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Forced Oscillation and Inter-Area Mode Resonance – Effect of the Location of the Oscillation Source

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***Abstract*— This paper investigates how the location of forced oscillation (FO) source affects the resonance phenomenon between the FO and inter-area oscillations. The analysis is performed in a simple two generator system and the full Nordic power system simulation model. The main finding is that when the FO source is moved from the "center of the inter-area oscillation mode" towards the "ends" of the system, the amplification of the FO increases approximately linearly as a function of the voltage angle difference (or electrical distance) from the center. This finding enables an easy evaluation of risks associated with FO sources in different locations. Such information is also valuable generally in transmission system planning and operation.**

***Index Terms*-- Electromechanical oscillation, forced oscillation, inter-area oscillation, power system dynamics and stability, resonance.**

I. Introduction

Electromechanical oscillations exist virtually in all power systems and in some systems the damping of inter-area modes limits the transmission capacity. Furthermore, poorly damped oscillations may risk the system stability.

In recent years, there has been an increasing research interest in studying the interactions between forced oscillation (FO) sources and inter-area electromechanical modes [1]–[5], and such interactions have been observed in various power systems [2], [4]. It has been shown that the resonance phenomenon of forced oscillations and inter-area modes may risk the system stability [1], [3]. In certain cases, even very low amplitude forced oscillation source may pose a risk of blackout in the entire system, if the damping of the inter-area mode is poor, forced oscillation occur at the same frequency as the inter-area mode natural frequency, and the location of the forced oscillation source is critical in the system [3].

Even though the beforementioned aspects are known, the risk related specifically to the location of the FO source has not been, to our knowledge, thoroughly investigated. [1] and [3] show that when the FO location is close to the "ends" of the system ("ends" refer to the generator groups oscillating against each other), the amplification of the forced oscillations (i.e., resonance phenomenon) seems to be the largest, and thus, most dangerous for the system stability. In addition, if the source is situated in the central parts of the system (in the "center of the inter-area oscillation mode" along its path) the amplification, and thus the risk, seems to be the lowest. However, it is not well known, how the FO amplification behaves when the FO source is located along the path of inter-area oscillation mode in different locations. Understanding this behavior would be very helpful in evaluating the FO risks related to different locations, and thus, important information for system planning and operation.

This paper investigates the effect of the FO source location first in a simple two generator system, and then, the full Nordic power system simulation model, used by the transmission system operators in the Nordic countries. The paper shows that when the FO source is moved from the "center of the inter-area oscillation mode" towards the ends of the system, the amplification increases approximately linearly as a function of the electrical distance from the center. A good indication of the electrical distance is simply the voltage angle difference between the center of the inter-area oscillation mode and the FO source. This result seems to be valid in different power flow conditions and in situations where the oscillating masses (participating generators) differ. This finding enables the evaluation of the risk of the FO source in different locations very easily and is an important analysis tool for system planning and operation.

This paper is organized as follows. Section II presents a brief explanation of the theory of resonance in physics. Section III presents the simulation results with the simple test system and Section IV with the full Nordic power system simulation model. Section V summarizes the paper.

II. Theoretical Background

In this section, the classic resonance theory in physics is briefly discussed. Fig. 1 presents a spring-mass system with a forced oscillation source $F\cos(\omega t)$, which is typically considered as a starting point in resonance analysis.

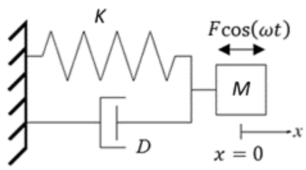

Figure 1. Spring-mass system with a forced oscillation source.

The motion of the system in Fig. 1 can be described by:

$$M\ddot{x} + D\dot{x} + Kx = F\cos(\omega t) \quad (1)$$

A similar equation can be also used to describe the oscillatory motion of a generator (or equivalent generator) around an operating point in a power system [11], if M is considered the inertia coefficient, D the damping coefficient, and K is the synchronizing power coefficient. From (1) it can be shown [6] that the natural frequency of the oscillation mode is $\omega_0 = \sqrt{\frac{K}{M}}$, and the damping ratio is $\zeta = \gamma/2\omega_0$, where $\gamma = \frac{D}{M}$. The amplitude A of the resulting oscillation in the spring-mass system is as follows [6]:

$$A = \frac{F/m}{\sqrt{({\omega_0}^2 - \omega^2) + (\omega\gamma)^2}} \quad (2)$$

Fig. 2 shows the resonance effect of forced oscillations and the natural mode in the simple spring-mass system. The oscillation amplification is the amplitude of the resulting oscillations in the system divided by the amplitude of the FO source. The highest amplification (i.e., resonance) occurs when $\omega_0 = \omega$.

