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# Coordination of the Positive and Negative Sequence Voltage Control by STATCOM in FSIG Based Wind Farm


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## ABSTRACT:
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. Under unbalanced grid voltage dips, the negative sequence voltage causes heavy generator torque oscillations that reduce the lifetime of the drive train. In this paper, investigations on an FSIG-based wind farm in combination with a StatCom under unbalanced grid voltage fault are carried out by means of theory,simulations, and measurements. A StatCom control structure with the capability to coordinate the control between the positive and the negative sequence of the grid voltage 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. With first priority, the Stat Com ensures the maximum fault-ride- through enhancement of the wind farm by compensating the positive-sequence voltage. The remaining StatCon current capability of the StatCom is controlled to compensate the negative-sequence voltage, in order to reduce the torque oscillations. The theoretical analyses are verified by simulations and measurement results on MATLAB.

**Key words**:

Induction generator, low-voltage ride through, STATCOM, wind energy

## I. INTRODUCTION:
To facilitate the investigation of the impact of a wind farm on the dynamics of the power system to which it is connected, an adequate model is required. Wind energy is playing a vital role on the way towards a sustainable energy future. As the wind energy penetration into the grid is increasing quickly, the influence of wind turbine on the power quality is becoming a major issue. The impact on power system stability is the wind power penetration. There are many different kinds of generators that could be used in a wind turbine such as Induction Generator, Permanent Magnet Alternators, and Brushed DC Motor. Among them the technical development has moved from fixed-speed to variable-speed concepts [1].

However in a newly installed wind turbines the variable-speed type covers a major part using either a doubly fed induction generator (DFIG) or permanent-magnet synchronous generator, but in some cases it is still of the fixed speed induction generator(FSIG)-type directly connected to the grid. But it cannot fulfill the demanding grid code requirements [3] without additional devices as this type cannot provide reactive power control.

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During voltage dips, large amount of reactive power might be consumed by the induction generators as their speed deviates from the synchronous speed that leads to collapse of voltage and further fault propagation in the network. In order to enhance the fault-ride-through capability and to fulfill grid code requirements, various methods have been analyzed.
Besides using the pitch control of the turbine or installing additional equipment like a brake chopper or anenergy storage system, the installation of a StatCom has been identified to provide the best dynamic stability enhancement capabilities[4]. A StatCom is a voltage source converter based device providing dynamic reactive power support to the grid. Multilevel [5], [6] or hexagram converter topologies [7] are usually chosen to implement the high-power converters. Due toits flexible dynamic control capabilities, the StatCom can helpto integrate wind power plants in a weak power system [8]. The capability of a static varcompensator compared to a StatComto increase the stability of FSIG-based wind turbines is given in[9] and [10]. The StatCom can also perform an indirect torquecontrol for the same kind of generators [11], [12] to decreasethe mechanical stress during grid voltage dip.

All these investigations have covered balanced grid faults,but the majority of grid faults are of the unbalanced nature.The unbalanced-voltage problem can cause unbalanced heatingin the machine windings and a pulsating torque, leading tomechanical vibration and additional acoustic noise [13]. TheStatCom 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. How these different current injection targets affect the operation of an FSIG-based wind farm is investigated. However, regarding the damping of the torque ripple of the generators, it is more effective to control the positive- and the negative-sequence voltage. A voltage balancing control of a StatCom connected to induction motors is presented. The negative-sequence voltage control can alsobe performed by a DFIG wind farm in the vicinity ofthe FSIG-based wind farm. So far, however, no studies have been found on the coordination between the positive- and the negative-sequence voltage control of a StatCom at an FSIGbasedwind farm.

