Analysis of low frequency interactions between DFIG wind turbines and series compensated systems

A. S. Trevisan, M. Fecteau, A. Mendonça, R. Gagnon, J. Mahseredjian

***Abstract* – New dynamics added by wind power plants to power systems are forcing reconsiderations in the way power systems are studied. Doubly-fed induction generator (DFIG) based wind turbines represent a considerable part of the existing parks and the ones to be interconnected in the future. Moreover, real life events and subsequent studies have indicated that DFIG systems might be susceptible to adverse interactions with series compensated systems. This paper focuses on the analysis of the interaction phenomenon. A new benchmark network is proposed to address the investigation of low frequency oscillations between wind generation and series compensated systems based on realistic system parameters. Nonlinear components and the representation of the wind farm are included. An analytical model for the generic DFIG based wind farm is developed considering all inner and outer loops as well as its mechanical parts. Participation factor analysis is then applied to the model to identify the states most contributing to the critical modes and to address suitable mitigation. Sensitivity analysis is used to support redesign of control parameters. Investigations indicate that resonance can be avoided with proper control tuning. All conclusions are verified with detailed electromagnetic transient (EMT) simulations.**

***Keywords*: wind power, doubly-fed induction generator (DFIG), series compensation, interaction, SSR, SSCI.**

I. Introduction

In the last years power systems have been experiencing fast and drastic changes. Also, modern energy market structures are pushing power systems to be operated in an economical optimal sense, in a constant attempt of maximizing the use of system's assets. As a consequence, there is an increasing interest for solutions capable of improving system use as well as techniques to support system stability assessment under these expected stressed conditions.

During the past decades, fixed series compensation has been one of the approaches successfully applied to increase system stability margins through improving active power transfer capabilities. On the other hand, series compensation has also been involved in severe interaction events. In the 70's a turbine-generator of the Mohave power plant, in the US, interacted with a series compensated transmission line resulting in serious material damages [1]. More recently, an incident involving a wind farm in Texas, US, called attention for risks involving the connection of wind generation to series compensated systems ([2], [3]).

The latter event yielded the need for a substantial revision of existing assessment methods involving low frequency interactions, which are often categorized as sub-synchronous resonance, torsional interaction or oscillations (SSR, SSTI or SSO, respectively). This is mostly due to the complexity added by power electronics and their controls. Moreover, recent dedicated analysis of the phenomena ([2]-[6]) identified a new category of interaction referring to it as sub-synchronous control interaction (SSCI).

Since then, considerable efforts have been made to improve the assessment and provide mitigation for SSO involving doubly-fed induction generator (DFIG) wind turbines ([5]-[10]). Similar work was also conducted for type-IV wind turbines, however recent publications indicated that these are less prone to interact with series compensation ([11]-[13]).

The development of an analytical state-space representation has been pointed out for a long period as a powerful technique for power system analysis and dynamic stability studies [14]. However, its requirement on formal development of full-order state-space representation in conjunction with the complex structures and inverter-based devices of modern power systems can become time consuming ([15]-[17]). Due to this fact, several analytical investigations involving inverter-based units with complex structures (such as DFIG systems) and series compensation make use of certain simplifications and/or neglect some control loops ([16], [18]-[20]).

Alternative methods try to detect unstable operating conditions by extracting frequency depended characteristics for converter and grid without the need for analytical equation development ([5],[6],[21]-[23]). These methods, however, do not provide insight into system states, modes and their damping characteristics, which is usually required to support studies of control modifications to reduce interaction risks.

This paper contributes to fill this gap and presents the results of a linear analysis for a complete DFIG wind farm system in conjunction with a series compensated grid. Electrical, mechanical and control components were considered. The methodology for the analytical model development is outlined.

Additionally, a new benchmark system is proposed for interaction studies involving wind farms and series compensated grids, with the consideration of relevant nonlinear equipment (e.g. arresters and transformer saturation characteristics) as well as collector system equivalent used in aggregation.