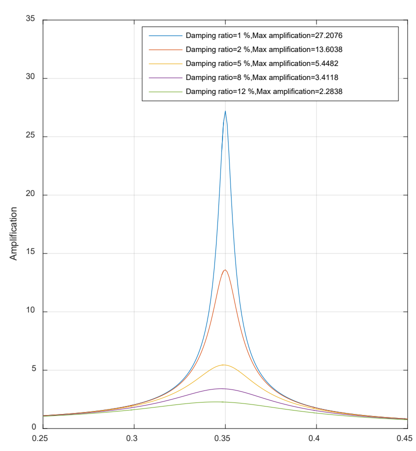

Figure 2. Amplification of the forced oscillations as a function of frequency in a spring-mass system. The resonance frequency is 0.35 Hz in this case. The curves are calculated with different damping levels and the parameters in (2) have been selected such that the amplification and frequency values are in line with observations from certain detected events in the Finnish power system.

III. Simulations with a Simple Test System

A. Test system and simulations

To understand the effect of the location of the FO source, simulations with a simple test system were first carried out. The used test system is presented in Fig. 3.

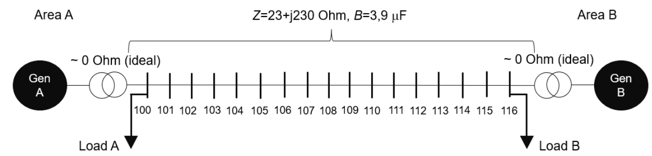

Figure 3. Simple test system.

Generator model parameters (round rotor generator model [10]) and excitation system model parameters (IEEE Type ST1A Excitation System [10]) were the same for Gen A and Gen B. The parameters were taken directly from the Kundur test system [7] (Area B generators in Kundur test system). No PSS or governor models were included in the simulation. The transmission line between area A and B was split into 15 parts with identical length. The test system was on purpose made very weak, so that the oscillation phenomena are easily observable.

This test system has an inter-area mode where both generators are participating. This mode has a frequency of approximately 0.4–0.6 Hz depending on the system operating conditions. The damping of the mode was rather low (damping ratio around 1–3 %), however not identical, in all analyzed cases.

The simulations were carried out as follows:

1. A FO source (a load model) was placed one at a time at each Bus 100–116 (in Fig. 3). The amplitude of the FO was 1 MW, and its frequency was set to be the same as the resonance frequency (such as the highest "peaks" in Fig. 2) at a ±0.01 Hz accuracy. The FO was a sinusoidal active power variation of the load model.
2. Simulations of 200 seconds for each FO location were performed and the active power flow between Bus 100 and 101 were measured.
3. The amplification of the resonance phenomenon was calculated from the ratio between the amplitude of observed real power flow between Bus 100 and 101 and the forced oscillation amplitude (1 MW). Fig. 4 presents a part of an example simulation with amplification approximately 3.

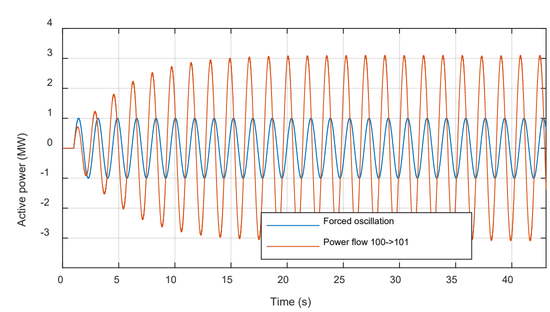

Figure 4. Part of a simulation where the FO amplification was approximately 3 and the resonance frequency 0.58 Hz. FO source location was in Bus 101.

The simulations were carried out in PSS/E software [10]. Two different sets of simulations were performed: 1) with the original system (where the generators had inertia constants

$H_{GenA} = H_{GenB} = 6.5$ s), and 2) with the system where the generator inertia constants were modified (to have lower and higher mass areas: $H_{GenA} = 4.5$ s, $H_{GenB} = 8.5$ s). In addition, the effect of power flow was investigated by changing the distribution of load between Load A and Load B, thus leading to power flow between areas A and B. Initially, Load A and B were 700 MW each, and there was no power flow, and to increase the power flow, one was scaled up and the other down.

The next subsections present the results of the simulations. Since the dynamic characteristics of the system differ in different simulations (i.e., different operating points), and especially, the damping of the oscillations differs between different cases, the absolute numbers of the FO amplification should not be compared between each other. However, the shapes of the curves can be compared.