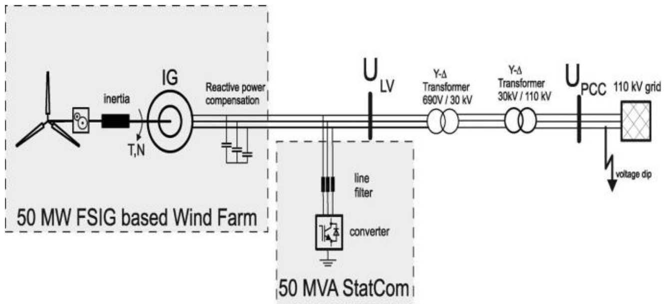


**Fig 1: Structure of the investigated system: FSIG-based wind farm and StatCom connected to the grid.**

This paper proposes the application of a StatCom that is connected to an FSIG-based wind farm and 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 negativesequence voltage compensation leads to a reduction of torque ripple, increasing the lifetime of the generator drive train. First investigations have been published, but here, deeperanalysis and measurement results are presented.

## II. POWER SYSTEM STRUCTURE:

The investigated power system is shown in Fig. 1 and consists of a 50-MW wind farm with squirrel cage induction generators 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. The StatCom is modeled as controlled voltage sources. Both devices are connected to the same low voltage bus and then connected to the medium voltage bus by a transformer.

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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 II. The power system is modeled with the power electronics.

## III. INDUCTION GENERATOR UNDER VOLTAGE DIP:

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

$$T^+(s) = 3.\frac{p}{2}\frac{R_r}{s\omega_s}\frac{(V_s^+)^2}{\left(R_s+{R_r}/{s}\right)^2+j(X_s+X_r)^2} \quad (1)$$

WhereRs, Rr, Xs, and Xrare the typical stator and rotor (subscripts s and r) resistance and impedance parameters of the machine equivalent circuit, p is the number of pole pairs,ωsis 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.

Transient torque peaks caused by the dynamic change of thegrid 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. 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 overspeed, 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., a small amount of negative sequence voltage $V_s^-$can lead to a high amount of negative sequence currents$I_s^-$, described by

$$I_{s,pu}^- = \frac{V_s^-}{\omega_s.\sigma.L_s.I_{s,N}} \quad (2)$$

Whereσ is the leakage factor, IS, Nis 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

$$T^+ \approx 3.\frac{p}{2\omega_s}.V_s^+.I_{sd}^+ \quad (3)$$

but the negative-sequence currents cause torque oscillations of double grid frequency. The magnitude of the negative-sequence torque T− can be calculated using

$$T^- \approx 3.\frac{p}{2\omega_s}.V_s^+.I_s^-. \quad (4)$$

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. The proposed StatCom control structure is presented in the next section.

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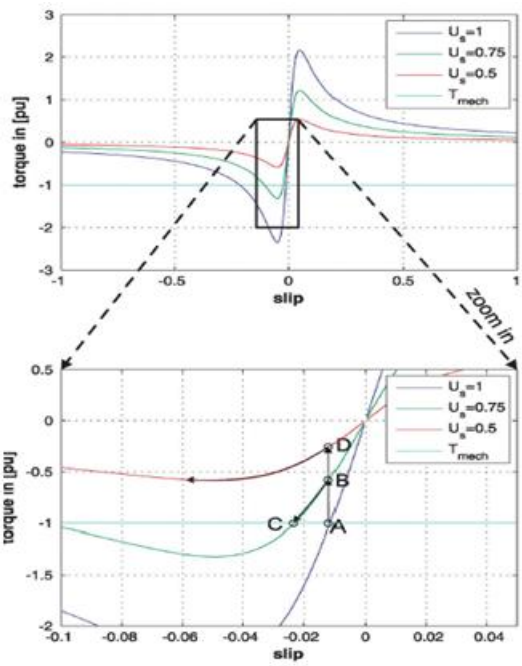


Fig 2: Theoretical torque–slip characteristics of the induction generatorunder different grid voltage levels

## IV. STATCOM CONTROL STRUCTURE:

The StatCom control structure is based on the voltage oriented vector control scheme 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 dereference frame with grid voltage orientation. The PI controller transfer function is

$$G_{PI}(s) = V_R \frac{1+s.T_n}{s.T_n} \quad (5)$$

The modeling and controller gain design of voltage-oriented controlled three-phase grid-connected converters are described. Resonant controllers (Res) tuned at 100 Hz in the same positive dereference frame are added to realize the negative sequence current control.

