A SIMPLE APPROACH FOR IDENTIFICATION OF COHERENT GENERATORS IN MULTI-MACHINE POWER SYSTEMS

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Abstract **– In this study coherency behaviour of two machines against an infinite bus is studied depending on their inertia constants and electrical distances from the disturbance. Then, it is shown in a seven machine part of Turkey's Interconnected System that the electrical distance between two generators is a determining parameter for their coherency behaviour.**

I. INTRODUCTION

Modern electric power systems cover very large geographic areas. To study the 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 equivalent models. While reducing the system it is necessary to preserve the general behavioural characteristics of the system.

The computer programs developed for stability studies have the capacitiy to handle thousands of generators and buses. However, it requires very much effort to solve thousands of non-linear differential equations and to get practical conclusions from these solutions for system planning, control system design and operating condition improvements. So it becomes necessary to reduce the order of the system and to represent some parts of the system by dynamic equivalents.

Dynamic equivalent studies can be taken up in two stages:

1- Identification of coherent groups of generators.
2- Representation of each coherent group by a dynamic equivalent machine.

Dynamic equivalencing studies goes back to 1960's [1,2]. The modal equivalents approach recognizes that some modes of oscillation will not be excited by disturbances in particular areas of the system and can therefore be eliminated. This method was never used extensively due to diffuculty in determining the modes to be eliminated and due to the need to modify stability simulation programs to use a state matrix form of the equations of the equivalent [3].

In 1970's an alternative approach is based on coherency [4]. Coherency means that upon a remote disturbance some groups of generators swing together and can therefore be represented by a single equivalent machine. Altough this approach found some applications, it was generally found that the coherent groups were dependent on the chosen disturbance, so confidence in the equivalent for other disturbances was limited.

In the early 1980's the slow coherency technique was developed for finding coherent machines and constructing dynamic equivalents [5]. This technique combined the insights of both modal and coherency analysis.

In another approach called 'Weak Links', which is developed in 1980's, coherency is determined by analyzing the coupling of generators in the state matrix [6]. A group of generators are identified as coherent if the coupling coefficients among them are high.

Tolerance Based Slow Coherency method is reported in 1990's [7]. This technique is similar to slow coherency but includes additional constraints to ensure that widely separated generators are not aggregated.

In literature, comparisons of all these techniques are reported considering various performance criteria such as the order of reducing the system, computer timing and the order of accuracy, applying them to very large power systems [8,9]. Even tough they have some differences depending on the application, as far as computer timing and the order of accuracy are concerned, reduced models abtained by these techniques reflect the general behavioural characteristics of the system and save the computer time about 50 %.

Despite all these improvements brough out by these techniques in obtaining reduced order models and saving the computer time, they never eliminate the need to calculate the eigenvalues of the system or the swing curves of the generators.

In many applications such as system planning they are all well enough. However, they are limited, at least for the moment, as to estimate the coherent groups in some situations such as those related with system security where a fast and quick decision may be vital.

This paper presents the first step of a simple approach to determine coherent generators without taking up computer simulations or eigenvalue calculations but just by considering the parameters of generators and system.

II. METHOD

In the study simplified generator models were used by the following assumptions:

- Coherent generator groups are independent of the size of the disturbance. This assumption may be confirmed by considering a fault on a certain bus and observing that the coherency behaviour of the generators are not significantly changed as the fault clearing time is increased.
- The coherent groups are independent of the amount of detail in the generating unit models [4]. For this reason, the 3rd order generator models were used.
- Simulations were done for the two second period after the disturbance during which automatic voltage regulators and speed governors are not in action. Those generators becoming synchronized during this period are identified as coherent.

The equation of motion of a synchronous generator is given by

$$\frac{2H_i}{\omega_R}\frac{d\omega_i}{dt} + D_i\omega_i =$$

$$P_{mi} - \left[E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{n} E_i E_j Y_{ij} \mathrm{Cos}(\theta_{ij} - \delta_i + \delta_j) \right]$$

$$\frac{d\delta_i}{dt} = \omega_i - \omega_R \qquad i = 1,2,\ldots n$$

where

P_{mi}: mechanical power input of the i^{th} generator

ω_i : electrical speed of the i^{th} generator

H_i : inertia constant of the i^{th} generator

E_i : terminal voltage of the i^{th} generator

D_i : damping coefficient of the i^{th} generator

$Y_{ii}\angle\theta_{ii} = G_{ii} + jB_{ii}$: driving point admitance for the node i

$Y_{ij}\angle\theta_{ij} = G_{ij} + jB_{ij}$: negative of the transfer admitance between nodes i and j.

