ENHANCED MODAL BASED TECHNIQUE FOR CONSTRUCTION OF POWER SYSTEM DYNAMIC EQUIVALENTS

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Abstract – This paper deals with the construction of dynamic equivalents on the base of modal system information. The modal method is recommended for use in connection with power system controller design techniques, which require lower order models. It is shown, that the criteria for replacing several generators by a single equivalent is similarity of the eigenvectors regarding amplitude and phase angle as well. This conclusion yields also for equivalencing in the time domain. It is recommended treating the problem of generator grouping as a clustering task. The variables describing the behavior of generators are assembled in properly chosen feature vectors. It is shown, that the weighting of generator Euclidian distances towards the centroid of the group by the eigenvalue participation factors allows an essential improvement of the equivalent. Examples calculated in a large-scale model of the European Interconnected Electric Power System show the applicability and accuracy of the proposed method.

Keywords: Dynamic Equivalent, Modal Analysis, Clustering, Interarea Oscillations

1 INTRODUCTION

Despite of the increasing performance of modern computers, power system dynamic simulation studies can be very time consuming. Especially the use of controller design techniques requires smaller system models. Usually real power systems consist of several thousand states. Handling such a large system within a controller design procedure is not possible yet. Moreover, it would lead to unrealistic high order controller models. However, in many cases, Dynamic Equivalents (DE) provide accuracy sufficient for most of the investigations. Furthermore, the system size of a DE is less, which provides the advantage of a better simulation time performance and less data requirements. In the competitive power market, utilities are not interested in sharing important data. In this situation, DE offers the option of covering information, so that the user cannot reach them directly. However, their effect will be considered.

Dynamic Equivalents are, apart from some special cases, reduced order models, i.e. the number of differential equations necessary for describing the system is less than of the full system. The reduction can be done based on:

- Redundancy in the system equations (e.g. because similar generators are working parallel)
- Output behaviour, which means that the outputs is restricted to selected modes

Redundancy in electric power systems can be recognized commonly by coherent generator swings. Therefore, coherency is the most used measure for identification of the model reduction opportunity. Since it is related to particular generators, it is evident representing these generators by a single equivalent one.

If some modes are not observable in the system output, it is obvious to neglect these modes. Modes are not observable either because they are not excited from the chosen inputs or generally, since the observability in terms of control theory is not given. It will be assumed, that not observable modes are stable and thus they are not from particular interest. It is also possible, that, even though modes are observable, they can be neglected or replaced by a single aggregated mode because they have no significant effect on the interested system behavior. For instance, interarea modes can be investigated without considering all local modes. That means, a reduced model focused on interarea oscillations is suitable in this case.

In the time domain, coherent generators can be identified by selecting generators, which show good correlated swing curves. However, the time behavior of generators depends on the simulated disturbance. Hence, the correlation and thus the coherency identification is always fault dependent in the time domain. This is on the one side a drawback because it is not always sure, that the corresponding equivalent will only be used for calculations of the considered faults. On the other hand it will be more accurate, if all faults and disturbances are known, for which the equivalent has to be produced, since the equivalent is fitted to them.

Modal equivalencing techniques are based on the eigenmotions, modes of the system. Modes are independent from the excitation, i.e. disturbances are not significant in this relation. Modal techniques require the selection of modes for which the equivalent should be fitted. In the time domain simulation, the interesting modes are the excited ones, which depends on the simulated disturbances as mentioned above. If the equivalent is used for a damping controller design, the interest is usually focused on a few preferred, e.g. weekly damped interarea modes. This is the reason why modal based equivalencing techniques are more favorable in connection with controller design techniques.

In this paper, the modal based equivalencing technique should be discussed. It will be shown, that the criterion generator coherency, which has been used until now in the equivalencing techniques, must be extended. Furthermore, treating the equivalencing problem as a clustering task, different standard software tools may be used. Further enhancements can be achieved by weighting the generators by participation factors within the clustering algorithm. Examples calculated with a model of the European Interconnected Power System, consisting of several hundred of generators, will demonstrate the applicability and the improvements of the proposed method.

2 MODAL BASED EQUIVALENCING TECHNIQUE

2.1 Modal approach

Modal methods are increasingly used for the analysis of the small-signal stability of large electric power systems. It became possible by modern and powerful computers on the one side and by development of efficient algorithms for the calculation of eigenvalues, eigenvectors, and other modal quantities on the other side.

