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Evaluation of Phase Imbalance Compensation for Mitigating DFIG-Series Capacitor Interaction

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***Abstract*—This paper assesses the suitability of the phase imbalance concept as an alternative approach for series compensating a transmission line, with the goal to eliminate adverse subsynchronous interactions between a DFIG and the transmission system. The performance of this concept, under a predefined degree of asymmetry, is compared with the classical series compensation scheme. First, it is concluded that the phase imbalance concept can reduce subsynchronous oscillations, as this concept results in lower resonance frequencies, which in turn lead to increased damping. Second, as these resonance frequencies remain in the DFIG's negative resistance region, the subsynchronous oscillations cannot be fully mitigated.**

Keywords—DFIG, MIGRATE, series compensation, subsynchronous oscillation, wind.

I. INTRODUCTION

The amount of wind generation is in the uplift due to the ambition of several countries to reduce their greenhouse emissions, where the doubly-fed induction generation (DFIG) based wind energy conversion system is among the most used for wind generation.

As wind power plants are usually located at a distance from load centres, high voltage AC or DC transmission lines are required. Transmission system operators are facing increasing difficulties to construct new AC overhead transmission lines due to public opposition. Depending on the transmission distance and capacity, high voltage DC transmission is not always a cost effective solution either. In these cases, upgrading the existing AC transmission lines is an option. One way to achieve this, is by compensation of the transmission line using series capacitors. Series capacitors reduce the impedance of the transmission line, allowing for increased power transfer. One main challenge with series compensation is the risk for subsynchronous oscillations (SSO) between the series capacitor and a conventional synchronous generator's turbine shaft. This phenomenon is also known as subsynchronous resonance (SSR) and happens at a fixed frequency. Similar adverse interactions can also occur between a DFIG and a series capacitor, where in this case the resonance frequency is variable.

The interaction between a DFIG and a series capacitor was discussed for the first time in [1] in 2003 and a STATCOM was proposed as mitigation solution in 2008 [2]. It was only after the adverse interactions occurred for real in 2009 in the power system of Texas [3], that this topic gained large interest from academia. Mitigation solutions such as converter parameter tuning, design of damping controllers and FACTS based solutions were developed to reduce the risk of this interaction.

The goal of this paper is to investigate whether the phase imbalance concept, initially proposed for mitigating classical SSR, is capable of mitigating adverse DFIG-series capacitor interactions. The phase imbalance compensation scheme, which is an alternative way of compensating a transmission line, introduces an asymmetry in the transmission line in such a way that the transmission system's impedance characteristic in the subsynchronous frequency range is altered. This paper creates insight to which extent this altered characteristic influences the subsynchronous oscillations.

The remaining part of the paper is structured as follows. Section II describes the nature of the adverse DFIG-series capacitor interaction and summarizes some of the existing mitigation solutions. Section III introduces the phase imbalance concept. In Section IV, the implementation of the power system model, the DFIG model and phase imbalance concept in PSCAD is explained. Section V provides the results and Section VI concludes this paper with the main conclusions and next steps.

II. LITERATURE REVIEW

A. DFIG-Series Capacitor Interaction

The interaction between a DFIG and a series capacitor can be explained using the DFIG's impedance model. With the parallel connection of the machine side converter (MSC) and the grid side converter (GSC), the impedance of the total DFIG system, Z_{DFIG}, can be approximated by the MSC impedance [4] as given by (1), where R_S and R_R are the stator and rotor resistances; L_S and L_R the stator and rotor leakage inductances; ω_0, ω_r, ω_s the fundamental frequency, rotor speed and subsynchronous frequency given by (2); $K_{p,dR}$ is the d-axis proportional gain of the current tracking control and $K_{d,MSC}$ the decoupling gain.

$$Z_{DFIG} = R_S + j\omega_s(L_S + L_R) + \omega_s \frac{R_R + K_{p,dR} - j\frac{K_{i,dR}}{\omega_s - \omega_0} - jK_{d,MSC}}{\omega_s - \omega_r} \quad (1)$$

$$\omega_s = \frac{1}{\sqrt{LC}} \quad (2)$$

From (1), it is observed that the DFIG damping $\Re(Z_{DFIG})$ is influenced by $K_{p,dR}$ and ω_r, of which the latter is determined by the wind speed. The interaction occurs when a disturbance in the grid excites the ω_s oscillation mode given by (2) and the net damping in the system is negative, i.e. $\Re(Z_{DFIG})$+R_{grid} < 0. This leads to a rapid amplification of the oscillations, as is illustrated in Fig. 1. As the DFIG's reactance is also influenced by its operating condition, the resonance frequency ω_s is not fixed.

