Slow Coherency-Based Islanding

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***Abstract*—This paper provides the analytical basis for an application of slow coherency theory to the design of an islanding scheme, which is employed as an important part of a corrective control strategy to deal with large disturbances [1]. The analysis is conducted under varying networks conditions and loading conditions. The results indicate that the slow coherency based grouping is almost insensitive to locations and severity of the initial faults. However, because of the loosely coherent generators and physical constraints the islands formed change slightly based on location and severity of the disturbance, and loading conditions. A detailed description of the procedure to form the islands after having determined the grouping of generators using slow coherency is presented. The verification of the islanding scheme is proven with simulations on a 179-bus, 29-generator test system.**

***Index Terms*—Determination of islands, nonlinear verification of grouping, sensitivity to loading conditions and network configuration, slow coherency-based grouping.**

I. INTRODUCTION

POWER systems are being operated closer to the stability limit nowadays as deregulation introduces several new economic objectives for operation. As open access transactions increase, weak connections, unexpected events, hidden failures in protection systems, human errors, and other reasons may cause the system to lose balance and even lead to catastrophic failures. In [1] a design of a self-healing strategy with emphasis on a new two-level load shedding scheme to deal with large disturbances has been presented. The proposed scheme separates the power system into smaller islands at a slightly reduced capacity, but with the advantage that the system can be restored very quickly. Then, by exploring a carefully designed load shedding scheme based on the rate of frequency decline, the extent of the disruption is limited. As a result, the system can be restored rapidly. The scheme is tested using the extended transient-midterm stability program (ETMSP) [2] on a 179-bus, 29-generator sample system and shows very good performance. This paper provides the analytical basis to form the islands. A slow coherency method [3] based on two-time-scale theory with a modification called tolerance based slow coherency [4] to deal with large systems, and achieve more precise results is adopted in this paper. The user can specify the tolerance value, the number of slow modes, and the number of eigenvalues being calculated. The slow coherency approach is based on a linearized model. The attributes of the slow coherency of the generators, which are a function of the structural characteristics of the system are discussed. After having determined the groupings of generators using slow coherency, an automatic islanding algorithm is described that takes into account certain physical constraints in forming islands. These include availability of tie lines, generation load imbalance, ease of restoration, etc. Out of step relays complemented with synchronized phasor measurement can be used to form the islands. The grouping of generators developed using the slow coherency approach is verified using nonlinear simulation on a 179-bus, 29-generator test system. The grouping algorithm is tested and verified over a wide range of operating conditions. Results indicate that even though the slow coherency approach uses a linearized model to obtain the coherent grouping, it accurately captures the dynamic behavior of the nonlinear simulation. The automatic selection of the islands is verified by examining the locus of the R-Rdot out of step relays [5], [6], which are used to create the islands at appropriately selected tie lines. These plots clearly indicate that under large disturbances the R-Rdot relays will be tripped and the chosen island will be formed.

The paper is organized as follows. Section II provides an overview of the slow coherency theory and its application to determine the weakest link in the system and identify the appropriate grouping of generators. Section III describes the automatic islanding program to form the islands. Simulation results are provided in Section IV to verify the effectiveness of the grouping and islanding procedure. Section V presents the conclusions and discussions.

II. SLOW COHERENCY-BASED ISLANDING

A. Introduction

In the controlled islanding self-healing approach, the determination of the islands for a given operating condition is the critical step. A reasonable approach to islanding can result in significant benefit to the corrective control actions that follow the islanding procedure. In determining the islands, the inherent structural characteristics of the system should be considered. In addition, the choice of these islands should not be disturbance dependent. These conditions are imposed in order to provide a corrective control scheme that is fairly general and easy to implement.

Slow coherency has originally been used in the development of dynamic equivalents for transient stability studies. Previously, several methods have been used to identify the coherent groups of generators [3], [4], [7]. They include electrical distance method; time domain approach; and frequency domain approaches utilizing Fourier transform and Laplace transform techniques. In these methods, two assumptions are made:

1) The coherent groups of generators are independent of the size of the disturbance—so that the linearized model can be used to determine the coherency.

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2) The coherent groups are independent of the level of detail used in modeling the generating unit—so that a classical generator model can be considered.

The first assumption is based on the observation that the coherency behavior of a generator is not significantly changed as the clearing time of a specific fault is increased. Although the amount of detail of the generator model can affect the simulated swing curve, it does not radically change the basic network characteristics such as interarea modes. This forms the basis of the second assumption.

