of the machine equivalent circuit, p is the number of pole pairs, ω_S is the grid frequency, and s is the slip. When the theoretical steady-state torque–slip characteristic of the induction machine is plotted based on the steady-state equivalent circuit of the machine for different stator voltages as shown in Fig. 2, the instability during balanced grid voltage dips becomes clear.

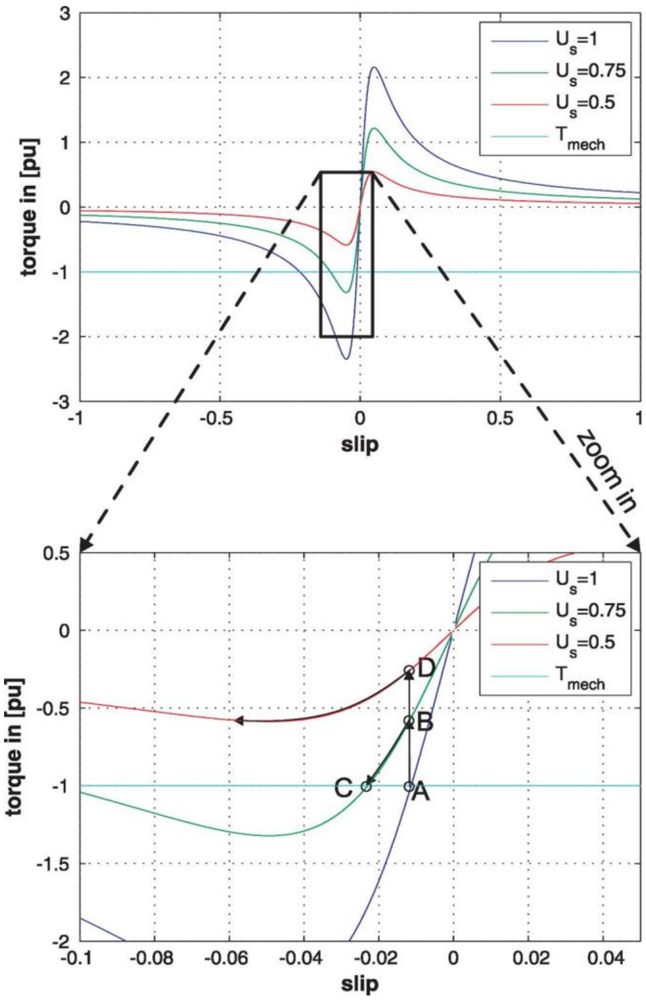


Fig. 2. *Theoretical torque–slip characteristics of the induction generator under different grid voltage levels.*

Transient torque peaks caused by the dynamic change of the grid voltage as identified in [11] are not addressed here.

Usually, the wind turbine operates at nominal stator voltage in operation point A where the electromechanical torque is the same as the mechanical torque. When the stator voltage is reduced due to a grid fault, the torque–slip characteristic changes. If the voltage dip is smaller, the induction generator may resume a stable operation point C via B. However, for a deep voltage dip, the induction generator will deviate from point D to an instable operation. The induction generators may have to be disconnected from the grid due to over speed, or there may be a voltage collapse in the network due to the high consumption of reactive power at higher slip. When the grid voltage is unbalanced, i.e., it contains a negative sequence, the stator currents become unbalanced too. According to Wang et al. [15], a small amount of negative sequence voltage V_s^- can lead to a high amount of negative sequence currents I_s^- , described by

$$I_{s,pu}^{-} = \frac{V_s^{-}}{\omega_s \cdot \sigma \cdot L_s \cdot I_{s,N}}$$

Where σ is the leakage factor, IS, N is the rated stator current, and Ls is the stator inductance. The negative-sequence currents do not contribute a lot to the average torque T^{+}; thus, they can still be calculated using

$$T^{+} \approx 3 \cdot \frac{p}{2\omega_s} \cdot V_s^{+} \cdot I_{sd}^{+}$$

But the negative-sequence currents cause torque oscillations of double grid frequency. The magnitude of the negative-sequence torque T^{-} can be calculated using

$$T^{-} \approx 3 \cdot \frac{p}{2\omega_s} \cdot V_s^{+} \cdot I_s^{-}.$$

It becomes clear that the average torque is reduced due to the decreased positive-sequence voltage. Additionally, there are high torque oscillations of double grid frequency due to the negative-sequence voltage. Thus, a reduction of the positive sequence stator voltage will lead to a reduction of the average torque and an acceleration of the turbine. An existing negative sequence stator voltage will cause torque oscillations, reducing the lifetime of the turbine drive train.