$$G_{Res}(s) = K_{res} \cdot \frac{s}{s^2+(2.\omega_0)^2} \quad (6)$$

Note that the control of the negative-sequence currents can also be performed in a negative rotating reference frame with

The overall control structure is shownin Fig. 3. The outer control loops are designed to control the dc voltageand the positive and negative sequences of the voltage at theconnection 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. Other sequence extraction methods could be applied. 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 $I_q^+$.

Thus, the StatCom ensures the maximum fault-ride-throughenhancement of the wind farm by compensating the positivesequence 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. A control strategy to smooth the torque transients is not focus of this paper and is investigated in [11].

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. Both methods are shown in the next section. In Section VI, simulation results for a coordinated positive- and negative-sequence voltage control are shown.

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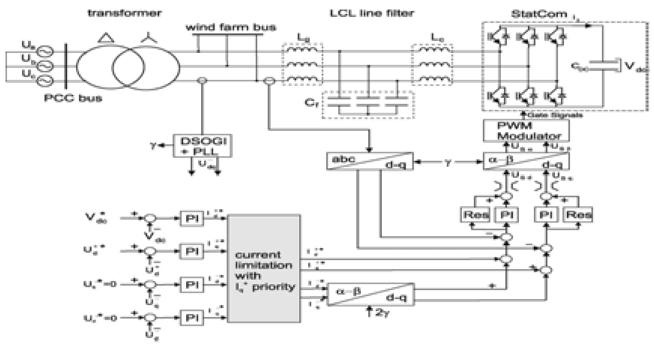


Fig 3: Proposed control structure of the StatCom to control the positive- and the negative-sequence voltage independently.

## V.SIMULATION RESULTS FOR UNBALANCED GRID FAULTS:

In this section, simulation results for the operation of the induction generators and the stabilization by the StatCom under an unbalanced grid voltage dip of 500-ms duration are presented and discussed. An unbalanced fault (single phase amplitude drops to 50%) is assumed at the high voltage bus of the power system. The simulation results are shown in Fig. 4. The unbalanced grid fault leads to a negative-sequence voltage at the medium voltage bus. The operation of the system without StatCom support is shown in the left part of Fig. 4.The reduction of the positivesequence voltage leads to a decrease in torque and an acceleration of the rotor.

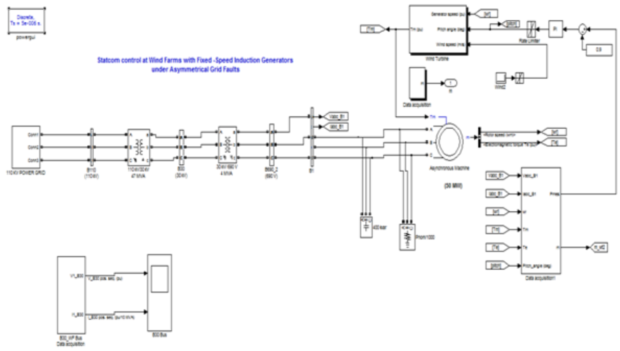

Fig 4: Simulink Model without STATCOM

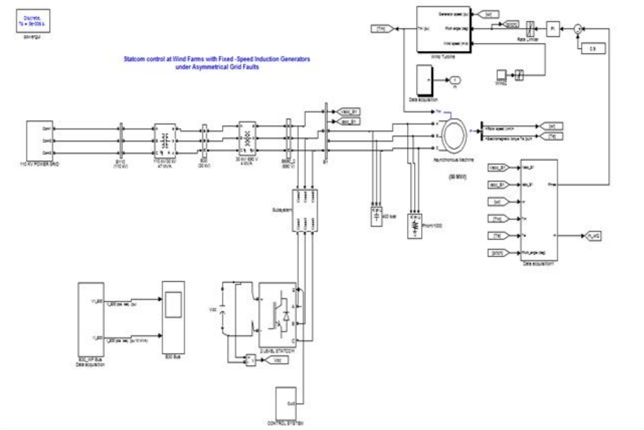

Fig 5: Simulink Model with STATCOM

Fig 4 shows the simulation results for an unbalanced SLG (Single line to ground) fault without STATCOM at the point of common coupling between the wind farm and the grid.