Assuming a linearized state equation, describing the power system

$$\begin{aligned} \Delta\dot{\mathbf{x}} &= \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u} \\ \Delta\mathbf{y} &= \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{u} \end{aligned} \tag{1}$$

the eigensolution for the states is given by the following equation:

$$\Delta\mathbf{x}(t) = \sum_{i=1}^{n} \underline{\mathbf{\Phi}}_i e^{\lambda_i t} (\underline{\mathbf{\Psi}}_i \Delta\mathbf{x}(0)) \tag{2}$$

where
- $\mathbf{x}$ state vector
- $\underline{\mathbf{\Phi}}_i$ *i*-th right eigenvector
- $\underline{\mathbf{\Psi}}_i$ *i*-th left eigenvector (row vector)
- λ_i *i*-th eigenvalue
- n system order

It is obvious, that the participation of each state on the mode $e^{\lambda_i t}$ regarding intensity and phase angle is described by the complex right eigenvector $\underline{\mathbf{\Phi}}_i$. The excitation of the modes depend on the left eigenvector $\underline{\mathbf{\Psi}}_i$ and the initial states $\Delta\mathbf{x}(0)$, respectively.

Many times, the interest is focused on the linkage of single modes and selected original state variables. For this purpose, the so-called participation factors can be used. They are defined as the sensitivity of the eigenvalue λ_i relating to a_{kk}, which is the *k*-th diagonal element of the system matrix $\mathbf{A}$.

$$\underline{p}_{ik} = \frac{\partial\lambda_i}{\partial a_{kk}} \tag{3}$$

p_{ik} describes the participation of the state variable x_k in the mode $e^{\lambda_i t}$. It is a complex value because of the complex character of lambda. The participation factors can be calculated from the right and left eigenvectors, respectively [1].

2.2 Conditions for replacing of generators by an equivalent

Coherency based on linear system swings means that frequency, damping, and initial phase shifting of the particular swings differ not too much. For one selected mode, the frequency and damping are common for all states by the term $e^{\lambda_i t}$ in Eq. (2). That means, coherency is described exclusively by the corresponding right eigenvector $\underline{\mathbf{\Phi}}_i$. Considering only the elements of $\underline{\mathbf{\Phi}}_i$ corresponding to the electromechanical states rotor angle (electromechanical element), one gets a reduced vector, which describes the so-called rotor mode shape. In this paper, these selected elements of the eigenvector are composed to the vector $\underline{\mathbf{\Phi}}_i^R$. Coherent generators relating to selected eigenmotions can be identified based on the small angles between the elements of the corresponding mode shape vector. It is shown in Figure 1.

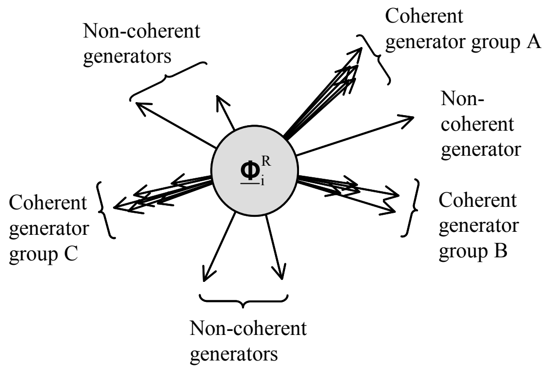

Figure 1: Identification of coherent generators based on generators electromechanical eigenvectors

Regarding the magnitudes of the vectors, still no conclusions are possible. This topic will be discussed in the next section.

For practical use, it is required to replace coherent generator groups by real single generators. The other alternative, modeling the generator groups by a few numbers of fictive algebraic-differential equations, is commonly not accepted, because people are expecting rather real equivalent generators. Calculation of the parameter of generators should not be discussed here. To this topic is referred e.g. in [2]. However, the electrical connection of the equivalent to the network, i.e. the replacement of several generators by only one without changing the power flow relationships, is in this paper of particular importance. The most applied solution for this purpose is shown in Figure 2, [3].

According to Figure 2, the equations in this study are written for two generators only. Nevertheless, the purpose of the authors is a generalization. The complex (underlined variables) driving voltages $\underline{E}_1^{''\angle N}(t)$, $\underline{E}_2^{''\angle N}(t)$ and $\underline{E}_E^{''\angle N}(t)$ are all in a common "network" (superscript $\angle N$) reference frame.