When the positive- and the negative-sequence voltage can be controlled independently by a StatCom, the average torque and the torque ripple can also be controlled independently.

But, the steady-state analysis does not represent the torque ripple [8]. A dynamic analysis as given in [8] may be used to calculate the torque ripple. To provide a graphical comparison the torque-slip characteristic of the machine for one specific acceleration process under a single phase to ground fault is taken from the simulation model and shown in Fig. 3. It becomes clear that the average torque is reduced due to the decreased positive sequence voltage and there is a high torque ripple due to the negative sequence voltage, which is also slip dependent.

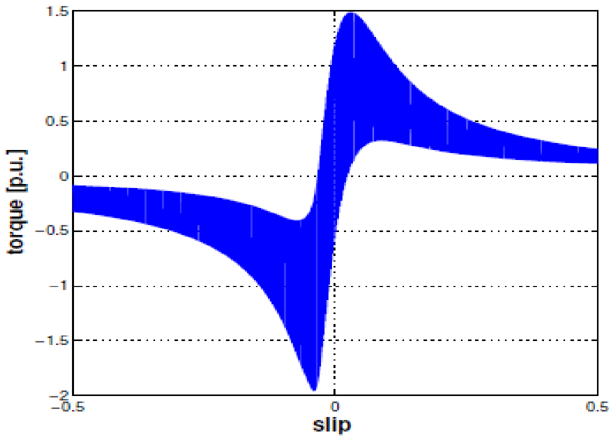


FIG 3. *Simulated torque-slip characteristic for a single-phase to ground fault (1ph→0)*

4. CONTROL STRUCTURE FOR STATCOM

The StatCom , the maximum compensating current is independent of system voltage, so it operates at full capacity even at low voltages. A STATCOMs advantages include flexible voltage control for power quality improvement, fast response, and applicability for use with high fluctuating loads.

Statcom control structure is based on the voltage oriented vector control scheme [16] as usually applied to three-phase grid-connected converters.

It is a cascade control structure with inner proportional integral (PI) current controllers in a rotating *dq* reference frame with grid voltage orientation. The PI controller transfer function is

$$G_{PI}(s) = V_R \frac{1 + s \cdot T_n}{s \cdot T_n}.$$

The modeling and controller gain design of voltage-oriented controlled three-phase grid-connected converters are described in [17]–[19].

Resonant controllers (Res) tuned at 100 Hz in the same Positive *dq* reference frame are added to realize the negative sequence current control.

$$G_{\mathrm{Res}}(s) = K_{\mathrm{res}} \cdot \frac{s}{s^2 + (2 \cdot \omega_0)^2}$$

Note that the control of the negative-sequence currents can also be performed in a negative rotating reference frame with PI controllers, but by using resonant controllers in a positive rotating reference frame, there is no need for a sequence separation of the currents [30]. The overall control structure is shown in Fig. 4.. Note that a possible StatCom converter topology is shown here as a two-level voltage source converter connected to the grid by an LCL filter, while multilevel topologies will be used for high-power applications.

The outer control loops are designed to control the dc voltage and the positive and negative sequences of the voltage at the connection point of the StatCom. Therefore, a precise sequence separation of the measured voltage into positive- and negative sequence components is necessary, which is performed based on dual second-order generalized integrators [12]. Other sequence extraction methods could be applied [19]. Using the sequence separation, the positive and the negative sequence of the voltage appear as dc values and can be controlled by PI controllers. To ensure a safe operation of the StatCom within its current capability, the current references given by the four outer controllers must be limited to the maximum StatCom current. The priority is on the positive-sequence reactive current Iq+. Thus, the StatCom ensures the maximum fault-ride-through enhancement of the wind farm by compensating the positive sequence voltage. If there is a remaining StatCom current capability, the StatCom is controlled to compensate the negative-sequence voltage additionally, in order to reduce the torque ripple during the grid fault.