The linearized state-space representation of the complete

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system is validated against its corresponding detailed electromagnetic transient (EMT) model in EMTP [24]. The validity of linearized system representation is investigated for SSR, SSTI and SSCI. Participation factor analysis is applied to identify the states most contributing to the critical modes and, therefore, to provide orientation for suitable mitigation. Sensitivity analysis is then used to support redesign of control parameters to reduce interaction risks. Finally, these results are verified with detailed EMT simulation.

This paper is structured as follows. Section II introduces a new benchmark for interaction studies between wind farms and series compensated grids. Section III describes the generic DFIG system used in these investigations. Section IV outlines the methodology used for the development of a linearized state-space representation for the complete system. This system is validated in Section V against its EMT detailed representation. Section VI deals with the interaction analysis focusing on the series compensation level and on possible mitigation approaches. Conclusions are drawn in Section VII.

II. Benchmark for Interaction Studies Between Wind Turbines and Series Compensation

Due to the radial electrical system structure present in the Mohave [1] and in the Texas events ([2],[3]), radial system structures are believed to be the most critical for SSR and SSCI phenomena. This has been again verified in the investigations presented in [25].

The proposed system is based on a wind integration project that Hydro-Québec had a few years ago, which was never realized for technical and economic reasons. It assumes, therefore, realistic components and parameters and serves already as a benchmark for testing wind turbines to be connected to series-compensated areas of Hydro-Québec. It consists of a radial series compensated system connected to a weak source. The planned system was supposed to connect three WPPs. In order to reduce the system complexity, only the WPP closest to the series compensated source is represented. Since studies had to be done before the wind farm was built, typical collector system data from [26] were used. Fig. 1 illustrates the test system used and Table I provides the system parameters.

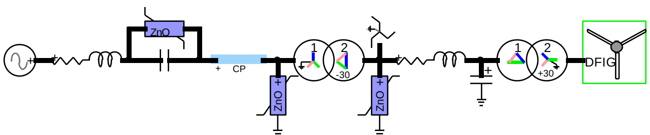

Fig. 1. Benchmark for studies involving WPPs and series compensated grids.

Nonlinearities from the varistor connected across the series capacitors, surge arresters and transformer saturation were considered. Surge arresters are used to limit transient overvoltages following grid events. Varistors are used to protect the series capacitor during transients limiting voltage across terminals between 2.1 and 2.6pu depending on design. For the test system, the protection level has been set at 2.3pu. Varistors also limit the voltage that can be trapped on the line side of the series compensation following a grid event. Such trapped voltages could contribute to transformer saturation leading, for example, to ferroresonance. In reality, varistors and surge arresters are usually composed of several ZnO (zinc oxide) discs. For the EMT modeling, just one is considered based on fitting. Their data is provided in Table II.

TABLE I
Electrical Parameters of the Benchmark Grid

Test system parameters
Grid equivalent : 230kV, 2 + j25 Ω, 60 Hz
Series compensation : 30 Ω, 1 kA, 2.3pu protection level
Line data : R1=5.96Ω, X1=50.9Ω, B1=324μS, R0=2.74 Ω, X0=120.75 Ω, B0=220.14μS, length=100km, continuously transposed
Main transformer data : 230/34.5kV, 115MVA, 11.5%, X/R=45
Grounding transformer: R0 = 0.28Ω, X0 = 7.5Ω
Collector system data : R1=0.22Ω, X1=0.147Ω, C1=7.17μF
Turbine (lumped) transformer: 34.5/0.575kV, 115MVA, 5.7%, X/R=15.2
Saturation characteristic for transformers [current magnitude (pu), Flux(pu)]: [0.002;1], [0.01;1.075], [0.025;1.15], [0.05;1.2], [0.1;1.23], [2;1.72]

TABLE II
Varistor and Arresters' Characteristics

Series Comp.		**230kV Substation**		**34.5kV Substation**	
I(A)	**V(kV)**	**I(A)**	**V(kV)**	**I(A)**	**V(kV)**
0.045	76.9	0.03	280.8	0.004	38.4
15	81.5	4	321.4	5	46.9
150	86	300	363.2	200	52.0
2250	93.6	2000	396.6	2000	57.2
15000	101.5				

III. DFIG Based Wind Power Plant

The analytical investigations conducted in the framework of this paper are focusing on possible low frequency interactions involving a DFIG based WPP (also known as type-III wind turbine system).