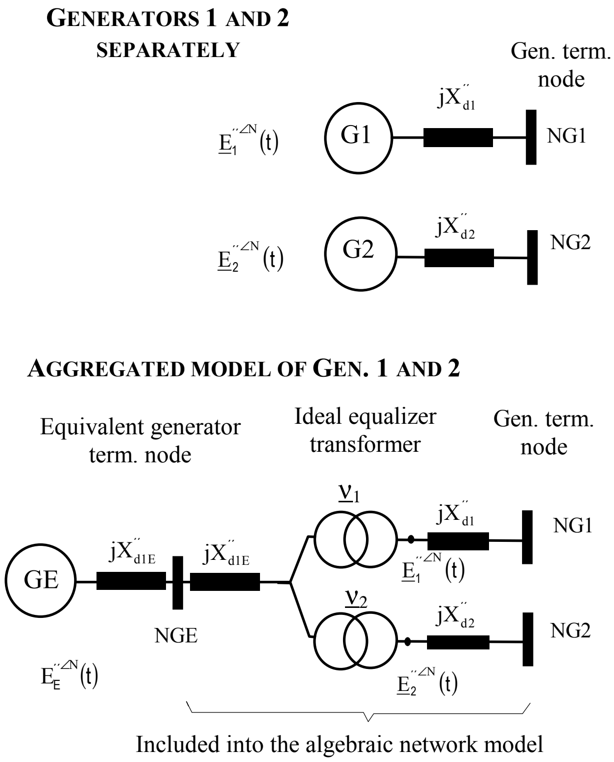

Figure 2: Electrical aggregation of coherent generators

This common treating is necessary for calculation of a multi machine system [1]. The turns ratios of the ideal equalizer transformers are given by

$$\underline{\nu}_1 = \frac{\underline{E}_E^{''\angle N}(0)}{\underline{E}_1^{''\angle N}(0)} \quad (4a) \qquad \underline{\nu}_2 = \frac{\underline{E}_E^{''\angle N}(0)}{\underline{E}_2^{''\angle N}(0)} \quad (4b)$$

which results from the steady state power flow conditions.
However, from the equivalent network in Figure 2 follows for the whole period of time

$$\underline{\nu}_1 \underline{E}_1^{''\angle N}(t) = \underline{E}_E^{''\angle N}(t) \quad (5a) \qquad \underline{\nu}_2 \underline{E}_2^{''\angle N}(t) = \underline{E}_E^{''\angle N}(t) \quad (5b)$$

since the equivalent generator should represent the individual behavior of the single generators not only in the initial state but during the whole time period. Considering this fact, changes in the driving voltage consist of two parts: one is derived from the rotor flux linkages, and the other part is caused by the torsion $\Delta\delta(t)$ of rotor and the corresponding reference frame $\angle dq$ related to the common reference frame $\angle N$. Therefore, it can be written:

$$\underline{E}_1^{''\angle N}(t) = \underline{E}_1^{''\angle dq}(t)\, e^{j(\delta_{10}+\Delta\delta_1(t))} = \underline{E}_1^{''\angle dq}(t) e^{j\delta_{10}}\, e^{j\Delta\delta_1(t)} \quad (6a)$$

$$\underline{E}_2^{''\angle N}(t) = \underline{E}_2^{''\angle dq}(t)\, e^{j(\delta_{20}+\Delta\delta_2(t))} = \underline{E}_2^{''\angle dq}(t) e^{j\delta_{20}}\, e^{j\Delta\delta_2(t)} \quad (6b)$$

This yields also for the equivalent generator

$$\underline{E}_E^{''\angle N}(t) = \underline{E}_E^{''\angle dq}(t)\, e^{j(\delta_{E0}+\Delta\delta_E(t))} = \underline{E}_E^{''\angle dq}(t) e^{j\delta_{E0}}\, e^{j\Delta\delta_E(t)} \quad (7)$$

From equations (5) and (6) follows

$$\frac{\underline{E}_E^{''\angle N}(t)}{\underline{E}_1^{''\angle N}(t)} = \underline{\nu}_1 = \frac{\underline{E}_E^{''\angle dq}(t) e^{j\delta_{E0}}}{\underline{E}_1^{''\angle dq}(t) e^{j\delta_{10}}}\, e^{j(\Delta\delta_E(t)-\Delta\delta_1(t))} \quad (8a)$$

$$\frac{\underline{E}_E^{''\angle N}(t)}{\underline{E}_2^{''\angle N}(t)} = \underline{\nu}_2 = \frac{\underline{E}_E^{''\angle dq}(t) e^{j\delta_{E0}}}{\underline{E}_2^{''\angle dq}(t) e^{j\delta_{20}}}\, e^{j(\Delta\delta_E(t)-\Delta\delta_2(t))} \quad (8b)$$