The positive- and negative-sequence current references are added. The negative-sequence current references must be transformed into the positive rotating reference frame by a coordinate transformation with twice the grid voltage angle. Note that the transient torques at the beginning and end of the grid fault remain uncompensated using this control strategy.

For the investigations under unbalanced grid fault, different control targets will be compared to clarify the effect of the positive- or the negative-sequence voltage compensation on the operation of the induction generators. The target of the first method is to compensate the positive-sequence voltage, while the negative-sequence voltage will remain unchanged. The target of the second method is to eliminate the negative sequence of the voltage, while the positive sequence voltage will remain unchanged.

5. RESULTS FOR UNBALANCED GRID FAULTS

An unbalanced fault (single phase amplitude drops to 60%) is assumed at the high voltage bus of the power system (see Fig. 1). The simulation results are shown in below figures with simulation diagrams. The unbalanced grid fault leads to a negative-sequence voltage at the medium voltage bus [see Fig. 5].

The operation of the system without StatCom support is shown in the left part of Fig. 5. The reduction of the positive- sequence voltage leads to a decrease in torque and an acceleration of the rotor. The important differences compared to a balanced grid fault are the heavy torque oscillations [see Fig. 7(c)] of the system caused by the negative-sequence voltage. For this simulation case, the grid voltage fault does not lead to voltage instability because the generator can return to the rated operation point after the fault.

In the middle of Fig. 7, the simulation results are shown for the same grid fault, but now, the system is supported by the StatCom. In this case, the StatCom is controlled to compensate the positive sequence of the voltage. Within the chosen current rating of the StatCom (here, 1 p.u.), the positive-sequence voltage at the low voltage level can fully be compensated [see Fig. 7(b)] by injecting a positive-sequence StatCom current [see Fig. 7 middle (e)]. Note that the current is purely reactive, which cannot be seen from the figure, as only the magnitude of the positive- and negative-sequence components is shown. The negative-sequence voltage component is not controlled and thus remains unaffected. The compensation of the positive-sequence voltage guarantees the full torque capability of the generator [see Fig. 7 middle (c)], and thus, the speed does not increase [see Fig. 7 middle (d)]. However, the presence of a negative- sequence voltage component leads to high torque oscillations. In the right part of Fig. 7, the StatCom is controlled to eliminate the negative-sequence component of the grid voltage. This is only possible by injecting a negative-sequence current into the grid [see Fig. 7 right (e)]. The chosen strategy leads to a complete elimination of the negative-sequence voltage at the StatCom voltage bus [see Fig. 7 right (b)], and thus, the heavy torque oscillations during the unbalanced grid faults are elim- inated too. The positive-sequence voltage is not compensated here, and thus, the generator accelerates [see Fig. 7 right (d)], leading to a continuous decrease in the positive-sequence volt- age component [see Fig. 7 right (b)] due to the reactive power consumption. However, the system does not reach the stability limit, and the generator returns to nominal operation after the grid fault. Note that the drawback of the chosen StatCom control strategy in this case might be the oscillating active and reactive powers of the StatCom [see Fig. 7 right (f)]. In Fig. 5, the torque is plotted against the speed of the induction generator taken from the same simulation results.

Now replacing the PMSG instead of asynchronous machine In FSIG simulation diagram for the variable speed operation shown in fig 8. The simulation results for that shown in fig 9 by comparing with the zero percent fault to the 60% fault percentage of asymmetrical grid faults. And the controlling circuit shown in fig 6. In fig 8 Simulation results for operation during unbalanced grid fault (1 ph → 60%) (left) without StatCom, (middle) with StatCom and positive-sequence voltage compensation, and (right) with StatCom and negative-sequence voltage compensation. (a) Positive and negative-sequence voltage components at PCC. (b) Positive- and negative-sequence voltage components at low voltage. (c) StatCom positive and negative current components. (d) StatCom P, Q. (e) Torque. (f) Speed.

