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Applying Bayesian Approach in Real-Time Monitoring of Converter-Driven Oscillation

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***Abstract*—Increased use of wind and solar power is leading to significant changes in various properties of power systems. As these inverter-based resources are replacing synchronous generators, the existing dynamic characteristics of power systems change, and new stability phenomena are introduced in the system. Especially, converter-driven stability and oscillations caused by converters are an urgent and growing concern in power systems. Consequently, it is highly important to develop methods for detecting and monitoring converter-driven oscillations. This paper proposes a Bayesian approach for monitoring converter-driven oscillations. The approach utilizes ambient measurements and is able to identify the modal parameters (such as frequency and damping ratio) of the converter-driven oscillations continuously, in real-time. The performance of the proposed method is validated with measurements from two real-life events observed in the Finnish power system. The results show that the proposed approach is highly effective in rapidly detecting and monitoring converter-driven oscillations. It is recommended that transmission system operators implement a real-time monitoring method, such as the method proposed in this paper, for detecting and monitoring converter-driven oscillations.**

***Index Terms*—Converter-driven oscillation, Inverter-based resources, PMU measurements, Bayesian method, power system oscillation.**

I. Introduction

Oscillatory behavior of power system has been and remains of great interest to engineers and researchers. Poorly damped or undamped oscillations on the power grid may lead to reduced power transfer capacities over critical corridor and system-wide breakups. Energy transition over the past decade has driven the proliferation of inverter-based resources (IBRs), such as wind farms, battery storages, solar photovoltaics which now contribute a substantial part of the electrical energy mix in many countries. These renewable energy technologies accompanying by phasing out of synchronous machines are changing the dynamic stability behaviors of power systems which is further complicating the task of oscillation management in power system operation. On one hand, the converter-based technology might participate in existing oscillation phenomena, on the other hand, it is also introducing new types of oscillations and interaction issues which behave significantly different from the conventional low-frequency electromechanical oscillation, hence making the problems even more complex. In recent years, the reported oscillation incidents related to increasing penetration of power electronic converters, installation of series compensation, and controllers associated renewable generation and HVDC have raised dramatically due to large-scale integration of the renewable energy [1]. Those reported oscillation incidents can broadly be associated with two new power system stability classes introduced in [2] i.e the converter-driven stability and resonance stability.

Converter-driven instability is a phenomenon that mainly occurs in IBRs when the grid system strength is low. This instability arises due to the interaction between the IBR and the transmission network, which may lead to unstable power system oscillation over a wide frequency range. Therefore, it is essential to monitor, detect and mitigate this instability to ensure reliable and stable operation of IBRs and the power grid. Due to the stochastic dynamic behavior of these new stability issues, the root cause, and its impact are still not well studies and fully understood [3]-[4]. One key challenge pertaining to that is the rapid detection of oscillation events caused by converters. Consequently, there is an urgent need to develop methods for monitoring and detection of converter-driven oscillation events. Most oscillation detection approaches reported in the past were focusing on detecting inter-area electromechanical oscillation which is associated with synchronous generator groups oscillating against each other[5]-[10].

This paper proposed to use Bayesian method to estimate the modal properties of converter driven oscillation from ambient measurements. The method was established in civil engineering [11] and has been also applied for monitoring inter-area electromechanical oscillation [12]. Field PMU measurement of two real-life events from Finnish power system are analyzed. The modal properties of the systems, as well as their estimation uncertainty are determined and tracked as a function of time. The results indicate that the Bayesian method is well suited for monitoring converter-driven oscillation, and it is recommended to use a real-time modal analysis method (i.e. mode meter) for

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monitoring the converter-driven oscillation in transmission systems.

The paper is organized as follow. Section II gives an outline of the Bayesian method for modal identification. Section III presents Finnish transmission network dynamic stability characteristic and related converter-driven stability challenge. Two real-life converter-driven oscillation recorded events used for the performance analysis are presented in Section IV. Section V discuss the performance analysis of the proposed approach. Section VI presents the discussion and key findings. The conclusion of this paper is given in Section VII.

