Introduction

Electromechanical oscillations exist in many interconnected power systems. In this context, if an oscillation is not very well damped, it can grow in magnitude and result in grid breakups followed by large-scale blackouts. In order to prevent such dramatic events, the first step is to monitor (estimate) such oscillations in a real-time (online) manner.

The R3LS method

R3LS is a regularized robust recursive least squares method for online estimation of power system oscillations [1]. It is based on power system data acquired through phasor measurement units (PMUs). The method uses an autoregressive moving average exogenous (ARMAX) model, which can be represented by a pseudo-linear prediction equation as shown below (see references [1,2] for details):

$$\hat{y}(k|\theta) = -a_1 y(k-1) - \cdots - a_{na} y(k-na) + b_1 u(k-1) + \cdots + b_{nb} y(k-nb) \\ + c_1 \varepsilon\left(k-1\middle|\hat{\theta}(k-1)\right) + \cdots + c_{nc}\varepsilon(k-nc|\hat{\theta}(k-nc))$$

In this equation, $y(k)$ represents the PMU signal from which oscillations are to be estimated. In our research, the PMU signal is the system operation frequency. The user may select a specific PMU signal among a set of 6 PMUs currently available.

The power system oscillations can be shown to be related to the poles of the ARMAX model. These poles are estimated through equation:

$$s_i = \ln(z_i)\, f_s$$

where f_s represents the PMU sampling frequency and z_i are the corresponding discrete-time poles of the model, calculated as being the roots of polynomial $1 + a_1 q^{-1} + \cdots + a_{na} q^{-na}$, where q denotes the forward shift operator.

Clusterization of R3LS estimates

The estimated poles s_i vary depending on the choice made for the model orders na, nb, nc. Instead of choosing these orders arbitrarily, which is a common practice in most R3LS implementations, we here propose to execute several R3LS implementations in parallel, where each implementation uses a different combination of values for na and nc (nb is set to zero since $u(k)$ refers to the possibility of using probing signals, where this possibility is not being analyzed in this research). This parallelization results in a multi-model R3LS approach where pole estimates obtained for all different combinations of na and nc can then fed into a clustering algorithm that groups poles into a prespecified number of clusters.

For each new PMU measurement $y(k)$, let us suppose that the pole estimates obtained by running several R3LS implementations in parallel are concatenated in a matrix X with dimension $m \times 2$, where m represents the total number of estimated poles. More specifically, let us consider that the first column of this matrix contains the real parts of the estimated poles (i.e., the mode attenuations), whereas the second column contains the pole frequencies in Hertz.

One can then apply the so-called k-means clustering algorithm to this problem as follows: First, let us preprocess matrix X by selecting only poles with attenuations within interval [-0,5; 1,5] and frequencies within interval [0; 2]. Second, for each pole in X, we assign it to the closest centroid (among a pre-specified number of centroids K). For each centroid k, we then compute its new position by averaging the position of all poles in X which have been previously assigned to this centroid. Once a new PMU measurement $y(k+1)$ is available, the R3LS implementations update their estimated poles and a new clustering step can then take place.

For this website application, it is being considered pole estimates generated by 64 parallel implementations of R3LS. Such implementations have been obtained by combining the following different values for na and nc: 10, 15, 20, 25, 30, 35, 40, 45. At each different sample k, pole estimates are grouped into 8 different clusters. Each cluster centroid is represented by a blue “X” symbol. A black vertical line is also used to indicate a weighted average calculated based on the attenuations of the centroids. The variation in time of this weighted average attenuation can be observed in the figure dedicated to this purpose.

Reference

[1] ZHOU, N.; TRUDNOWSKI, D. J.; PIERRE, J. W.; MITTELSTADT, W. A.. Electromechanical Mode Online Estimation Using Regularized Robust RLS Methods. IEEE Transactions on Power Systems, vol. 23, no. 4, 2008.

[2] LJUNG, L. System Identification: Theory for the User. 2 ed. New Jersey: Prentice Hall, 1999.

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