The results of this section enhance the understanding of the voltage control performed by the StatCom and the resulting operation of the induction generators. By compensating the positive-sequence voltage, the torque capability of the induc- tion generators is increased, and an acceleration during grid voltage dips can be decreased or avoided. By compensating the negative-sequence voltage (the unbalanced component of the voltage), the torque oscillations of the induction generators can be decreased or avoided. The capability of the StatCom to compensate a voltage component depends on the chosen current rating of the StatCom and the impedance of the power system. For a high current rating of the StatCom and a weak power sys- tem (with high system impedance), the voltage compensation capability of the StatCom is also increased.

Fig 4. Basic Diagram for Simulation

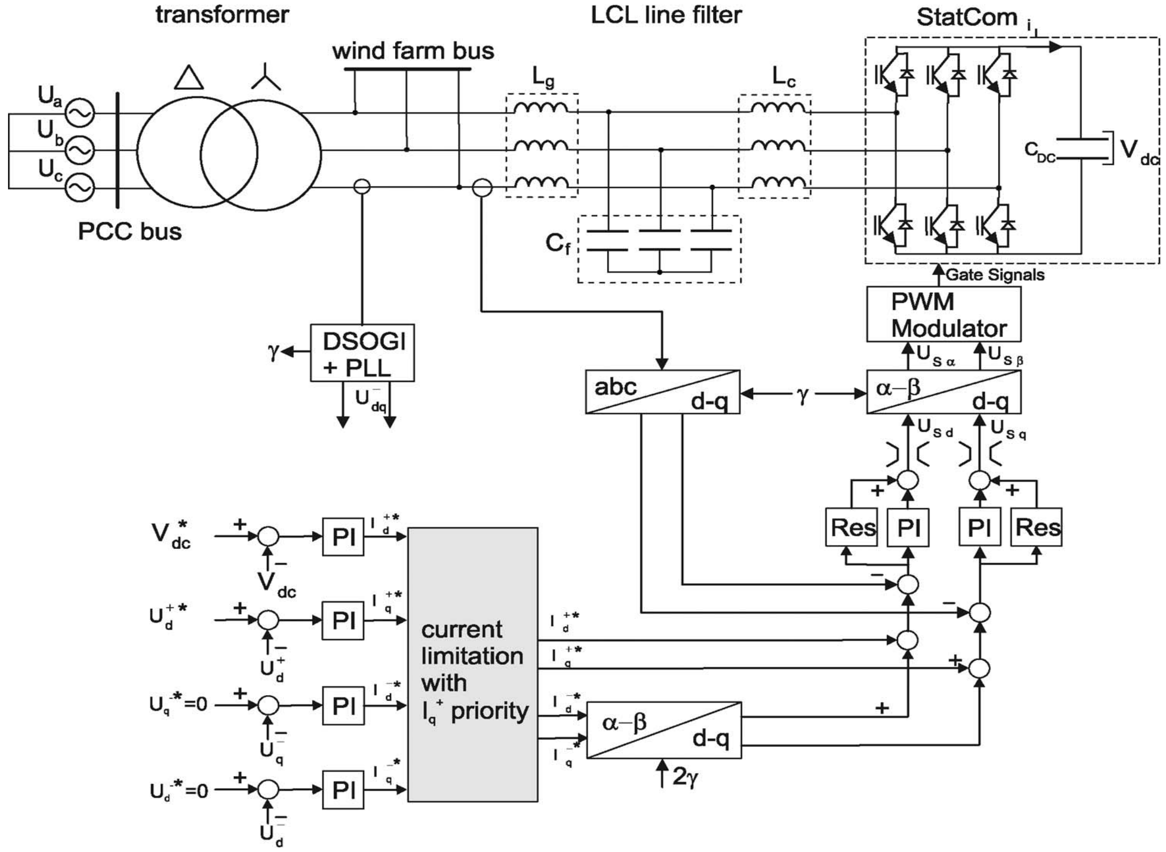


Fig. 4. *Proposed control structure of the StatCom to control the positive- and the negative-sequence voltage independentl*

