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Long Term Characteristics of Ultra Low Frequency Oscillations in the Nordic Power System

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Abstract—In the Nordic power system, the frequency of the system oscillates constantly around the nominal 50 Hz value with a period of around 40 to 90 s, i.e., in the frequency range around 0.011–0.025 Hz. This ultra low frequency oscillation (ULFO) deteriorates the frequency quality in the entire system, causes unnecessary control actions and may cause wear and tear of turbines. In the worst case, the oscillation may endanger frequency stability of the system. This paper analyzes the properties of this oscillations during a period of seven years using an ambient modal identification method (mode meter). The paper shows that the ULFOs can be analyzed using ambient modal identification methods and a similar approach is recommended to be used for analyzing ULFOs in other power systems as well. Furthermore, the paper gives insight into the long term characteristics of the ULFOs in the Nordic power system and the results indicate that for example the amplitude of the ULFOs has an increasing trend during the analysis period (and their damping has a decreasing trend). These findings indicate a need for monitoring the ULFOs and develop actions for mitigating them.

Index Terms—Frequency control, frequency stability, inertia, modal identification, ultra low frequency oscillation.

I. INTRODUCTION

Continuous oscillations at a period varying between 40 to 90 s (in the frequency range around 0.011–0.025 Hz) have been observed in the Nordic power system. This oscillation is observable especially at the system frequency, i.e., the frequency oscillates around its nominal value near 50 Hz. In the Nordic power system, the amplitude of the oscillation has typically been around 20–40 mHz. Similar oscillatory characteristics have been observed recently also in several other power systems, such as the Chinese, Colombian and Turkish power systems [1]–[8].

This type of ultra low frequency oscillation (ULFO) deteriorates the frequency quality of the system. In some cases, the ULFOs cause the system frequency to drift outside the normal operating range, which is 49.9–50.1 Hz in the Nordic power system. ULFOs might deteriorate the operational security and endanger frequency stability of the system, for example, if a dimensioning fault occurs at the time instant when the frequency is below the 49.9 Hz limit. Furthermore, the ULFOs can cause unnecessary control actions for frequency regulating units and possible wear and tear of their mechanical systems.

The root causes of the ULFOs in the Nordic power system are related to the response of the hydro power plants controlling the frequency of the system (i.e., the frequency containment reserves, FCR plants). However, all characteristics of the ULFOs have not been thoroughly investigated. Especially, the properties and development of ULFOs over long time periods are not well known.

This paper analyses the ULFO phenomenon with an ambient modal identification method (mode meter) which is able to analyze the characteristics of the oscillation continuously from ambient measurement data. To our knowledge, similar approach has not been proposed before. There are several ambient modal identification methods available in the literature [9]–[16]. In this paper, we have used the method proposed in [12], [16], which is based on (multivariate) autoregressive model. A long data set of 7 years is analysed in this paper. The paper shows that the (multivariate) autoregressive model is well suited for analyzing the ULFO phenomenon. Similar analysis is recommended also for other synchronous systems which have the ULFO phenomenon.

The results of the analysis show that the ULFO in the Nordic power system has a clear yearly cycle. The characteristics of the oscillation are related to, for example, the inertia of the system. Furthermore, the results show that the amplitude of the ULFOs has increased during the analyzed years and their damping has decreased. This indicates that the frequency quality in the Nordic power system is deteriorating and there is a need to analyze and mitigate the ULFOs.

This paper is structured as follows. Section II presents the ULFO phenomenon in the Nordic system. Section III presents the analysis methods (i.e., mode meter) used in this paper. Section IV presents the analysis results. Section V discusses the main findings and Section VI concludes the paper.

II. ULTRA LOW FREQUENCY OSCILLATION IN THE NORDIC POWER SYSTEM

In the Nordic power system, superimposed periodic oscillations in the system frequency have been observed with varying time periods from 40 to 90 seconds. The oscillation, where all the generators are oscillating coherently, can be observed throughout the system. Fig. 1 shows an example of the oscillation. Two frequency measurements are shown in the figure, from Espoo in Southern Finland and from Herslev in Eastern Denmark (opposite ends of the system). As the
figure shows, the measurements are perfectly aligned, and with respect to this oscillation, all the generators in the system are oscillating coherently.

![Fig. 1. Example of ULFO oscillation of the Nordic power system. This type of oscillation exists continuously in the Nordic power system. The normal operating range is 49.9–50.1 Hz. The measurements are from Espoo in Southern Finland and Herslev in Eastern Denmark.](image)

The process of applying the MAR model to ambient data from a power system is illustrated in Fig. 2 and more information is available in [12], [16].