As shown in Fig. 2, the voltage source converter (VSC) of a DFIG is divided into a Rotor-Side Converter (RSC) and a Grid-Side Converter (GSC). The RSC is responsible for controlling the generator speed and the reactive power flow through the turbine terminals. The GSC regulates the dc-bus voltage to a constant value.

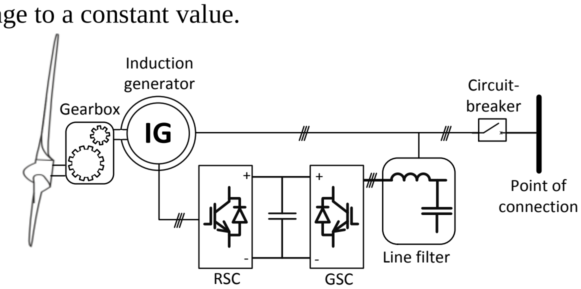

Fig. 2. Generic type-III Wind Turbine System.

The DFIG system used is the same presented in [27] and used in [28]. Its details are similar to the system extensively described in [22]. For the representation of a wind farm in the next investigations, a lumped model consisting of 66 DFIGs (each of 1.7 MW) is assumed.

IV. State-Space Representation of Complete System

The complete system is composed of several linear and nonlinear components on the grid as well on the wind farm side. Its dynamic representation can be generically given as

$$\begin{cases} \dot{x} = f(x,u) \\ y = g(x,u) \end{cases} \tag{1}$$

where x_i, u_i, y_i denote the vector of states, inputs and outputs for the *i*-th component, respectively.

To conduct the investigations outlined in the next sections, a linearized state-space representation in the form of (2) is required for the complete system. Linear analysis has been preferred due to the existence of a broader range of available techniques whose results are easier to grasp if compared to nonlinear ones. Identifying the root causes of oscillations is much simplified when based on the application of classic control techniques to linear models.

Since the linearization of a nonlinear system presupposes a steady-state condition for all system states, *abc*-to-*dq* transformation was required to allow for the consideration of only constant quantities.

$$\begin{cases} \Delta\dot{x} = \boldsymbol{A}\Delta x + \boldsymbol{B}\Delta u \\ \Delta y = \boldsymbol{C}\Delta x + \boldsymbol{D}\Delta u \end{cases} \quad (2)$$

There are several methods for obtaining a complete system representation based on the connection of several dynamic systems as given by (2), as for example the methodologies described in [29] and [31]. In this paper, a Matlab based solution has been preferred. More specifically, the function *connect* was used to allow for the development and connection of separate state-space systems [32]. By developing separately state-space representations for portions of the complete system and well-defining the names of input and output variables for each system (connection points), it is possible to combine several state-space systems of different sizes to obtain a final multiple-input multiple-output (MIMO) state-space representation. The biggest advantage of this method is the possibility of freely defining boundaries in the system to be modelled. This becomes particularly useful in cases where separate control blocks are used or internal measurements for specific control parts are available. It provides, therefore, the ability to develop, linearize and validate each state-space system representation for a specific system part separately.

Based on the aforementioned approach, separate linearized state-space representations were developed and validated for each single electrical, mechanical and control block. All nonlinear systems were considered, however since a normal steady-state condition is assumed for the linearization, some nonlinear functions (such as the transformers' saturation characteristic) do not appear in the linearized equations. The only simplification made on the grid side concerns the representation of the transmission line, for which a pi-representation for the rated frequency was assumed.

On the WPP side, all inner and outer control loops of the DFIG system as well as mechanical components were considered. Averaged representations were used for the power electronic stages. However, it should be emphasized that these assumptions are not expected to have impacts in the low frequency region being addressed in this work [30].