Supposed that

$$\frac{\underline{E}_E^{''\angle dq}(t) e^{j\delta_{E0}}}{\underline{E}_1^{''\angle dq}(t) e^{j\delta_{10}}} \approx \frac{\underline{E}_E^{''\angle dq}(0) e^{j\delta_{E0}}}{\underline{E}_1^{''\angle dq}(0) e^{j\delta_{10}}} = \underline{\nu}_1 \quad (9a)$$

$$\frac{\underline{E}_E^{''\angle dq}(t) e^{j\delta_{E0}}}{\underline{E}_2^{''\angle dq}(t) e^{j\delta_{20}}} \approx \frac{\underline{E}_E^{''\angle dq}(0) e^{j\delta_{E0}}}{\underline{E}_2^{''\angle dq}(0) e^{j\delta_{20}}} = \underline{\nu}_2 \quad (9b)$$

equation (8) is only fulfilled if

$$\Delta\delta_E(t) - \Delta\delta_1(t) = 0 \quad (10a)$$

$$\Delta\delta_E(t) - \Delta\delta_2(t) = 0 \quad (10b)$$

From this follows:

$$\frac{\Delta\delta_1(t)}{\Delta\delta_2(t)} = 1 \quad (11)$$

Equation (11) allows developing the basic requirements for replacing several generators by a single equivalent generator according to Figure 2. These are:

1) Similar amplitude of rotor swings
2) Similar phase angle of rotor swings

These are extended conditions compared with those of coherency shown in Figure 1. In the equivalencing techniques, based on time series and modal quantities as well, the first condition has not considered yet. However, it allows a significant enhancement of power system equivalents as shown in section 3.

It should be mentioned, that the assumption in equation (9) requires similarity of rotor flux linkages too, since the flux linkages are forming the driving voltages. However, in this paper, these additional conditions are not considered yet. It should be investigated in a future work.

From the general solution of the linear state equation (2) follows

$$\Delta\delta_1(t) = \sum_{i=1}^{n} \underline{c}_i \underline{\varphi}_{1i}^R e^{\lambda_i t} \quad (12a) \qquad \Delta\delta_2(t) = \sum_{i=1}^{n} \underline{c}_i \underline{\varphi}_{2i}^R e^{\lambda_i t} \quad (12b)$$

where

$\underline{c}_i$ is a complex constant corresponding to eigenvalue i, which depends on the initial conditions

$\underline{\varphi}_{1i}^R, \underline{\varphi}_{2i}^R$ are elements of the right eigenvector to λ_i corresponding to the state variable $\Delta\delta$ of generators 1 and 2;
elements of the rotor mode shape vectors $\underline{\boldsymbol{\Phi}}_i^R$

If the generators 1 and 2 should fulfill the conditions 1) and 2) for equivalencing, it is necessary that

$$\underline{\varphi}_{1i}^{R} \approx \underline{\varphi}_{2i}^{R} \tag{13}$$

In general:

Only generators, which show similar rotor mode shapes in respect of both amplitude and phase angle for all considered modes, can be replaced by a single equivalent generator.

The conditions, similarity of amplitudes and phase angles of the elements of the rotor mode shape, are the criteria for grouping generators.

Grouping is a clustering task. Therefore, in the next section the grouping of generators for equivalencing will be treated by clustering algorithms.

2.3 Clustering of Generators

In terms of clustering generators are objects, which are characterized by so-called feature or attribute vectors. According to the derivations in the previous section, the feature vectors can be formed as follows:

$$\begin{aligned}
&\text{Gen 1} \quad \underline{\mathbf{f}}_1 = [\underline{f}_{11},\ \underline{f}_{12} \ \cdots\ \underline{f}_{1m}] = \left[\underline{c}_1\underline{\varphi}_{11}^{R},\ \underline{c}_2\underline{\varphi}_{12}^{R}\ \ldots\ \underline{c}_m\underline{\varphi}_{1m}^{R}\right]\\
&\text{Gen 2} \quad \underline{\mathbf{f}}_2 = [\underline{f}_{21},\ \underline{f}_{22} \ \cdots\ \underline{f}_{2m}] = \left[\underline{c}_1\underline{\varphi}_{21}^{R},\ \underline{c}_2\underline{\varphi}_{22}^{R}\ \ldots\ \underline{c}_m\underline{\varphi}_{2m}^{R}\right]\\
&\qquad\qquad\qquad\vdots\\
&\text{Gen g} \quad \underline{\mathbf{f}}_g = [\underline{f}_{g1},\ \underline{f}_{g2} \ \cdots\ \underline{f}_{gm}] = \left[\underline{c}_1\underline{\varphi}_{g1}^{R},\ \underline{c}_2\underline{\varphi}_{g2}^{R}\ \ldots\ \underline{c}_m\underline{\varphi}_{gm}^{R}\right]
\end{aligned} \tag{14}$$

where the second subscript in the range of 1…m denotes the modes considered by forming the equivalent.