As seen in the equation of the motion the constant parameters relating the swing of a generator to that of another one are the inertia constants and the electrical distance between those generators. Damping coefficient effect only the amplitude of the oscillation can therefore be ignored.

Another parameter that may effect the coherency behaviour of the generators are their electrical distances from the disturbance. For this reason coherency behaviour of two machines against an infinite bus is experimentally studied depending on their electrical distances from the disturbance beside their inertia constants.

III. TWO MACHINE SYSTEM AGAINST AN INFINITE BUS

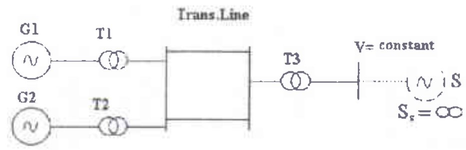

Fig.1 Two machines against an infinite bus

The electrical distances from the disturbances and the transfer admitances between the generators were measured from the generator terminals. The ratios of distances and inertia constants were changed from 1 to 8 and from 1 to 4, respectively. A 0.1 second three-phase short circuit on the front end of the transmission line was chosen as the disturbance. For each distance ratio corresponding to a certain inertia constant ratio coherency behaviour of the generators were observed obtaining generator swing curves.

Two machine experiments were done for two cases: First, the two generators are identical except the distance from the disturbance. Second, generators are entirely realistic in both parameters and operating conditions.

The generator data presented in appendix.

While increasing the electrical distance of the smaller inertia generator, that of the larger inertia generator was kept constant.

The synchronization times of two generators obtained from computer simulations depending on the inertia constants and the electrical distances are presented in Table 1.

Since generally the inertia time constants for practical generators changes from 4 to 16 seconds on 100 MVA base, these values were used in calculations.

As far as the system is stable, for a certain inertia ratio, as the electrical distance from the disturbance of the smaller inertia generator increases the synchronization time also increases but never exceeds 2 seconds. On the other hand, for a certain distance ratio, as the inertia constant of the larger inertia generator increases the synchronization time first decreases and then increases. If the inertia ratio exceeds 3.5 the two generators do not synchronize in two seconds, whatever the distances from the disturbance are. So it is possible to define an optimum range of the inertia constant ratio for coherency behaviour of two generators against an infinite bus, that is in between 2 and 2.5.

Table 2, which is very similar to Table 1, presents the results for entirely realistic generators in entirely realistic operating conditions.

So, by the tests made on the two machine system against an infinite bus, it has been shown that for the inertia time constants whose ratios change from 1 to 3.5 corresponding a certain electrical distance ratio from disturbance between 1 and 4 two generators synchronizes in two seconds, that is to say they are coherent.

Table 1

	Electrical distance ratio from disturbance										
Inertia ratio		1	1.5	2	2.5	3	3.5	4	5	6	7	8
	1	0.73*	0.75	0.76	0.8	0.81	0.84	0.86	x**			
	1.5	0.63	0.64	0.66	0.70	0.73	0.75	0.79	0.87	x		
	2	1.09	1.13	0.54	0.56	0.61	0.64	0.66	0.70	0.78	0.86	x
	2.5	1.01	1.06	1.1	1.14	1.16	1.20	0.58	0.65	0.70	0.81	xx***
	3	0.95	1.0	1.05	1.09	1.13	1.16	1.19	0.59	0.66	0.81	xx
	3.5	0.89	0.93	0.99	1.03	1.06	1.10	1.16	1.25	0.65	Xx	
	4	x	x	x	x	x	x	x	X	x	x	x

