

INVESTIGATION OF SUB-SYNCHRONOUS RESONANCE PHENOMENA IN DFIG BASED WIND FARM WITH TCSC IN DIFFERENT APPROACHES

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Abstract

In the connection of Doubly Fed Induction Generator (DFIG) based wind farms to the grid, it is important to ensure the stability of the system by determining the series compensation ratios in the line in the most appropriate way. If these ratios are not determined well, an increase in electromechanical oscillations called Sub-Synchronous Resonance (SSR) may occur. In order to eliminate such problems, in this study, the changes in different series compensation ratios in the transmission line were examined in detail with the approach of different wind speeds using Thyristor Controlled Series Compensator (TCSC) in DFIG based wind farms. In these analyses, while different wind speeds in DFIG were selected as 9 m/s, 12 m/s and 15 m/s, the series compensation ratios in the transmission line were considered as 60%, 70% and 80%. In these analyses performed in MATLAB/SIMULINK environment, DFIG active power, reactive power, DC bus voltage and angular speed values were examined in detail. As a result of the obtained results, it was observed that when the wind speed in DFIG is 12m/s and the series compensation ratio in the system is 60%, system stability is ensured and the oscillations that occur are quickly damped.

Keywords: DFIG Based Wind Farm, Sub-Synchronous Resonance (SSR), Different Wind Speeds, Different Series Compensation Ratios, TCSC

ÇBAG TABANLI RÜZGAR ÇİFTLİĞİNDE TCSC İLE FARKLI YAKLAŞIMLARDA ALT SENKRON REZONANS OLAYLARININ İNCELENMESİ

Özet

Çift Beslemeli Asenkron Generatör (ÇBAG) tabanlı rüzgar türbinlerinin şebekeye bağlantısında hattaki seri kompanzasyon oranlarının en uygun şekilde belirlenmesi ile sistemin kararlılığın sağlanması önemli bir konudur. Bu oranlar iyi belirlenmez ise Alt Senkron Rezonans (SSR) isimli elektromekanik salınımların artması durumu meydana gelebilmektedir. Bu gibi problemleri ortadan kaldırmak için bu çalışmada ÇBAG tabanlı rüzgar türbinlerinde Tristör Kontrollü Seri Kompanzator (TCSC) kullanılarak farklı rüzgar hızları yaklaşımı ile iletim hattındaki farklı seri kompanzasyon oranlarındaki değişimler detaylı olarak incelenmiştir. Bu analizlerde ÇBAG'da farklı rüzgar hızları olarak 9 m/s, 12 m/s ve 15 m/s olarak seçilirken, iletim hattındaki seri kompanzasyon oranları olarak %60, %70 ve %80 değerleri ele alınmıştır. MATLAB/SIMULINK ortamında gerçekleştirilen bu analizlerde ÇBAG aktif güç, reaktif güç, DC bara gerilimi ve açısal hız değerleri detaylı bir şekilde incelenmiştir. Elde edilen sonuçlar neticesinde ÇBAG'da rüzgar hızının 12m/s rüzgar hızında olduğu durumda ve sistemdeki seri kompanzasyon oranının %60 olduğu durumda sistem kararlılığının sağlandığı ve oluşan salınımların hızlıca sönümlendiği görülmüştür.

Anahtar Kelimeler: ÇBAG Tabanlı Rüzgar Türbini, Senkron Altı Rezonans (SSR), Farklı Rüzgar Hızları, Farklı Seri Kompanzasyon Oranları, TCSC

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1. Introduction

In recent years, due to reasons such as increasing consumer demands and new loads being added to the system, the capacity of power systems has increased and it is inevitable that power systems will become more

complex. In particular, the operating conditions of the system can be adjusted to a certain extent by making improvements without a new structure on the existing system. For this purpose, the use of TCSC one of the elements of the Flexible AC Transmission System

