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Influence of the Increasing Non-Synchronous Generation on Small Signal Stability

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Abstract—The increasing installation of aggregated renewable generation based Full Rated Converters (FRC) in current power systems is modifying their dynamic characteristics. This paper analyses the influence of large scale inclusion of non-synchronous generation through back-to-back Voltage Source Converters' (VSC) connection on power systems, by presenting the dynamic changes on inter-area oscillations in different penetration level cases. The aggregated model of VSC units is assumed. The Small Signal Stability Analysis (SSSA) is used to show the dynamic behaviour and presents the performance of the power systems related to the domain frequency modes in a test grid system. From the analysis, it is shown that the mode shapes and participation factors are displaced according to the penetration levels. Eigenvalue sensitivity analysis according to the inertia is also applied, showing the impact of the large penetration of non-synchronous generation.

Index Terms—Non-Synchronous Generation, Small Signal Stability, Full Rated Converter, Sensitivity, System Inertia.

I. INTRODUCTION

THE global concern about green house emissions and high pollution indexes have motivated the development, improvement and investment in new technologies for Renewable Energy Sources (RES) (mainly Photovoltaic and Wind Power). The integration and expansion of RES into the grid, requires of an adequate operation and planning to make the interconnection and supply for future energy demands possible.

Countries like Denmark, Germany, Spain and Ireland have a significant percentage of their energy from RES, which use Full Rated Converters (FRC), have experienced several challenges integrating them to the energy pool and portfolio [1]. The European Union has targeted that 20% of the energy usage should be produced by renewable generation [2]. The use of RES based FRC in Sweden has been slow compared to other countries in the region, however, it is being considered as a possible strategy to be added to the existing generation or to replace other forms of generation in the country [3], [4].

Some of the aspects which can be affected by the inclusion of non-synchronous generation are the frequency control and inertia, the local system protection schemes, and the oscillatory stability [5], [6].

Different transmission system operators and power planners, have reported a decline in the frequency response and inertia due to the inverter interfaced generation on the conventional generation (synchronous generators) during the last years. The most important reports among them are HydroQuebec [7], the Electric Reliability Council of Texas (ERCOT) [8], the Western Electricity Coordinating Council (WECC) [9], and California System Operator [10]. All of them agree that the massive penetration and integration of energy converter systems has had a significant impact on the system inertia and the dynamic characteristics.

The use of back-to-back Voltage Source Converters (VSC) by non-synchronous generation, decouples them from the power system, making them insensitive to any change in the system frequency, and consequently unable to contribute dynamically to the system, thereby displacing synchronous machines [11], [12].

Different proposals and contributions have been studied the oscillation modes under non-synchronous integration.

A study about the large scale of wind integration is presented in [13], where some bifurcation diagrams with the eigenvalues movement according to the placement of wind power addition is observed. The impact of wind power systems on inter-area oscillations in small and large power systems has been studied in [14], where different patterns of wind and load showing a decrease in the damping factor is also considered.

Reference [15], studies the impact of wind power on small signal stability by depicting the trajectory of the eigenvalues, while varying the wind power penetration level and its location. The results show that the replacement of synchronous generators by wind turbines has more influence in the inter-area than in the intra-area oscillations.

A dynamic assessment methodology of wind power is presented in [16], where the DFIG machines are converted into conventional synchronous machines. There is shown that the oscillatory modes movement by the increasing introduction of wind farms and is evaluated the eigenvalue sensitivity according to the inertia. The results also mention the impact on the above according to the location of the plants. In a subsequent study [17], the indirect effects of non-synchronous generation in the displacement of the inter-area modes of the system and the damping performance by altering the synchronisation torques and the displacement of synchronous machines is mentioned.

Regarding Photovoltaic (PV) power plants, in [18] its effect on the Small Signal Stability (SSS) is investigated, and it is shown that it has a detrimental effect depending on its location

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and penetration level.

This paper, however, analyses the effect of the increasing replacement of synchronous generators by high penetration of aggregated non-synchronous generation on the SSS, including full converters as an interface on it. The analysis is illustrated in the Nordic test system. Modal analysis is applied to show how the dynamic behaviour changes under high penetration of wind power identifying the displacement of the synchronous machines with and without PSS (Power System Stabilizers). Eigenvalue sensitivity according to the inertia is also applied

The paper is structured as follows: In Section II a basic overview of SSS Analysis concepts is given. Section III presents the case studies regarding the gradual increasing of non-synchronous generation integration on a test system. In Section IV SSSA is applied. Finally, the conclusions and future work of this research are given.

