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Coherence indicators of generators for express assessment of electric power system transient stability

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Abstract. A brief overview of the generator coherence indicators is presented, the areas and limitations of their applicability are indicated. The application of the area method for the rapid assessment of the transient stability of complex multi-machine electric power system based on the features of the dynamics of the system behavior, determined by the heterogeneous structure of the electrical network, is considered. A distinctive feature of the proposed approach is the use of the characteristics of the heterogeneity of the power system structure, which determine the presence of weak links (or cut-sets) of the electrical network, which are critical from the point of view of a possible violation of the system stability.

1 Introduction

Due to the instability of the electricity market and the growing demand for electricity, modern EPSs (electric power systems) are forced to work closer and closer to the limits of their stability. This makes the system more vulnerable to internal failures and external disturbances and increases the risks of stability loss.

Conventionally, the assessment of transient stability comes down to detailed simulation of EPS responses to disturbances – that is, to calculations of transients (this is the numerical integration of a system of nonlinear differential equations of large dimensions). However, a disturbance is unpredictable, and the calculations should be carried out at least with a minimum, but in advance - the calculation itself takes a lot of time, and it still takes time to develop control actions.

The key points of the proposed approach to the analysis of the transient stability of EPS are the following:

1. Study of heterogeneities in electric power systems.
2. Revealing the coherence of the movement of generators under disturbances.
3. Reducing the models of dynamics of electric power systems.
4. Study of stability using reduced models.

In view of the foregoing, an express assessment of the transient stability of a complex EPS using the area method for a given studied conditions, including a given network topology, electric mode and disturbance, is performed as follows:

1) Using structural analysis algorithms, weak (dangerous from the point of view of a possible violation of the stability of the system under a specific disturbance) cut-sets of the studied network are determined and ranked according to the degree of weakness;
2) For each weak section, as the degree of weakness decreases, a two-machine equivalent is formed;
3) An assessment of the transient stability by the area method is carried out for each of the obtained two-machine equivalents as the weakness of the sections decreases. The evaluation ends at the section for which the applied area method no longer violates the stability of the system;
4) If for any of the network cut-set, according to the above algorithm, a violation of the stability of two-machine equivalents is not recorded, we can assume that the stability of the EPS in a given studied conditions is not violated. Otherwise, the estimates show a violation of the stability of the system for a given network topology, electric mode and disturbance.

2 Heterogeneity of EPS and coherence of movement of generators

Structural heterogeneity is a fundamental property of any systems with a complex structure. The structure of the electrical network of a complex EPS is always heterogeneous and includes strongly connected subsystems and weak connections between them. It is important to identify this heterogeneity, quantify it and use it in modeling the EPS, its study and control of electric modes [1].

During the operation of the EPS, it is subject to disturbances and reacts to them by changing the parameters of the system electric mode. This reaction is determined both by the magnitude and location of the disturbance, and by the internal properties of the system itself. The nodes and connections (sections) of the system, the electric mode parameters of which reach unacceptable values first of all, are called weak points.

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When simulating electromechanical transients and evaluating the stability of EPS during disturbances, the presence of strong connections between the generators of a strongly coupled subsystem determines the coherence (identity, consistency in time) of the movement of generators in transients. Besides the presence of large reserves of throughput for connections between generators, which guarantees their mutual stability within the subsystem. On the contrary, weak connections between strongly connected subsystems create threats of stability violation. Due to the limited transmission capacity of weak links, it is along them that violations of the stability of the system usually occur during disturbances. Therefore, the identification and quantitative assessment of weak links in the structure of the electrical network are important tasks in the process of studying stability and determining control actions to ensure it [2].

The purpose of the study of heterogeneities is to identify weak links in the structure of the electrical network and thereby determine the strongly connected subsystems in this structure. Violations of the EPS stability and cascade development of emergency processes during regime changes will occur primarily through weak links (between subsystems) and less likely through stronger links (within subsystems). Therefore, the stability of the EPS must be analyzed primarily in relation to weak links.

Structural inhomogeneity of the EPS determines the specifics of the movement of the system generators in the transient electromechanical process, namely, their coherent movement. The coherence of the movement of generators is an objective basis for reducing the mathematical model of the EPS dynamics by aggregating (combining) generators included in the same subsystem.