(FACTS) is widespread. There are many studies on TCSC in power systems. Stability analyses in power systems are examined with TCSC. Different control models have been developed in TCSC to ensure system stability and dampen oscillations in case of faults in the system and better results have been obtained [1, 2]. Stability conditions are analyzed by using the power system stabilizer model, which is used as a synchronous generator controller with TCSC in power systems. It is observed that the models used in different systems give good results in both short-term stability and oscillation damping when used together [3, 4]. In steady and transient operations, the load busbar operating limits must be within certain limits in power systems. TCSC is effectively used to ensure these limits in power systems at all times. It is seen in related studies that the system capacity and loadability increase with the use of TCSC [5, 6]. In recent years, the demand for renewable energy sources has grown due to the increase in the price of fossil fuels and their depletion. Especially, generating electrical energy from wind energy is one of the most popular ones. DFIG, which is used in wind turbines and has many advantages, is preferred to obtain electrical energy from wind energy. Different impedance approaches are preferred for more precise determination of relay coordination in the circuit breakers with the use of TCSC in the system [7-9]. In another application in DFIG, TCSC is used in the oscillation control of load models that are activated at different times. It has been seen in the relevant studies that TCSC is used effectively to eliminate system instability and minimize oscillations during the activation and deactivation of ohmic and inductive loads [10,11]. In multi-machine power systems, TCSC is used in various analyses by integrating DFIG into the system. It is aimed to provide appropriate power flow and reduce power losses in grid integration of DFIG-based wind turbines [12]. In power systems, appropriate values must be determined in order to dampen the oscillations in the system parameters in the fastest way in stability situations. The most appropriate parameter determination processes using TCSC in DFIG-based wind turbines were carried out in the relevant study [13]. One of the application areas of TCSC in DFIG is SSR analysis. Different models have been preferred in the studies conducted in the literature with the use of TCSC in DFIG [14-16].

In most of the literature studies given above, less space is given to the analysis of wind speed, series compensation ratios and simulation study parameter results compared to the developed models. In this study, all analyses are discussed more comprehensively. In this study, the effects of different series compensation ratios as well as the interactions of SSR analysis at different wind speeds using TCSC on DFIG based wind turbines are emphasized. In the study examined in different scenarios, the oscillation situations in active power, reactive power, DC bus voltage and angular speed values are discussed in

detail. In which cases the use of TCSC in DFIG is more effective and preferable is revealed by this study. In addition, the electromechanical oscillations in the examined parameters are compared according to the cases where TCSC is used and not used. This study offers a different approach for SSR events in the use of DFIG together with TCSC.

2. Doubly Fed Induction Generator (DFIG)

DFIG is called a rotor wound asynchronous machine. DFIG wind energy conversion systems can produce power from kW to MW. DFIG based wind turbine grid connection model is given in Figure 1.

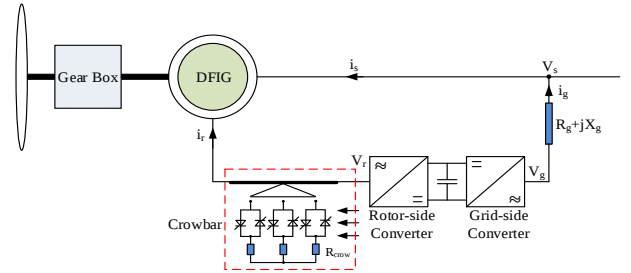


Figure 1. DFIG modeling.

DFIG generally consists of a gearbox, crowbar, generator, an converter on the rotor side and an converter circuit on the grid side. The stator circuit of the DFIG is directly connected to the grid. The rotor circuit is connected to the grid through power electronic converters. These back-to-back connected converter circuits consist of two voltage source converter circuits with pulse width modulation switching having bidirectional current flow. While the converter circuit on the rotor side is used to control the generated power in DFIG, the converter circuit on the grid side is used to keep the DC bus voltage constant [17]. In the circuit modeling in DFIG, calculations are made according to park-clark transformations as p.u. The d-q axis voltage and flux equations in DFIG are given between equation 1 and equation 8.

$$v_{ds} = R_s i_{ds} + w_s \lambda_{qs} + \frac{d}{dt} \lambda_{ds} \quad (1)$$

$$v_{qs} = R_s i_{qs} - w_s \lambda_{ds} + \frac{d}{dt} \lambda_{qs} \quad (2)$$

$$v_{dr} = R_r i_{dr} - s w_s \lambda_{qr} + \frac{d}{dt} \lambda_{dr} \quad (3)$$

$$v_{qr} = R_r i_{qr} + s w_s \lambda_{dr} + \frac{d}{dt} \lambda_{qr} \quad (4)$$