B. Slow Coherency

Slow coherency is an application of the singular perturbation or two-time-scale method [8] in power systems. The method assumes that the state variables of an nth order system are divided into r slow states Y, and (n-r) fast states Z, in which the r slowest states represent r groups with the slow coherency. The user provides an estimate for the number of groups. The automatic islanding program then takes into account the mismatch between generation and load and availability of the tie lines to form islands and appropriately combines groups when islands cannot be formed. Both the linearized and nonlinear power system models can be used to apply the two-time-scale method.

C. Slow Coherency and Weak Connection

Slow coherency solves the problem of identifying theoretically the weakest connection in a complex power system network. Previous work shows that groups of generators with slow coherency may be determined using Gaussian elimination on the eigensubspace matrix after selection of r slowest modes σ_a. In [3], it has been proven through linear analysis that with selection of the r slowest modes, the aggregated system will have the weakest connection between groups of generators.

The weak connection form best states the reason for islanding based on slow coherency. That is, when the disturbance happens, it is required to separate in the transient time scale the fast dynamics, which could propagate the disturbance very quickly, through islanding on the weak connections. In the transient time scale, however, the slow dynamics will mostly remain constant or change slowly on the tie lines between the areas. In other words, once fast dynamics are detected on the tie lines, it means fast dynamics are being propagated through these weak connections.

Actually, slow coherency is a physical evidence of a weak connection, which is a network characteristic. The linearized generator electromechanical model is sufficient for determining the areas. In many large-scale practical systems, there always exist groups of strongly interacting units with weak connections between groups. But even very weak connections will become strong connections with significant interactions after a short period of time. When a large disturbance happens, it is imperative to disconnect the weak connections before the slow interaction becomes significant, or before the fast dynamics propagate.

As a summary of the section, the slow coherency based grouping method has the following explicit advantages:

1) Slow coherency among the groups of generators does not vary significantly by the change of initial condition and disturbance.
2) The two-time-scale weak connection form inherently describes the oscillation feature of large-scale power systems: the fast oscillation within a group of machines and the slow oscillation between the groups via weak tie lines.
3) The slow coherency method also preserves the features of the coherency-based grouping. It is independent of the size of the disturbance and the generator model detail.

III. SWITCHING TO FORM THE ISLANDS

In the previous section the procedure to determine groups of generators based on slow coherency is presented. In this section we address the issue of where to exactly select the cut sets.

A. Considerations Regarding Islanding

Having decided the coherent generators in each island, we utilize a set of criteria for the determination of the physical boundary of each island shown:

1) Consideration of Generation Load Imbalance: The reduction of generation load imbalance in each island reduces the amount of under-frequency load shedding to be done once the islands are formed. It also makes it easier for each island to be capable of matching the generation and load within the prescribed frequency limit and is beneficial during restoration.

2) Topological Requirement: In order to form the islands and specifically isolate one island from the other, all the lines connecting the islands need to be determined and disconnected.

B. Automatic Islanding Program

A C++ program has been developed based on the above criteria to identify from the grouping information the exact locations in the network where the islands can be formed. The program considers the boundary topology conditions and provides an exhaustive search-based list of all the possible cut sets with the generation load imbalance information. The approach begins with the characterization of the network structure or connectivity using the adjacent link table data structure [11]. This structure is appropriately modified to apply to this case. The network topology data are basically stored in two types of basic data structures: *Bus_Configuration*: contains information related to the bus, bus number, bus name, bus type (generator, load or connection bus), voltage level, etc. For generators, the data of inertia, active power and reactive power will also be stored. This facilitates the calculation of generation load imbalance. *Link_Configuration*: contains information related to the transmission lines or bus connections. It only contains the bus number which is connected and a pointer to the next *Link_Configuration* structure, which is also connected to the head bus. All the buses can be retrieved using the bus number in the array index. Then each bus will have a chain of the data structure *Link_Configuration*, which contains all the buses the head bus is connected to. So with the above data structures, the information of power system network topology and necessary information for the islanding problem can be easily saved, retrieved and manipulated with convenience.

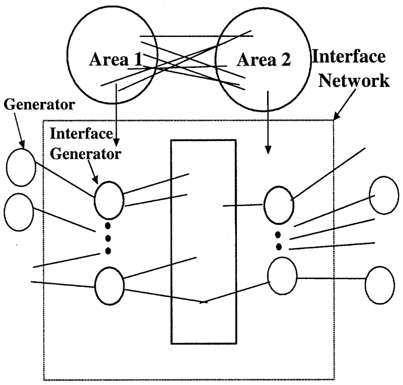

Fig. 1. Illustration of interface network.