This phenomenon is a form of self-excitation and is similar to the induction generator effect (IGE) as is shown in [5]. Eigenvalue analysis performed on a DFIG connected to an infinite bus through a series compensated transmission line in [5], found four SSO modes. Using participation factors, three modes (2.65, 3.23 and 6.74 Hz) were identified as torsional modes of the three mass drive train and the fourth mode (24.76 Hz) was identified as a network mode, with high participation of the series capacitor and the DFIG's four generator states (stator and rotor fluxes). The participation factors of the MSC, DC link and GSC in the network mode were found to be practically zero. Based on this finding, it is concluded that the adverse interaction occurs between the DFIG's generator and the series capacitor. As this is a form of SSR, this phenomenon is defined in this work as *DFIG-SSR*. An overview of reported DFIG-SSR events is given in Table I.

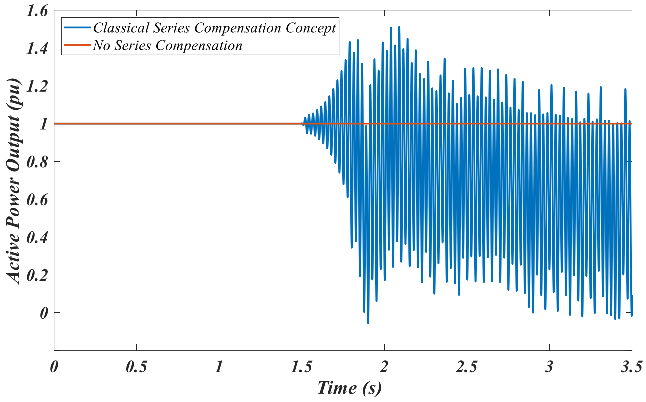

Fig. 1. Active power of DFIG with and without series compensation

TABLE I
Overview of Related DFIG-SSR Events

Event	Frequency
Texas, USA – 2009 [3]	20 Hz
Hebei, China – 2010 [6]	6.3 Hz
Minnesota, USA – 2011 [7]	9 – 13 Hz
Hebei, China – 2012 [8]	6 – 8 Hz
Hebei, China – 2013 [9]	8.1 Hz
Texas, USA – 2017 [10]	25.6 Hz
Texas, USA – 2017 [10]	22.5 Hz
Texas, USA – 2017 [10]	26.5 Hz

B. *Reported Mitigation Solutions*

Several measures are reported in literature to mitigate DFIG-SSR. Control modification through parameter tuning of the converter was performed in [11]. Tuning could come at the expense of reduced fault ride through behaviour and power quality. Other solutions include new control concepts (e.g. direct power control [12]), FACTS devices equipped with a supplementary damping controller (e.g. STATCOM [13]) and protection relays to trip either the wind farm or the series capacitor (e.g. [7]).

Two requirements for DFIG-SSR to occur are (i) the net negative resistance and (ii) the presence of a subsynchronous frequency as a result of series compensation. Parameter tuning as well as new control concepts are solutions that eliminate the first requirement, i.e. the negative resistance characteristic inherent to a DFIG. The FACTS device equipped with a supplementary damping controller and the protection relay do not influence either requirements, but merely act once the SSO is observed.

Another way to possibly mitigate DFIG-SSR would be the elimination of the second requirement, i.e. the existence of a subsynchronous frequency. The applicability of the phase imbalance compensation concept [14], introduced initially for the mitigation of classical SSR, is assessed in this paper. First, the phase imbalance compensation concept is explained in the next Section.