The resulting systems formed a type of library that, finally, were connected to each other to obtain a complete linearized state-space representation for grid and wind farm. Moreover, the importance of defining well all existing reference frames and their relation when working with the *dq*-transformation should be also emphasized. Inverter-based systems (as the case of the DFIG) make use of an internal reference frame, defined by their synchronizing unit. Most inverters rely on a phase-locked loop (PLL) to track the voltage phase at their terminals. To take these dynamics into consideration, the state-space systems are developed for each controller in their own *dq*-reference frame (e.g. PLL-based). They are later translated to a common reference frame, to which all equations are referred to, as described in [31].

After linearizing and developing a state-space representation in the form of (2) for all single components and connecting them accordingly, a final MIMO state-space representation with a total of 81 states was obtained. This system was then validated against its detailed nonlinear representation, which was simulated in EMTP, as demonstrated in Section V.

V. Validation of Linearized System Representation

A series of small perturbations were applied to the inputs of the linearized system to validate its response against its detailed nonlinear representation. Due to space constraints, the validation plots for each of the states and outputs of the system are not shown in this paper. Fig. 3 to Fig. 5 were selected to provide an insight into the validation procedure by demonstrating how the currents through the transmission line, the PLL states and the dc-bus voltage from the linearized state-space system compare against their detailed representation in EMTP. Four system inputs were perturbed. Perturbations were applied sequentially as ideal steps, up and down, of same amplitude, separated by 0.5s. First, the *d* and *q* components of the grid source were perturbed by 0.025pu. Then, the reference values for the dc-link voltage and the GSC *q*-axis current were varied by 5V and 0.1pu, respectively.

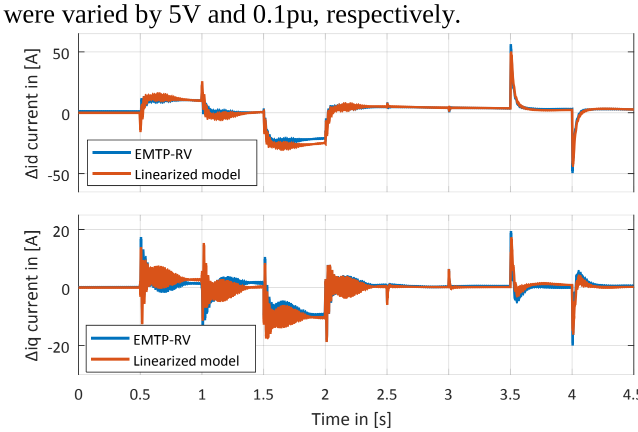

Fig. 3. Comparison for Δid and Δiq currents through transmission line.

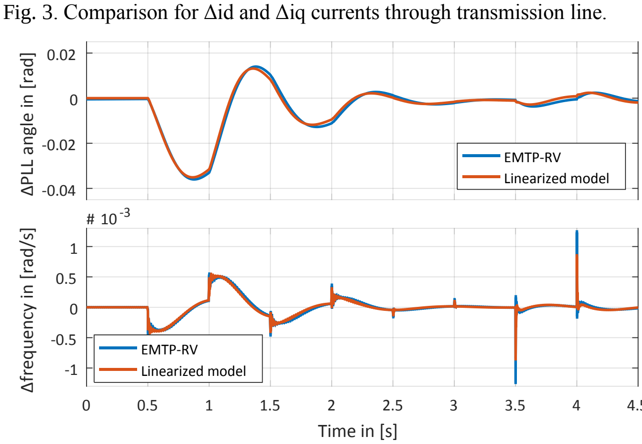

Fig. 4. Comparison for ΔPLL reference angle and Δfrequency (PLL).

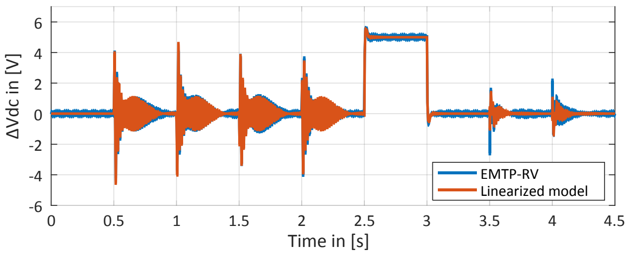

Fig. 5. Comparison for ΔVdc.