Having identified the groups of coherent generators, the tie lines or the cut sets between the coherent groups are identified. The interface buses between the coherent groups are then determined.

The concept of the interface network can be illustrated with Fig. 1. In the figure, the exact boundary between two groups of generators, which are represented with two areas in the figure, needs to be identified. The small network between the two areas is called interface network, and the generators in the interface network are called interface generators.

In doing this, the search concentrates only on the buses associated with the coherent groups under consideration or the groups to be islanded, since the tie lines or cut sets must come from the interface buses. Before forming these interface buses, some reductions on the original network should be done. The part of the network for all the groups except for the coherent groups under consideration is reduced. Several steps are taken in reducing the network. They include:

1) Reduce all generator internal buses to their terminal buses.
2) Remove generators not included in groups considered. They can be removed because we only search for the cut sets in one place between two or even more coherent generator groups.
3) Search and remove the isolated buses.

After these steps, a smaller network is formed. The search for the interface buses is based on the smaller network and this significantly reduces the computational burden. The program will start from one of the buses or the center node from the user input in the interface between the groups, that is to be determined. Two important issues need to be considered. At first, we should decide where the tie lines should be cut to form the islands, and select one of the buses as the center bus. Second, we need to consider how deep the network tree should expand to form the sub-network. Regarding the first question, one option to solve the problem is to determine the generator buses on the island boundary. We then choose a bus near that generator bus as the starting point. To determine the generator bus on the island boundary, we need to calculate the minimum distance between the outside and inside of the island. The generator bus with the minimum distance is the boundary generator bus. There can be more than one bus under the consideration, but not too many. To address the second issue, we need to consider the topology of the whole system. In the automatic islanding program, at least 3 layers (3 adjacent nodes) and at most 8 layers of the system network around the center node are searched as a sub-network depending on the physical distance of the node from the center node. This sub-network is referred to as the interface network. A brute force search is then conducted on the interface network to determine the cut sets where the islands are formed.

Two assumptions regarding the cut sets are made during the search, which are applicable to most power system topological networks:

1) All the cut sets or combination of lines to be tripped come from the lines of the interface network.
2) A cut set is limited to a small number of lines since not too many tie lines are expected to be tripped during islanding.

By running the program, the optimum tripping lines are located once we have the coherent groups' information. The generation and load information stored in the data structure helps us determine the generation load imbalance in each island that is formed. Based on this information, the optimal cut sets considering the criteria of the topological requirement and the minimum generation load imbalance requirement are obtained.

IV. Simulation Results

A. Grouping Result for the Base Case

In this section we will demonstrate the efficacy of the slow coherency grouping and the automatic islanding program on a 179-bus, 29-generator test system. The system has a total generation of 61 410 MW and 12 325 Mvar. It has a total load of 60 785 MW and 15 351 Mvar. The simulations are made using a detailed generator model with governors, exciters and power system stabilizers (PSS). The dynamic reduction program (DYNRED) in the power system analysis package (PSAPAC) [12] was chosen to form groups of coherent generators based on an improvement to the slow coherency method developed by GE [4] to deal with large systems and achieve more precise results. The user can specify tolerance value, the number of slow modes, and the number of eigenvalues being calculated. Then with the help of the automatic islanding program, we determine the cut sets of the island taking into account the least generation load imbalance and topological requirements.

The DYNRED program was employed to find groups of generators with slow coherency on the 179-bus system on a base case. The 29 generators are divided into 4 groups by the slow coherency program as shown by the dotted lines in Fig. 2. Fast dynamics are propagated through the weak connections determined by the boundary between groups of generators. Since this is a network characteristic, the boundary won't change much with the variation of the power flow base case.

B. Islanding for Different Disturbances

To test the proposed method for different disturbances, we consider a series of cases where different sets of lines are removed. This represents a large disturbance since the base case is heavily loaded. The cases tested are shown in Table I.

Set 1: Faults placed in the western portion of the system.