Different aspects play a role selecting the eigenvalues in the modal based equivalencing. It depends on the interest, on which the investigations are focused. So one can select:

- Dominant eigenvalues, which are in the rule the slowest interarea modes
- Critical modes with small or negative damping
- Modes, which will be particularly perturbed by the investigated disturbances

A new aspect should be discussed in connection with the coefficients $\underline{c}_i$, also considered in the feature vectors (see also Eq. (12)). These factors measure the different initial perturbation of modes. For calculation of these, it is necessary to know the initial perturbation, which is equivalent to the assumption of disturbances in time domain equivalencing techniques. Therefore, initial conditions are usually not considered in the modal based equivalencing, but all coefficients $\underline{c}_i$ are assumed to be 1.0. However, in [4], [5] has been shown, that by considering the initial conditions, the accuracy of DE will be improved. Therefore, in the equations of this paper the coefficients c_i will be included formally, however without discussing this topic in detail.

Clustering is performed on the base of closeness or distance measures, which quantify the similarity or dissimilarity of objects, i.e. generators in respect of their chosen attributes. Different distance/closeness measures can be utilized. It depends on the problem being under investigation and the setup of the particular feature vectors, respectively. The Euclidian distance, e.g. is defined as follows:

$$d_{ij}^{E} = \sqrt{(\underline{\mathbf{f}}_i - \underline{\mathbf{f}}_j)(\underline{\mathbf{f}}_i - \underline{\mathbf{f}}_j)^{t}} \tag{15}$$

where the superscript “t” denote the transposed, in case of complex features, the conjugate transposed vector. With the normalized scalar product

$$d_{ij}^{D} = \frac{\underline{\mathbf{f}}_i\underline{\mathbf{f}}_j^{t}}{\sqrt{(\underline{\mathbf{f}}_i\underline{\mathbf{f}}_i^{t})(\underline{\mathbf{f}}_j\underline{\mathbf{f}}_j^{t})}} = \cos(\theta) \tag{16}$$

the distance is measured by the cosines of the angle θ spanned by the feature vectors. Most of the clustering software, such as those incorporated into the Matlab package, provide several options for distance measuring. The distance according to Eq. (16) is widely used in the modal based equivalencing techniques [6], [4], [5]. However, this measure evaluates only the phase information of the feature vectors. It is not suitable for both phase angle and amplitude as well as required in section 2.2. Hence, in the following the Euclidian distance is used.

Clustering of generators can be performed by different algorithms. The description in this paper is still restricted to the K-means algorithm, however, conclusions and the general procedure can be easily transferred to other methods, too. The K-means algorithm forms a given number of clusters by minimizing the within cluster square distances (Euclidian distances) to a centroid feature $\bar{\mathbf{f}}_k$ in each group.

$$T = \sum_{k \in K} \sum_{l \in L_k} g_l\,(\mathbf{f}_l - \bar{\mathbf{f}}_k)(\mathbf{f}_l - \bar{\mathbf{f}}_k)^{t} = \min! \tag{17}$$

where K denotes the number of clusters and L_k the set of generators within the cluster k. The weights g_l allow weighting the distance between each generator and the centroid of the corresponding group. The centroid feature vector is calculated by

$$\bar{\mathbf{f}}_k = \left[\sum_{l \in L_k} g_l \underline{f}_{l1},\ \sum_{l \in L_k} g_l \underline{f}_{l2}\ \cdots\ \sum_{l \in L_k} g_l \underline{f}_{lm}\right] \frac{1}{\sum_{l \in L_k} g_l} \tag{18}$$

Weighting of generators is a new option not used in the equivalencing yet. However, how can the weights be chosen properly? It is obvious, that large generators with large nominal power and large inertial constants have more impact on the system dynamics than smaller ones. But this impact of generators differs from mode to mode. The weights need to take into account, how much a selected eigenvalue will be influenced by a particular error in the generator modeling. The error is caused by approximation of the generator model by an equivalent. The variable, that provides the required property, is the participation factor. It is supposed to use the participation factors corresponding to the mechanical generator state variables angle velocity or rotor position angle as weights in the clustering algorithm. Since in the target function, equation (17), the distance appears as a square value (compare Eq. (15) and (17)), the participation factors have to be squared, too. Thus, the weights are calculated by

$$g_i = p_{i\omega}^2 \tag{19}$$

It will be shown in section 3, that the DE will be more accurate using a weight function.