It should be emphasized that a perfect match between the linear model and its detailed representation in EMTP was not expected, since the latter has all nonlinear dynamics included, whereas these are linearized in the former. Nevertheless, Fig. 3 to Fig. 5 confirm that the original discrete nonlinear system can still be sufficiently well approximated by a continuous linear representation for small perturbations around a stable operating point, which corresponds to its validity region.

VI. Analysis of Interaction between DFIG and Grid

Investigations were carried out for the linearized state-space representation of complete system (Fig. 1) presented in Section II and III and validated in Section V. Initial simulations with the detailed nonlinear model in EMTP indicated no adverse interaction for a line series compensation level below 10%. This will be now investigated in the next subsections.

A. *Impact of series compensation*

To investigate the impact of varying the series compensation level, a modal analysis was conducted. For this, the linearized state-space representation for the complete system was used and the eigenvalue traces were plotted for small increments in the series compensation level: starting at 1% and varying until 15% in steps of 1%. Fig. 6 shows the eigenvalue traces for some low frequency modes and indicates that a complex conjugate pair of modes is strongly affected by the compensation level. The analysis also indicated that these modes cross to the right-half plane (RHP) when the compensation level is equal or higher than approximately 10%, confirming the expectations obtained by the detailed nonlinear model.

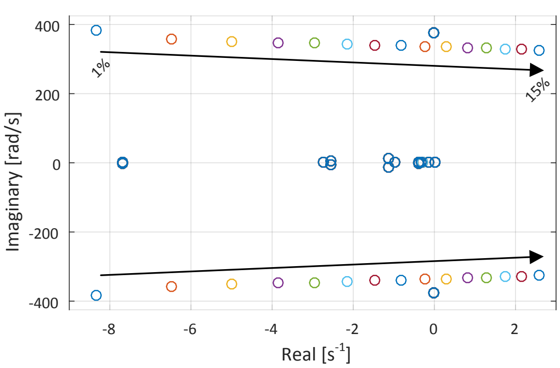

Fig. 6. Eigenvalue traces for varying series capacitance.

To validate these results, the detailed EMTP model (presented in Fig. 1) was used. A three-phase high impedance fault (1.35kΩ) at the point-of-connection, which is assumed at the 230kV side of the substation transformer, was applied at time t=1s for 100ms. It results in a voltage drop of around 5%, which can be understood as a small perturbation for the given operating point. Different line series compensation levels were simulated. The system responses are shown in Fig. 7 for the instantaneous active power measured at the WPP terminals and the dc-link voltage of the DFIG system. Since the system is stable for any line series compensation level below 9% and unstable for any level above 10%, only three cases were selected to be illustrated Fig. 7 to increase figure readability.

Note that the results illustrated in Fig. 7 are in accordance with the eigenvalue traces shown in Fig. 6. The damping of the critical modes is decreased when the line compensation level is increased, until the limit of around 10% compensation achieved, above which unstable operation is indicated. Also, a frequency of 52 Hz can be extracted from the waveforms of the detailed EMTP analysis, which, again, is in accordance with the results presented in Fig. 6.

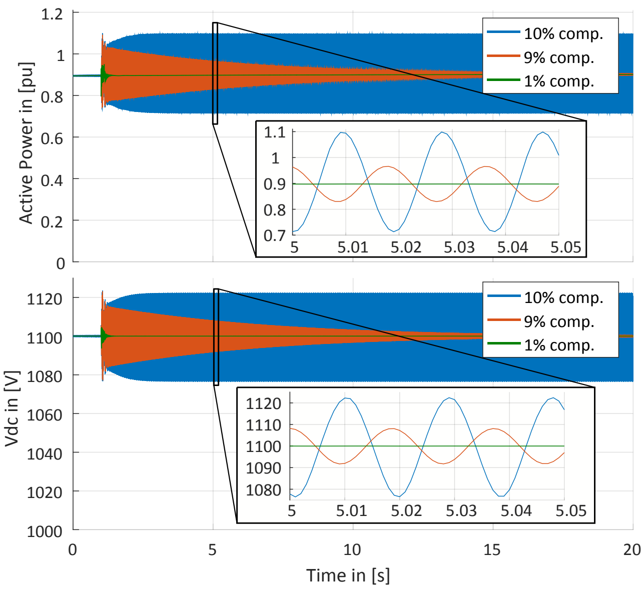

Fig. 7. Active power and Vdc responses for different line compensation.

