A RANK CORRELATION BASED COHERENCY MEASURE FOR POWER SYSTEMS

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Abstract – This study presents a coherency measure for use in multi-machine power systems. This measure was based on the electrical distance and inertia concepts. To develop such a measure, after redefining the electrical distance between two generators as coherency distance depending on their inertias we investigated the correlation between two generators considering their coherency distances to all the generators in the system. To do this rank correlation function was used. Tests on a test system verified the validity of this coherency measure.

I. INTRODUCTION

Modern interconnected power systems cover very large geographic areas. To study stability of such systems, it is neither practical nor necessary to model in detail the entire interconnected system. It is a common practice to represent parts of the system by some form of reduced order equivalent model.

There exist basically three approaches for power network reduction: Modal analysis [1, 2], which reduces the system preserving the most dominant modes, coherency approach [3, 4], which produces a physical equivalent, and estimation [5], which needs no system parameter.

The first step of a coherency based power network reduction algorithm is the identification of coherent generators. This is done either by running transient stability analysis program for full system, or by predicting those generators by some kind of a coherency measure.

Coherency means that some generators swing together upon remote disturbance and can be represented by an equivalent generator.

Although electrical distance is dominant for coherency behaviour, to develop a coherency measure independent of the location of the fault the effects of generator inertias must be taken into account also. Further, such a coherency measure should be simple enough in order to avoid computation complexity.

In literature, there are several studies improving such a measure [6, 7, 8].

Although the techniques reported in literature predict coherent generators with sufficient accuracy, they are generally lack of computational simplicity. In addition, they need a predefined tolerance to identify whether two generators coherent or not, which has to be determined for every system separately.

In this study we developed a coherency measure based on both electrical distances between generators and generator inertias.

The electrical distance between two generators was redefined using a weighting factor depending on their inertias. Since it is expected that two generators electrically very close to each other and with nearly the same inertias swing together whatever the fault position is, we identified those generators mostly satisfying these criteria as coherent. To obtain such generator groups, we investigated the correlation between every two generators in the system using redefined electrical distances between them. The correlation function we used was the rank correlation function, which was more reliable statistically than the simple correlation function. Generators were grouped from mostly coupled to least coupled according to rank correlation coefficients between them.

We tested our coherency measure on a sample system called New England test system, which is used by many investigators. We compared transient stability curves of predicted generator groups. Results were satisfactory.

We found that the rank correlation based coherency measure was simple enough and proper for identification of coherent generators.

II. METHOD

One of the reasons why two generators swing together upon a disturbance is the strict geometric coherency condition between them [9]. This condition can be expressed for two generators, G_3 and G_4, on a sample system shown in Figure – 2.1 as

$$\frac{t_{13}^0}{m_3} = \frac{t_{14}^0}{m_4} \quad \text{ve} \quad \frac{t_{23}^0}{m_3} = \frac{t_{24}^0}{m_4} \qquad (2\text{-}1)$$

Where t_{ij} is the synchronizing power coefficient between generators and m_i is inertial time constant of the generator G_i. Assuming $E_3 \approx E_4 \approx 1$, synchronizing power coefficient is mostly determined by the electrical distances.

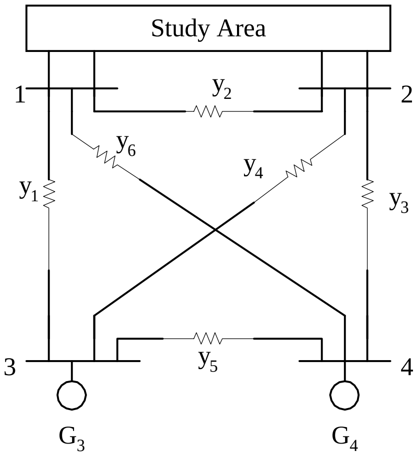

Figure – 2.1 Sample system

Thus, for nearly perfect coherency behaviour this condition can be interpreted as the following two separate conditions:

- There should be a very large admittance between generators.
- Inertias should be nearly the same.

To unify these two separate conditions in a compact coherency measure, we first define the 'coherency distance' between two generators.

Coherency Distance

We define the 'coherency distance' between two generators as

$$B'_{ij} \overset{\Delta}{=} B_{ij} * \min[H_i \ H_j] / \max[H_i \ H_j] \tag{2-2}$$

Where B_{ij} is the corresponding term to the generator i and generator j in the reduced admittance matrix of the system and H_i is the inertia of the generator i. The matrix $B^{'}$, which is comprised of all B_{ij}'s was named as 'coherency distance matrix'.

Depending on this definition we determine the tendency of two generators to swing together by simply measuring the correlation between those two corresponding columns, or rows, in this matrix.