* : in seconds

** : generators do not synchronize in two seconds

***: system unstable

Table 2

	Electrical distance ratio from disturbance										
Inertia ratio		1	1.5	2	2.5	3	3.5	4	5	6	7	8
	1	x**	x	x	0.63*	0.64	0.66	0.68	0.71	0.78	x	
	1.5	1.58	0.75	0.81	0.89	0.96	1.04	1.14	xx***			
	2	0.68	0.68	0.68	0.69	0.70	0.71	0.73	0.74	0.77	0.81	0.84
	2.5	0.95	0.95	0.99	1.01	1.03	0.75	0.79	0.54	0.58	0.60	0.63
	3	1.39	1.45	1.49	0.68	0.69	0.73	0.75	0.83	0.88	0.95	x
	3.5	1.39	1.45	1.50	0.68	0.70	0.73	0.75	0.86	1.01	xx	
	4	x	x	x	x	x	x	x	X	x	x	x

* : in seconds

** : generators do not synchronize in two seconds

***: system unstable

As for a multi-machine power system determination of the coherency behaviour of a generator with other generators requires considering and additional parameter, the electrical distance between the generators. It is obvious that closer the two generator electrically more probable they are coherent. This situation can be pointed out in a 7-machine 15-bus part of Turkey's Interconnected System.

IV. TEST SYSTEM AND REDUCED BUS ADMITANCE MATRIX

Data of the system on which 3-phase short circuit tests were done is presented in appendix. Reduced bus admitance matrix of the system is given in Table 3.

Coherent groups will be estimated depending on the electrical distances between generators provided that the above conditions for inertia constants and electrical distances from the disturbance are satisfied.

Table 3

*	1	2	3	4	5	6	7
1		-2.3j	-5.8j	-0.3j	-0.5j	-1.0j	-1.1j
2			-2.2j	-1.4j	-2.7j	-5.2j	-6.0j
3				-0.3j	-0.5j	-1.0j	-1.0j
4					-4.5j	-0.6j	-0.7j
5						-1.2j	-1.3j
6							-2.3j

*: generator no.

It is certain that two machines coherent with a third machine are also coherent with each other.

Considering the Table 3 the seven machines can be reduced to 3 coherent groups:

- 2-6-7
- 4-5
- 1-3

To confirm the estimated coherent groups swing curves of the generators were studied, which have been obtained computer simulations of 3-phase short circuit tests made on various buses of the system. The curves satisfies the estimations.

V. COMPUTER SIMULATIONS

Simulations were made by using Electrical Interconnected System Analysis program.

Swing curves obtained at the result of the disturbances at all buses except bus-12 and bus-13 confirm the above estimation. The estimation is not valid for these two buses because they are both so close to all generators that a 3-phase short circuit at these buses entirely disconnects the generators, especially those with large inertia constants.

The ratios of electrical distances from each bus to the transient reactance of each generator are given in Table 4.

Table 4

	8**	9	10	11	12	13	14	16
2*	6.1	4.5	3.5	6.5	0.7	1.1	3.8	5.1
6	5.0	3.8	2.9	5.4	0.6	0.5	3.1	4.2
7	4.9	3.6	2.9	5.2	0.6	0.9	3.0	4.0
4	23.3	17.3	13.3	23.3	2.7	4.2	1.0	1.4
5	7.5	0.5	4.0	7.5	0.8	1.3	0.3	0.2

* : generator no.

**: Bus no.

Some sample swing curves are given in appendix.

To verify the electrical distance from the disturbance condition for coherent groups Table 5 gives the distances of the generators from some buses. The larger inertia generators are electrically closer to short circuit points than smaller inertia generators, as should be.

Table 5

	8**	9	10	11	12	13	14
2*	-33.6	-46.1	-58.9	-32.0	-300.0	-189.3	-55.3
4	-0.4	-0.54	-0.7	-0.4	-34.9	-22.0	-92.9
5	-0.7	-10.0	-12.8	-0.7	-65.3	-41.2	-173.8
6	-14.7	-20.2	-25.8	-14.0	-131.6	-150.0	-24.2
7	-16.8	-23.0	-29.4	-16.0	-150.0	-94.6	-27.6

* : generator no

**: bus no

VI. CONCLUSIONS

It is possible to summarize some of the conclusions arrived at by studying a two machine system against an infinite bus and a sample multi-muchine power system as the following:

