Identification of coherent generators using energy function

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Indexing terms: System protection, Generators, Mathematical techniques

Abstract: A new method of identifying coherent generators for multiple faults in a power system is presented. A tentative coherent group of generators is initially determined by evaluating the energy function at different approximate unstable equilibrium points of the system. The final coherent groups for individual faults are obtained by checking relative rotor angles in the faulted system. The method is fast and saves a great deal of computation time. The proposed method was tested on three power networks and the results obtained perfectly matched with those found from classical simulation studies.

List of symbols

n = number of generator
P_m = mechanical input power
M = inertia constant
δ = rotor angle in synchronous reference frame
θ = rotor angle in centre of angle (COA) reference frame
ω = angular speed in COA reference frame
E = generator internal voltage
$D_{ij} = E_i E_j G_{ij}$
$C_{ij} = E_i E_j B_{ij}$
$Y_{ij} = G_{ij} + jB_{ij}$
Y = reduced admittance matrix

1 Introduction

The computation required in power system dynamic studies can be reduced by combining some of the generators in that part of the system which is less affected by the disturbance called the external system. Those generators whose detailed dynamics are required are included in the study system. A method of replacing a number of generators in the external system with one or more equivalents is based on coherency [1–3].

The reduced system consisting of less generators, may be obtained by replacing each group of coherent generators with an equivalent generator. Contingency analysis through the reduced order model will save a lot of computation time [4].

A generator pair (i, j) in the external system is said to be coherent if there exists a constant a_{ij} such that

$$\delta_i(t) - \delta_j(t) = a_{ij} \pm \varepsilon \quad \text{for all } t \tag{1}$$

where $\delta_i(t)$ and $\delta_j(t)$ are the rotor angles of the ith and jth generators, respectively, and ε is a small positive number. A group of generators is said to be coherent if each pair of generators in the group is coherent. Each generator pair (i, j) is said to be perfectly coherent if $\varepsilon = 0$.

Various methods for the identification of coherent generators have been suggested. Podmore proposed the solution of linearised swing equations and identification of machines swinging together through a clustering algorithm [3]. This method is computationally prohibitive, especially in the case of large systems. Several authors used the linearised swing equations to develop some coherency identification criteria without explicitly solving the equations [5–8]. The linearised model is only valid for small perturbations so these methods may produce erroneous identification when the disturbance is severe. Lee and Schweppe suggested a pattern recognition approach based on criteria which depend on the faulted machine acceleration, the inertia constant and the admittance distance [2]. The authors recently proposed an improvement of this method in which both the faulted and part of the post fault system dynamics are considered [9].

Ohsawa *et al.* [10] determined coherent generators using the Liapunov function (LF). They proposed a criterion based on the fact that the LF component for a group of coherent generators is not significant when compared to the total value of the entire system. The components of the LF are computed using the faulted system states around the critical clearing time. The machines which are coherent during the faulted period may not remain so in the post fault region, and so this method may not yield the correct result. The method also requires *a priori* knowledge of the critical clearing time.

Spalding *et al.* [11] suggested another method for coherency identification using singular points and admittance distances. The method is based on the comparison of the relative rotor angle deviations, among a group of electrically close generators. This is done at two points: the prefault stable operating point and the post fault unstable equilibrium point (UEP) corresponding to the expected mode of instability for a given fault. A group of generators which satisfies the relative angle deviation criteria at these two points may not necessarily remain coherent during the excursion from prefault to post fault state. Identification of the expected mode of instability and computation of the corresponding UEP by iterative method is not easy. The iterative scheme may not even converge to the proper UEP [12].

The methods reported in the literature determine the coherent generator groups for a particular fault location. This paper proposes a method in which the coherent generators for any fault location are found from a

Paper 7286C (P9, P10), received 27th June 1989

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tentative coherent group. The tentative group is expected to remain the same irrespective of fault location. The coherent groups for an individual fault location are then obtained by refining the tentative groups. The proposed method has been tested on three different power networks and the results were found to be in perfect agreement with those obtained by simulation of the system dynamics.

2 Coherency determination during the fault-on period

Coherent generators should swing together for the entire transient period, both faulted and post fault. Determination of coherency during the fault-on period is relatively easy because the machine acceleration remains approximately constant for short duration faults. Generators which are coherent during the faulted period may not remain coherent in the post fault period. In general, coherency determination in the post fault period is difficult and time consuming because of the higher order dynamics required to represent the post fault system accurately and the fact that the equations must be solved over a longer period.