II. DESCRIPTION OF PROPOSED BAYESIAN APPROACH

The Bayesian method adopted in this work is outlined here. Due to space limitation, details are referred to [11]-[12]. The method makes use of the scaled Fast Fourier Transform (FFT) of power measurement data, say, D within a resonance band of the subject mode for estimating the modal properties, say, θ. The latter include the natural frequency, damping ratio and mode shape. In addition, the power spectral density (PSD) of the 'excitation process' driving the oscillations and measurement noise are also estimated. The excitation process and noise are not measured, and they are assumed to be 'band-limited white', in the sense that their PSDs within the resonance band are constant. In a Bayesian perspective, the modal properties θ are random variables whose probability density functions (PDF) are updated from their 'prior' $p(\theta)$(i.e., before data) to 'posterior' (i.e., after using data) PDF $p(\theta|D)$. Using Bayes' theorem, i.e., $p(\theta|D) = p(D|\theta)p(\theta)/p(D)$, and assuming a uniform prior, i.e., $p(\theta)$ =constant, one concludes that the posterior PDF is proportional to the 'likelihood function' (LLF), i.e., $p(\theta|D) \propto p(D|\theta)$. The LLF is derived using a remarkable but standard result in statistics, that for long data (e.g., a few hundreds of natural periods) the FFTs (D) are asymptotically independent, each with a complex Gaussian PDF. The posterior PDF of θ, however, is non-trivial and generally does not belong to any standard PDF. Nevertheless, with sufficient data (often the case in applications), $p(\theta|D)$ can be approximated by a Gaussian PDF. The most probable value (MPV) of the PDF maximizes $p(\theta|D)$, or, equivalent, minimizes the 'negative log-likelihood function' (NLLF) $L(\theta) = -\ln p(D|\theta)$. The covariance matrix of the PDF is equal to the Hessian of L evaluated at the MPV.

For the potentially large number of variables and nonlinearity of $L(\theta)$, efficient algorithms are required for both the MPV and covariance matrix. In addition to calculating uncertainty when data is given, recent theory in the area reveals closed form asymptotic expressions that govern the achievable precisions. E.g., for high signal/noise ratio, the coefficient of variation (c.o.v.) of damping ratio is at least $1/2\pi\zeta$, revealing that it is the most challenging parameter to estimate.

III. FINNISH TRANSMISION NETWORK DYNAMIC CHARACTERISTIC CHALLENGE

The Finnish transmission network is an integral part of larger Inter-Nordic power system network which is synchronously operated system connecting Swedish, Norwegian, and Eastern Danish power systems. As illustrated in Fig. 1, the main transmission system in Finland consists of main 400 kV lines and HVDC connections to neighboring countries. In Finnish transmission system, series compensation has also been applied since 1997 to enhance the North-South transmission capability of the Finnish transmission system.

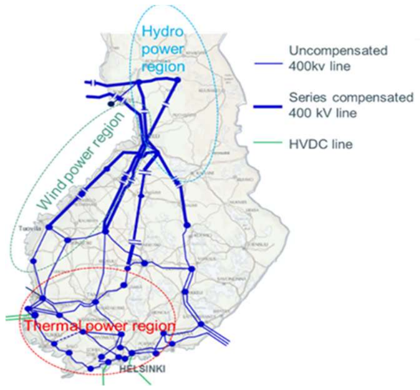

Fig. 1 Main transmission system in Finland and transmission lines with series compensation

The power flow direction varies depending on market situation while the main direction of flow is from the hydro in Northern Finland, Sweden and Norway towards Southern Finland. Historically, transferring power to South Finland is often limited by dynamic and long-term voltage stability. In recent year, great number of wind generation sites are being planned and commissioned in coastal area of western Finland. As more wind farm on the West Coast and new nuclear power plant located in South-West Finland starting to generate more power, the power flow direction will switch with excessive power being transferred towards Sweden through the Northern interconnection between Finland and Sweden. This switch of power flow direction will reduce the damping of inter-area power oscillations which limit power transfer capacity. The increased penetration of wind power in west coast has started also to introduce new types of stability limits due to converter driven stability and sub synchronous oscillation phenomena which further complicated the situation.

Finnish transmission system operator has been facing new planning and operational challenges due to the high penetration of onshore wind particularly apparent on the west coast, where there is a shortage of transmission capacity. In addition, the stable operation of wind farm is closely linked to the amount of system strength available on the network, the adequacy of the wind farm control system design and tuning, and the sufficient provision of reactive power and short-circuit current through auxiliary equipment such as Synchronous Condenser and SVC/STATCOM. The declining amount of online synchronous generators in the network and the electrical remoteness of the wind farms have resulted in the absence of sufficient system strength to support the stable operation of the wind farms. Converter-driven stability will be greatly impacted especially during weak network connection and high-power production.

Over the past three years, several events involving multiple wind farms participating in converter driven stability have been detected. These events are mainly associated with low system strength weak grid challenge [3]-[4] and have been recorded by both Phasor measurement unit (PMU) and Point-on-wave (POW) devices in the Finnish Transmission Grid. Those events normally persist in the system for minutes or even hours. If these associated oscillation amplitudes remain high or undamped, the high amplitude voltage and current components may damage wind power plant or series compensation equipment unless proper countermeasures are implemented both at generation and transmission equipment. Underestimating the adverse impact of converter-driven stability can lead to potential disruption in power supply or potential blackout. The occurrence of such unstable oscillation is difficult to predict due to uncertainty in modelling and the wide range of contingency and operating conditions that would not normally be explored in simulation studies.