- The most important parameter for coherency behaviour of generators is the electrical distance between them.
- As far as it is between 1 and 3.5, which is generally the case, the ratio of inertia constants of two generators does not have much effect on their coherency behaviour.
- As far as it is between 1 and 4 the ratio of the electrical distances from the disturbance of two generators does not have much effect on their coherency behaviour provided that the larger inertia generator is closer to the disturbance than the smaller inertia generator.
- It is possible to estimate the coherent generator groups just by considering generator and system parameters without taking up time consuming calculations and simulations. This approach is promising for applications where a fast decision is needed.

VII. REFERENCES

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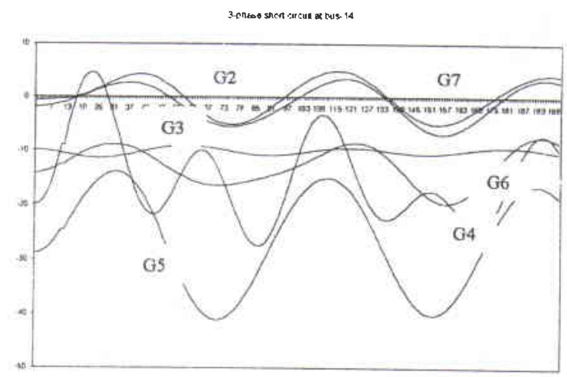
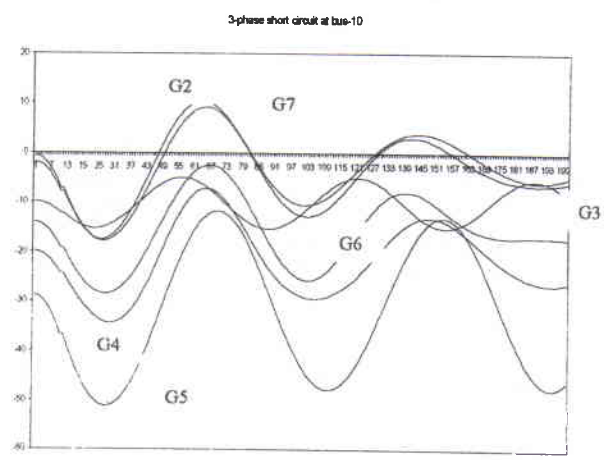
VIII. APPENDIX





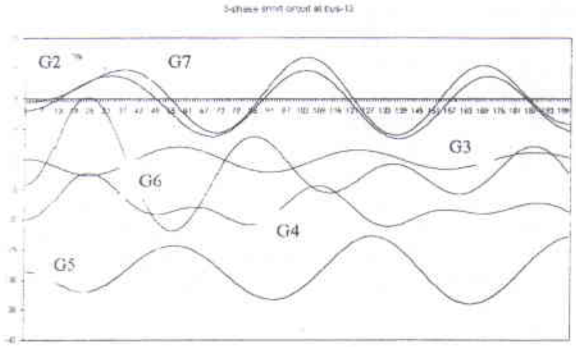


Table 1 Generator data

Generator No	Power (MVA)	T'_{d0} (sec.)	H (sec.)	X_d	X_d'
G1	494	6,4	13,9	0,43	0,07
G2	360	8,3	15,6	0,53	0,05
G3	388	6,2	12,2	0,7	0,1
G4	126	3,0	2,7	1,63	0,1
G5	150	6,1	6,8	0,72	0,19
G6	188	6,8	6,8	1,0	0,13
G7	188	6,1	7,2	1,06	0,12

Table 2 Transmission line and transformer data

Line No	Bus No	Z_t (p.u.)
1	1 – 11	0,03j
2	2 – 12	0,03j
3	3 – 8	0,04j
4	4 – 15	0,08j
5	5 – 16	0,04j
6	6 – 13	0,07j
7	7 – 12	0,07j
8	8 – 9	0,02j
9	9 – 10	0,01j
10	10 – 11	0,03j
11	10 – 12	0,06j
12	12 – 13	0,01j
13	12 – 14	0,07j
14	14 – 15	0,03j
15	14 – 16	0,02j