FIG 5: S*imulation diagram of FSIG with Statcom*

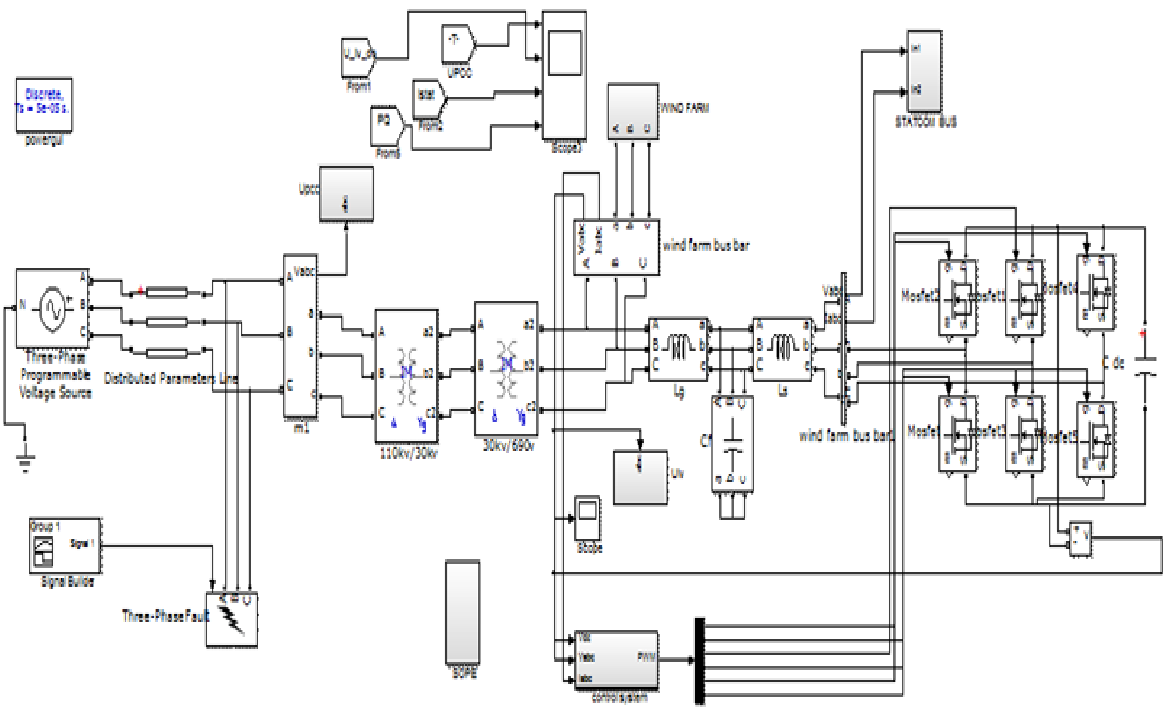
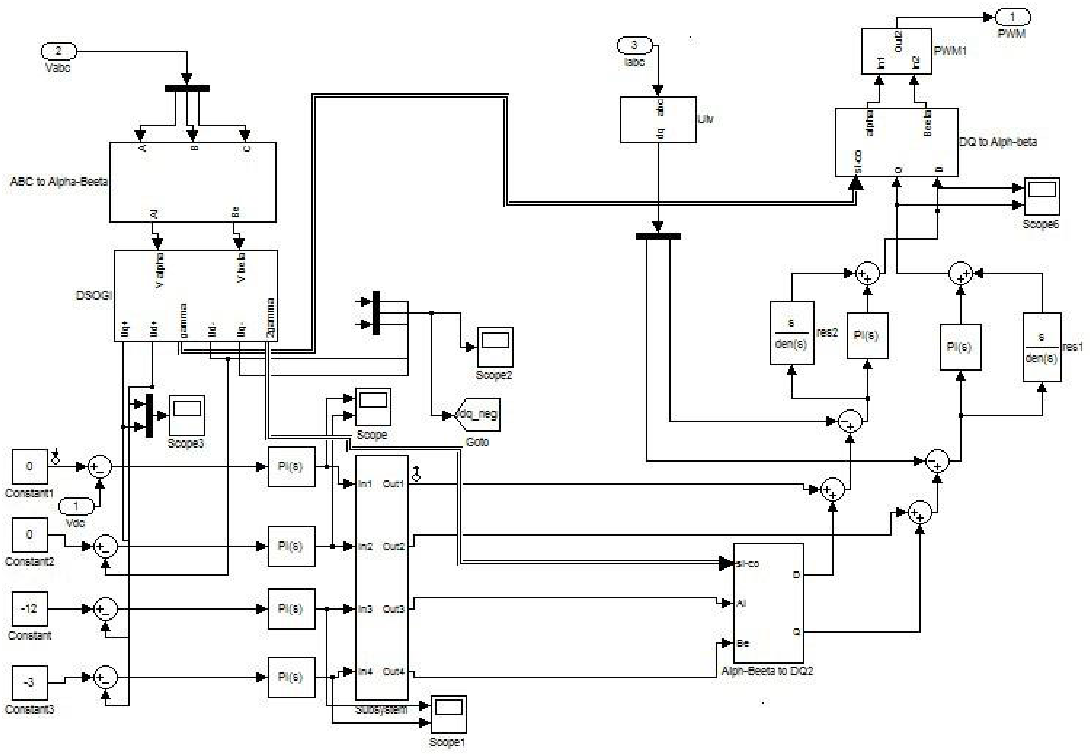