To address this issue with the primary objective of maintaining a reliable and resilient future power grid, a compelling need on uplifting control room operational visibility on wider bandwidth oscillation encompassing converter-driven and resonance stability has risen. This dynamic monitoring capability is critical to enhance situational awareness and to create a more actionable operational insight for grid stability control and handling of stressed network situation. One crucial task pertaining to this is to detect the oscillation event and to access its modal properties including oscillatory mode, damping ratio and mode shapes to identify potential stability issue and support the designing of effective counter measure. Time-synchronized measurement including PMU and Waveform Measurement Unit (WMU) have evolved substantially over the past decade and have become a mature grid measurement technology. Applying effective modal analysis on these real-time measurements to uplift grid visibility may help to address the challenges poses by converter-dominated grid dynamic and uncertainty.

IV. REAL-LIFE MEASURED TEST DATA

Two real-life converter-driven oscillation events originated from Wind Power Plants (WPPs) are presented in this paper to assess the performance of the Bayesian method. Both events are captured on PMU with 50 Hz data rate.

A. Case A

A wind farms related control mode of 4.8 Hz was frequently captured in a wind farm dominated substation especially during high wind production period. These converters-driven oscillations were observable in both PMU and WMU measurement installed in the substation. Such events usually last between 2-9 hours.

Reactive power PMU measurement recordings in one of the recent events are presented in Fig. 2. These measurements are collected from two transformer feeders connected to a wind farm dominated substation. The oscillation can be observed also in voltage waveform of the WPP. Some reactive power can be seen oscillating in phase with voltage while some reactive power is observed oscillating out of phase with the voltage. Such oscillation has propagated also to 400kV line which posed the risk of SSO with nearby series compensated line.

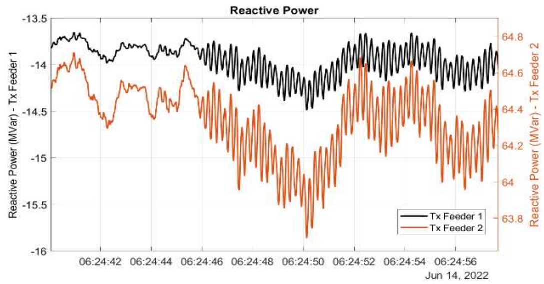

Fig. 2 Reactive Power Oscillation of two adjacent WPPs.

B. Case B

Fig. 3 shows a recorded voltage PMU measurement for a wind power plant instability event involving several wind power plants oscillating in a west coast region of Finland. The ~5Hz mode oscillation occurred during a grid outage situation which altered the normal grid configuration.

The simplified normal operation grid topology and topology change carried out during the event are presented in Fig. 4. In the original topology, half of the power plants were connected to BUS 1 and another half were connected to BUS 2. After the topology change, all WPPs were connected to only BUS 1. This resulted in relatively weak grid configuration [3] [4].

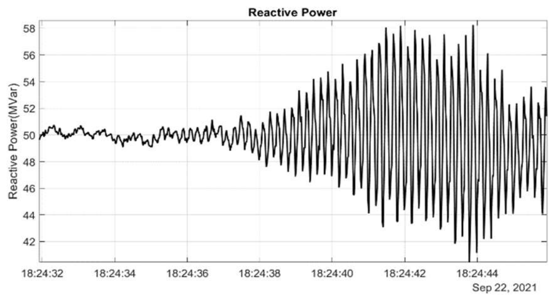

Fig. 3 PMU Measurement on Wind power Instability Event

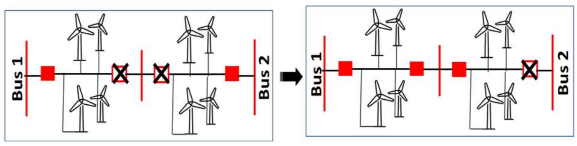

Fig. 4 Topology change that leads to voltage control instability

The oscillation event lasted about 50 minutes until an operation mode change (V-control to Q-control) was initiated by operator in one of the wind powers plants which damped the oscillation.