III. Phase Imbalance Compensation

The phase imbalance compensation concept (PIC) implements a phase wide compensation with different combinations of capacitive and inductive elements per phase. These combinations are chosen in such a way, that their frequency characteristics give equal reactance at the fundamental frequency, ω_0, but unequal reactance at other frequencies. Therefore, compared to classical series compensation (CSC), the system characteristics at ω_0 remain unchanged. The electrical circuits of both concepts are shown in Fig. 2.

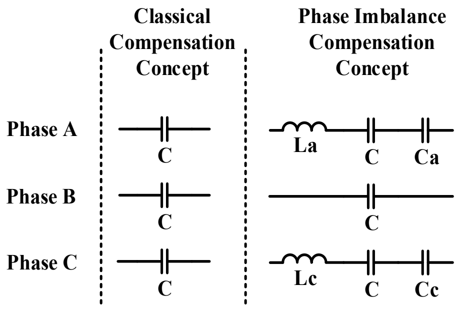

Fig. 2. Concepts for classical and phase imbalace compensation

In order to achieve the same the $Z(\omega_0)$ under both compensation schemes, the passive elements of the PIC have to follow (3).

$$\left.\begin{aligned} \omega_0 &= \sqrt{\frac{1}{L_A C_A}} = \sqrt{\frac{1}{L_C C_C}} \\ K_A &= \frac{C}{C_A} \\ K_C &= \frac{C}{C_C} \end{aligned}\right\} \tag{3}$$

The degree of asymmetry (K_A and K_C) denotes the extent to which the compensation in the imbalanced phases (A and C) differ from the balanced phase (B).
Solving (3) for inductances L_A and L_C yields (4), resulting in a single degree of freedom per phase.

$$\begin{aligned} L_A &= \frac{C}{{\omega_0}^2} K_A \\ L_C &= \frac{C}{{\omega_0}^2} K_C \end{aligned} \tag{4}$$

IV. Modelling

A. *Power System Model*

Owing to its highly local nature, the investigation of DFIG-SSR requires a detailed model of the DFIG in question. Modelling of the grid is required in such a way that it excites the oscillation mode, which ultimately will result in the interaction between the DFIG and the grid. Therefore, almost all investigations on DFIG-SSR reported in publications use the structure of the IEEE First Benchmark Model [15]. The model in the current work is modified in two ways. First, the synchronous generator model is replaced by a detailed DFIG model. Second, the equivalent grid is modelled as a voltage source with a series impedance, so that the grid contains a subsynchronous resonance point at 30 Hz. The single line diagram of the power system under consideration is given in Fig. 3. Several practical studies have used similar models for investigating DFIG-SSR [16]–[19].

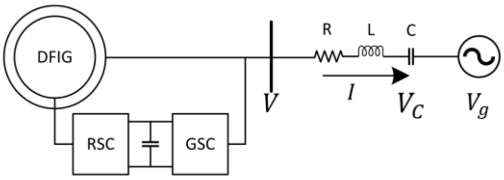

Fig. 3. Modeling of DFIG with series capacitor

B. Doubly Fed Induction Generator Model

Detailed modelling of the DFIG is crucial, as the adverse interactions are influenced by the damping available at the DFIG terminal. A generic wind turbine model following the IEC standard 61400-27-1 [20] was developed. The mechanical dynamics of the wind turbine generator were modelled using a two mass model. The grid- as well as the machine side converter of the DFIG are modelled using the classical double loop control. The implemented controls are shown in Fig. 4 (grid side converter) and Fig. 5 (machine side converter). $K_{p,dc}$ and $K_{p,Q}$ are the proportional gains of the GSC's outer control and $T_{i,dc}$ and $T_{i,Q}$ are the associated integral time constants. $K_{p,ds}$ and $K_{p,qs}$ are the proportional gains of the GSC's current tracking control and $T_{i,ds}$ and $T_{i,qs}$ are the associated integral time constants. The same proportional gains and integral time constants for the RSC are $K_{pP,PCC}$, $K_{pQ,PCC}$, $T_{iP,PCC}$, $T_{iQ,PCC}$, $K_{p,dR}$, $K_{p,qR}$, $T_{i,dR}$ and $T_{i,qR}$. More details on wind turbine parameters are given in Appendix A.