B. *Case 1: Original system*

Fig. 5 presents the amplification of the FO in a case where the power flow is 0 MW, 200 MW from Area A to B and 200 MW from Area B to A.

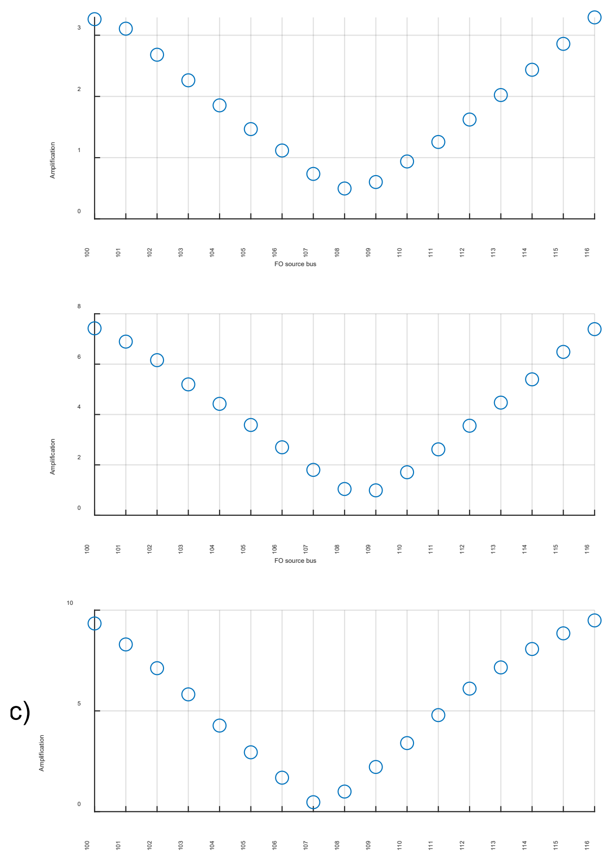

Figure 5. a) FO amplification with zero power flow, b) FO amplification with 200 MW power flow from area A to B and c) FO amplification with 200 MW power flow from area B to A. Generator inertia constants were $H_{GenA} = H_{GenB} = 6.5$ s.

As shown by the figure, when the FO source is located in the "center of the inter-area oscillation mode" (approximately at Bus 107–109 depending on the power flow), the amplification is lowest. The amplification rises rather linearly when the FO source is moved towards the ends of the system. In this case, the power flow slightly "shifts" the center of the inter-area oscillation mode to the direction of the power flow.

C. *Case 2: Different inertia constants in the generators*

Fig. 6 presents the amplification of the FO in a case where the power flow between areas A and B is zero MW, 200 MW from A to B and 200 MW from B to A and the generators have different inertia constants ($H_{GenA} = 4.5$ s, $H_{GenB} = 8.5$ s).

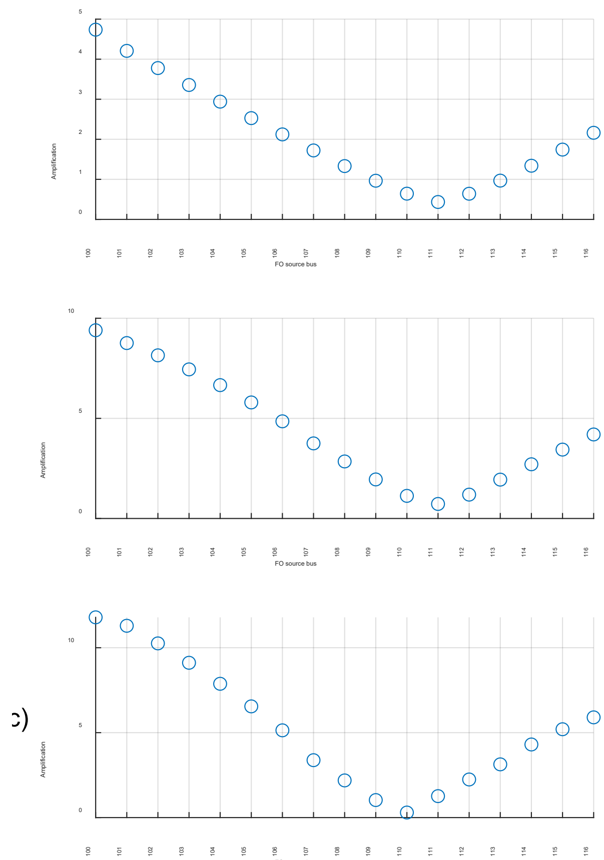

Figure 6. a) FO amplification with zero power flow, b) FO amplification with 200 MW power flow from area A to B and c) FO amplification with 200 MW power flow from area B to A, when the generators have different inertia constants ($H_{GenA} = 4.5$ s, $H_{GenB} = 8.5$ s)

As Fig. 6 shows, the location of the FO with the lowest amplification (i.e., center of inter-area oscillation mode) is approximately at Bus 110–111 in this set of simulations. This location is significantly closer to the heavier part of the system (Gen B with inertia constant 8.5 s). Again, the amplification increases rather linearly as the FO source is moved towards the ends of the system. However, the amplification is much higher when the FO source is located in the lighter end of the system (Gen A with inertia constant 4.5 s). The power flow may shift the center of the inter-area oscillation mode slightly towards the receiving end, however, its effect is not as clear as in the previous case.