An ideal method for determining coherency is to check the relative rotor angle deviations. A generator pair (i, j) is considered to be coherent during the faulted period if [9]

$$|\delta_{ij}(t_1) - \delta_{ij}(0)| \leqslant \sigma_1 \tag{2}$$

where $\delta_{ij}(t_1)$ and $\delta_{ij}(0)$ are the relative angles at any time during the fault t_1 and before the fault $(t = 0)$, respectively. σ_1 is a predetermined, small number. The faulted rotor angle of the ith generator can be expressed in terms of the following Taylor series expansion [9, 13]:

$$\delta_i(t) = \delta_i(0) + \delta_i^{(1)}t + \delta_i^{(2)}\frac{t^2}{2!} + \delta_i^{(3)}\frac{t^3}{3!} + \delta_i^{(4)}\frac{t^4}{4!} + \cdots \tag{3}$$

where $\delta_i(0)$ is the prefault angle of the ith generator; $\delta_i^{(m)}$; $m = 1, 2, 3, \ldots$ is the mth derivative of δ_i at $t = 0$. Note that the speed ω_i of the ith machine equals $\delta_i^{(1)}$ and all odd order derivatives of δ_i in eqn. 3 are zero at $t = 0$. The authors showed in Reference 9 that eqn. 3 can predict the rotor angles fairly accurately for a duration of 0.20–0.30 s, considering terms up to 4th order derivatives. Thus computation of eqn. 2 for short duration of fault requires only the 2nd and 4th order derivatives of rotor angles

$$\begin{aligned} \delta_i^{(2)} &= \frac{P_{mi}}{M_i} - \sum_{j=1}^{n} (C_{ij} \sin \delta_{ij} + D_{ij} \cos \delta_{ij})/M_i \\ \delta_i^{(4)} &= \sum_{j=1}^{n} \delta_{ij}^{(2)}(-C_{ij} \cos \delta_{ij} + D_{ij} \sin \delta_{ij})/M_i \end{aligned} \tag{4}$$

Once the generators which are coherent during the faulted period are identified, it is necessary to check whether or not they will swing together in the post fault period. Most of the methods reported in the literature ignore the dynamics of the post fault system [2, 10, 11, 14]. Some of the methods which include the post fault dynamics in determining coherency are fault dependent [3, 9]. The following method is proposed to determine which generators will be coherent in the post fault period. It is expected that they will remain coherent irrespective of fault location. The effect of fault dependence is considered by properly selecting the study system.

3 The proposed method

The proposed method of coherency identification begins with finding the tentative coherent generator groups in the post fault period. This is based on the computation of the energy function at different approximate unstable equilibrium points. These tentative coherent groups of generators are expected to swing together in the post fault period, irrespective of fault locations, subject to the condition that they are not severely disturbed and maintain coherency during the faulted period. The identification process for the tentative groups is presented below.

3.1 *Identification of tentative coherent generator groups in the post fault period*

The energy-type Liapunov function, V, of an n-machine system, generally used for transient stability analysis by the direct method, can be written as [15]

$$V = V_{KE} + V_{PE} \tag{5}$$

where

$$\begin{aligned} V_{KE} &= \frac{1}{2}\sum_{i=1}^{n} M_i \omega_i^2 \\ V_{PE} &= -\sum_{i=1}^{n} P_i(\theta_i - \theta_i^s) - \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \\ &\quad \times [C_{ij}(\cos\theta_{ij} - \cos\theta_{ij}^s) - I_{ij}] \\ I_{ij} &\simeq D_{ij}\frac{\theta_i + \theta_j - \theta_i^s - \theta_j^s}{\theta_i - \theta_j - \theta_i^s + \theta_j^s}\sin(\theta_{ij} - \theta_{ij}^s) \end{aligned} \tag{6}$$

and θ is the generator rotor angle measured in the centre of angle (COA) reference frame.