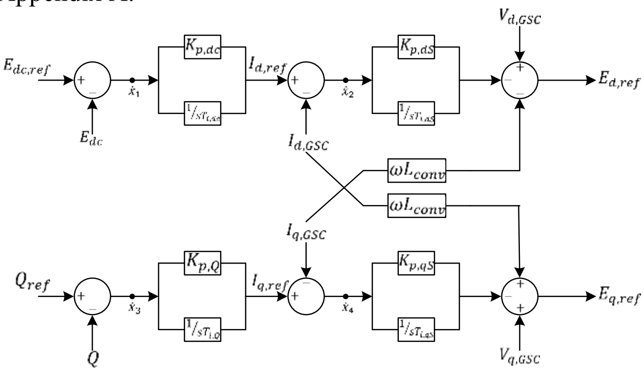

Fig. 4. Grid side converter control

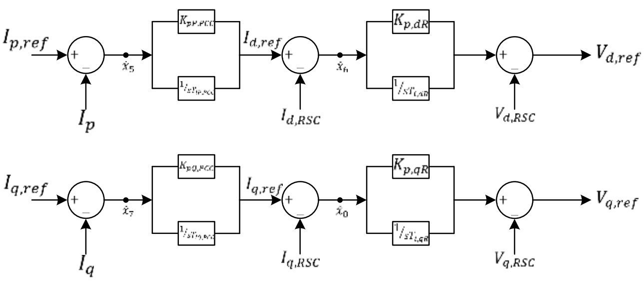

Fig. 5. Machine side converter control

As mentioned in Section II.A, the damping of the DFIG plays a crucial role in the occurrence of DFIG-SSR. In order to get insight in the damping of the developed wind turbine generator, a frequency scan was performed using the perturbation method. The resulting damping of the DFIG in the subsynchronous frequency range is shown in Fig. 6. From this figure it is observed that the DFIG has a negative damping in the frequency range 7-42 Hz. This range is also known as the negative resistance region. When the transmission system has a resonance frequency that falls in the DFIG's negative resistance region, oscillations will be amplified if the net damping remains negative.

C. Phase Imbalance Compensation

Equations (3) and (4) were implemented in PSCAD with the aim to investigate the influence of the degree of asymmetry (K_A and K_C) on the effectiveness of the phase imbalance compensation scheme to mitigate DFIG-SSR.

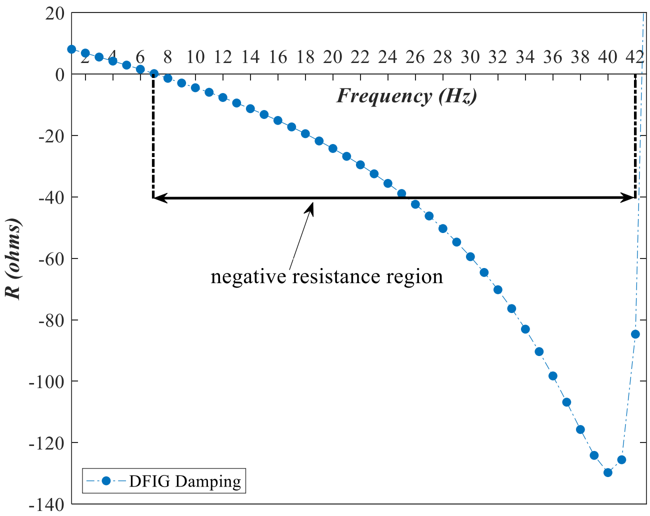

Fig. 6. Damping of the DFIG

In the simulations, K_A and K_C were independently varied from 0.01 to 1.00, leading to 10,000 permutations. The influence of the degree of asymmetry was assessed using a newly designed index η, i.e. the reduction of the oscillation energy, and is defined as given in (5).

$$\eta = \frac{\int_{t=x}^{y} P_{CSC}(t)dt - \int_{t=x}^{y} P_{PIC}(t)dt}{\int_{t=x}^{y} P_{CSC}(t)dt} \times 100\% \quad (5)$$

t=x time instance when DFIG-SSR occurs
t=y end of simulation time
$P_{CSC}(t)$ active power waveform of CSC signal
$P_{PIC}(t)$ active power waveform of PIC signal

This index should be interpreted as follows:

- $\eta = 100\%$: the combination of K_A and K_C in the PIC fully mitigates the adverse interactions;
- $\eta < 100\%$: the combination of K_A and K_C in the PIC leads to a better performance, compared to the CSC;
- $\eta = 0\%$: the combination of K_A and K_C in the PIC leads to the same performance as the CSC.