II. MODAL ANALYSIS PRELIMINARIES

Small signal stability is associated with the oscillatory stability problem which increases due to insufficient damping torque [19]. The dynamic of a power system can be described by

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \quad (1)$$

where, x is a state vector of order $n_x \times 1$, y is a output vector of order $m \times 1$, u is a system inputs vector of order $r \times 1$, A is a state matrix of order $n_x \times n_x$, B is a input matrix of order $n_x \times r$, and C is an output matrix of order $m \times n_x$. The eigenvalues of the system are defined as

$$\det(A - \lambda I) = 0 \quad (2)$$

where, $\det$ stands for the determinant, and I is the identity matrix. Each eigenvalue λ_i is associated with a mode of the system, and is expressed by

$$\lambda_i = \sigma_i \pm j\omega_i \quad (3)$$

The oscillation frequency and the damping ratio of the mode are given by

$$f_i = \frac{\omega_i}{2\pi}, \quad \zeta_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \quad (4)$$

The mode shape vector is the corresponding right eigenvector which satisfies

$$AV_i^r = \lambda_i V_i^r \quad (5)$$

The mode shape determines how generators participate in the oscillations which is defined by each mode λ_i .

The left eigenvectors V_i^l satisfies

$$V_i^l A = \lambda_i V_i^l \quad (6)$$

The product of V_i^r and V_i^l are the participation factors, which is a measure of the relative participation of the k -th state variable in the i -th mode.

The sensitivity of the eigenvalue with respect to generator inertia is expressed as [16]:

$$\frac{\partial \lambda_i}{\partial H_j} = \frac{V_i^l \frac{\partial A}{\partial H_j} V_i^r}{V_i^{lT} V_i^r} \quad (7)$$

where, H_j is the inertia of the j -th synchronous generator.

III. STUDY CASES

Figure 1 shows the single-line diagram of the Nordic test system presented in [20]. This system contains 32 high voltage buses. The transmission system is designed for 400 kV with some regional systems at 220 kV and 130 kV. This system has three identified areas of operation: North, Central and South. The simulation of this test system has been performed by the software SIMPOW®[21].

Figure 1. Test System

The impact of the integration of non-synchronous generation on the test system small signal stability is analysed by replacing some of the synchronous generators with back-to-back FRC with the same active and reactive power outputs. Note that the power outputs are fixed through the simulation. Case 1 to Case 6 represent the replacement of synchronous generation by the integration of non-synchronous generation based FRC gradually, in order to analyse different levels of power penetration. For example Case 1 considers the replacement of one generation only, and Case 2 considers the replacement of two generators including the one in Case 1, and so on. It is assumed that the dispersed generation is connected to one established substation. These six scenarios are summarised in Table I:

Power System Stabilizers have been located in the test system connected to the following synchronous machines: 1042, 1043, 4011, 4042, 4047, 4051, 4062, 4063.

Table I
GENERATOR REPLACEMENT FOR EACH CASE

Case	1	2	3	4	5	6
Generator	G_7	G_{16}	G_{17}	G_{14}	G_6	G_{18}
Bus	1043	4051	4062	4042	1042	4063
Power (MW)%	1.2	5.4	9	13	15	20

IV. SMALL SIGNAL STABILITY ANALYSIS

The analysis starts with the power flow in order to get the initial conditions to initialise the dynamic simulation. Then, from simulation, two critical modes have been identified in the test system based on the low damped and frequency values, which reflect the inter-area oscillations (0.2-0.8 Hz). Frequency and damping ratio of these modes are 0.56/0.07 and 0.78/0.09 respectively.

This analysis emphasises on the inter-area modes and their changes according to the increased non-synchronous generation penetration cases mentioned and compared to base the case, which only has synchronous generation.

A. Eigenvalue Analysis

The eigenvalues plotted in Figure 2a are based on the cases mentioned before. The movement of the eigenvalues according to the inclusion of non-synchronous generation for different penetration levels is shown. In Figure 2b, the movement of the dominant eigenvalues according to the cases is presented. In the first two cases there is a slight change. However in the other cases the variation is significant, changing also the damping ratio region. This is related to the dynamics change and the absence of PSS.

Figure 2. Movement of System Eigenvalues (Positive Imaginary Plane)

B. Mode Shapes

The mode shapes for the dominant modes without any penetration of wind power are plotted in Figure 3a and 3b. In the present analysis only the largest magnitude are taken into account.

Figure 3. Mode Shapes (Case 0)

The operative areas mentioned above are colored as follows: North (in blue), South (in Orange) and Central (in Green). For the first dominant mode, the oscillation of generators 4063, 4062, 4051, 4042, 4047 and 1042 against the rest of the power system is reflected, in other words Central and South are oscillating against the North area. For the second dominant mode, generators 4063, 4062 and 4072 are oscillating against 1042, 4051, 4047, 4042.