$$\lambda_{ds} = (L_s + L_m) i_{ds} + L_m i_{dr} \quad (5)$$

$$\lambda_{qs} = (L_s + L_m) i_{qs} + L_m i_{qr} \quad (6)$$

$$\lambda_{dr} = (L_r + L_m) i_{dr} + L_m i_{ds} \quad (7)$$

$$\lambda_{qr} = (L_r + L_m) i_{qr} + L_m i_{qs} \quad (8)$$

where; v_{ds} , v_{dr} , v_{qs} , v_{qr} are the d-q axis stator and rotor voltages, respectively. i_{ds} , i_{dr} , i_{qs} , i_{qr} are the d-q axis stator and rotor currents, respectively. λ_{ds} , λ_{dr} , λ_{qs} , λ_{qr} are the d-q axis stator and rotor linkage fluxes, respectively. w_s is

the angular speed, s is the slip, R_s and R_r are the stator and rotor resistance, respectively. L_s and L_r are the stator and rotor inductances, respectively. L_m is the magnetic inductance [18].

3. Sub-Synchronous Resonance (SSR)

The SSR event is defined as the situation where the wind power plant exchanges one or more natural frequencies with the electrical grid. The natural frequency calculation in a capacitive series compensated power system is shown as in equation 9.

$$f_n = f_s \times \sqrt{\frac{X_c}{X_L}} \quad (9)$$

where, f_n is the natural frequency, f_s is the natural frequency, X_c is the series capacitive value of the line, and X_L is the series inductive value of the line. The percentage of line reactance is defined as compensation percentage (K). The shift expression (s_n) depending on the natural frequency is calculated as in equation 10.

$$s_n = \frac{f_n - f_r}{f_n} \quad (10)$$

where, f_r is the rotor electrical frequency. When the natural frequency is less than the rotor frequency, the slip is negative. Therefore, the rotor equivalent resistance $R_{re} = R_r/s_n < 0$ is negative at sub-synchronous frequency. Since the magnitude of this resistance increases the total resistance of the network and generator armature, the total resistance of the system will be negative at the sub-synchronous frequency. In other words, the line current will have an exponential function. The exponential increase in the line current will be due to the capacitive series compensation in the system, a component with the resonant frequency will be seen in the stator current and a component with the complementary frequency of this component will be seen in the rotor current [19-21]. In order to determine this well at SSR instant, the capacitive series compensation ratio must be determined well.

4. Thyristor Controlled Series Compensator (TCSC)

Thyristor controlled series compensator (TCSC) is one of the series FACTS devices connected in series to the transmission line. In addition to controlling the impedance of the line, it also provides series compensation to the line, thus reducing the inductive reactance of the transmission line and eliminating possible voltage drops. The circuit model of TCSC is shown in Figure 2.

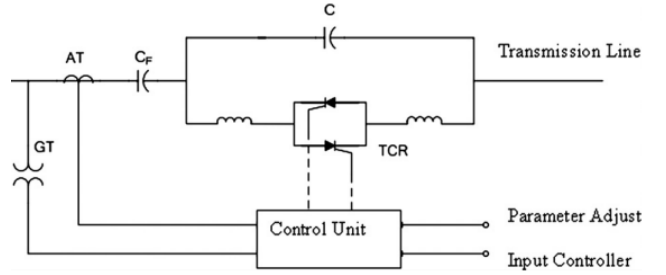


Figure 2. TCSC circuit modeling.

As seen in Figure 2, TCSC consists of series inductance, thyristor groups, parallel connected capacitors and control unit. The basic circuit characteristic of TCSC is found depending on the reactances found in the capacitor and thyristor circuit triggering [22]. TCSC capacitive reactance calculation is shown in equation 11.

$$X_c = \frac{X_c X_L}{X_c [2(\pi - \alpha) + \sin 2\alpha] / \pi - X_L} \quad (11)$$

The basic circuit characteristic of TCSC varies depending on the circuit component reactance of the capacitor groups and thyristors used in the system. The reactance expression of these branches is shown in equation 12.

$$X_c = X_L \frac{\pi}{2(\pi - \alpha) + \sin 2\alpha} \quad (12)$$

where, X_c is the capacitive reactance, X_L is the inductive reactance, α is the triggering angle of the thyristors.

5. Simulation Study

The system used in the simulation study is shown in Figure 3 [23].

