European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality (ICREPQ'12)
Santiago de Compostela (Spain), 28th to 30th March, 2012

Power System Monitoring using Phasor Measurements

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Abstract. The paper describes investigation of the new opportunities for power system monitoring and control using phasor measurements. Phasor measurements are used for power system model identification in the form of state-space model. Implementing the modal analysis to identified state-space model gives the opportunity to control proximity of the operation point to the feasibility boundary. Also, identified state-space model allows predicting power system transient. All time domain simulations of the research are conducted for two-generator-swing-bus system. Calculations were carried out in Matlab.

Key words

WAMS, WACS, system identification, MOESP, modal analysis

1. Introduction

Stability margin monitoring was always of paramount importance for power system operation. Conventional method for stability margin evaluation is a number of continuation power flows for typical topological and operation cases of power system. From these calculations a number of sections of the power system is provided for a dispatcher, with maximum power transfer is evaluated for each section. The main drawback of this approach is inaccuracy of the power system model used for power flow. For instance, reactance of power line may vary from -10% to 8% due to conductors attitude and lightning conductor grounding. Such reactance variation impacts stability margins significantly. Recently, new devices for measuring power systems parameters, namely phasor measurement units, were developed. Application of the devices brings us to new opportunities for power system operation and control.

Another important power system operation task is preventing transient instability and dumping low frequency oscillations. The most effective approach here is coordinated control of generators and other devices that impact on dumping. The aim of coordinated control may also be achieved by implementation of phasor measurements.

The idea of the research is to use dynamic model identification techniques for power system dynamic equivalent evaluation based on phasor measurements. The equivalent is presented as a state-space model.

After the state-space model of the power system is identified, modal analysis is applied to the state matrix for small-signal stability evaluation. Also, the identified state-space model is used for power system transient prediction.

In the paper first step of the research is presented. The aims of the first step were to test the identification technique, to investigate the relation between real and identified power system model and to evaluate prediction procedure accuracy.

2. Identification technique

A number of dynamic model identification techniques is described in [2,3]. For the purpose of the research Multivariable Output Error State Space (MOESP) method was chosen. This choice is driven by that the order of the equivalent dynamic model is expected to be great, and MOESP is fast, non-iterative method. Further, brief description of the method is presented.

Dynamic equivalent of the power system is identified in the form of discrete-time state-space model [2]:

$$\begin{aligned} x_{k+1} &= A \cdot x_k + B \cdot u_k \\ y_k &= C \cdot x_k + D \cdot u_k , \end{aligned} \quad (1)$$

where x_k - model state n x 1 vector at time k;

y_k - model output m x 1 vector at time k;

u_k - model input p x 1 vector at time k;

A - state matrix of the model;

B - control matrix of the model;

C - output matrix of the model;

D - feedforward matrix of the model.

Structure of discrete-time state-space model is depicted in figure 1.

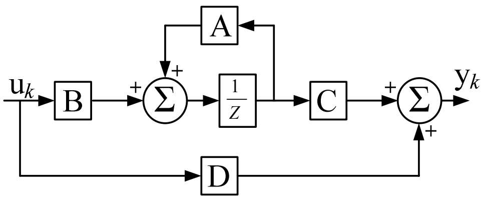


Fig. 1. State-space model structure

The idea of the method is to exploit linear algebra procedures and least-squares methods to get parameters of A, B, C, D from a sampled input and output data.

3. Transient prediction for power system optimal control

Study case for investigation of transient prediction was three-phase fault at the generator terminals in the two-generators-swing-bus system. Initial steady-state was P1=3000 MW and P2=3000 MW. For exciting identification, real power of the first generator was change to 3015 MW at time 1 sec.

For identification sampling interval of 0.02 sec was used. Prediction horizon was chosen as 5. Consequently, prediction time was 0.1 sec. Voltage phasors (simulate synchronized measurements) used as output of the system. Mechanical power of the generators is used as input of the system. Simulation results presented at the figure 2.

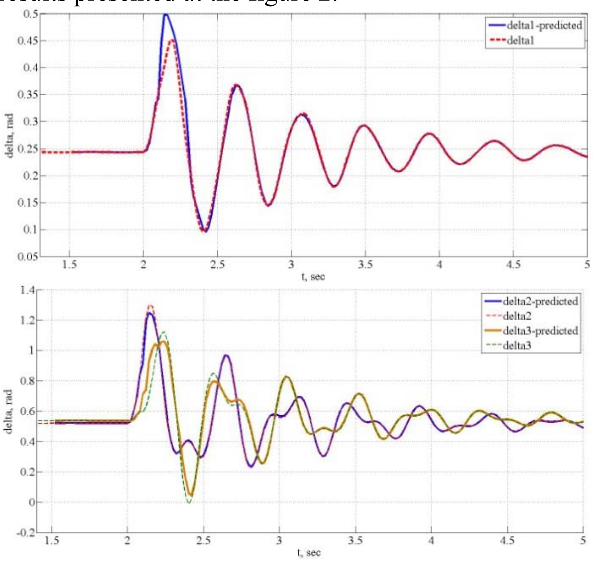


Fig. 2. Simulation and predictions results

It can be seen from the figure that prediction gave very good results. System considered is very simple and prediction interval is short. Hence, for more complex system the results are expected to be less optimistic, but the approach proves to be further investigated.

