Koopman Mode Decomposition of Synchrophasor Data in Japan's Western Power System

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Abstract Inter-area oscillations (oscillations occuring in a group of generators) are predominantly governed by electromechanical modes with relatively slow time-scales in electric power systems. The stability of these oscillations is of vital concern for reliable operation of power systems. The inter-area oscillations are currently observed with synchronous measurement based on multiple phasor measurement units, called synchrophasor data. We apply the so-called Koopman mode decomposition to synchrophasor data in Japan's western power system and conduct a statistical analysis of the damping characteristics of the inter-area oscillation occurring in the practical system.

1 Outline

In recent years, with the development of Wide Area Measurement System (WAMS) technology, it has become possible to monitor the complex physics of large-scale electric power systems in real time: see e.g. [1] in Japan. The so-called Phasor Measurement Unit (PMU) is a device for collecting GPS-synchronized, high-sampling data on amplitudes and phases of AC voltages.

Due to the deployment of multiple PMUs, the so-called inter-area oscillation has been observed in the middle and western 60-Hz areas in Japan: see e.g. [2,3]. This inter-area oscillation is an inherent mode with a period between 2 and 3 seconds and has the characteristic of weak damping [4]. The weak damping is a cause of system-wide instability after a disturbance. Therefore, it is important to monitor and analyze the characteristics of the inter-area oscillation. The analysis of the inter-area oscillation has been reported with applications of Wavelet and Fourier analyses to synchrophasor data : see e.g. [5–7].

Following [8], in this report we analyze the damping characteristics of the inter-area oscillation by applying Koopman Mode Decomposition (KMD) [9] to synchrophasor data. KMD is a nonlinear time-series analysis based on spectral properties of the Koopman operator and derives from a given multi-channel signal a set of nonlinear modes oscillating with single frequencies [9]. The authors of [8] show that KMD is capable of extracting the inter-area oscillation from synchrophasor data collected in Campus WAMS [1]. Here we apply KMD to a large set of synchrophasor data and conduct a statistical analysis of the damping characteristics of the inter-area oscillation.

2 Synchrophasor Data

In this report, we use synchrophasor data (i.e. time-stamped data on voltage phasors) that have been continuously collected by PMUs at 12 universities in Japan since 2002 as shown in Figure 1. The PMUs collect the phasor data of 30 samples per a second in the 60-Hz areas and 25 samples in the 50-Hz areas.

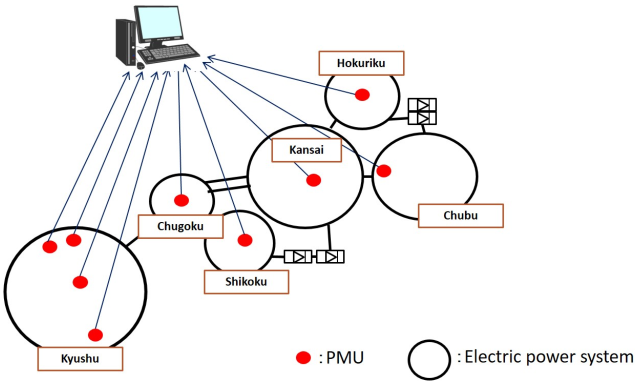

Figure 1: Installation of PMUs in Campus WAMS

3 Analysis of Inter-Area Oscillation

First of all, we summarize the analysis procedure conducted in this paper. 5-hours synchrophasor data (14 o'clock to 18 o'clock) were addressed for the 6 universities (Miyazaki University, Kyushu Institute of Technology (KyuTech), Osaka University, Fukui University, Nagoya Institute of Technology, and Hiroshima University). In order to analyze the weather dependence of the damping characteristics, we selected the days that were the same weather in Osaka and Fukuoka: July 31, 2015, August 5, 2015, July 28, 2016, and August 3, 2017 (Sunny days); July 22, 2015, August 31, 2015, July 8, 2016, and August 29, 2016 (Rainy days). First, we computed the difference of phases between Hiroshima University and the other universities listed above. Second, we subtracted the steady components from the computed phases. Third, we picked up multiple time-series with 10-minutes length start-