According to our experience with the described algorithm, it is favorable to cluster generators for different modes separately. In this case, the reduction degree, i.e. the number of generator groups can be adapted individually to the characteristics of modes, e.g. based on the mode shapes. Groups, which fulfill the requirements for all modes are determined by the intersection of single mode clusters, as shown in Figure 3.

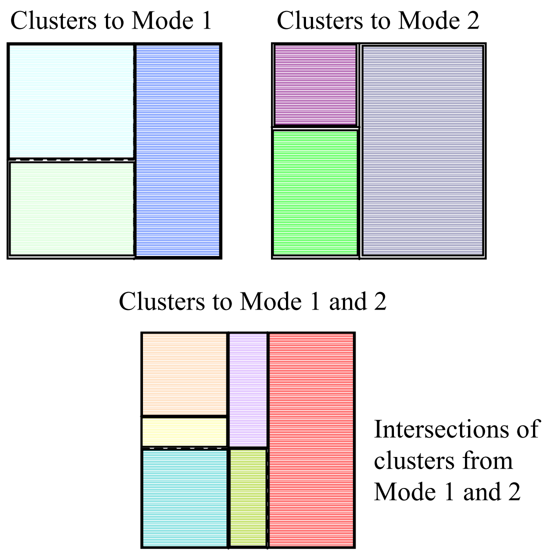

Figure 3: Determination of joined generator groups for several modes

The drawback of this method is that it requires a manual control of equivalencing process. However, producing DE is usually not a time-critical task. By varying the number of groups for each mode individually, different DE may be created, whereas the quality can be quantified by an accuracy index.

For clustering, it is recommended to use library routines. In our work, the K-means algorithm of the IMSL statistic library has been utilized [7].

3 EXAMPLES

The following examples are calculated on the base of a dynamic model of the European Interconnected Electric Power System. The model consists of about 500 generators and several thousand nodes and branches, respectively (see Figure 4). All control devices, excitation and governor control are considered by different models. For investigations of interarea oscillations in the European Interconnected Power System and for developing suitable controller to damp these oscillations, it was necessary to create a reduced order dynamic model.

Germany: 67 generators, 514 nodes, 8 branches
Western Europe: 50 generators
Eastern Europe: 236 generators
Southern Europe: 111 generators

Figure 4: Investigated European test network

Using modal analysis techniques, three critical modes were selected, which should be influenced by controller actions. To handle the controller design procedure, it was necessary to reduce the system order considerably without changing the selected three interarea modes appreciably. Furthermore, the German network should be remaining unreduced. Thus, only the neighbor networks were involved into the model reduction procedure. Figures 5, 6, 7 show the rotor mode shapes of the selected three European interarea modes. The locations of generators in the map are marked by a dot at the origin of the arrows. The first mode describes a swing in East-West direction. The second is characterized by the swing of the Balkan networks. Figure 7 shows the third mode, which is a North-South swing in Middle Europe. Mode 2 and 3 are very poor damped, whereas mode 1 shows an acceptable damping at the investigated operating point. However, this third mode is very sensitive regarding specific load flow scenarios and thus it may cause undamped swings.

Dynamic equivalences are produced by three methods, which differ in the used features for generator grouping:

Method 1: Only phase angles of the eigenvectors have been used

Method 2: Phase angles and amplitudes as well of the eigenvectors have been used

Method 3: Phase angle and amplitudes of the eigenvectors have been used; additionally generators are weighted by participation factors.

Figure 8 shows the eigenvalues of the corresponding equivalent models compared with the unreduced model.

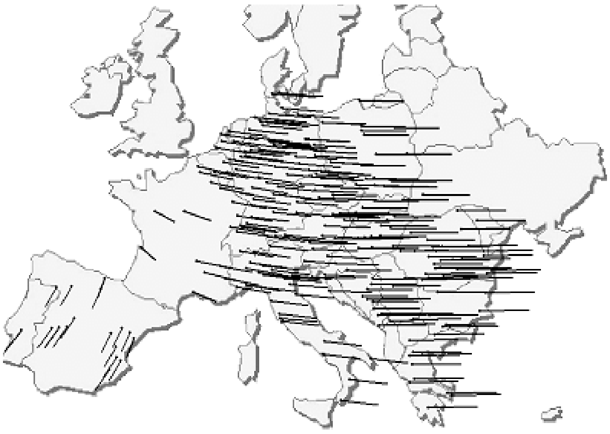

Figure 5: Rotor mode shape of the European East-West-Mode, λ_1=-0.183±1.095i s^{-1}, Damping=16.5%, Frequency=0.17 Hz