FIG 6: ***Design of control circuit***



Simulation Results

Fig 7. FSIG with statcom control undrer asymmetrical grid faults

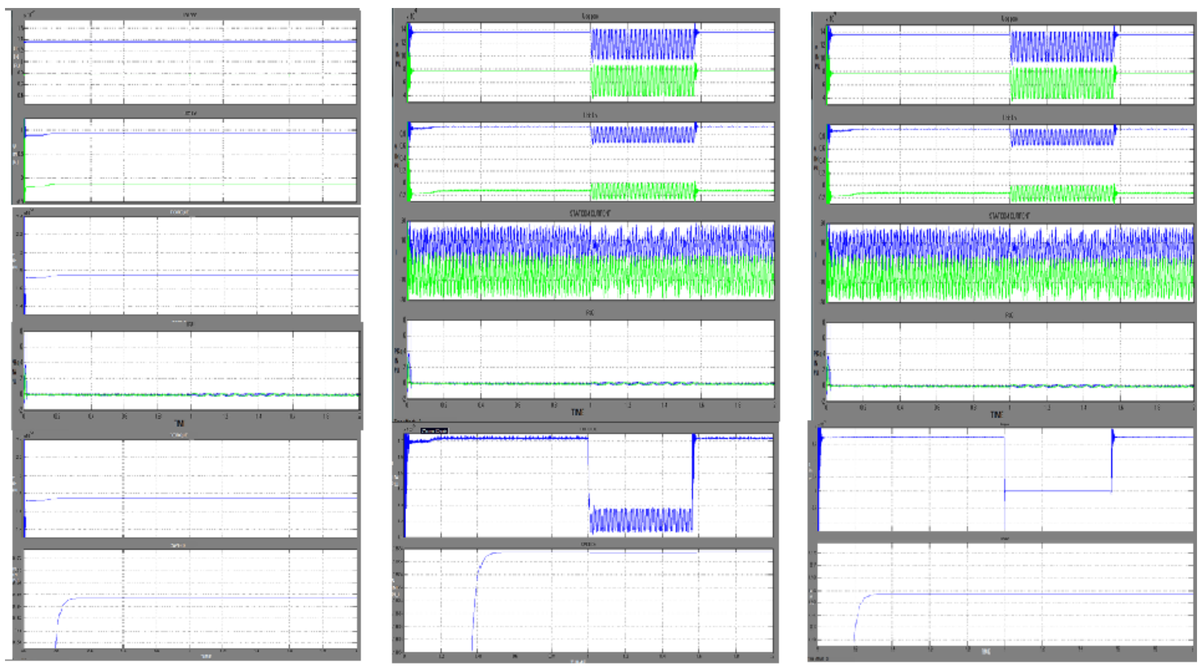


Fig 7: Simulation results for operation during unbalanced grid fault (1 ph → 60%) (left) without StatCom, (middle) with StatCom and positive-sequence voltage compensation, and (right) with StatCom and negative-sequence voltage compensation. (a) Positive and negative-sequence voltage components at PCC. (b) Positive- and negative-sequence voltage components at low voltage. (c) StatCom positive and negative current components. (d) StatCom P, Q. (e) Torque. (f) Speed.