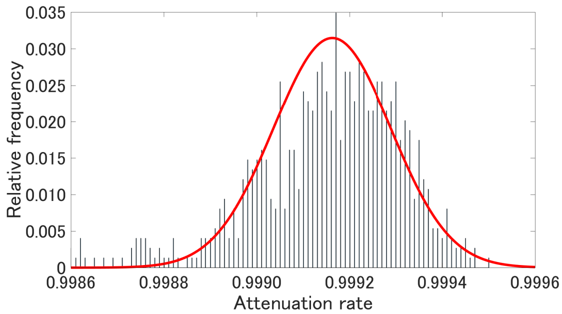

Figure 2: Relative frequency of the attenuation rate on August 29, 2016

ing at 14:00.00, 14:30.00, 15:00.00, 15:30.00, 16:00.00, 16:30.00, 17:00.00, and 17:30.00, then applied KMD to every time-series, and obtained a set of pairs of (approximations of) Koopman eigenvalues and Koopman modes: see [9] for the numerical algorithm of KMD. Lastly, from the obtained set, we extracted a pair of Koopman eigenvalue and mode such that it showed a modal oscillation with a period between 2 and 3 seconds and had the difference of augments of components in the Koopman mode between KyuTech and Osaka University within $[3\pi/4, 5\pi/4]$. The magnitude of the extracted Koopman eigenvalue tells us about how the associated modal oscillation is damped in time: the unity magnitude implies *no* damping. We call the magnitude of Koopman eigenvalue the *attenuation rate* in the following.

Here, using the above procedure we obtain a large number of the pairs of Koopman eigenvalues and modes. To visualize the result statistically, we calculate the relative frequency of the attenuation rate for the inter-area oscillation and show one example in Figure 2 for the synchrophasor data on August 29, 2016. In this example, the 554 pairs were obtained, and the resultant relative frequency was approximated with the normal distribution denoted by the *red* line. This approximation of probability distribution holds for the other days. Thus, using the probability distribution, we are able to calculate the confidence interval of the computed attenuation rate: see [10] for the scheme of the interval calculation.

Figure 3 shows the results on the attenuation rate with the 95% confidence intervals. As seen in the figures, the attenuation rate in the sunny days shows a slightly smaller value than in the rainy days. We speculate that this is related to the change of inertia constants of power systems [11]. It is here mentioned in [7] that the decrease of the inertia constants and the attenuation rate is correlated. Further analyses of the characteristics of the attenuation rate and their dynamical origin are in future work.

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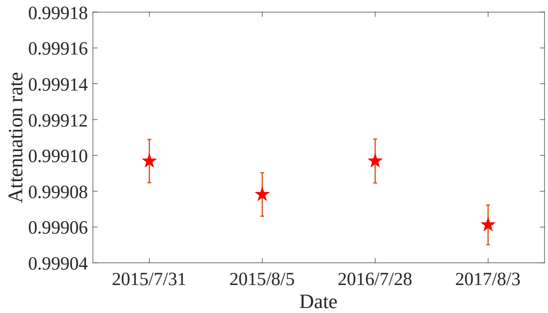
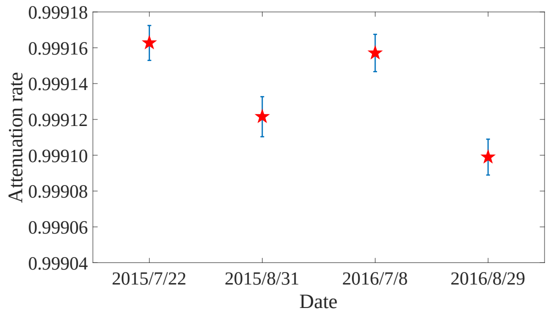


(a) Sunny days



(b) Rainy days

Figure 3: Weather dependence of the attenuation rate of the inter-area oscillation in Japan's western power system

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