The motion coherence of generators i and j is defined as

$$\delta_i(t) - \delta_j(t) = const \tag{1}$$

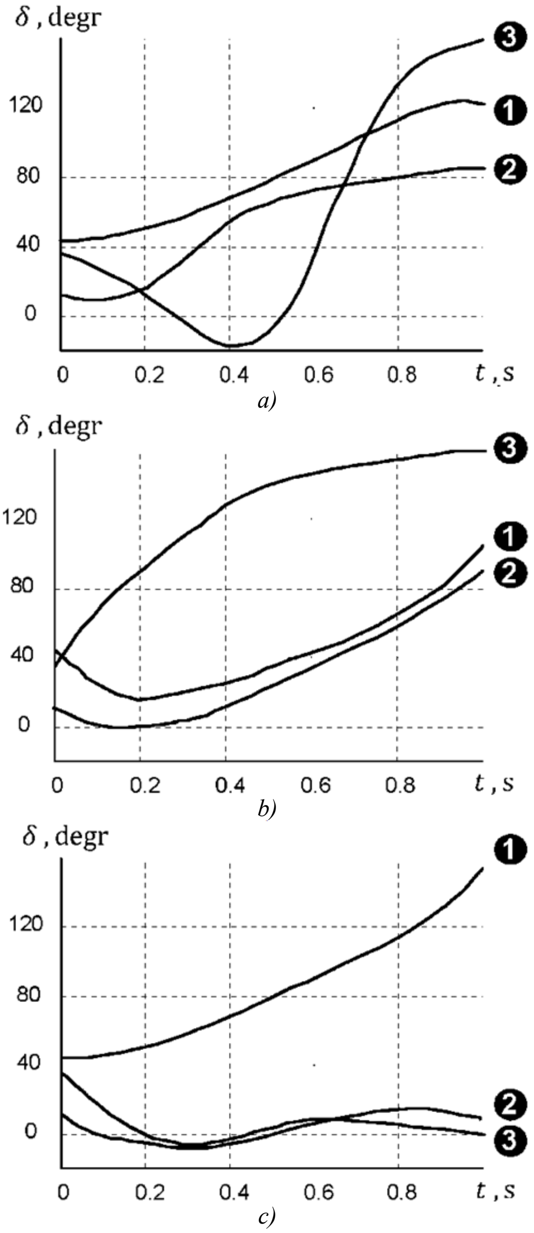
where $\delta(t)$ are the angles of the rotors of generators i and j as functions of time in a single coordinate system.

Identification of the coherence of the movement of generators during disturbances is the identification of groups of generators, the mutual (relative to each other) movement of which in the transient is close to coherent.

3 Metrics and similarity/difference matrices for identifying coherent groups of generators

Coherence can be determined by directly comparing the motion curves of the generators (which requires numerical integration of the transient). So, in Fig. 1, in the studied conditions *a)* and *b)*, generators 1 and 2 are more coherent to each other than each of them is to generator 3. In case *c)*, generators 2 and 3 have the greatest mutual coherence.

In addition, coherence can be estimated by formal indicators of mutual similarity or difference in the movement of generators in the transient, based on the admittances of the equivalent network, inertia and acceleration of machines.



a)

b)

c)

Fig. 1. An example of the change in time of the angles of the generators in three studied conditions.

The equivalent network of the investigated EPS for calculating the indicators of similarity (coherence) or difference (non-coherence) of generators, in structural analysis is obtained from the conventional network used to calculate steady-state electric modes, by:

- representation of loads by constant admittances, generators by a two-node equivalent (bus – transient impedance – transient electromotive force (EMF)), power of the primary engine (in the equations of motion of the generator rotors) – by a constant,
- exclusion of all nodes that do not contain EMF.

Any pair of equivalent network nodes turns out to be interconnected by an equivalent connection. From the point of view of interaction and mutual influence of generators, EPS can be represented as a complete graph, at the vertices of which generators are connected, and the edges represent the relationship between generators. Edges can be assigned some numerical characteristics that determine the degree of interaction and mutual influence of generators. Then the response of the system as a whole to the disturbance, instead of the curves of the movements of the generators, can be described by a matrix of similarity or difference indicators of the movements of the generators in pairs. On the basis of such matrices, a classification (identification of coherent groups) of generators can be made. The result of it is a set of nested subsystems (groups of generators of greater or lesser coherence) for a given studied conditions.