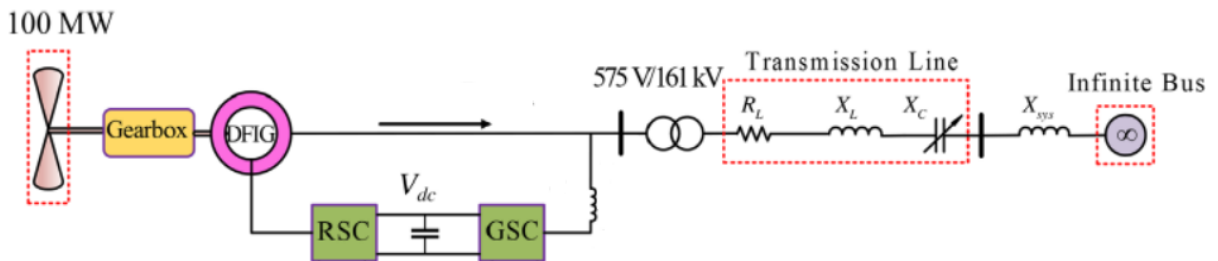


Figure 3. System used in the simulation study.

In this study, a 100 MW DFIG based wind Farm is used. The voltage at the DFIG output is 575 V. This voltage is increased to 161 kV with a step-up transformer. The power of the transformer used here is determined as 100 MVA. In addition, while the transformer is connected in delta-star, respectively. The saturation state of the

transformer is neglected. Both a series capacitor and a series capacitor with a bypass connection to it are used on the grid side. The capacitor breaker connected to the system is activated. The series compensation ratio is specified as 60%, 70% and 80% in this study. Different wind speeds are used in the analyses in the simulation

study. Wind speeds are selected as 9 m/s, 12 m/s and 15 m/s in this study. In the analysis of different series compensation ratios being included in the system, 3-phase fault is preferred. 3-phase fault occurs between 1 and 1.1 seconds. In the system, series compensation is activated via the circuit breaker in the 1st second. In addition, 2 different analyses are performed in the system. In the first analysis, the analysis of the situation where there is no TCSC in the system was examined, while in the second analysis, the analysis was carried out with the serial connection of 100 MVA TCSC to the system. With the two analyses, the active power, reactive

power, DC bus voltage and angular speed values in the DFIG were compared in detail.

6. Simulation Study Results

In this study, the analyses of the cases where TCSC is used and not used were carried out respectively. In the DFIG, The series compensation ratios were determined as 60%, 70% and 80% in the cases where the wind speed is 9 m/s, 12 m/s and 15 m/s, respectively the active power, reactive power, DC bus voltage and angular speed values of DFIG were examined in detail in cases where TCSC was used and not used. The simulation study results are shown in Figure 4 to Figure 7.