The Liapunov function, V, has a minimum value (zero) at the stable equilibrium point (SEP) θ^s and has relative maxima at an unstable equilibrium point (UEP) θ^u. Let V_i be the value of the V-function at an UEP θ_i^u, at which only the ith machine runs out of step. The kinetic energy component (V_{KE}) is zero at all the equilibrium points, so V_i is only the potential energy component (V_{PE}) of the energy function. The value of V_i can be interpreted as the minimum energy required to force the machine i to run out of step. Similarly, V_{ij} is the minimum energy required to force a pair of machines (i, j) to run out of step. If the machines i and j move in different directions (noncoherent) then, from an energy point of view

$$V_{ij} \approx (V_i + V_j) \tag{7}$$

i.e., the energy required to pull a pair of noncoherent machines from their SEP is almost the same as the sum of the energy required when they are pulled independently. If the machines i and j are coherent, it is expected that

$$V_{ij} \simeq \max(V_i, V_j) \tag{8}$$

An index ρ, which will determine the degree of coherency between a pair of machines, can be defined as

$$\rho_{ij} = \frac{V_{ij} - \max(V_i, V_j)}{\min(V_i, V_j)} \tag{9}$$

The index ρ_{ij} represents the normalised energy required by machine i to pull another machine j or vice versa. From eqns. 7, 8 and 9, it is obvious that the value of ρ_{ij} is close to zero for a pair of coherent machines and is close to unity for a noncoherent pair. A pair of machines (i, j) may be considered to be tentatively coherent in the post fault period if they satisfy the following criterion

$$\rho_{ij} < \sigma_2 \tag{10}$$

where σ_2 is a predetermined quantity. The index ρ_{ij} depends on the post fault network parameters.

Determination of tentative coherent generators in the post fault period requires computation of the V-function at $n(n + 1)/2$ UEPs for an n-machine system. Exact computation of these UEPs through iterative procedure is very time consuming. Prabhakara and El-Abiad [16] showed that the variation of V-function around an UEP is not significant and an approximate unstable equilibrium point (AUEP) can be used to estimate the value of the function. If the machines i and j are running out of step, by acceleration, then the corresponding AUEP can be written, from the prefault operating point θ°, as [13]

$$[\theta_1^\circ, \theta_2^\circ, \ldots, \pi - \theta_i^\circ, \pi - \theta_j^\circ, \theta_k^\circ, \ldots, \theta_n^\circ] \tag{11}$$

In general, coherency is determined for a particular fault location irrespective of the mode of fault clearing. The post fault dynamics of the system will depend on whether or not the fault clearing was followed by line switching. It has been observed on several systems that the values of V_i, V_{ij} and hence ρ_{ij} change, only for those generators which are in the vicinity of the line that opened to clear the fault. The corresponding quantities for the generators in the external system are virtually unchanged because of the remoteness of the fault. Since the generators in the study system are not considered in the coherency identification process, the tentative coherent generators may be determined by using the prefault network and assuming that the fault is cleared without any line switching. The effect of the fault location and the mode of clearing can be considered by excluding the generators in the study system which form the tentative coherent generators.

Once the tentative groups of coherent machines have been identified, the generators which will be coherent for a particular fault location are determined. The steps involved are:

(*a*) Choose the study system depending on the fault location.

(*b*) Obtain the faulted rotor angles of the different machines through Taylor series expansions given in eqn. 3. Exclude the generators which are in the study system.

(*c*) Apply coherency eqn. 2 for the faulted system. The generators satisfying eqn. 2 will be coherent for the particular fault location.

The steps required to determine the coherency of the machines in the system are summarised as in the next Section.

3.2 The algorithm in brief

Determination of coherent generator groups by the proposed method has the following steps:

(1) Obtain the tentative coherent generator groups by satisfying eqn. 10. The AUEPs required for this computation are obtained from eqn. 11.

(2) Consider a three phase fault or disturbance at a particular location. Identify the set of generators which are in the vicinity of the disturbance (or in the study system).

(3) Identify the final coherent generator groups by checking the relative rotor angle deviation eqn. 2 among the generators which were found to be coherent tentatively in step (1). Exclude the generators which are in the study system.

Identification of coherent generators for a different fault location involves the computation of the last two steps. Step 1 is to be computed only once for a given operating condition. The method is very efficient, especially when the identification of coherent generators for a number of fault locations is desired.

4 Simulation results

The proposed method of identifying coherent generators was tested on three different power networks of different sizes. The systems studied were:

(1) The 10 machine New England system
(2) The 11 machine Bangladesh system
(3) The 17 machine Iowa system.