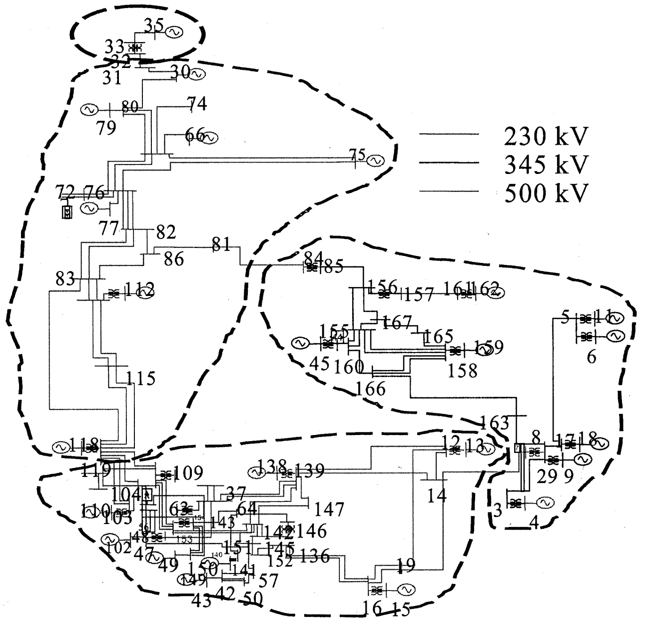

Fig. 2. Generator groups formed by slow coherency.

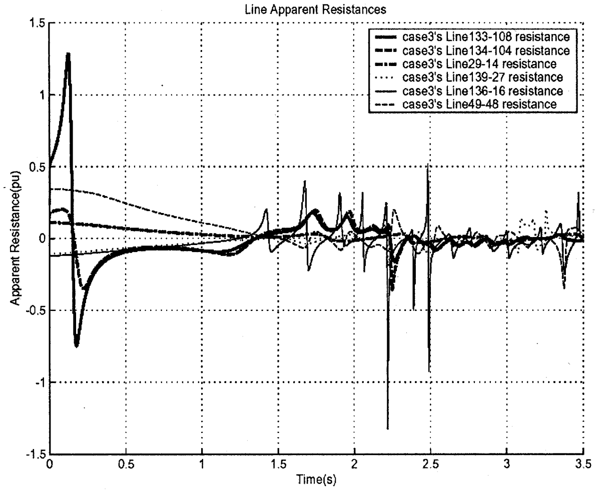

Fig. 3. Line apparent resistance plots for Set 1–Case 3.

TABLE I
CASES ANALYZED

Set 1		
Case #	Lines Removed	Lines Monitored
1	Bus 83- 168	Bus 133 – 108, Bus 134 – 104 Bus 29 – 14, Bus 139 – 27 Bus 136 – 16, Bus 49-- 48
2	Bus 83- 168, Bus 83- 170	
3	Bus 83- 168, Bus 83- 170 Bus 83 –172	
Set 2		
Case #	Lines Removed	Lines Monitored
1	Bus 12 - 139	Bus 133 – 108 Bus 134 – 104 Bus 29 – 14 Bus 37 – 64 Bus 104 – 135 Bus 154 – 143 Bus 49 -- 48
2	Bus 12-139, Bus 27-139	
3	Bus 12-139, Bus 27-139 Bus 16 -136 (Ckt1)	
4	Bus 12-139, Bus 27-139 Bus 16 -136 (Ckt1, Ckt2)	

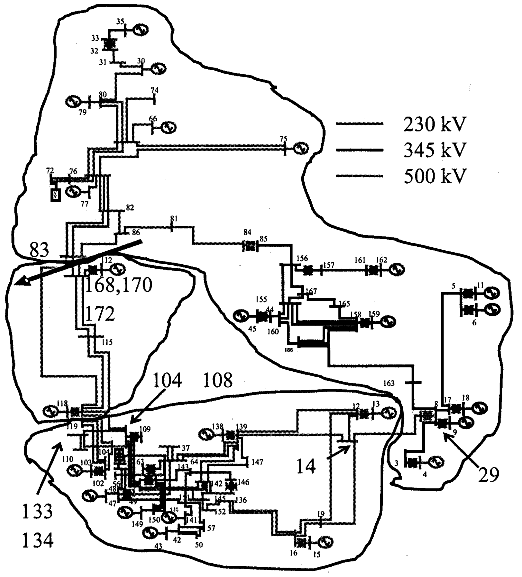

Fig. 4. Slow coherency Set 1: Disturbance and islands formed.

Case 1) From the transient simulation, there is not much change of system frequency at each bus, so islanding is not needed.

Case 2) This case is very similar to case 1 and leads to the same type of behavior.

Case 3) Simulations conducted on the system indicate that this disturbance will result in the system being unstable. In these simulations, no conventional protection settings were considered. Line apparent resistance plots are shown in Fig. 3.