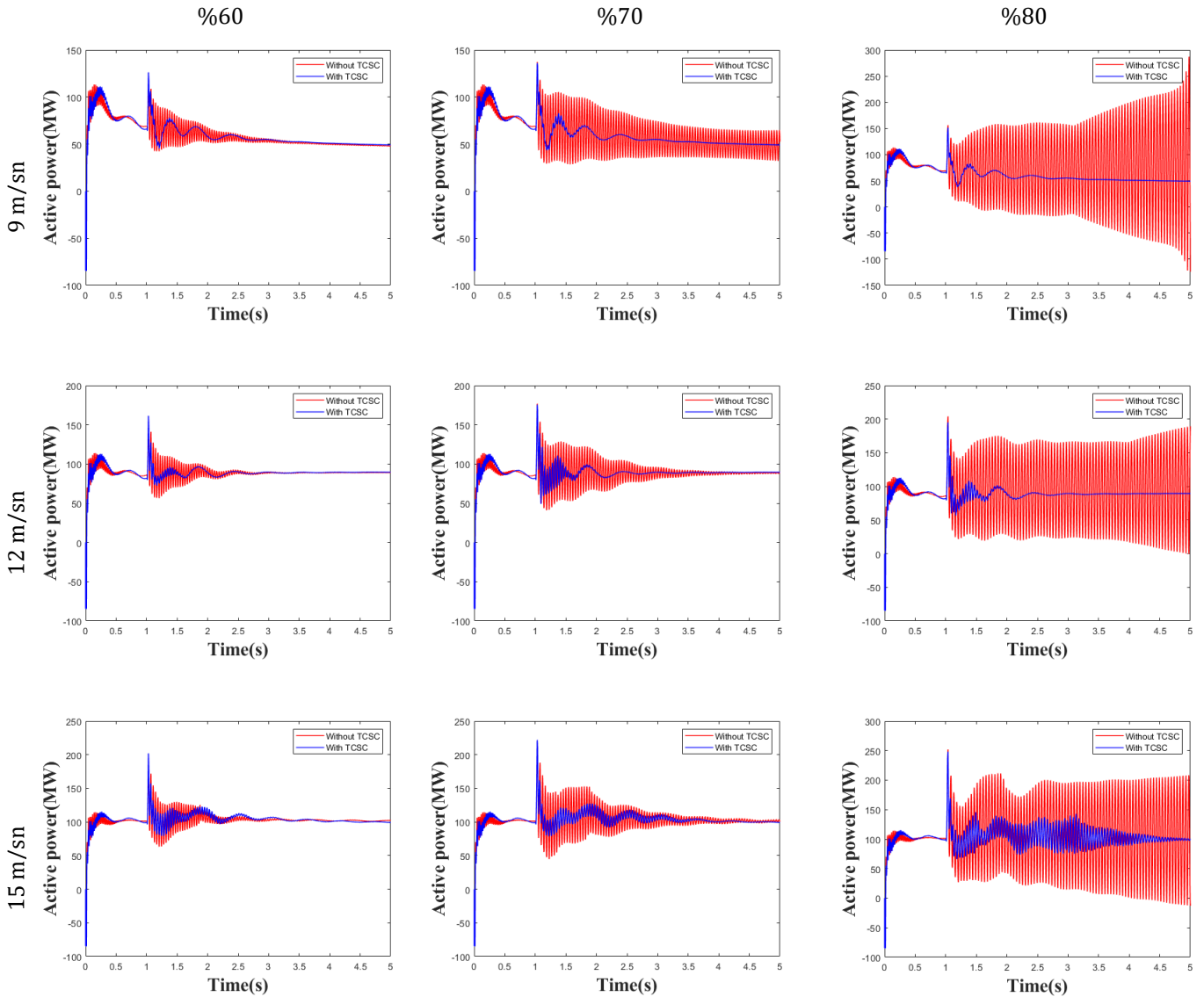


Figure 4. Active power comparisons when wind speeds are 9 m/s, 12 m/s, 15 m/s and series compensation ratios are 60%, 70% and 80%.