The relative rotor angle deviation eqn. 2 was checked in all the systems for a fault duration of $t_1 = 0.20$ s. A Taylor series expansion considering terms up to 4th order derivatives was used to estimate the angle at t_1. From a large number of studies, the values of σ_1 and σ_2 were selected to be 3.5° and 0.35, respectively. Note that the constitution of the coherent generator groups may depend, to some extent, on the choice of these values. Results obtained by the proposed method were then checked by simulation of the total system dynamics.

4.1 The New England system

The New England system consists of 10 machines, 39 busbars and 46 lines. The single line diagram is shown in Fig. 1. The system data and initial operating conditions

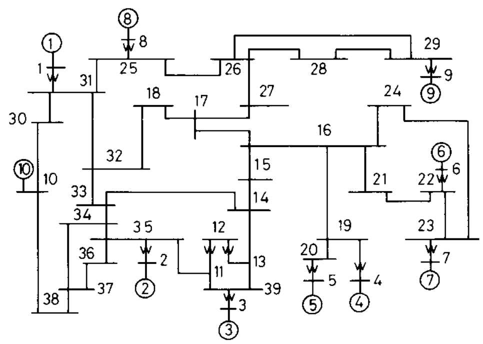

Fig. 1 *New England system*

are obtained from Reference 17. This system represents 345 kV bulk transmission networks of New England. Generator 10 is an equivalent power source representing parts of the USA–Canadian interconnection system. It has an inertia constant, H = 500. The inertia constants (H) of all the other generators in the system are in the range 24.3 to 42 s. Generator 10 was not considered in the coherency identification process because of its very high inertia constant. The values of ρ_{ij} between the other generators in the system are given in Table 1. Assuming

Table 1: Coherency index matrix ρ for the New England system

	1	2	3	4	5	6	7	8	9
1		0.78	0.76	0.85	0.85	0.85	0.86	0.11	0.15
2	0.78		0.34	0.86	0.90	0.85	0.88	0.86	0.84
3	0.76	0.34		0.82	0.86	0.81	0.85	0.85	0.78
4	0.85	0.86	0.82		0.24	0.69	0.71	0.88	0.71
5	0.85	0.90	0.86	0.24		0.68	0.74	0.90	0.88
6	0.85	0.85	0.81	0.69	0.68		0.05	0.88	0.70
7	0.86	0.88	0.85	0.71	0.74	0.05		0.90	0.76
8	0.11	0.86	0.85	0.88	0.90	0.88	0.90		0.44
9	0.15	0.84	0.78	0.71	0.88	0.70	0.76	0.44	

the fault is cleared without any line switching, the prefault network and the corresponding AUEPs were used to compute the index p. It is seen from the table that generator pairs (2, 3), (4, 5), (6, 7), (1, 8) and (1, 9) satisfy eqn. 10 and can be considered to be the tentative coherent generator pairs.

A 3-phase fault on bus 20 which cleared without any line switching was considered. Since generators 4 and 5 are in the vicinity of the fault, they may be considered to be in the study system and were excluded from the coherency identification process. Table 2 gives the prefault and faulted angles at $t_1 = 0.20$ s for all the generators in the system. It is clear from Table 2 that only the generator pairs (2, 3), (6, 7) and (1, 8), among the previously obtained tentative coherent generator pairs, satisfy the relative rotor angle deviation eqn. 2. For this particular fault the proposed method identifies the following coherent generator groups

I: (2, 3)
II: (6, 7)
III: (1, 8)

Fig. 2 shows the swing curve of generators 1, 2, 3, 6, 7, 8 and 9 for the fault of 0.20 s duration. It can be observed

Table 2: Prefault and faulted generator rotor angles

Gen. No.	Prefault angle	Faulted angle
1	10.74	15.52
2	30.40	37.26
3	30.46	37.95
4	27.99	58.56
5	40.04	81.59
6	30.22	43.25
7	30.93	44.87
8	28.56	36.07
9	41.50	50.15
10	3.22	3.74

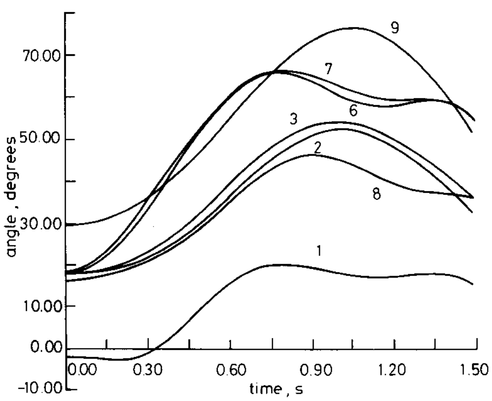

Fig. 2 *Swing curve for 3-phase fault on bus 20 of New England system*

from the Figure that only generator pairs (2, 3), (6, 7) and (1, 8) are coherent.