V. Results

Fig. 7 shows the impedance angle of the transmission system that is series compensated using the classical scheme.

From this figure it is observed that the subsynchronous resonance frequency is indeed 30 Hz and falls in the DFIG's negative resistance region. This simulation case leads to growing subsynchronous oscillations following a disturbance in the system (see Fig. 1).

For this case, different permutations of K_A and K_C were simulated, while η was monitored. For none of the permutations $\eta = 100\%$ was achieved, implying that the PIC was not able to mitigate DFIG-SSR when K_A and K_C have values between 0.01 and 1.00. The time domain simulations for a case with K_A=0.25 and K_C=0.75 is given in Fig. 8. These degrees of compensation resulted in one of the highest reductions in oscillation energy η. From this figure it is seen that although the PIC does not fully mitigate DFIG-SSR, it is able to reduce the energy that is associated with the oscillations. This can be explained by examining the impedance characteristics of the PIC with different degrees of asymmetry, i.e. different values for K_A and K_C. Fig. 9 shows the impedance angle of the transmission system for three different cases of series compensation:

- classical compensation scheme;
- phase imbalance compensation scheme with K_A and K_C=0.1, and
- phase imbalance compensation scheme with K_A and K_C=0.1.

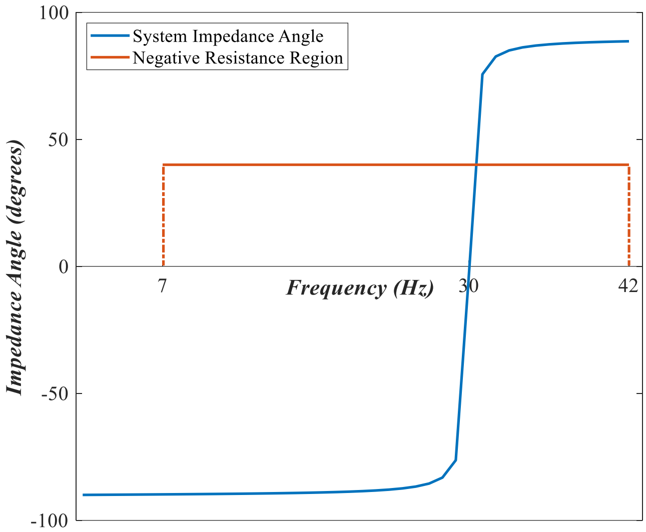

Fig. 7. System impedance angle of the transmission system with classical series compensation

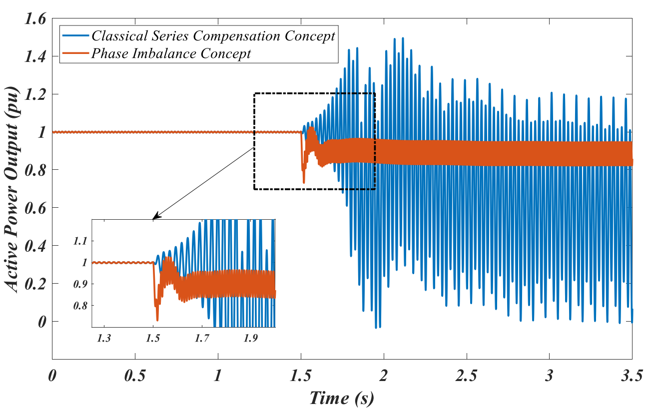

Fig. 8. Performance comparison of the classical series compensation and phase imbalance compensation concepts (K_A=0.25 and K_C=0.75)

It is observed that the PIC scheme results in lower resonance frequencies of the system, when compared to the CSC scheme. However, these smaller resonance frequencies remain in the negative resistance region and therefore continue to exhibit DFIG SSR. The reduction in the oscillation energy can be explained by examining the DFIG's damping for the frequencies 17 Hz and 27 Hz (see Fig. 6). As the damping is less negative for these frequencies, the amplification of the subsynchronous oscillations is less pronounced, which is observed by a reduced oscillation energy.