V. RESULT PERFORMANCE ANALYSIS

A. Modal Identification Result for Case A

Fig. 5 shows the PSD of Case A data described in Section IV A. A one-hour data set are collected from PMU measurement of one of the 400kV transformer feeders connected to the substation for the analysis. Fig. 6 shows the modal identification result for Case A using the method. Modal identification is performed using an 8-minute moving analysis window, and each analysis window is overlapping with 2-

minute interval. In this event, the 4.8Hz mode converter-driven oscillation originated from the WPPs which propagates to 400kV feeder is clearly seen.

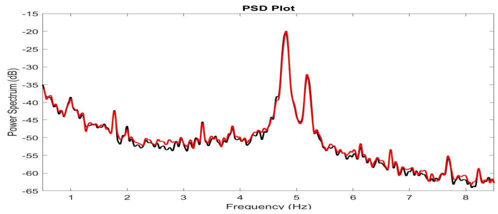

Fig. 5 PSD Plot for Case A

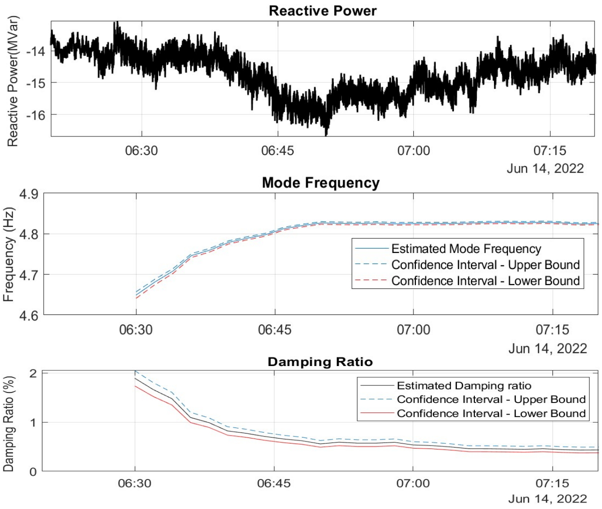

Fig. 6 Bayesian Modal Identification Result for Case A

As the 4.8 Hz starts to excite at around 06:24, the method is able to identify the dominant 4.8Hz mode quickly. The estimated mode frequencies obtained through the method show high degree of accuracy and reliability as evidenced by the narrow one sigma bound (i.e., measure of confidence interval). The gradual decrease of the damping ratio towards a constant value is also consistent with the dynamic behavior of the oscillation event seen throughout this 1-hour analysis window time, as no control action has been taken to damp the oscillation during the event.

Fig. 7 shows the modal identification result with different analysis window lengths.

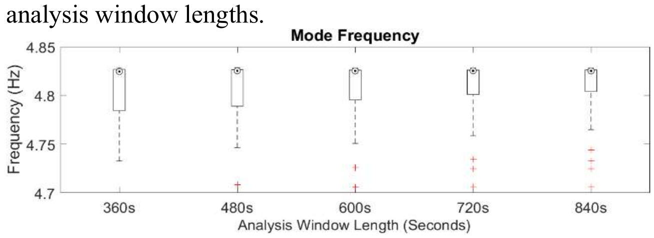

Fig. 7 Case A modal identification result with different window length

Boxplot is used to visually represent the distribution of the estimated mode frequencies. The median value indicated by circled dot is positioned mainly in the third quartile (upper line of the rectangle box) indicating that there is a cluster of majority data concentrated between 4.8-4.85 Hz. The size of the box becomes smaller as the window length increase which implies that the estimate has less variability and becomes narrower and more centered towards the mode frequency of the oscillation.

B. Modal Identification Result for Case B

Fig. 8 shows the modal estimation result for Case B using the method. A one-and-half hour data set are collected from one of the PMU measurements nearest to the WPPs instability event where the 5 Hz mode oscillation is visible in reactive power measurement and further amplified due to network topology change. Similar approach of 8-minute moving analysis window with each analysis window overlapping with 2-minute interval is applied.

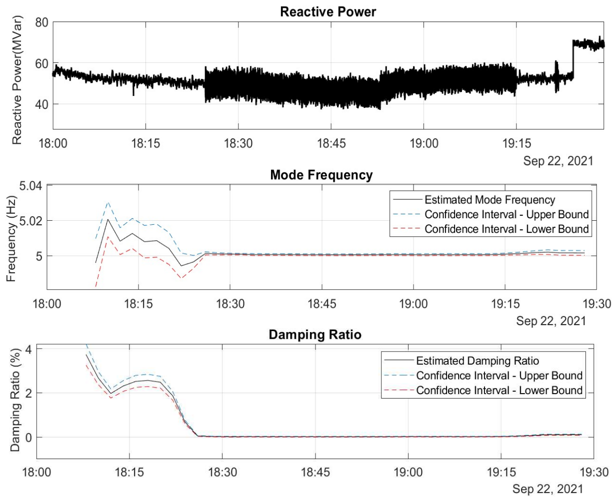

Fig. 8 Bayesian Modal Identification Result for Case B

Between 18:08 to 18:24, the results of Bayesian Analysis show consistent 5 Hz mode converter-driven oscillation seen in the reactive power originated from WPPs' voltage control loop.