In proposed approach, final objective of the transient prediction is to use in optimal coordinated control of all power system. Structure of the proposed system is presented at the figure 3.

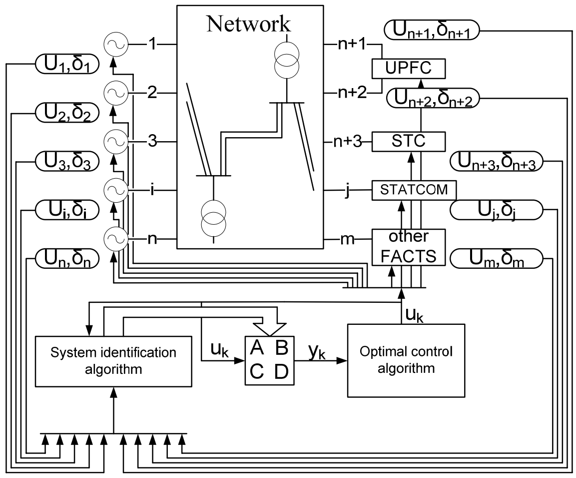


Fig. 3. Wide area control system

Optimal control itself don`t considered in this paper, but for, the brief looking: having predicted generator speeds, objective function can be constructed and minimized to get optimal control for dumping low-frequency oscillations.

4. Small-signal stability analysis

For small-signal stability studies, modal analysis is usually applied. System of differential equations describing system dynamics is linearized:

$$\begin{pmatrix} \frac{d\Delta\omega_1}{dt} \\ \frac{d\Delta\omega_2}{dt} \\ \frac{d\delta_1}{dt} \\ \frac{d\delta_2}{dt} \end{pmatrix} = \begin{pmatrix} k_1 \cdot k_{D1} & 0 & k_1 \cdot \frac{dP_{e1}(\delta_{10},\delta_{20})}{d\delta_1} & k_1 \cdot \frac{dP_{e1}(\delta_{10},\delta_{20})}{d\delta_2} \\ 0 & k_2 \cdot k_{D2} & k_2 \cdot \frac{dP_{e2}(\delta_{10},\delta_{20})}{d\delta_1} & k_2 \cdot \frac{dP_{e2}(\delta_{10},\delta_{20})}{d\delta_2} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} \Delta\omega_1 \\ \Delta\omega_2 \\ \delta_1 \\ \delta_2 \end{pmatrix} \quad (2)$$

where ω_1, ω_2 - speed deviation of the generators, [rad/s];

δ_1, δ_2 - generators angles, [rad];

P_1, P_2 - mechanical power of the generators, [MW];

P_{e1}, P_{e2} - electromagnetic power of the generators, [MW];

k_{D1}, k_{D2} - damping coefficients of the generators, [MW·sec/rad];

k_1, k_2 - coefficients, [rad/sec^2·MW].

Coefficients k_1, k_2 in *(2)* are calculated as follows:

$$k_i = \frac{2\pi \cdot f}{H_i \cdot P_{ni}},$$

where f - nominal frequency, [Hz];

H_i - inertia constant of i-generator, [sec];

P_{ni} - nominal power of i-generator, [MW].

Further, modal analysis is implemented to coefficient matrix of *(2)*. Eigenvalues of the matrix characterize power system oscillations. One of investigation aims was to compare coefficient matrix of *(2)* and state matrix A of *(1)*. It will be shown below that eigenvalues of both matrices are the same.

Three simulation cases were chosen for the study:

1. Power system operation point is far from feasibility boundary;
2. The operation point is close to feasibility boundary with the second generator is heavy loaded;
3. The operation point is on the feasibility boundary, second generator is out of synchronism after the disturbance.

Above operation points are presented at the figure 4. As a disturbance 10 MW power increase of the second generator was chosen.