D. *Summary*

Based on the simulations with the simple test system, the following conclusions can be made:

1) The amplification of the FO increases approximately linearly when the FO source is moved from “the center of the inter-area oscillation mode” towards the ends of the system.

2) If one area of the system is heavier than the other, the “center of the inter-area oscillation mode” shifts towards the heavier part of the system.

3) The amplification is higher when the FO souce is located closer to the lighter part of the system than to the heavier part.

In addition, it seems that in most cases the power flow shifts the center of the inter-area oscillation mode to the direction of the power flow (i.e. closer to the receiving end) but this effect is rather minor. It should be noted that these findings apply when the FO is sinusoidal active power variation and the FO amplitude is rather small (compared to the system size). If the FO amplitude is high, and simultaneously the amplification is high, the response of the system may become partly nonlinear when different components and control systems hit their limiters.

These findings enable the evaluation of the risk of FO in different locations also in real power systems. In a power system with two distinct areas (such as the Nordic power system), the risk is highest within the lighter area and when the electrical distance is highest from the center of the inter-area oscillation mode. In real power systems, however, it may be difficult to calculate the electrical distance from the center due to the highly meshed nature of the real system. Thus, it is may be beneficial to use for example the voltage angle difference from the center of the inter-area oscillation mode as a measure of the electrical distance since this information is often available. This is more closely investigated in the next section with the full simulation model of the Nordic power system.

IV. Simulations with Full Nordic System

A. Nordic power system

The Nordic power system is a synchronous system consisting of the systems of Finland, Sweden, Norway, and Eastern Denmark. The grid map of the Nordic power system is presented in Fig. 7. Most of the load and largest generators (i.e. nuclear plants in Finland and Sweden) are located in the southern parts of the system. There exists also large amount of hydro power production in the north and also an increasing amount of wind power production.

The system has a 0.3 Hz inter-area mode (shown in Fig. 7). In the 0.3 Hz inter-area mode, the generators located in the southern parts of Finland oscillate against the generators in southern parts of Sweden and Norway. The oscillation “path” (the blue arrow in Fig. 7) goes through most of the Nordic system, and thus, a significant part of the generators is participating in the mode. [8] The Finnish part of system has typically lower inertia compared with the Swedish (combined with Norwegian) part. Thus, the center of the inter-area oscillation mode of the 0.3 Hz mode is in the Swedish side of the grid. The figure also shows the investigated FO source locations.

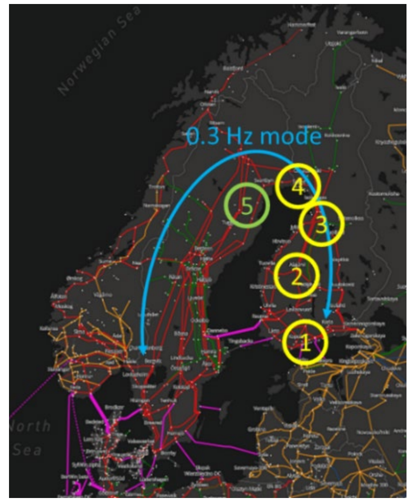

Figure 7. Nordic power system [9] and the 0.3 Hz inter-area mode. The blue arrow shows the path of the inter-area mode in the AC network. Numbers 1: FO source location southern Finland, 2: FO source location central Finland, 3: FO source location northern Finland, 4: FO source location Finland-Sweden border area, 5: “center of inter-area oscillation mode” area of the 0.3 Hz mode.