There are rapid changes on line apparent resistance. The change first occurs at line 133-108 and 134-104 (around 0.2 s after the disturbance). These lines are also identified as the weak connections by the slow coherency program. As the disturbance progresses, we notice the change in line 136-16 and 139-27 (around 1.4 s). These lines are located south and east of the disturbance. About 1.8 s after the fault, the R-Rdot relay detects a big change on line apparent resistance at line 29-14. This line lies at the eastern edge of the boundary of the southern island. This is because it takes some time for the disturbance to propagate through the system. With the grouping information of the base power flow condition provided in Fig. 2, the automatic islanding program determines that three islands should be formed after the disturbance that can be characterized as the northeast island, the central island, and the south island as shown in Fig. 4. The following lines are tripped in order to create the islands:

1) bus 133-bus 108;
2) bus 134-bus 104;
3) bus 29-bus 14.

In Fig. 4, there are 11 generators in the south island and three generators in the central island. The biggest arrow shows the location of the fault, and as a result the connection to the west in the north-south direction is lost. The automatic islanding program determines the optimal cut sets for the south island.

TABLE II
CANDIDATE CUTSETS FOR CASE 3

Cutset	Load-Generation Imbalance(MW)
133 – 134 104 – 134 14 – 29	North: Gen=40814.63 Load=36405.90 South: Gen=15477.70 Load=17373.60 Central: Gen=5118.00 Load=7005.91
133 – 132 104 – 107 104 – 135 104 – 102, 14 – 29	North: Gen=40814.63 Load=36405.90 South: Gen=15477.70 Load=17068.60 Central: Gen=5118.00 Load=7310.91
133 – 132 104 – 135 104 – 102 108 – 135, 14 – 29	North: Gen=40814.63 Load=36405.90 South: Gen=15477.70 Load=16763.60 Central: Gen=5118.00 Load=7615.91
132 – 119 104 – 102 107 – 108 108 – 135, 14 – 29	North: Gen=40814.63 Load=36405.90 South: Gen=15477.70 Load=16763.60 Central: Gen=5118.00 Load=7615.91

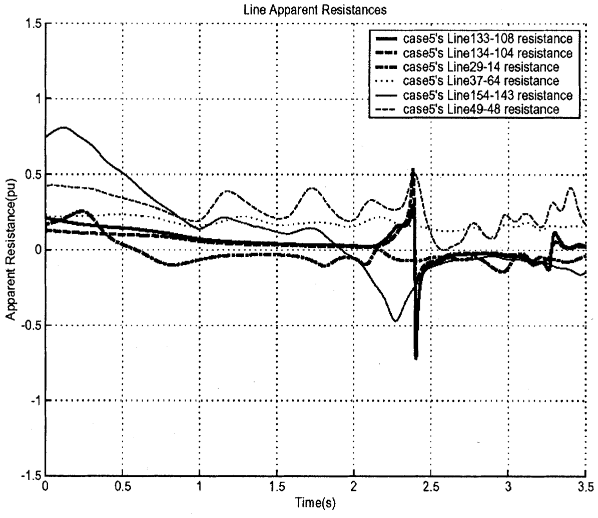

Fig. 5. Line apparent resistance plots for Set 2-Case 2.

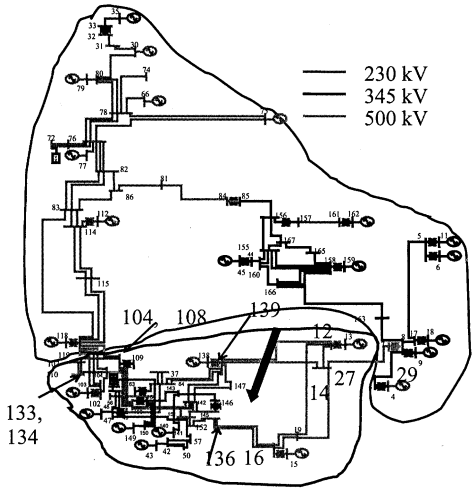

Fig. 6. Slow coherency Set 2-Case 2: Disturbance and islands formed.

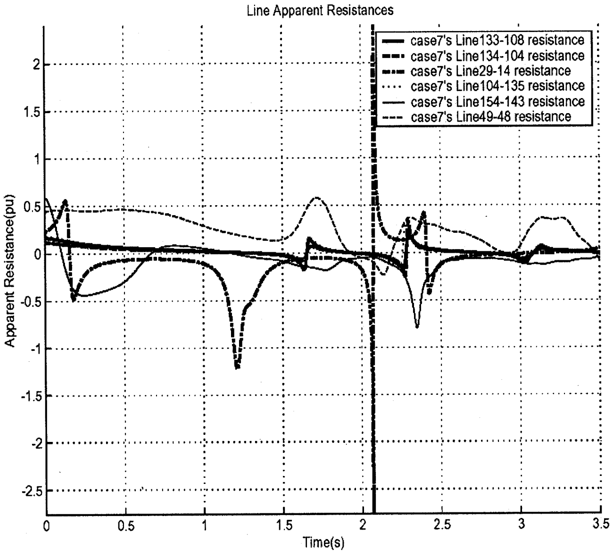

Fig. 7. Line apparent resistance plots for Set 2-Case 4.