Figure 6: Rotor mode shape of the European Balkan-Mode, λ_2=-0.059±1.835i s^{-1}, Damping=3.2%, Frequency=0.29 Hz

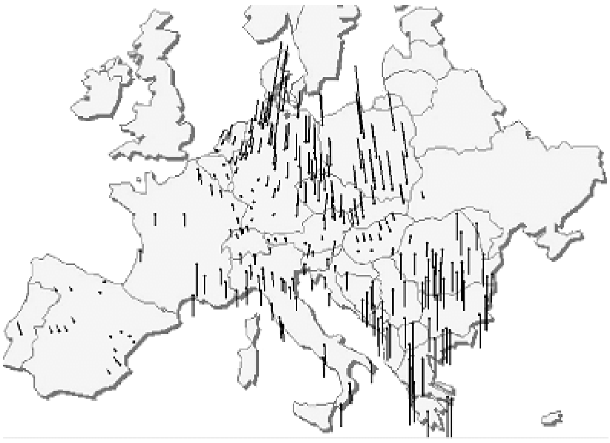

Figure 7: Rotor mode shape of the European North-South-Mode λ_3=-0.022±2.312i s^{-1}, Damping=0.9%, Frequency=0.37 Hz

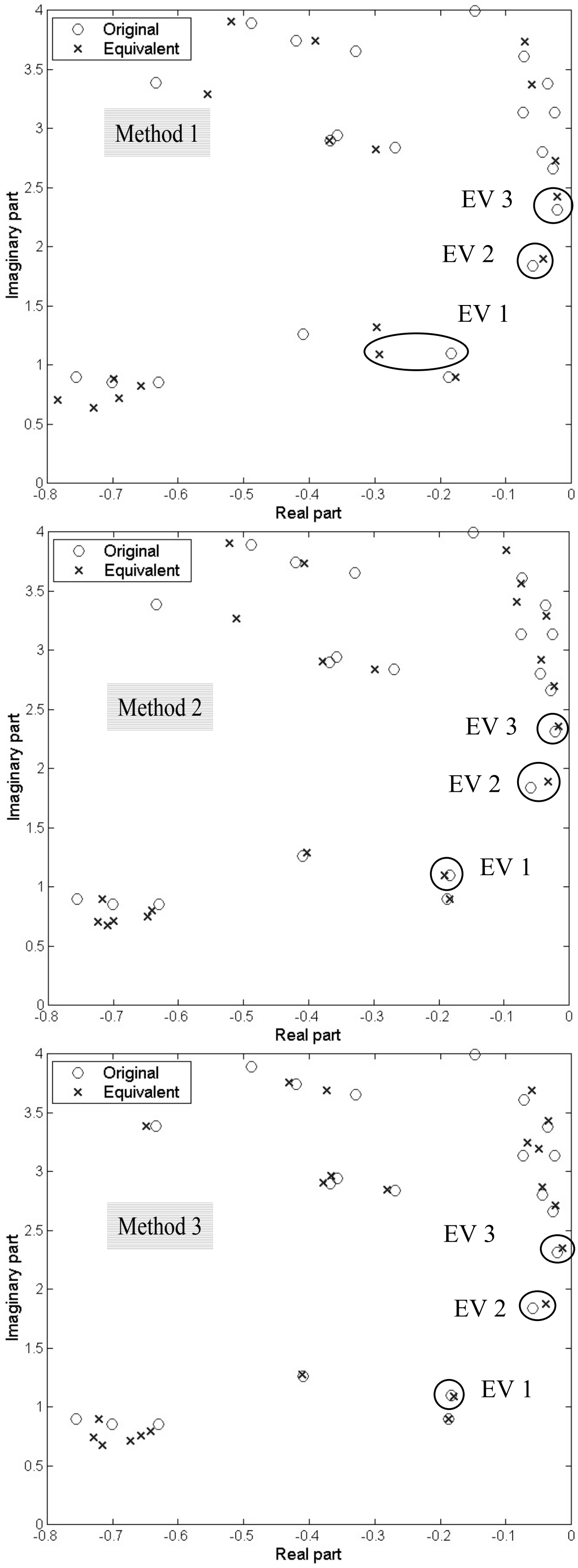

Figure 8: Comparison of eigenvalues of the original unreduced system model and the equivalents

The model accuracy related to the selected eigenvalues increases with the refinements of the generator-grouping algorithm (Table 1).