The simplest indicators of coherence are determined through the admittance of the electrical network, in other cases they take into account the electric mode parameters and dynamic parameters of the EPS. In this case, the force of mutual influence of two generators can be interpreted as the strength of the connection between them and as the similarity (coherence) of their movement in the transient.

Of the formal indicators of the similarity of generators, two have been conventionally and most widely used (see, for example, [3, 4]):

- *“Distance-admittance”*, defined as the admittance of connections of the equivalent network obtained from the initial network (for generator models “EMF behind transient impedance”) with the exception of all nodes that do not contain EMF. These measures describe how closely two generators are electrically connected.
- *“Distance-reflection”* as the magnitude of the acceleration components (or active unbalance on the shaft) of one machine due to a change in the angle of the other. Unlike distance-admittance, this measure reflects the dynamic influence (synchronizing power) of one generator on others as a result of disturbance.

Note that here the historically accepted term “distance” is inaccurate, since both of the indicators are essentially measures of similarity (proximity).

In addition, the problem of determining coherence was solved using such features as:

- symmetry of generators relative to the system, initial mutual accelerations of the rotors [5, 6],
- differences in the angular deviations of the EMF of generators in a pair from their initial value at a given time interval, determined by a linearized model, [7, 8],
- equality of synchronizing powers, observance of stability conditions within the group, and a number of others [3, 4, 9–11].

In various sources, the following were considered as indicators of the similarity of generators:

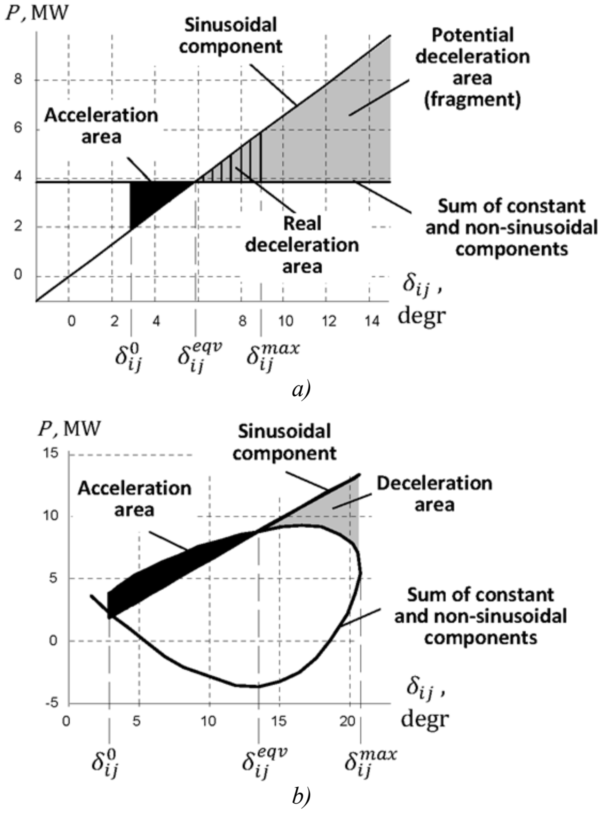
- electrical connectivity (structural maximum as the capacity of an equivalent connection) [12];
- dynamic (taking into account inertia) connectivity [11] or dynamic connectivity, determined using pairs of eigenvalues of the linearized model of EPS dynamics [13];
- the severity of the disturbance for a pair of generators based on the values of the Lyapunov function, written as an integral of energy for the mathematical model of the EPS dynamics in positional idealization [14].

For a more accurate assessment of coherence, it is often recommended to numerically calculate the initial stage of the transient using a linearized or nonlinear model [4, 15]. An analytical algorithm for estimating motion coherence based on the area method for pairs of generators was developed in [10, 13] using the assumption of invariance in the transient of the mutual acceleration component of a pair of machines, determined by the change in the angles of the machines of the remaining part of the system. For the same purposes, indicators of the influence of disturbances on the behavior of EPS elements can be used, additionally taking into account the parameters of the disturbance and the dynamic characteristics of generators [9, 10].