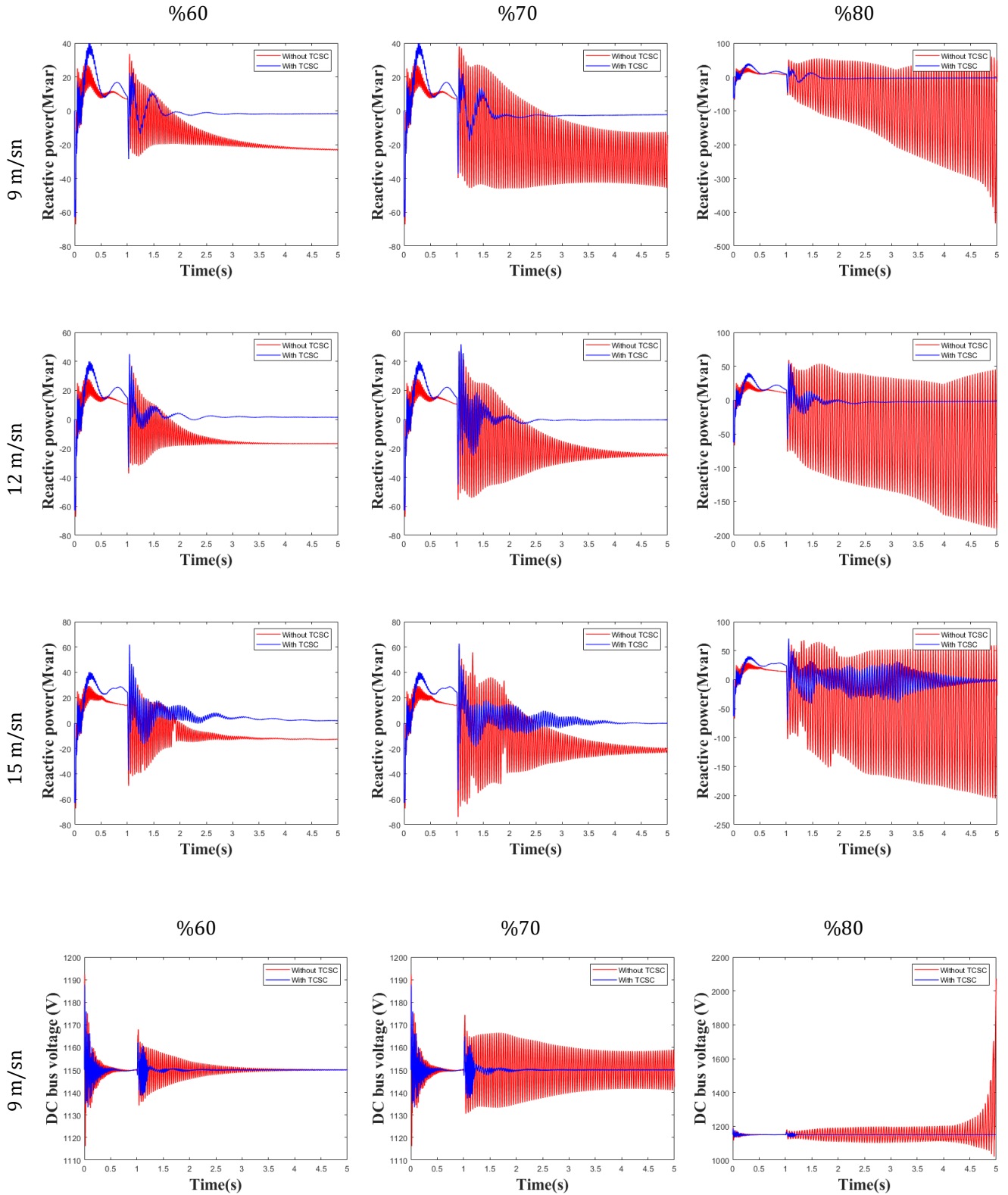


Figure 5. Reactive power comparisons when wind speeds are 9 m/s, 12 m/s, 15 m/s and series compensation ratios are 60%, 70% and 80%.