The variation of these modes according to the inclusion of non-synchronous generation is now presented. Figure 4 shows the variation of the mode shapes with the largest magnitudes under the gradual replacement of synchronous machines for the first three cases (C_1 , C_2 , C_3). The magnitude of the 4072 mode shape remains constant, the magnitudes of 1042, 4042 and 4047 present slight changes while 4063 shows some significant changes.

Figure 4. Mode Shapes Movement for First Domain Mode (First Three Cases)

Cases C_4 , C_5 , C_6 show drastic changes in the mode shapes distribution immediately is replaced the fourth machine by non-synchronous generation. In Figure 5, it can be seen that for Case 4, North area is oscillating vs the South and Central areas, but with the replacement of the fifth machine, the oscillation changes to North and South vs the Central area. Finally Case 6 reflects the oscillation of Central vs North areas. This is due to the fact that the larger synchronous generator in South has been replaced.

For the second dominant mode, the mode shapes do not show significant variations for the first three cases as well as the first domain mode. The generator's mode shape 1042 does not vary its magnitude and position. The most significant changes are presented for the 4063 and 4072 modes, which change their magnitudes and angles for Cases 2 and 3.

Figure 5. Mode Shapes Movement for the First Dominant Mode (Final Cases)

Figure 6. Mode Shapes Displacement: First Three Cases (Second Dominant Mode)

With the replacement of the fourth machine, the 4072 and 4063 modes change their angles and magnitudes but 4047 and 4063 have the same trend. With the replacement of the fifth machine, 4072 and 4063 returns to a previous position trend, but 4047 slightly changes. Finally in case 6, with the change of the sixth machine (4063), the 4072 mode shape change its angle magnitude completely and the 1021 mode shape's magnitude increases.

Figure 7. Mode Shapes Displacement: Final Cases (Second Dominant Mode)

C. Participation Factors

In order to identify how the dynamic state variables are affected, the participation factors are plotted, where ω_i is the internal rotor angle of the synchronous machines, δ_i the angles that have the same behaviour. There are only participation factors greater than 0.1 included. For the first dominant mode, participation factors show a trend from cases 1 to 5, which explain that the more non-synchronous generation is included, the less 4072 machine (in blue) is participating, while 4063 (in green) is participating more, which belongs to the Central and South areas respectively. Case 6 shows a different behaviour

showing the increased participation of 4047. For the second dominant mode, Figure 8 shows an increasing participation of generator 1042 till it is replaced. Besides, the increasing participation of generators 1021, 4047 and 4072 can be seen. Generator 4063 remains participating.

Figure 8. Participation Factors

D. Sensitivity Analysis with Respect to Inertia

Following the analysis presented in [16], eigenvalue sensitivity according to the inertia is developed for the base case and the first two cases, with the two dominant modes identified before. The corresponding real and imaginary parts sensitivity values for the generators are presented in Figures 9 and 10.

In this case, the more non-synchronous generation is added, the more detrimental or beneficial effects have been caused in the system. From Figures 9b and 10a, it can be seen that most of the sensitivity values reduce their magnitude when the inertia in the system is also reduced. Some of them are less negative, becoming more unstable, or less positive becoming less positive. Positive in sign means that with the decrease of inertia in the system the mode is moving to the left half of the plane, but negative means the opposite, the modes will move closer to the right half of the plane. For the first dominant mode, it can be seen that the sensitivity according to the inertia in generators 1042 and 4047, present a change in their beneficial effect according to the new inclusion of FRC. Furthermore, the second mode (Figure 10b), generators 1022 and 4021 show a detrimental effect due their change from negative to positive.

V. CONCLUSIONS

This paper presents a Small Signal Stability analysis by the inclusion of non-synchronous generation based Full Rated Converters in the test Nordic power system.

Two dominant modes have been identified in the system and their variation according to the gradually penetration cases is presented. Mode shapes movement show the oscillations between the operative areas. The replacement of the fourth machine (9% of the power in the system) seems to be a drastic change in the system due to the new orientation and change in magnitude mode shapes.

The participation factors confirm which machines are contributing more in each case, and they shows a pattern according to the test system studied.

Figure 9. Sensitivity Variation (First Dominant Mode)

Figure 10. Sensitivity Variation (Second Dominant Mode)

Sensitivity analysis with respect to the inertia shows how the modes are affected by the inclusion of non-synchronous generation and the critical generators which can detriment the stability in the system is identified.

Even though in these cases can be seen a trend, sensitivity analysis also shows that it depends on which case (penetration level) is analysed. Every case has different equilibrium points and should be analysed more in detail.

Generators who have PSS contribute more in the stability and are most invariant to changes in the inertia diminution.

Future work requires the addition of PSS to non-synchronous generation and other control loops, e.g. synthetic inertia.

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