For the western part of the island, a sub-network of 30 lines is formed at first as an interface network. For the eastern part of the island, a sub-network of 17 lines is formed to be the interface network. The possible cutsets along with the load generation profile are stored in a file. A list of the candidate cutsets for this case is shown in Table II.

Among these, we observe that the first cutset has a slightly larger imbalance for the south island which has inertia of 966.66 s, but a smaller mismatch for the central island which has inertia of 343.39 s, in comparison to the other candidate cutsets. Consequently, the first cutset will result in islands that have significantly lower frequency oscillations than the other cutsets. Hence, this cutset is chosen as the optimal islanding strategy.

Set 2: Faults placed in the southeast portion of the system.

Case 1) This case does not require islanding.

Case 2) This case results in rapid changes of line apparent resistance shown in Fig. 5. The change first occurs at line 29-14 (around 0.4 s after the disturbance) because it is near the disturbance. Then the R-Rdot relay at line 154-143 (around 1.8 s) detects a large oscillation. About 2.4 s after the fault, the R-Rdot relay detects a big change on line apparent resistance at lines 133-108 and 134-104.

To save the system from an impending blackout, we split the system into two islands. The cutset identified by the automatic islanding program results in the following lines being tripped:

1) bus 133-bus 108;
2) bus 134-bus 104;
3) bus 29-bus 14.

The two islands are shown in Fig. 6. There are nine generators in the south island. The biggest arrow shows where the disturbance takes place.

Case 3) This case also results in a severe disturbance. Rapid changes on line apparent resistance are observed. The resistance change on line 134-104 is very large. The islands determined are the same as those for case 2.

Case 4) This is again a very severe disturbance. Rapid changes of line apparent resistance are observed in Fig. 7 as in the two previous cases with a similar

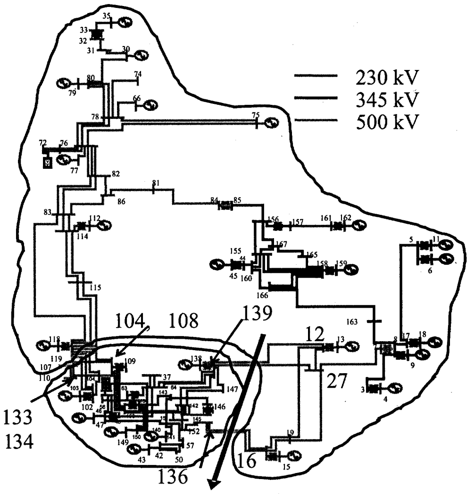

Fig. 8. Slow coherency Set 2-Case 4: Disturbance and islands formed.

TABLE III
LOAD CHANGE AT BUSES IN SOUTHERN AREA (SCENARIO I)

Load Bus	Base Load(MW)	New Load(MW)	Change(%)
136	856.00	898.80	-5
141	3191.00	3350.55	+6
142	204.20	214.41	-7
143	377.40	396.27	+8

TABLE IV
LOAD CHANGE AT BUSES IN SOUTHERN AREA (SCENARIO II)

Load Bus	Base Load(MW)	New Load(MW)	Change(%)
136	856.00	898.80	+5
137	175.00	183.75	+5
139	902.30	947.42	+5
141	3191.00	3350.55	+5
142	204.20	214.41	+5
143	377.40	396.27	+5
145	3098.00	3252.90	+5

pattern of behavior. Two islands as shown in Fig. 8 are formed and the connection to the southwest of the system is lost.

In these set of cases, the apparent impedance first undergoes a significant change in the line 29-14 that is close to the disturbance. As the disturbance progresses, we observe that the apparent impedances on the lines in the central portion and the western portion of the south island change at later times as the disturbance propagates toward the western portion of the system.

C. Grouping and Islanding Under Different Load Conditions

The advantage slow coherency based grouping has is that it is generally initial condition independent. To verify this, we design several scenarios based on Set 1, case 3 in Section VI, part B, with different loading conditions by randomly picking some load buses and changing the loads by a certain amount.

Basically, the northern area is generation rich and the southern area is load rich. Therefore, the buses picked are located in the southern area to see how the grouping changes with the change of flow from the northern area to the southern area.