Moreover, to better understand the interaction phenomenon, a participation factor analysis was conducted for the linearized state-space representation of the complete system. The participation factors provide a measure of the contribution that a *k*-th state has to a specific *i*-th mode of the system [33] and are defined as:

$$p_{ki} = u_{ik} w_{ki} \tag{3}$$

Where u_{ik} and w_{ki} are the *k*-th elements of the *i*-th left and right eigenvectors, respectively.

Table II presents the participations of the system states in the critical mode in descending order of magnitude. The line compensation level was assumed at 10% for this analysis (unstable). For convenience, the participation factors were normalized so that their sum adds to the unit.

The participation factor analysis, summarized in Table II, allowed the verification that, for this particular case, the states that participate most in the critical mode are of electrical nature (currents and voltages). They indicate an interaction between the IG's inductances and the capacitor of the series compensation, since their corresponding states are the ones mostly contributing to the critical mode. Although a complete system representation for the grid and WPP was considered, no states associated with the mechanical or control systems appear listed among the most contributing states and were, therefore, grouped with all other system states, which combined participate less than 4% in the critical mode.

TABLE II
PARTICIPATION FACTORS FOR CRITICAL MODE

State	*p*
I_{s_d} (d-axis stator current of IG)	0.2383
I_{s_q} (q-axis stator current of IG)	0.2014
I_{r_d} (d-axis rotor current of IG)	0.2087
I_{r_q} (q-axis rotor current of IG)	0.1766
V_{Cs_d} (d-axis voltage of series cap.)	0.0623
V_{Cs_q} (q-axis voltage of series cap.)	0.0604
I_{line_d} (d-axis transmission line current)	0.0057
I_{lime_q} (q-axis transmission line current)	0.0093
All other system states	0.0373

B. Impact of RSC current regulator gains

Additional investigations were conducted to assess the impact of DFIG control parameter changes in the stability of the complete system. Since the participation factor analysis presented in the previous subsection (see Table II) indicated that the IG stator and rotor currents belong to the states most contributing to the critical mode and given the fact that only the rotor currents are controlled in the DFIG system, mitigation approaches were oriented towards the RSC current controller. Therefore, the following analyses are focusing on assessment of the impact of the RSC current controller gains in the complete system stability.

To assess their impact, sensitivity analysis was conducted and the low frequency eigenvalue traces were investigated. For simplicity, it was assumed that both the proportional and integrator gains of the RSC control were varied simultaneously and proportionally to their original values. More specifically, they were decreased to 30% of their original values in steps of 10%. Additionally, a line series compensation level of 20% was assumed for this analysis, which, as demonstrated in the previous subsection, corresponds to an unstable condition for the original case. The resulting eigenvalue traces are illustrated in Fig. 8.

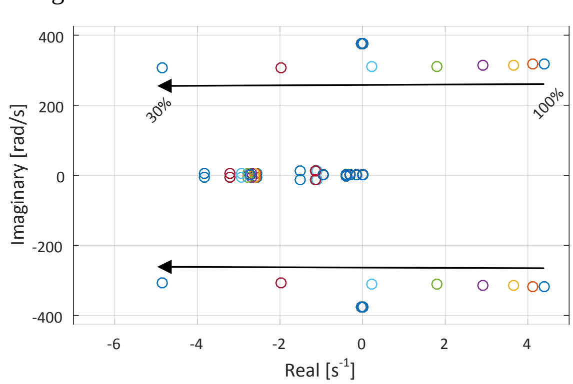

Fig. 8. Eigenvalue traces when varying RSC current control gains.