FIG 8: Placing PMSG instead of asynchronous machine of FSIG:

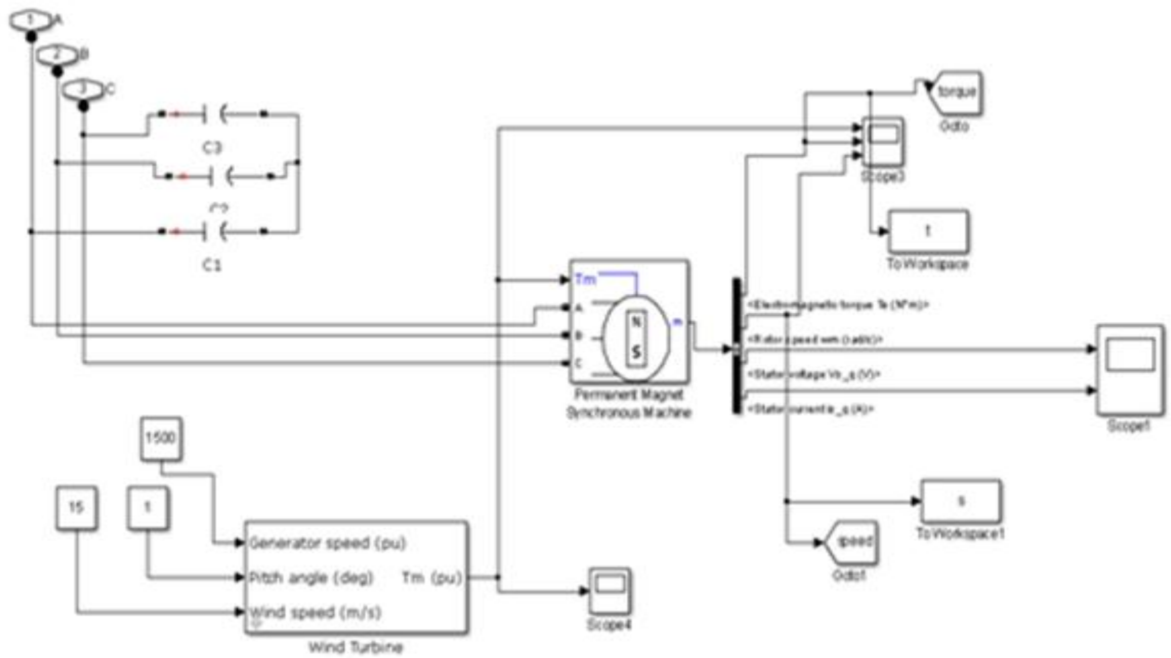


Fig 9: PMSG with statcom control undrer asymmetrical grid faults

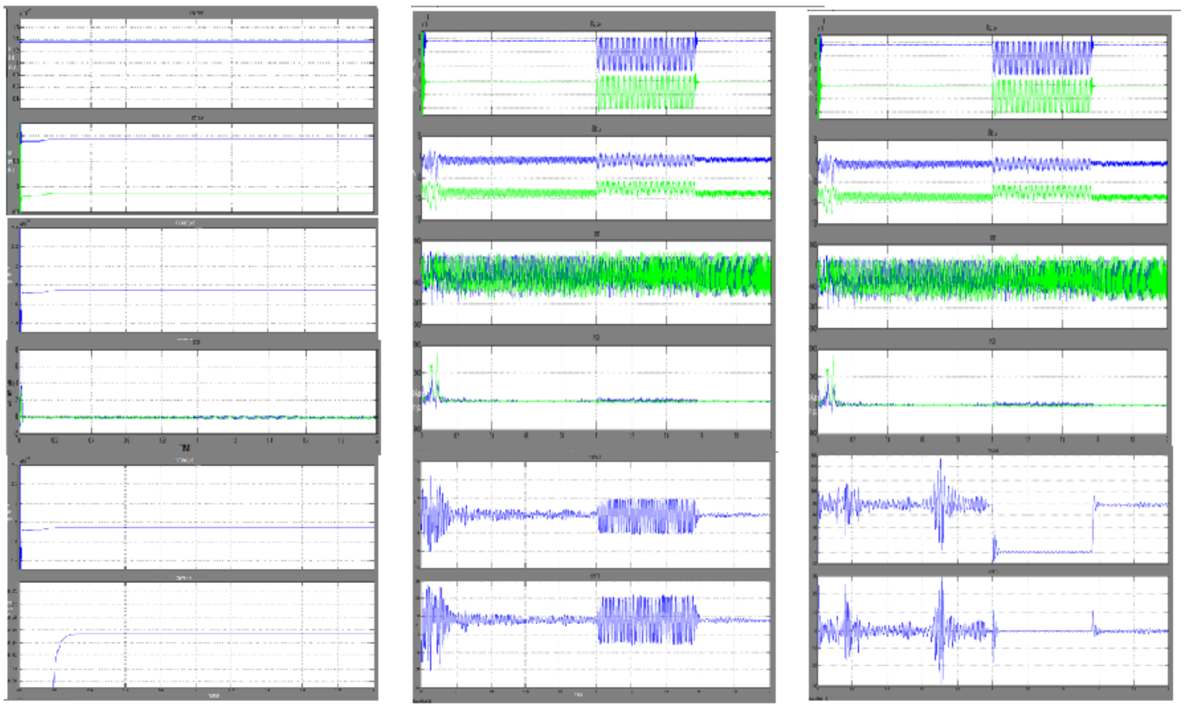


Fig 9: Simulation results for operation during unbalanced grid fault (1 ph → 60%) (left) without StatCom, (middle) with StatCom and positive-sequence voltage compensation, and (right) with StatCom and negative-sequence voltage compensation. (a) Positive and negative-sequence voltage components at PCC. (b) Positive- and negative-sequence voltage components at low voltage. (c) StatCom positive and negative current components. (d) StatCom P, Q. (e) Torque. (f) Speed.

6. Coordinated Positive and Negative -Sequence Voltage Control and Limitations

In the previous section, either the positive-sequence volt- age or the negative-sequence voltage was compensated by the StatCom. For smaller voltage dips, there might be a certain amount of unused current capability of the StatCom. The current capability of the StatCom can be further exploited if positive- and negative-sequence voltage components are compensated in coordination. A prioritization of the positive sequence is proposed here in order to increase the voltage stability of the wind farm. If the StatCom has remaining current capability, it is used for the negative-sequence voltage compen- sation, leading to a reduction of torque ripple and increasing the lifetime of the generator drive train.