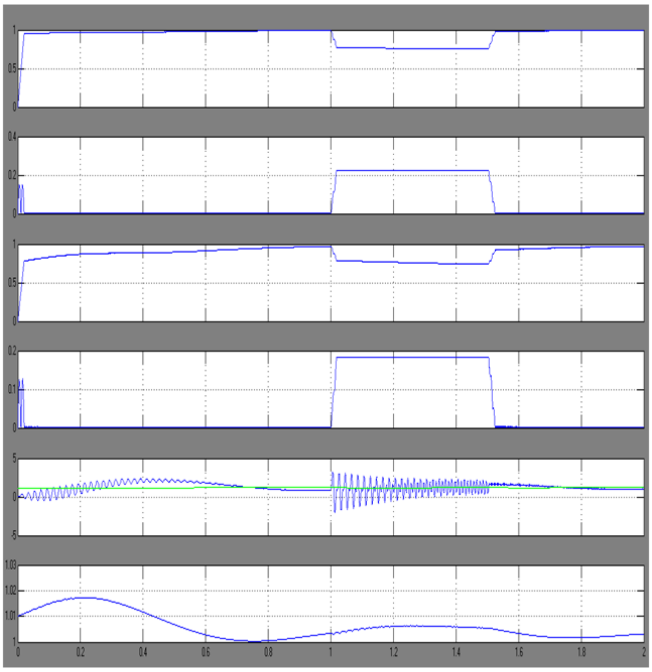

Fig 6: Showing waveforms without STATCOM for a Unbalanced SLG fault (a) positive and negative sequence voltages at PCC (b) positive and negative sequence voltages at low voltage bus (c)STATCOM current (d)Torque (e) P,Q of STATCOM.

As shown in the fig 6 fault is created for a short duration of 0.1 second. Fig 6(a) shows the oscillations produced in the positive sequence and negative sequence voltage components of the grid voltage

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during the period of fault at point of common coupling. Fig 6(b) shows the positive sequence and negative sequence voltage oscillations produced at the low voltage bus during the period of fault. Fig 6(c) shows the torque oscillations that are produced during the period of fault. Fig 7 shows the simulation results for an unbalanced SLG (Single line to ground) fault with STATCOM (positive sequence voltage) connected at the point of common coupling between the grid and the wind farm.

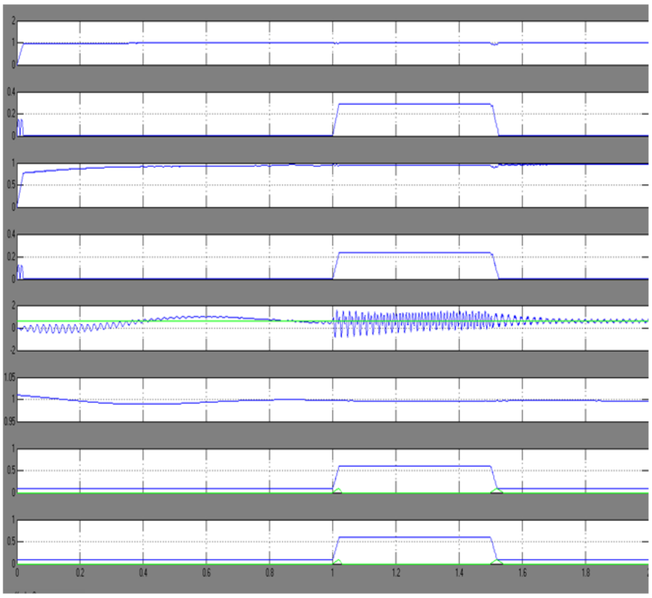

**Fig 7: Showing Waveforms with a STATCOM for a Unbalanced SLG fault (a) P,Q of STATCOM (b) Positive and negative sequence voltages at PCC (c) Positive and negative sequence voltages at Low voltage bus (d)STATCOM Current (d)Torque**