Equivalencing method	λ_{1_orig} -0.183±1.095i	λ_{2_orig} -0.059±1.835i	λ_{3_orig} -0.022±2.312i
	Error %	Error %	Error %
Method 1	9.97	3.51	4.77
Method 2	0.72	3.2	1.81
Method 3	0.49	2.19	1.59

Error = $|(\lambda_{orig}-\lambda_{equi})/\lambda_{orig}|*100$

Table 1: Accuracy of different equivalents

Significant accuracy improvement results from using the real and imaginary parts as well of the complex eigenvectors and weighting by the participation factors. Although the algorithm considered only the three selected eigenvalues, the accuracy of the other eigenvalues has been improved, too. The equivalents are produced for the three modes separately. The superposition resulted for each method in 73 joined generator groups. This corresponds to a reduction degree of 82%.

No	Clusters to Mode 1	Cluster to Mode 2	Clusters to Mode 3
1	1F, 3CR, 16IT, 1AT	5FR	6FR
2	72PL	4FR	9CZ, 5AT, 10PL
3	3DK	4CZ, 3CR, 8AT, 48PL, 13SK, 3SL	1CZ, 1CR, 37PL, 3SK
4	33CZ, 34PL	33CZ, 3IT, 17AT, 24PL	3AT
5	2AT, 1PO, 6SK, 16SP, 15HU, 2WU	1CR, 2SK, 15HU, 2WU	6GR, 1AT, 14PL, 12SK, 5HU
6	3FR, 27IT, 1CR	16SP	2DK
7	3BE, 7FR, 5IT, 5AT, 6CH	1PO	3AT, 6IT
8	2FR, 7AT, 10RO, 3SL, 1HU	2DK, 31IT, 3AT, 1CH	1FR
9	2AL, 7BG, 1F, 2MA, 34RO, 10SE	5BE, 6FR, 14IT, 5NL, 1AT, 5CH	27CZ, 3CR, 10AT, 11PL, 3SL
10	7BG, 14GR	2AL, 2MA, 44RO, 3SE	2GR, 3AT, 11HU, 2WU
11	1FR, 8GR, 21RO, 6SE	14BG, 14GR, 1RO	1PO
12		16RO, 13SE	5BE, 1CH, 5FR, 5IT
13		8GR, 4RO, 1HU	37IT, 5NL, 2AT, 5CH
14			2AL, 2MA, 19RO, 14SE
15			3FR
16			12BG, 11GR, 1AT, 45RO, 2SE
17			10SP
18			1AT, 2BG, 3GR, 1RO
19			6SP

AL: Albania, AT: Austria, BE: Belgium, BG: Bulgaria, CZ: Czech Rep., CR: Croatia, DK: Danmark, FR: France, GR: Greece, HU: Hungary, IT: Italy, MA: Macedonia, NL: Netherlands, PO: Portugal, RO : Romania, SE: Serbia, SK : Slovakia, SL: Slovenia, SP: Spain, WU: West-Ukraina

The items in the Table marks the number of generators followed by the country short cuts where the generators are from.

Table 2: Assignment of generators to the groups

Table 2 contains the assignment of generators to the groups using method 3. It should be emphasized, that the clusters in Table 2 do not describe joined groups but those formed only for one particular mode. It is noticeable, that the number of groups differs from mode to mode. The possible number of groups formed for each mode is controlled manually depending on the mode characteristics. For the shown examples, a systematic searching algorithm was applied to find the optimal grouping for each of the three investigated methods. It is necessary for a serious comparison.

4 CONCLUSION

This paper introduces several enhancements for modal based equivalencing techniques. It is shown, that for replacing generators by a single equivalent the right electromechanical eigenvectors must be similar in respect of their amplitude and phase angle as well.

The term “coherency”, used in the past many times, does not cover these requirements exactly. Therefore, it is recommended to use the term “similarity” instead of “coherency” in the future. From the shown derivations follows, that similarity is required also for the rotor flux linkages. However, this topic is not investigated in this paper in detail yet. Similar generators are identified by a regular clustering algorithm utilizing the right eigenvectors as features. However, it is obvious, that large and small generators must be treated differently. For this purpose, it is suitable to weight the generators by their participation factors within the clustering procedure. Examples for the European Interconnected Electric Power System showed in this paper demonstrate the accuracy enhancements by using the suggested approaches.

5 REFERENCES

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