It is readily visible from Fig. 8 that the RSC controller gains have significant impact in the critical mode and, therefore, can affect the stability of the complete system in the same manner. The results also indicate that reducing the RSC current controller gains to around 48% (or less) of their original value should help stabilizing the system, even for the considered line series compensation level of 20%.

To validate these conclusions, the detailed representation of the system in EMTP was again used. A line series compensation level of 20% was assumed in the simulation model accordingly. The RSC current controller gains were reduced to 40% of their original value. The system was perturbed by the same high impedance fault for t=1s, described in the previous subsection. The results are shown in the next Fig. 9.

The results in Fig. 9 demonstrate that it is possible to avoid the risk of interaction between the DFIG based WPP and the radial series compensated grid by tuning the RSC current controller gains. Moreover, by comparing these results to the ones previously addressed in Fig. 7, it is also apparent that a higher damping could be achieved for the system response, although the line series compensation level of 20%. These results are also in line with the eigenvalue traces illustrated in Fig. 6 and Fig. 8, respectively.

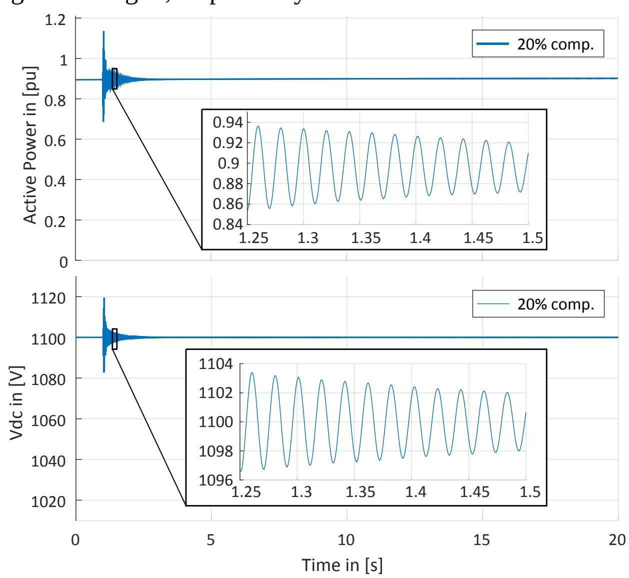

Fig. 9. EMTP results for RSC controller gains reduced to 40% of their original value and line compensation level of 20%.

Finally, it is important to mention that these results apply to the specific system investigated in this paper and that different DFIG controller and characteristics may yield different results. Furthermore, it should be also pointed out that reducing the RSC controller gains, although appealing due to their impact in reducing SSO risks, may impact the performance of the DFIG in other aspects as well, such as in its low-voltage ride through (LVRT) performance. One should verify if the new RSC parameters are still corroborating with the compliance of other requirements on the DFIG control system. These investigations were left outside of the scope of this paper.

VII. CONCLUSIONS

This work deals with a fundamental investigation of possible low frequency interactions involving DFIG based WPPs and series compensated power systems.

A new benchmark study system is proposed to support investigations of low frequency interactions involving wind farms based on realistic data. Nonlinear components, such as series compensation varistors and transformer saturation, as well as collector system representation are considered.

The development of a linearized MIMO state-space representation for the complete system was outlined. All inner and outer control loops as well as mechanical components of the DFIG system were taken into account.

The impact of increasing line series compensation level was evaluated with eigenvalue analysis. Participation factor analysis was applied to the resulting system representation and helped identifying the states that are most contributing to critical modes. It was seen for this particular case that these states are most of electrical nature. These results were also used to provide orientation for mitigation approaches with the aim at reducing the interaction risks.

It was shown that the gains of the RSC current controller of the DFIG system can significantly affect the system stability. Sensitivity analysis was then applied to support redesigning the RSC current controller gains with the aim of stabilizing the system even for higher series compensation levels. It was also demonstrated that these parameters, if properly tuned, can support mitigating the issue.

Finally, it was seen that the assessment of low frequency interaction based on the state-space approach and linear analyses allowed for proper identification of risks and supported mitigation of interaction. All results were verified by detailed EMT simulations of the corresponding systems.

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