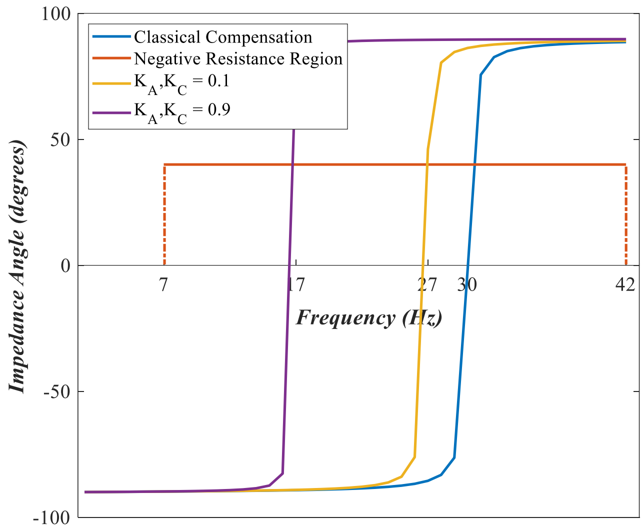

Fig. 9. System impedance angles for the classical as well as phase imbalance compensation schemes. For all the investigated cases, the resonance frequency remains in the negative resistance region.

VI. Conclusions

This paper investigated to what extend the phase imbalance compensation scheme was able to mitigate subsynchronous interactions between a DFIG wind turbine generator and a series compensation transmission system. The main difference between the phase imbalance compensation concept and the classical series compensation concept is that the former implements a phase wide compensation, where the impedance of each phase is different. This introduces an asymmetry. The degree of asymmetry that was investigated in this work varied from 0.01 to 1.00. Based on the performed analysis, two main conclusions were obtained.

First, the phase imbalance concept was able to reduce the aforementioned adverse interactions. The phase imbalance concept lowered the resonance frequencies of the system, which in turn resulted in increased damping from the DFIG.

Second, the phase imbalance concept was not able to completely eliminate the adverse interactions for the considered degrees of asymmetry. As the lower resonance frequencies still fall in the negative resistance region of the DFIG, the net damping remains negative and consequently, the adverse interactions remain in the system (albeit in a reduced form).

This paper investigated the effectiveness of the phase imbalance compensation scheme for degrees of asymmetry varying between 0.01 and 1.00. The next step is to investigate the effectiveness of larger degrees of asymmetries (larger than 1.00) in mitigating DFIG-SSR. Ultimately, hardware in the loop analysis will be performed using a control cubicle of a DFIG to validate the achieved results.

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APPENDIX A

The table below provides information on the wind turbine generator and converter parameters.

TABLE A
Generator and Converter Parameters

Parameter	**Value**
GENERATOR	
Machine rating	4 MVA
Nominal system frequency	50 Hz
Rated voltage	0.9 kV
Stator leakage inductance	0.10 p.u.
Rotor leakage inductance	0.11 p.u.
Magnitizing inductance	4.5 p.u.
Stator resistance	0.0054 p.u.
Rotor resistance	0.00607 p.u.
Stator/rotor turns ratio	0.391
Angular moment of inertia	6 seconds
Drive train stiffness	200 p.u.
Drive train damping	1.7 p.u.
CONVERTER	
$K_{p,dc}$, $K_{p,Q}$, $K_{p,dS}$, $K_{p,qS}$	5, 1, 1.2, 1.2
$T_{i,dc}$, $T_{i,Q}$, $T_{i,dS}$, $T_{i,qS}$	0.05, 0.1, 0.02, 0.02
$K_{pP,PCC}$, $K_{pQ,PCC}$, $K_{p,dR}$, $K_{p,qR}$	0.2, 0.3, 1.5, 2
$T_{iP,PCC}$, $T_{iQ,PCC}$, $T_{i,dR}$, $T_{i,qR}$	0.5, 0.06, 0.02, 0.02