Rank Correlation Function and Coherency Measure

The most widely used measure of association between variables is the linear correlation coefficient:

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}} \tag{2-3}$$

where $\bar{x}$ is the mean of x_i 's, $\bar{y}$ is the mean of y_i 's for at least 20 measurements, where x_i 's and y_i 's represent generator distances between each other in this study.

However, r is a poor statistic for deciding whether an observed correlation is statistically significant, or whether one observed correlation is significantly stronger than another [10].

The uncertainity in interpreting the significance of the linear correlation can be overcome by nonparametric or rank correlation, where value of each x_i is replaced by the value of its rank among all the other x_i 's in the sample that, is, 1, 2, 3, ...N.

Let R_i be the rank of x_i among the other x_i 's, S_i be the rank of y_i among the other y_i 's, then the rank-order correlation coefficient is defined to be the linear correlation coefficient of the ranks,

$$r_s = \frac{\sum_i (R_i - \bar{R})(S_i - \bar{S})}{\sqrt{\sum_i (R_i - \bar{R})^2 \sum_i (S_i - \bar{S})^2}} \tag{2-4}$$

is the measure of the degree of the 'coupling' or 'coherency' of two generators, or any two buses, where R_i and S_i correspond to the ranks of magnitutes of their coherency distances to other buses.

Using the relation (2-4) the degree of coupling between generator i and generator j can be defined as

$$C(i, j) \overset{\Delta}{=} r_s [B'(:, i), B'(:, j)] \tag{2-5}$$

And corresponding matrix can be named as 'coherency matrix' whose dimensions were determined by the number of the generators in the system.

III. RESULTS

To test the validity of our cohererency measure we used the New England test system shown in Figure – 3.1. This system include 10 machines, 39 buses and 46 lines.

Table – 3.1 presents the correlation matrix of the system and Table - 3.2 gives generator groups according to the correlation level.

Figures – 3.2 - 6 present generator swing curves obtained upon a 0.12 second three-phase short circuit at bus 29.

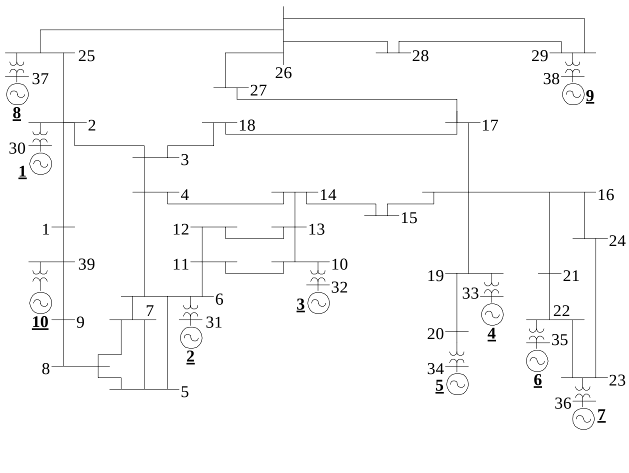

Figure – 3.1 New England test system

Table – 3.1 Correlation matrix of the New England system

	1	2	3	4	5	6	7	8	9	10
1	1.0									
2	0.4	1.0								
3	0.4	0.9	1.0							
4	0.4	0.3	0.3	1.0						
5	0.3	0.2	0.2	0.9	1.0					
6	0.4	0.3	0.4	0.8	0.7	1.0				
7	0.4	0.3	0.4	0.8	0.7	0.9	1.0			
8	0.8	0.3	0.3	0.4	0.3	0.4	0.4	1.0		
9	0.7	0.1	0.2	0.4	0.3	0.4	0.4	0.7	1.0	
10	0.5	0.6	0.6	0.0	0.0	0.0	0.0	0.4	0.1	1.0

Table – 3.2 Generator groupings of the New England system according to correlation levels

Correlation level	Generator groups							
r = 0.9	1	2	3	4 5	6 7	8	9	10
r = 0.8	2 3	4 5	6 7	1 8	9	10		
r = 0.6	2 3	4 5 6 7	1 8 9	10				

r = 0.7 with r = 0.8 and r = 0.5 with r = 0.6 produces the same groupings.