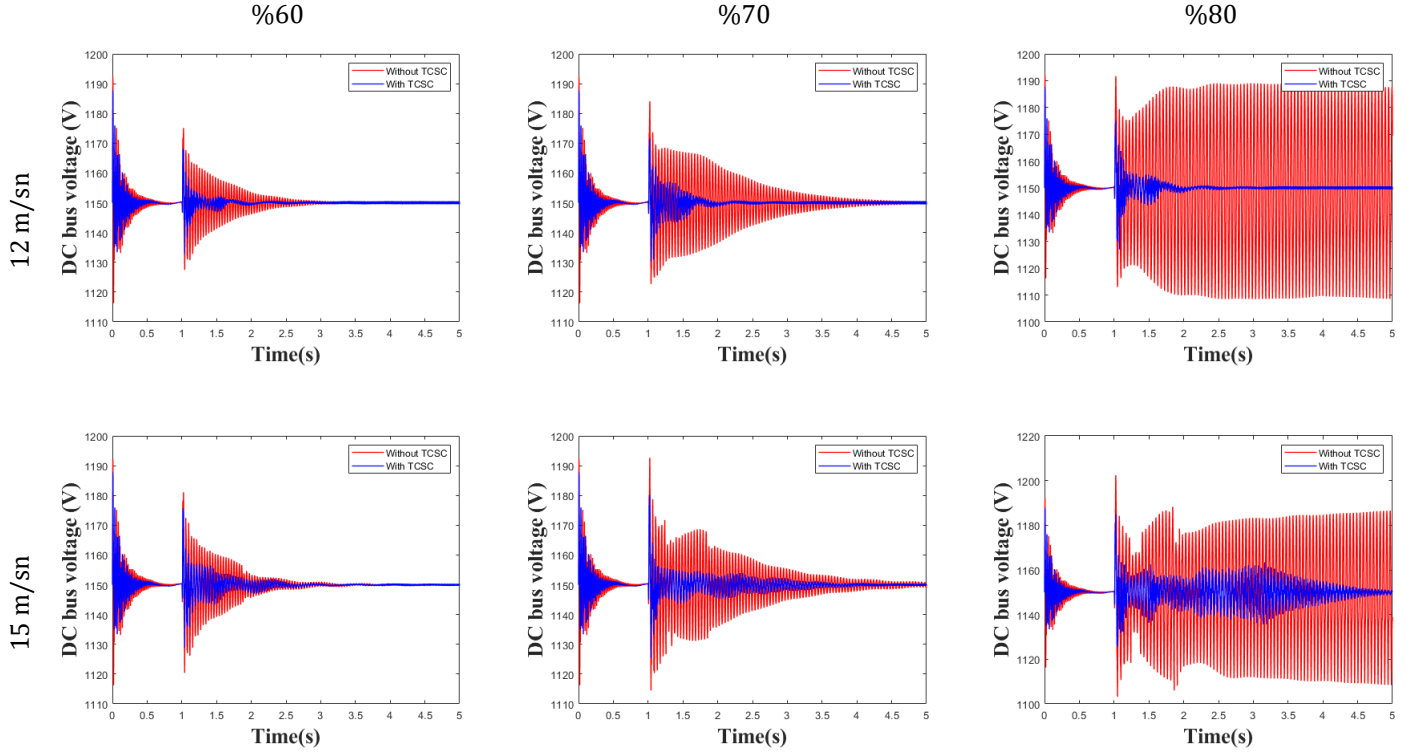
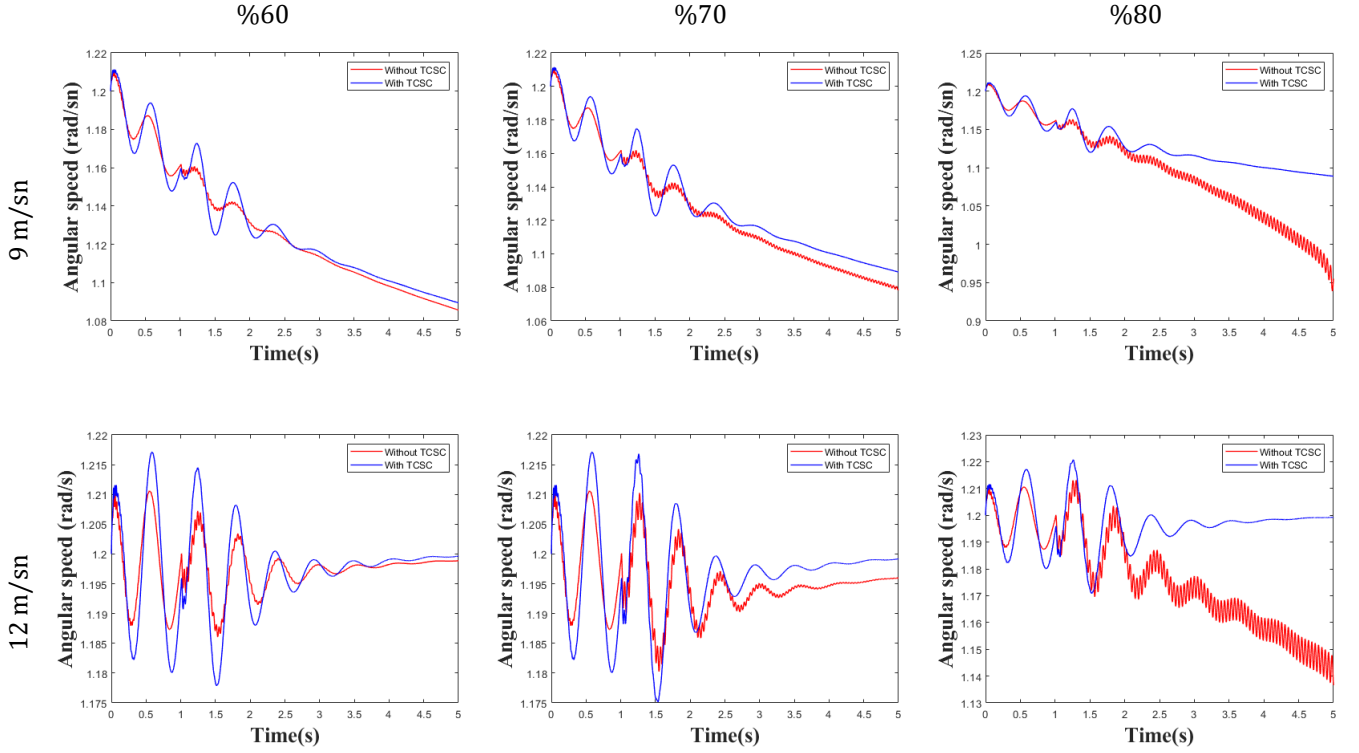


Figure 6. DC bus voltage comparisons when wind speeds are 9 m/s, 12 m/s, 15 m/s and series compensation ratios are 60%, 70% and 80%.