A fault on bus 31 cleared by opening the line between buses 31 and 32 was considered next. In this case generators 1, 8 and 10 may be considered to be in the study system. Table 3 shows the values of the V-function at different AUEPs (only one machine running out of step) using prefault and post fault networks. Table 3 shows that the variation of the V-function for the two network configurations are not significant for the generators which are not in the vicinity of the disturbance. The prefault network can thus be used to check eqn. 10 and identify the tentative coherent generators. These are the same

Table 3: Values of V-function at different AUEPs for different network configurations

Unstable generator number	Values of V-function using: Prefault network	Post fault network
1	34.70	30.86
2	9.07	8.40
3	10.98	10.15
4	14.51	13.99
5	5.48	5.21
6	15.17	14.64
7	12.78	12.34
8	12.33	11.38
9	4.97	4.82
10	132.97	131.55

as in the last case for a fault on bus 20. For this fault only generator pairs (2, 3) and (6, 7) satisfy eqn. 2. The generator pair (4, 5) has a relative rotor angle deviation of 6.2° at t_1 and may not be considered to be coherent. Fig. 3 shows the swing curves of all the generators in the external system for this fault condition. Fig. 3 clearly indicates that only generator pairs (2, 3) and (6, 7) are coherent.

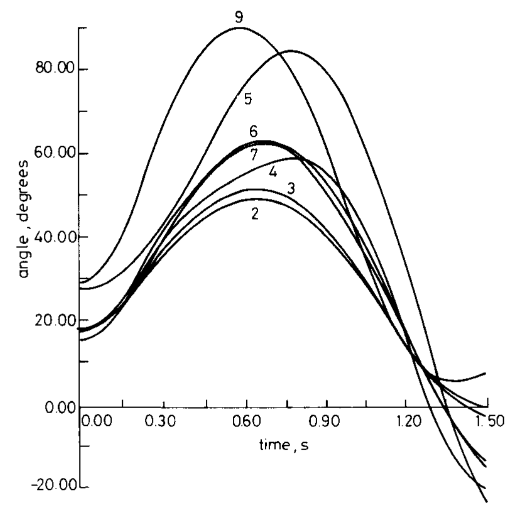

Fig. 3 *Swing curves of all the generators in the external system for 3-phase fault of 0.22 s duration on bus 31 of New England system*

4.2 The Bangladesh system

The Bangladesh planned power network (reduced) consists of 11 machines, 33 buses and 63 lines. The single line diagram of this system is shown in Fig. 4. The system data with initial operating conditions are given in Reference 18. The tie line between buses 23 and 24 connects the eastern and western grids of this country. A three phase fault of 0.25 s duration on bus 9 was considered. For this fault, generators 7, 8 and 9 may be considered in the study system. The swing curves for the rest of the generators in the system are shown in Fig. 5. Examination of the swing curves indicate that only generators 5 and 6 are coherent.

Application of the proposed method shows that generator pairs (1, 2) and (5, 6) satisfy eqn. 10 and so form the tentative coherent groups. Since the generator pair (1, 2) does not satisfy the relative rotor angle deviation eqn. 2 for the particular fault condition, the final coherent group is identified as consisting of generators 5 and 6. This agrees perfectly with the simulation results.