Let's assume that the reference (accepted obviously correct) process of classification of generators is known, obtained on the basis of numerical integration of the electromechanical transient process and visual analysis of integral curves. Then, evaluating the similarity with it of classification processes based on matrices of formal indicators of similarity or difference of generators, it is possible to determine to what extent this or that indicator is adequate to the task of identifying groups of coherent generators - that is, whether and in what cases this indicator is a measure of coherence generator movements.

4 Energies of acceleration and deceleration

The indicators based on the values of the energies of the mutual acceleration and actually implemented in the transient braking of generators are determined by integrating the mutual acceleration over the mutual angle (Fig. 2).



a)

b)

Fig. 2. Determination of the energies (areas) of mutual acceleration and deceleration of generators i and j for a simple disturbance by integrating over the mutual angle.

Fig. 2a illustrates the result of analytical integration with the assumption of the constancy of the non-sinusoidal component, and fig. 2b – the result of numerical integration without that assumption.

The integration result contains three components:

1) *Constant* component reflects the difference in the design and operating parameters of a pair of generators (turbine power, moments of inertia, EMF modules and modules of self-admittances of driving points),
2) *Sinusoidal* component reflects the influence of direct connection between generators,
3) *Non-sinusoidal* component reflects the influence of the remaining part of the system (asymmetry in the location of two generators relative to all other generators, manifested through the difference in power flows related to the moments of inertia).

5 Reducing the Power System Dynamics Models – Two-Machine Equivalent

Identification of dangerous sections from the point of view of a possible violation of the stability of the system under a specific disturbance is carried out by means of a cluster analysis of indicators that estimate the degree of coherence of the movement of generators in the transient [1, 2].

Classification of generators can also be made on the base of analysis and comparison of transient curves for various studied conditions. However, this way eliminates the very need for classification (since the detailed calculations necessary to obtain the curves in themselves provide an answer to most of the questions that arise in the study of a given conditions).

Hence, it is obvious that it is necessary to use the most simplified models of the movement of generators in the transient, or to search for the possibilities of classifying without resorting to numerical integration at all. To organize and visualize the hierarchical structure of the electrical network, dendrograms (classification trees) are used, i.e. a graphical method for presenting the results of hierarchical clustering, which shows the degree of proximity of individual energy objects and clusters, and also graphically demonstrates the sequence of their combination or separation. Dendrograms store information about further divisions (or associations) of the electrical network into smaller (larger) islands.

The transient stability of an EPS is conventionally estimated by numerically integrating its model offline for different studied conditions (network topologies, electric modes, and accident scenarios). The simplest classical positional model of EPS dynamics is written for the i-th generator in the form

$$\frac{d^2\delta_i}{dt^2} = \frac{\omega_0}{T_{Ji}} \cdot \frac{P_{\text{T}i} - P_i}{S_{\text{НОМ}i}} \ , \ i = \overline{1, N} \ . \tag{2}$$

Here t is time, δ_i is the angle of the generator rotor relative to the synchronous axis, $P_{\text{T}i}$ and P_i are electrical active powers (power, created by the accelerating torque of the turbine, and the generator power output to the network), $S_{\text{НОМ}i}$ is the rated power of the generator, T_{Ji} is the rotor inertia constant, ω_0 is the rated angular speed of the rotor, N is the number of generators in the EPS. The power supplied to the network is defined as

$$P_i = \sum_{j=1}^{N} E_i' E_j' y_{ij} \sin\left(\delta_{ij} - \alpha_{ij}\right) \ , \ i = \overline{1, N} \ , \tag{3}$$

where $\delta_{ij} = \delta_i - \delta_j$ is the mutual angle of the rotors of generators i and j, E_i' and E_j' are transient EMFs of generators i and j, y_{ij} and α_{ij} are the modules and complementing to 90° the angles of the complexes of intrinsic and mutual admittances of the electrical network.

Different elements of the EPS react to disturbances in different ways. However, the behaviors (reactions) of some elements are more similar to each other than to others. This creates the possibility of aggregating information in order to reduce computational costs.

Reducing the dynamics models of electric power systems is an aggregated representing of each of the coherent groups of generators by one equivalent generator. The conventional task of aggregation is to reduce the dimension of analyzed network (electromechanical equivalencing).