TABLE V
LOAD CHANGE AT BUSES IN SOUTHERN AREA (SCENARIO III)

Load Bus	Base Load(MW)	New Load(MW)	Change(%)
136	856.00	813.20	-5
137	175.00	166.25	-5
139	902.30	857.19	-5
141	3191.00	3031.45	-5
142	204.20	193.99	-5
143	377.40	358.53	-5
145	3098.00	2943.10	-5

TABLE VI
LOAD CHANGE AT BUSES IN SOUTHERN AREA (SCENARIO IV)

Load Bus	Base Load(MW)	New Load(MW)	Change(%)
5	2350.00	2232.50	-5
31	4400.00	4180.00	-5
44	2053.00	1950.35	-5
80	5000.00	4750.00	-5
119	5661.00	5377.95	-5
141	3191.00	3031.45	-5
150	3118.00	2962.10	-5

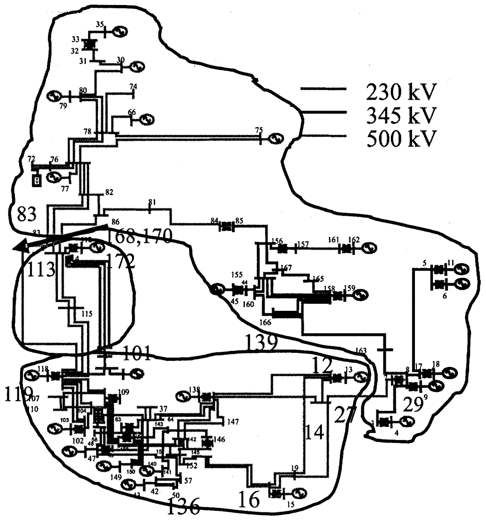

Fig. 9. Islands formed by islanding program (scenario III).

1) Scenarios I and II: Tables III and IV show the scenarios of the load change in the southern area. The slow coherency grouping program indicates that both scenarios have the same generator grouping. As a result, we obtain the same islands shown in Fig. 4. But in other scenarios, which are listed in Tables V, VI, the generator grouping is slightly different.

2) Scenarios III and IV: Figs. 9 and 10 denote the islands formed by the islanding program for these two loading scenarios.

The optimal cutsets and generation-load imbalance for Scenario III and IV are shown in Table VII. From Figs. 9 and 10 we note that the islanding scheme for the two cases is slightly different. With the different loading conditions, the slow coherency grouping program returns different results. This is because generator buses (112, 116, and 118) in the central island are loosely

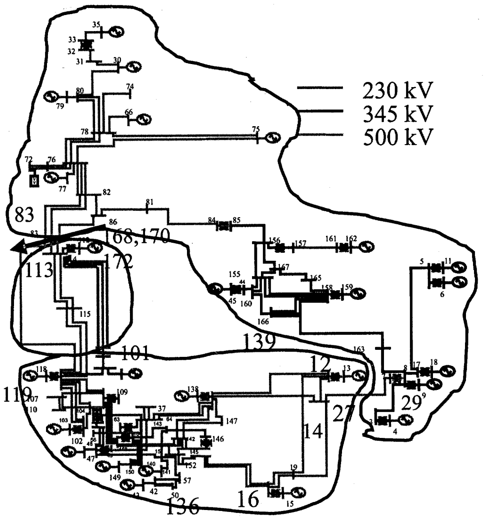

Fig. 10. Islands formed by islanding program (scenario IV).

TABLE VII
OPTIMAL CUTSET AND GENERATION-LOAD IMBALANCE

Scenario	Cutset	Load-Generation Imbalance(MW
III	119 - 123 119 - 129 119 - 131 101 - 113 29 - 14	North: Gen=40814.63 Load=36405.90 South: Gen=19538.70 Load=23881.02 Central: Gen=1057.00 Load=247.30
IV	83 - 89 83 - 94 83 - 98 29 - 14	North: Gen=40814.63 Load=36744.90 South: Gen=20595.70 Load=23939.32

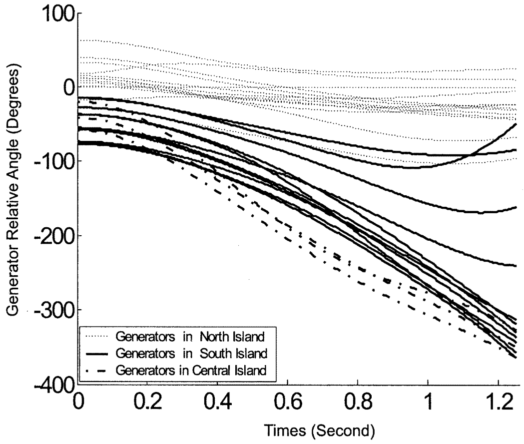

Fig. 11. Scenario II–Fault-on generator relative angle curves.