In this paper, only one PMU measurement was used as an input to the MAR model. Thus, the model simplifies to a univariate model and the matrices $A_l$ in (1) become simply scalars. Since in the ULFOs, the frequencies of all generators in the Nordic synchronous area swing coherently, it is sufficient to use only one input signal. The input signal was the frequency at Kangasala 400 kV substation in Southern Finland.

The selected model order (in Fig. 2) was 22. The sampling frequency of the data was 50 Hz, but the data were downsampled to 1 Hz and filtered before inputting to the model (since the frequency of the ULFO is low, there is no need to use high sampling frequencies). A 24-hour period of data was always analysed at a time. The reason to analyse such long segments at a time is that the ULFO frequency is very low, and if for example 1-hour long segments were analysed individually, the number of oscillation periods in the data would have been too small for obtaining accurate estimates. The results given by the MAR method were also validated by comparing them

\[
y_k = \omega + \sum_{l=1}^{p} A_l y_{k-l} + \epsilon_k, \quad (1)
\]

where the matrices $A_l$ are the coefficient matrices of the MAR model. The parameter vector $\omega$ is a vector of intercept terms that may be included to model a nonzero mean of the time series. The vector $\epsilon_k$ represents white noise (i.e. random vectors with mean zero). In this paper, we have used the least squares algorithm [19] for estimating the MAR model. When the parameters of the model have been estimated, a state matrix can be formed using the different $A_l$ (details represented in [12]). The eigenvalues of the state matrix (when converted to continuous time) correspond the modes in the system. The modal parameters, damping ratio $\zeta_i$ and (damped) angular frequency $\omega_{d,i}$, can be calculated for mode $i$ from the eigenvalues as follows:

\[
\lambda_i = \alpha_i + j\omega_{d,i}, \quad (2)
\]

\[
\zeta_i = -\frac{\alpha_i}{\sqrt{\alpha_i^2 + \omega_{d,i}^2}}. \quad (3)
\]

The selected model order (in Fig. 2) was 22. The sampling frequency of the data was 50 Hz, but the data were downsampled to 1 Hz and filtered before inputting to the model (since the frequency of the ULFO is low, there is no need to use high sampling frequencies). A 24-hour period of data was always analysed at a time. The reason to analyse such long segments at a time is that the ULFO frequency is very low, and if for example 1-hour long segments were analysed individually, the number of oscillation periods in the data would have been too small for obtaining accurate estimates. The results given by the MAR method were also validated by comparing them
with another ambient analysis method (the Bayesian method presented in [15], [16]).

IV. ULFO ANALYSIS FROM 2015 TO 2021

Fig. 3 presents the frequency, oscillation period, damping ratio and amplitude of the ULFO analyzed from the data covering the years from 2015 to 2021. Fig. 4, on the other hand, shows the yearly duration plots of the frequency, damping and amplitude of the ULFO. The modal parameters were estimated with the MAR method presented in Section III.

As shown by Fig. 3, the frequency and oscillation period of the ULFO have a clear yearly cycle during the analyzed period. The system is heaviest during winter (i.e. has highest inertia) and this clearly affects the ULFO frequency by lowering it.

Fig. 3 also shows that the damping ratio of the ULFO is very high during the whole analysis period (more than 15 % in all hours from 2015 to 2021). The damping does not have as clear yearly cycle as the frequency and amplitude. However, there is a clear decreasing trend in the damping during the analyzed years. The decreasing trend can be also observed in the duration plots of Fig. 4. For example, the average value of the damping ratio during 2015 was approximately 34 %, and in 2021, approximately 25 %. Even though the decreasing trend in damping is somewhat alarming, the damping has remained very high even in the most recent years, and thus, is not currently a concern for system security. At the moment, it is not known what is causing the damping of ULFOs to become lower.

The amplitude of the ULFO also has a yearly cycle, as shown by Fig. 3. The amplitude seems to be lowest during winter and highest during summer which indicates that the amplitude is also connected to the inertia of the system. Furthermore, the amplitude has an increasing trend during the analysis period. The increasing trend can be also observed in Fig. 4, and it seems that the amplitude has especially increased in the latest three years (2019–2021). The increasing trend of the amplitude is concerning since it causes the system frequency quality to deteriorate, causes unnecessary control actions, and could, in principle, risk the frequency stability of the system. Currently, it is not clear, why the ULFO amplitude is increasing, however, it might be connected to the diminishing inertia of the system, and the decreasing damping of the ULFOs.