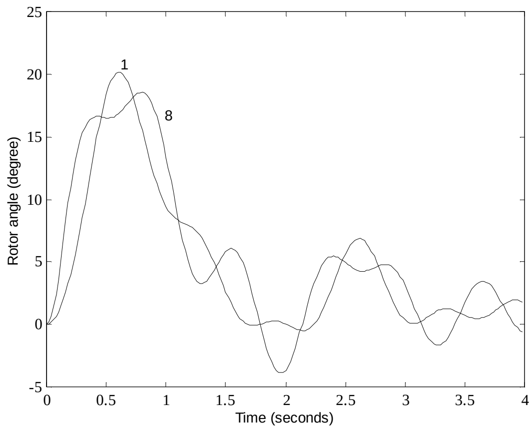

Figure – 3.2 Swing curves, units: 1, 8

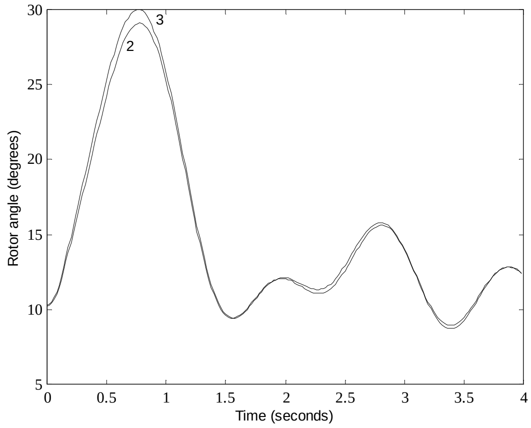

Figure – 3.3 Swing curves, units: 2, 3

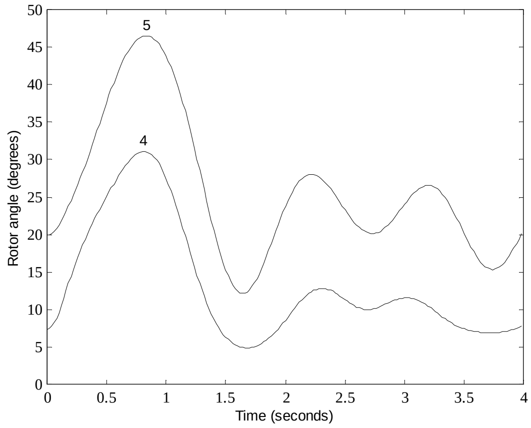

Figure – 3.4 Swing curves, units: 4, 5

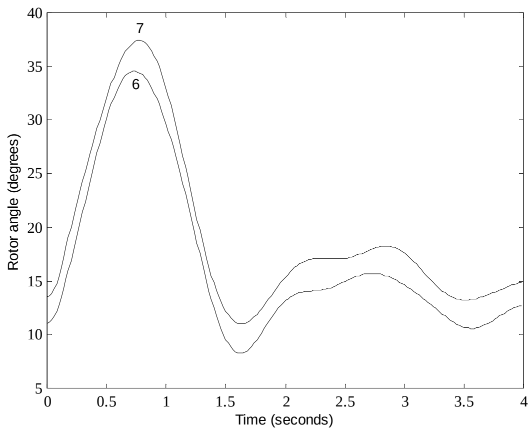

Figure – 3.5 Swing curves, units: 6, 7

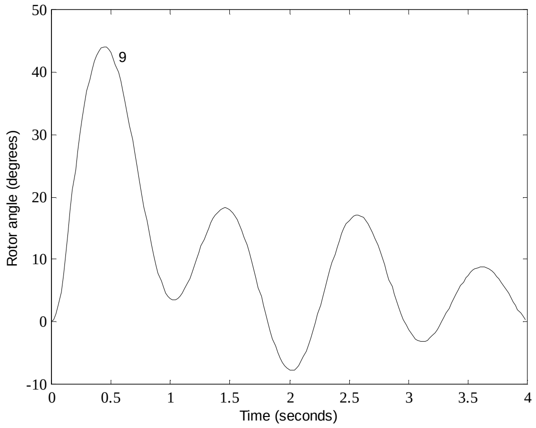

Figure – 3.6 Swing curve, unit: 9

IV. CONCLUSIONS

Swing curves verifies the coherent generator groups predicted by the coherency measure we developed. Coherency behaviour expected by high correlation levels, r > 0.6, is clear. On the other hand, correlation level r = 0.6 produces still coherent generator groups even if they are not strictly coherent. Multi-frequency behaviour of the generating unit 8 descends from the fact that its inertia is very small than that of unit 1 and they are both electrically close to the disturbance. Despite the high frequency components included by the unit 8's stability curve it still swings together with the unit 1. In order to express the role of the generator inertias on the coherency behaviour Table – 4.1 presents the inertial time constants in the New England system.

Table – 4.1 Generator inertias in the New England system

Generators

1	2	3	4	5	6	7	8	9	10
42.	30.3	35.8	28.6	26.	34.8	26.4	24.3	34.5	500.

Inertial time constants (seconds)

Coherency behaviour of the unit 9 is a little bit vague with the units 1 and 8. However, in a network reduction process aggregation of these generators would have little effect on the behaviours of preserved generators under study.

Another point is that grouped generators are generally electrically close to each other. This verifies the dominant nature of the electrical distance on coherency behaviour of generators. And our coherency measure takes this account.

Results show that the coherency measure we developed on the electrical distance and inertia concepts is valid and proper for identification of coherent generators in power systems.

V. REFERENCES

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