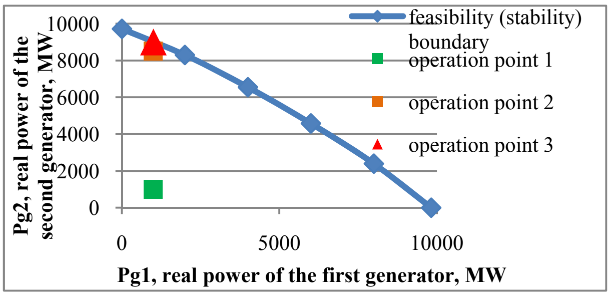


Fig. 4. Feasibility area of the power system state

For each case, eigenvalues of the power system were calculated from coefficient matrix of *(2)*. Then from voltage phasors of the generators power system model of the form *(1)* were constructed using the identification technique.

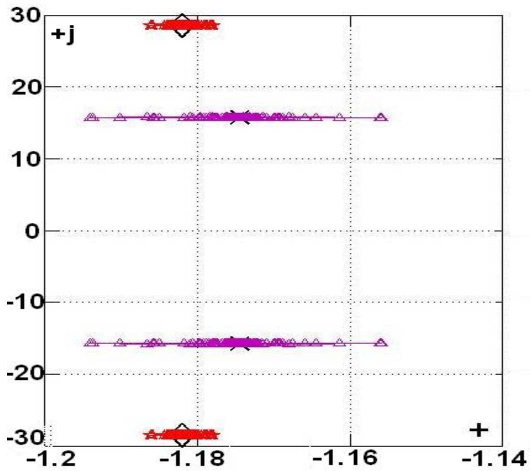
Although real dynamic system *(2)* is of order 4, from the trial-and-error, order of the identified system was chosen 6. It is explained by the necessity to take into account the swing bus. After that, eigenvalues of the identified state matrix of *(1)* were calculated. Since the state matrix is 6x6 it has six eigenvalues. The last two eigenvalues are related to the swing bus. For this reason these eigenvalues don`t considered. Comparison of the rest eigenvalues is presented at the figure 5.

It can be seen from fig. 5 that for operation point both far from feasibility boundary and close to it, eigenvalues of the identified and the real system are in close vicinity. This phenomenon indicates that identified model reflects dynamics of the real power system and can be used for power system dynamics monitoring (control of the distance to feasibility boundary, monitor oscillation modes and coherent groups of generators, etc.).

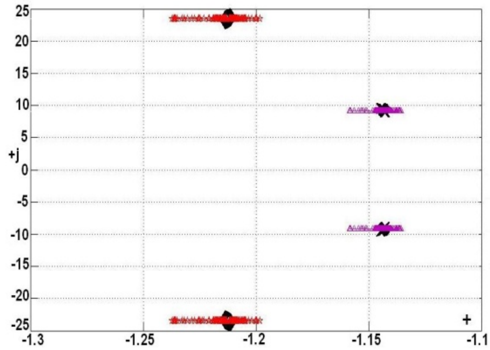
5. Conclusion

System identification based control is used in power system to govern individual units [4], [5]. Implementation of the identification techniques for monitoring and control of whole power system is the novel approach. Advantages of this approach are:

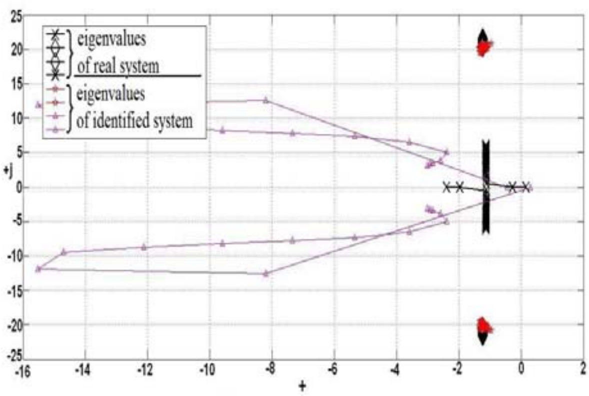
o Since identification procedure is supplied by the phasor measurements, the identified system contains actual information about power system (power system models used nowadays are



a) operation point 1



b) operation point 2



c) operation point 3

Fig. 5. Eigenvalues of the power system

predescribed and contain errors as it was mentioned in the introduction);

o On-line identified system presents current operation point (nowadays limitations on power system operation are evaluated off-line for the "worse case");

o Identified model can be applied for both control and monitoring aims through the implementation of the different techniques (modal analysis, optimal control, etc.).

The main drawback of the approach is a communication delay for collecting the phasor measurements from wide area and sending control commands. This aspect requires further investigation.

Other investigation objectives include:

- o Testing on large models of real power systems with communication delays to be taken into account;
- o Investigation of different identification algorithms [6,7,8] and tuning the algorithm to improve its implementation for the specific task (power system has features that should be exploited, another objective of the algorithm tuning is the prediction horizon increasing);
- o Development of the “control part”.

The research conducted has shown that the approach worth further investigation.

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