V. DISCUSSION AND FUTURE RESEARCH

This paper analyzed the ULFO phenomenon over a 7-year long analysis period in the Nordic power system using an ambient modal identification method (mode meter). The results indicate that mode meters can be utilized for analyzing the ULFOs and it is recommended to carry out similar analyses for other power systems, in addition to the Nordic system, to monitor the development of the ULFO phenomenon in those systems. These analyses are relevant especially for power systems that are hydro dominated, and thus, have an inherent ULFO phenomenon.
The analysis shows that the frequency of the ULFO in the Nordic power system varies during a year: the frequency is lowest during winter and highest during summer. This indicates that the frequency is related to the inertia (or kinetic energy) of the system. The inertia in the Nordic power system is highest during winter periods and lowest during summer. Also, [5] has previously indicated that higher inertia in the Chinese system leads to lower ULFO frequencies, and our findings support the same observation in the Nordic power system. The exact relation between inertia and ULFO frequency in the Nordic system is a topic of future research.

The damping of the ULFO in the Nordic power system had a decreasing trend during the analysis period, but not a very clear yearly cycle. However, the damping ratio of the ULFO was high during the whole analysis period. This indicates, for example, that the risk of resonance phenomenon between ULFO and a forced oscillation source (with a corresponding frequency) is low. Theoretically, a resonance could occur for example if a power plant started "forcing" the ULFO oscillations at the same frequency as the ULFO natural frequency. However, since the ULFO damping still seems to be high, such risks can be considered low. Furthermore, the ULFO damping is related to the properties of the frequency containment reserve (FCR) in the Nordic system. Since the damping has been decreasing, there is a need to investigate the properties and improve the requirements of frequency containment reserves, and this is also a topic of future research.

Also, previous studies [1]–[3], [6]–[8] have indicated that the damping of the ULFOs is often related to the settings of the turbine governors of the primary frequency control plants, especially hydro power. The past studies have proposed several different schemes [1]–[4], [6]–[8] for modifying the controllers and the settings of hydro turbine governors. For example, [8] concluded that making the turbine governor control slower might improve the damping of the ULFOs, however, it also slows the system overall response. The study [4] proposed a wide area control structure for mitigating ULFOs. In [5] it was discussed that, in the Chinese system, a higher load level in the system might lead to higher damping of ULFOs. However, similar relationship between load level and ULFO damping was not clearly observed during the 7 year analysis period in the Nordic power system. Nevertheless, it is useful to investigate some of the previously proposed schemes [1]–[4], [6]–[8] when defining new requirements for the FCR plants and for improving the ULFO damping in the Nordic power system. However, the main goal of new FCR requirements should be to decrease the amplitude of the ULFOs (even though damping might have an effect on the amplitude levels).

As shown in Section IV, the amplitude of the ULFO has a clear yearly cycle in the Nordic power system. It is highest during the summer months and lowest in wintertime. This indicates that the amplitude is also related to the inertia (or kinetic energy) of the system. The reducing inertia is an important cause for the need of further analysis of ULFOs and developing mitigating methods. The study [5] indicated that the ULFOs are more serious during low load situations.
in the Chinese system. Observations from the Nordic power system also support this. Thus, the effect of load level on the ULFO characteristics is also a topic of future research.

Furthermore, the ULFO amplitude in the Nordic system has a clear increasing trend during the analysis period. This is a concern since it indicates that the frequency quality in the Nordic system is deteriorating and this may be a risk for the future system security. In addition, this causes unnecessary control actions and could cause wear and tear of frequency controlling power plants. In the worst case, the increasing amplitude could endanger frequency stability of the system, for example if a dimensioning fault occurred at the time instant when the frequency has oscillated below the 49.9 Hz limit. Since the ULFO amplitude is increasing, actions should be taken to mitigate the ULFOs in the Nordic power system. One concrete action proposal is improving the FCR requirements in the Nordic system.

VI. CONCLUSION

This paper used an ambient modal identification method (mode meter) for analyzing ultra low frequency oscillations (ULFO) in the Nordic power system over a time period of seven years: 2015–2021. The governor tuning of the hydro generators controlling the system frequency affect the ULFO as observed in other (hydro dominated) power systems as well. The paper shows that a mode meter suits well for analyzing the ULFO phenomenon and it is recommended to use a similar approach for analyzing ULFOs in other power systems as well.

The analysis results show that frequency of the ULFOs have a clear yearly cycle – the frequency is lowest during winter when the system is heaviest and highest during summer when the system is lightest.

The damping of the ULFOs does not have such a clear yearly cycle, but it had a decreasing trend during the analysis period. However, the damping ratio remained high during the whole analysis period thus indicating that the damping does not likely endanger the operational security of the system.

The amplitude of the ULFOs, however, had a clear yearly cycle, and more importantly, a clear increasing trend during the analysis period. This indicates that the frequency quality in the Nordic system might be deteriorating and actions need to be taken to mitigate the ULFOs. One concrete action is to improve the frequency containment reserve requirements in the Nordic system. Furthermore, similar analysis as carried out in this paper is recommended for other power systems (especially hydro dominated systems) to investigate if similar trends and characteristics are also observable in those systems.

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