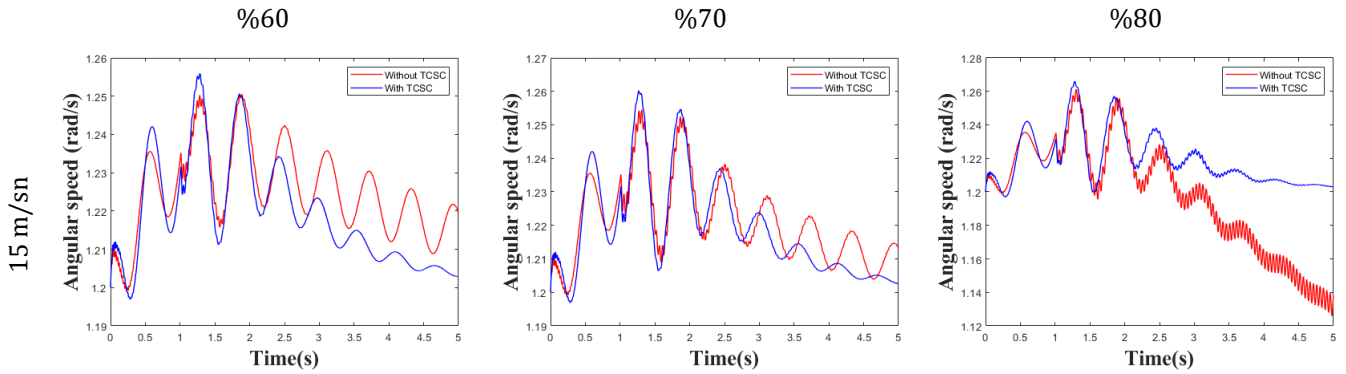


Figure 7. Angular speed comparisons when wind speeds are 9 m/s, 12 m/s, 15 m/s and series compensation ratios are 60%, 70% and 80%.

The most successful result of TCSC in active power changes is the case where the wind speed is 9 m/s and the serial compensation ratio is 60%. The least successful part of DFIG in active power changes is the analysis where the wind speed is 15 m/s and the serial compensation ratio is 80%. It has been observed that the system becomes stable with the use of TCSC at other wind speeds and serial compensation ratios.

With the use of TCSC in the system, the DFIG reactive power changes were examined in detail. The parts where TCSC gave the most successful results in reactive power changes were when the wind speed was 9 m/s and the series compensation ratio was 80%. The parts where TCSC gave the least successful results in reactive power changes were obtained when the wind speed was 15 m/s and the series compensation ratio was 80%. In other reactive power results, the system became stable with the use of TCSC.

In the examination of DC bus voltages in DFIG, the most successful results with TCSC were obtained when the wind speed was 9 m/s and the series compensation ratio was 80%. In the examination of DC bus voltage, the least successful results with TCSC were obtained when the wind speed was 15 m/s and the series compensation ratio was 80%. It is observed that the system becomes stable at other wind speeds and series compensation ratios.

With the use of TCSC in the grid-connected DFIG, it is seen that the angular speed changes are most successfully stabilized when the wind speed is 12 m/s and the serial compensation ratios are 60% and 70%. The analysis in which TCSC is least successful is the analysis in which the wind speed is 9 m/s, 12 m/s, 15 m/s and the serial compensation ratios are 80%. Apart from these, it is seen that the angular speed changes are relatively stable in other analysis results.

2. Conclusion

In this study, SSR events that occur as a result of series compensation during the connection of DFIG based wind farms to the grid were examined in detail. Comparisons were made between the cases where TCSC was used and

when it was not used in the system. Active power, reactive power, DC bus voltage and angular speed values from DFIG parameters were used in the comparisons. According to the results obtained, it was obtained that the system became stable and the oscillations were damped by using TCSC in the power system. However, it was observed that the results varied in all wind speeds and series compensation ratios. While the results were seen to be good with the use of TCSC in DFIG active power, reactive power and DC bus voltages, it was seen that the system became relatively stable with the use of TCSC in DFIG angular speed changes. Each wind speed and series compensation ratios show differences according to the cases where TCSC is used and not used. This study prepares the ground for examining different series compensation ratios and impedance model development in grid-connected DFIG based wind farms in more detail. In addition, it paves the way for the selection of various optimization algorithms so that the controllers used in TCSC operate according to the most optimum values.

3. References

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