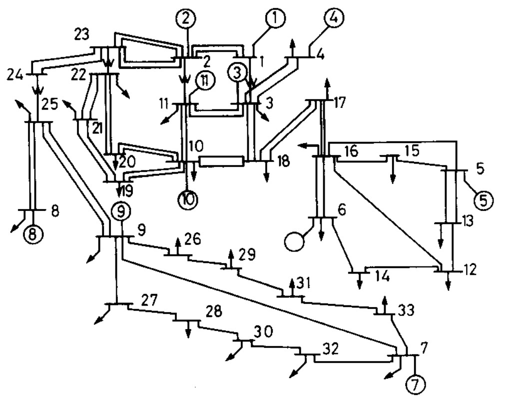

Fig. 4 *Bangladesh system*

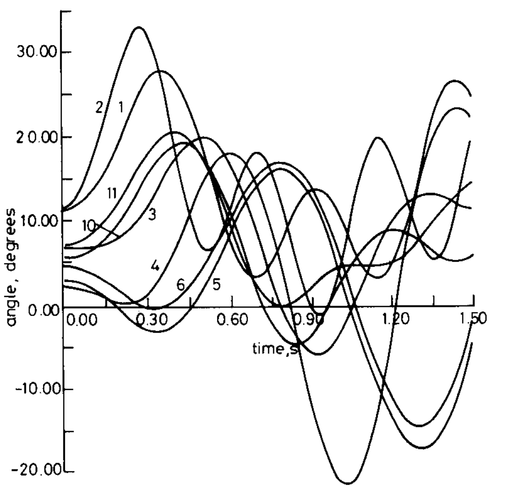

Fig. 5 *Swing curves of generators in external system for 3-phase fault on bus 9 of Bangladesh system*

4.3 Iowa system

The Iowa system, consisting of 17 machines, 163 buses and 284 lines, repesents the reduced power network of the State of Iowa. The system data with initial operating conditions are obtained from Reference 19. Four tentative coherent generator groups were identified in this system by applying eqn. 10. These are shown in Table 4.

Table 4: Tentative coherent generator groups of the Iowa system

Group no.	Generator number
I	1, 2, 17
II	4, 15
III	5, 6
IV	7, 9, 13, 14

For a 3-phase fault on bus 6 (at the terminal of generator 2), generators 2, 10, 12, 16 and 17 may be considered to be in the study system. Relative rotor angle deviation eqn. 2 was then applied to the groups identified as tentatively coherent (Table 4). All of them satisfy eqn. 2 except group I consisting of generators 1, 2 and 17. Thus the network consists of 3 coherent generator groups formed by the generators (4, 15), (5, 6) and (7, 9, 13, 14).

Fig. 6 shows the swing curve of generators 4, 5, 6 and 15 for the fault of 0.22 s duration. The swing curves

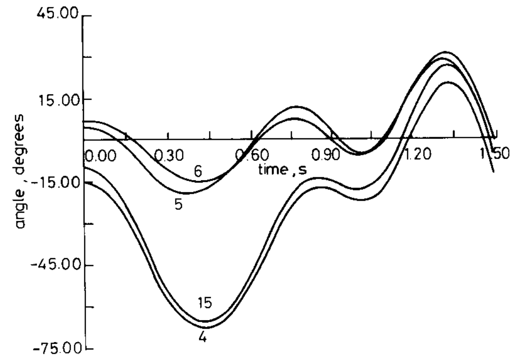

Fig. 6 *Swing curve of generators 4, 5, 6 and 15 for 3-phase fault on bus 6 of Iowa system*

obtained by digital simulation were processed through a clustering algorithm to find the groups of coherent generators in the external system. For a tolerance of 7° (ε in eqn. 1), the clustering algorithm identifies three coherent groups comprising the generators (4, 15), (5, 6) and (7, 9, 13, 14). This agrees perfectly with the results obtained by the proposed method.

5 Conclusion

A novel method of determining the coherency of generators in a power system is presented in this article. The method identifies coherent groups of generators for various fault locations in the system very effectively and with a minimum of computation. A tentative coherent group is determined only once for a given operating condition which remains invariant for any fault condition in the system. The tentative group is identified by the evaluation of the energy function at different approximate unstable equilibrium points and by satisfying a proposed coherency criterion. The final group of coherent machines for a particular fault condition is obtained by checking the conditions on relative angles of the faulted machines, excluding those in the study system. The relative angles are obtained through Taylor series expansions.

The proposed method was tested for various fault conditions on three power networks. Coherency was also determined using the classical method, checking the swing curves generated by solving the total system dynamics. The results obtained by the proposed method were observed to match these perfectly.

6 Acknowledgment

The authors wish to thank the King Fahd University of Petroleum and Minerals and the University of Bahrain for the facilities provided towards this research.

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