Reducing the EPS dynamics model during the express assessment of transient stability consists in constructing a two-machine equivalent – that is, a two-node network, each of the nodes of which is an equivalent generator (that is, it aggregates a group of coherently moving generators).

The most common models of equivalent generators are:

- The center of inertia, characterized by aggregated (summed over the group) parameters, when the power, constant of inertia, admittance of connections with the nodes of the external network are taken equal to the sums of the values of the corresponding parameters of the generators of the aggregated group, and the equivalent EMF – equal to the sum of EMF of equivalent branches weighted by their admittances [10].
- A representative generator that reflects the dynamic characteristics of a coherent group to the greatest extent (compared to other generators). The degree of representativeness is determined by the value of the “participation factor” (the contribution of the movement of the generator to the movement of the entire group). Such approaches are common when using selective modal stability analysis (see, for example, [16]).

The dynamic equivalent of REI (Radial Equivalent Independent), similar in implementation to the center of inertia model, but providing equality of power losses in the steady state for the initial and equivalent networks. This is achieved by introducing a temporary fictitious “network of zero power balance”, electrically connecting the nodes of these networks with each other [17, 18].

By analogy with (2) and (3), the dynamics model of the two-machine (machine I and machine K) EPS equivalent can be written as

$$\frac{d^2\delta_{IK}}{dt^2}=\frac{d^2\delta_I}{dt^2}-\frac{d^2\delta_K}{dt^2}=\frac{\omega_0}{T_{JI}}\cdot\frac{P_{\text{т}I}-P_I}{S_{\text{ном}I}}-\frac{\omega_0}{T_{JK}}\times \\ \times\frac{P_{\text{т}K}-P_K}{S_{\text{ном}K}}=\omega_0\left(\frac{P_{\text{т}I}-P_I}{T_{JI}S_{\text{ном}I}}-\frac{P_{\text{т}K}-P_K}{T_{JK}S_{\text{ном}K}}\right), \tag{3}$$

where

$$P_I=E_I'^2y_{II}\sin(-\alpha_{IK})+ \\ +E_I'E_K'y_{IK}\sin(\delta_{IK}-\alpha_{IK})\,, \tag{4}$$

$$P_K=E_K'^2y_{KK}\sin(-\alpha_{KI})+ \\ +E_I'E_K'y_{IK}\sin(\delta_{KI}-\alpha_{KI})\,. \tag{5}$$

6 Summary of the Results

The highest accuracy of coherence recognition is achieved when using the acceleration and deceleration energies, which require numerical integration of the transient. However, the suitability of these indicators for rapid recognition is limited by the complexity of the calculation. At the same time, determined from a simplified model of generator motion, these indicators are suitable for identifying groups of coherent generators in cases of complex disturbances.

For simple disturbances, the most accurate identification of groups of coherent generators is made by the matrix of absolute values of the initial mutual accelerations of their rotors. If it is necessary to use indicators of mutual similarity or difference not only for generators, but for any nodes of the studied network (which is required in a number of tasks), indicators such as mutual admittance modules, synchronizing powers and structural maxima are acceptable.

To identify groups of coherent generators under complex disturbances, the use of indicators based on numerically determined acceleration and deceleration energies is preferable to indicators of the quality of the transient (since energy-based indicators, firstly, provide a quantitative measure of stability and, secondly, do not require expert assignment of the integration interval).

The identification of groups of coherent generators based on energy indicators determined through the analytical integration of mutual acceleration over the mutual angle of generators is less reliable than the identification based on numerically determined energy indicators. The reason is the assumption about the constancy of the influence of the system on the mutual motion of the generators, introduced to create the possibility of analytical integration. In addition, these indicators (as well as the rest, determined without numerical integration) do not allow taking into account complex disturbances (sequences of several commutations that do not coincide in time).

Energy-based indicators can be used to identify groups of coherent generators, provided that among the mutual movements of the generators there are no movements that are unstable on oscillations greater than the first. With this limitation, the most universal indicators are the absolute and relative values of the acceleration pads. The main advantage of energy indicators in comparison with visual analysis of curves and indicators of the quality of the transient is in their completely formal (not requiring expert decisions) calculation.

The time interval of integration and the complexity of obtaining indicators of the quality of the transient and indicators based on numerically determined energies are comparable.

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