Special focus is put on the maximum current capability of the StatCom that cannot be exceeded in order to unbalanced-voltage dip (1 ph → 60%) when both the positive- and the negative-sequence voltage components are compen sated are shown in Fig. 9 (left). The current capability of the StatCom is sufficient to compensate both voltage components. For a more severe voltage dip (single phase to ground at high voltage level) as shown in Fig. 9(right), the current capability of the StatCom is no more sufficient to compensate both voltage components. Thus, the current limitation with positive sequence priority ensures a maximum compensation of the positive- sequence voltage. The drawback is obviously that there is no current capability left to compensate the negative-sequence voltage, and therefore, the torque oscillations are present and stress the mechanical parts of the generator.

7. Conclusion and Future Work

In this project a wind turbine fed fixed speed induction generator is modeled under asymmetric grid fault 1ph-50%.To mitigate these faults a static compensator is injected into the wind turbine fed fixed speed induction generator. It also compensates the positive and negative sequence voltage and current. The respective waveforms are verified for without and with static compensator. Similarly the same procedure is evaluated 1ph-60% and 1ph-0% and the wind turbine characteristics have been worked out.

Instead of fixed speed induction generator wind turbine fed doubly fed induction generator can be evaluated under asymmetric grid faults. Instead of statcom, DVR (dynamic voltage restorer), Unified power quality conditioner can used to attenuate the asymmetric faults in wind turbine fed FSIG and DFIG as both DVR and UPQC have the fault mitigation capability. Instead of PI controller, hysteresis controller can be employed and instantaneous theory; pq theory can be used in place of dq theory and evaluated.

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