B. Nordic power system simulation model

Here, the detailed Nordic power system simulation model is used for studying the inter-area resonance phenomenon. The model represents the Nordic synchronous power system, and it contains around 6000 buses, 1700 machines, and 2600 loads. It includes the dynamic models of the generators with their main control systems as well as HVDC links and FACTS devices. The model is used by the Nordic transmission system operators in their planning analyses. [12]

The simulations were carried out in three different cases with different damping and frequency values of the 0.3 Hz inter-area mode. The different cases (and the different modal frequency and damping levels) were created by changing the active power flow of a HVDC link between Finland and Sweden, thus affecting the power flow and modal characteristics of the system. The base load in the simulations represented a high-load winter situation with close to 60 GW load in the Nordic power system. Three cases were studied: 1) Case with very low damping (damping ratio 1 %), 2) case with rather low damping (damping ratio 3 %), 3) case with normal damping level (damping ratio 7 %) of the 0.3 Hz mode.

The simulations were performed by creating forced oscillations to the system by varying the active power of a selected load sinusoidally at the resonance frequency. The amplitude of the FO was 10 MW. The amplification of the FO was calculated by observing the resulting active power oscillations on the AC tie lines between Finland and Sweden. The FO source was placed in different locations in the Finnish system (FO source locations are shown in Fig. 7).

C. Simulation results

Fig. 8 shows the amplification of the FO, when the FO source was placed in different locations (locations shown in Fig. 7).

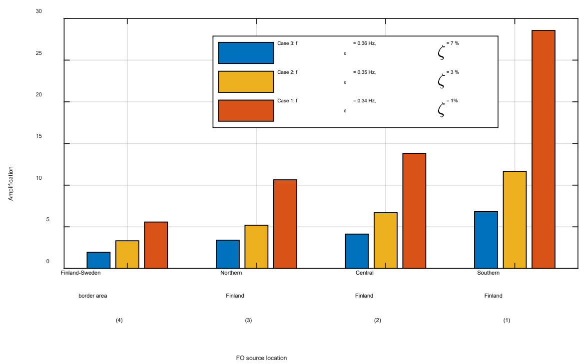

Figure 8. Amplification of FO in the full Nordic simulation model. The numbers (1)-(4) refer to the locations in Fig. 7.

As Fig. 8 shows, the amplification is highest in the end of the system (southern Finland). The amplification is lower in the central parts. This observation is in line with the results presented in Section III and in some previous studies [1], [3].

To investigate the amplification as a function of the "distance" from the center of the inter-area oscillation mode, the amplification is plotted in Fig. 9 as a function of the voltage angle difference from the center (in location 5 in Fig. 7).

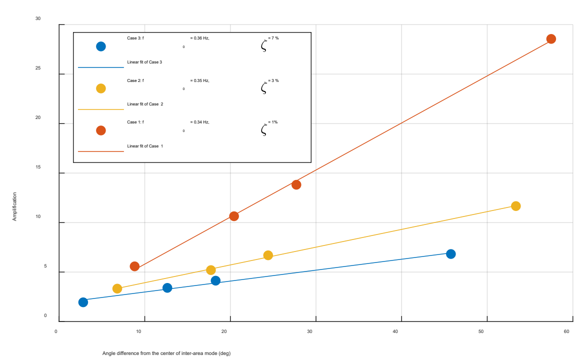

Figure 9. Amplification of the FO as a function of the voltage angle difference from the center of the inter-area oscillation mode.

As shown by Fig. 9, the amplification as a function of the voltage angle difference from the center of the oscillation indeed increases linearly when moving towards the end of the system. This supports the findings of Section III. The slope of the linear curve in the three analyzed cases is as follows:

- Case with very low damping (damping ratio 1 %): 0.48/deg → as voltage angle difference between the FO source and the center of the inter-area oscillation increases one degree, FO amplification increases 0.48.
- Case with rather low damping (damping ratio 3 %): 0.18/deg → as voltage angle difference between the FO source and the center of the inter-area oscillation increases one degree, FO amplification increases 0.18.
- Case with normal damping level (damping ratio 7 %): 0.11/deg → as voltage angle difference between the FO source and the center of the inter-area oscillation increases one degree, FO amplification increases 0.11.

These results apply for the "worst case" of the FO frequency, i.e., the FO frequency is identical to the natural frequency of the inter-area mode. These findings can be used for example in easily analyzing the high-risk locations for the FO source and inter-area resonance and is valuable information for the system operators.

V. Conclusion

This paper investigated the effect of the FO source location on the inter-area electromechanical mode resonance phenomenon. The analysis was carried out with a simple two generator system and the full Nordic power system simulation model.

The main finding of the paper is that when the FO source is moved from the "center of the inter-area oscillation mode" towards the "ends" of the system, the amplification increases approximately linearly as a function of the electrical distance from the center. A good measurement of the electrical distance is simply the voltage angle difference. This result seems to be valid in different power flow conditions as well as in situations where the oscillating masses (participating generators) differ.

This finding enables easy evaluation of the FO risk in different locations, which is important in power system planning and operation.

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