As shown in the Fig 5 the STATCOM injects a compensating real and reactive power during the period of fault. As a consequence of that the voltage oscillations at the point of common coupling and the low voltage bus die down as shown in fig 7(b) and 7(c) respectively. Fig 7(d) shows the positive and negative sequence currents of STATCOM controlled to reduce the torque oscillations. The reduction in the torque oscillations is shown in fig 7(e). Fig 8 shows the simulation results for an unbalanced SLG (Single line to ground) fault with STATCOM (negative sequence voltage) connected at the point of common coupling between the grid and the wind farm.

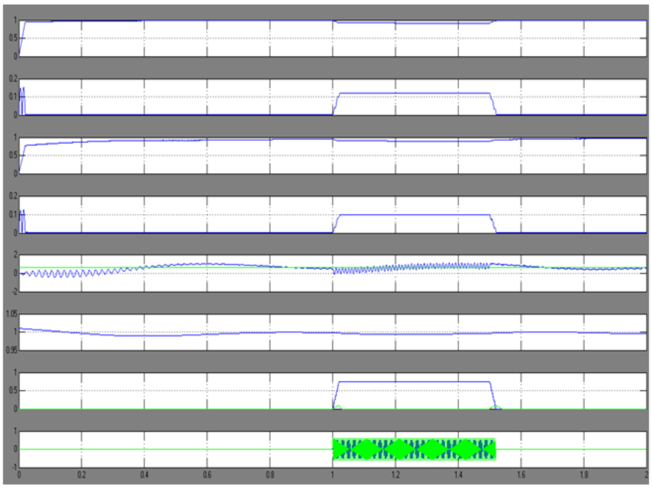

**Fig 7: Showing Waveforms with a STATCOM for a Unbalanced SLG fault (a) P,Q of STATCOM (b) Positive and negative sequence voltages at PCC (c) Positive and negative sequence voltages at Low voltage bus (d)STATCOM Current (d)Torque**

## VI. COORDINATED POSITIVE- AND NEGATIVE-SEQUENCEVOLTAGE CONTROL AND LIMITATIONS

In the previous section, either the positive-sequence voltage 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 compensation, 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 avoid tripping of the converter. Simulation results for the operation during an unbalanced-voltage dip (1 ph → 60%) when both the positive and the negative-sequence voltage components are compensated is shown in Fig. 7.

The current capability of the StatCom is sufficient to compensate both voltage components.

## VII. CONCLUSION:

Voltage control structure for a STATCOM for fixed speed induction generator based wind farm under balanced and unbalanced grid voltage condition has been implemented. The adapted structure controls both the positive and the negative sequence of the voltage independently with priority on the positive sequence voltage. During the balanced faults the positive sequence voltage variations are high and they will be compensated by STATCOM. During the unbalanced grid faults both positive sequence and negative sequence voltage variations will occur and they will be compensated to a great extent using this STATCOM control structure.

This work relates to 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 life time of the generator drive train. The coordination is realized by prioritizing the positive sequence voltage control. If there is remaining STATCOM current capability, the STATCOM is controlled to compensate the negative sequence voltage additionally, in order to reduce the torque ripple during grid faults.

## Future Scope:

The STATCOM structure used in this work concentrates mainly on compensating for positive sequence voltages. The remaining STATCOM current capability is used to compensate for negative sequence voltages, which may be insufficient. Investigations can be carried out with STATCOM having larger capability to compensate both for positive and negative sequence voltages under very severe faults. Appropriate STATCOM capability can be determined for the specified grid rating.

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