When the oscillation starts to grow at around 18:24, the damping ratio decreases significantly towards near zero percent. By taking a closer look of the PSD plot of the signal at this period reveals that zero damping MPV arises due to the emergence of pure sinusoidal signal of large amplitude on top of the existing ambient signal as depicted in Fig. 9. The pure sinusoidal dominates the ambient signal and in this case the method has tendency to prioritize fitting the pure sinusoidal component over the ambient signal. This observation indicates that the method has the capability to effectively and quickly capture and emphasize the dominant oscillatory behavior providing valuable insights for further exploration.

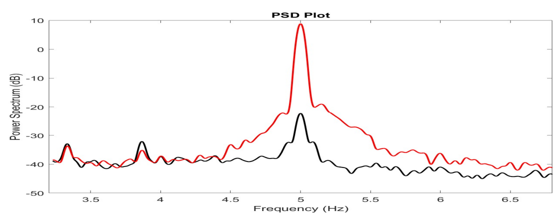

Fig. 9 PSD plot for Case B

VI. DISCUSSION

Both real-life event case studies result presented in Section V have demonstrated the effectiveness of the proposed Bayesian analysis approach for identifying modal characteristic of converter-driven oscillatory mode. The two dominant mode of 4.8Hz and 5Hz due to WPPs' voltage control loop are revealed and consistent with the known converter-driven dynamic behavior.

The results from both cases show that the one sigma bounds for each mode frequency estimate are relatively small, indicating a high degree of certainty in the estimated values. For example, for Case A's mode frequency estimate, as the actual mode being excited, the one sigma bound converge to smaller value, in the range ±0.001 Hz, indicating that the true mode frequency is likely to be within a very narrow range of values around the estimated value. When implementing a real-time monitoring application using estimated value, it is important to ensure that the algorithms are properly tuned to provide accurate and reliable results. One sigma bound can be a useful metric to define the thresholds for identifying potential outliers.

Case B presents a unique case study with signals containing both ambient and isolated peak component. The event started with an ambient oscillation and then developed to contain both ambient and pure sinusoidal oscillation. It is worth noting that from real-time monitoring perspective, the analysis result for Case B present two key information which prove to be useful for control room operator. Firstly, the prompt identification of 5 Hz mode before 18:24 provides good opportunity for operator to introduce necessary mitigation or control action before the sinusoidal oscillation started and the situation deteriorated. Secondly, the sudden decrease of damping ratio towards zero after 18:24 could serve as an alarming indication for the potential onset of larger oscillation risk which might impact the stability of power grid. However, the challenge on identifying the right modal properties accurately for a case including both ambient and sinusoidal oscillation might require a shift to a new regime of methodological solution. This could involve method in disentangling the different signal component, introducing the right likelihood function to capture both ambient and pure sinusoidal component and adapt a more complex model account for the present of isolated peak, which is a topic for future research.

Furthermore, we plan to extend this research work to investigate and access mode shape parameter in identifying the source of converter-driven oscillation. Mode shapes can potentially be used for identifying the oscillation source location, depending on the specific characteristics of the oscillation and help in understanding the dynamics of the system. If the oscillation is associated with a specific component or subsystem for example particular WPP control mode, the mode shapes may show a characteristic pattern that reflects the spatial distribution of the driving force. Specifically, comparing the mode shapes of the two signals can provide valuable insight into how the oscillations are coupled between different components.

Additionally, comparing the mode shapes of the two signals can also provide information about the stability and dynamics of the system. If the mode shapes of both signals change significantly over time, it suggests that the system is undergoing dynamic changes depending on operating condition that may affect its stability. On the other hand, if the mode shapes remain relatively stable over long period of time, it may suggest that the system is more stable and less prone to dynamic changes.

VII. CONCLUSIONS

In this paper, we have presented the result of applying Bayesian method on two real-life converter-driven oscillation The results show that the method is highly effective in rapidly detecting and monitoring converter-driven oscillations. It is recommended that transmission system operators will further the apply this method (or other similar methods) for real-time oscillatory stability monitoring to enhance situational awareness and to create a more actionable operational insight for grid stability control.

Future research works involve, for example, assessing the effectiveness of utilizing Bayesian method's mode shape parameter in identifying the source of oscillation.

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