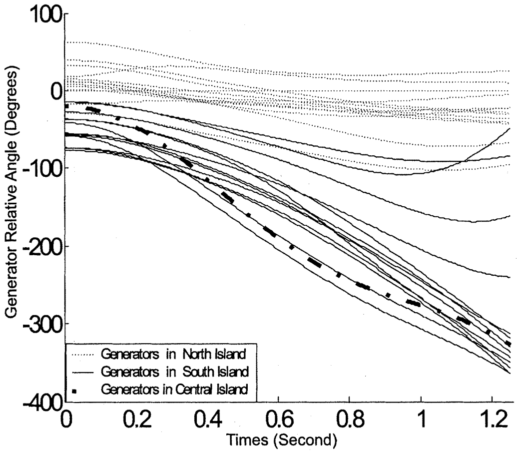

Fig. 12. Scenario III–Fault-on generator relative angle curves.

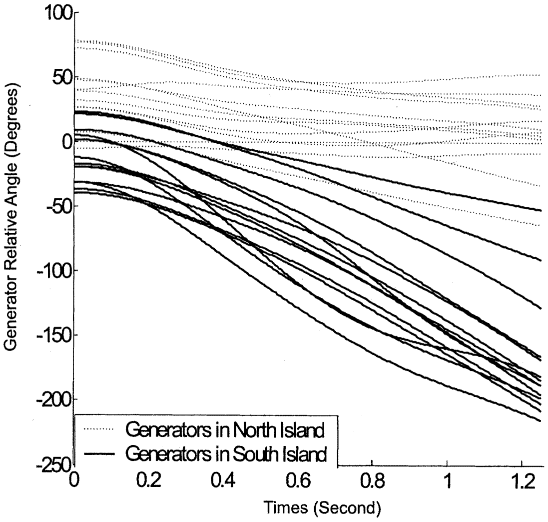

Fig. 13. Scenario IV–Fault-on generator relative angle curves.

coherent with other generators. With slight change in load, these generators can jump from one coherent group to another.

This set of cases essentially shows that the slow coherency based grouping can change slightly with change in loading conditions. The difference among the cases lies in the grouping among the loosely connected generators. The automatic islanding program determines the appropriate optimal cutset and creates islands that have an optimal imbalance of generation and load. However, the islands are not significantly different, and we observe that the system is broken up into either two or three islands, and in the Scenario IV the central island is merged with the south island. The loosely coherent generators are the ones the form the central island in Scenario III.

D. Nonlinear Simulations

The verification of the principal basis for the islanding scheme is done by conducting nonlinear simulations for different operating conditions. Figs. 11–13, depict the generator rotor angle curves without any islanding action and any load shedding action during the fault-on period for Scenarios II, III, and IV, respectively. These plots obtained from EPRI's ETMSP package include the complete nonlinear model of the system and provides a verification of the ability of the slow coherency approach in picking up the weak connections in the system independent of the loading and disturbance. In Section IV–C above, the slow coherency grouping and islanding were obtained using the changed power flow cases independent of the disturbance. In order to verify the accuracy of the weak connection determination, it is important to check if the predicted machines are indeed coherent in the nonlinear simulations before islanding actually takes place. Once islanding occurs, other corrective actions like underfrequency load shedding [1] will be applied to maintain the stability of the system.

The solid lines show the generators' relative rotor angle curves in the south island; the dashed lines show the generators' relative rotor angle curves in the central island, and the dotted lines show the generators' relative rotor angle curves in the north island. As one can see from Figs. 3, 5, and 7, large changes in apparent resistance have been monitored well within 0.5 s after the disturbance. The generators in each island have almost constant angle difference with each other during this period or they are coherent with each other. With the ability of remote tripping, in practice, islanding action will have been taken place before the group generators lost their coherency. This clearly indicates that the slow coherency based group accurately captures the structural characteristics of the system under arbitrary load changes and correctly identifies the weak connections. Therefore, the groups maintain coherency well beyond the time at which a significant rate of change of impedance occurs on tie lines separating these groups. Hence, our premise of utilizing the slow coherency approach to identify the weakest links is well justified.

V. DISCUSSION AND CONCLUSIONS

In this paper, a slow coherency based islanding strategy is developed for large disturbances. This includes the development of the procedure for grouping and the identification of the weakest link in the network based on the slow coherency grouping. The slow coherency grouping is based on a linearized electromechanical model of the system [3], [4]. This raises the issues of its applicability to highly nonlinear power systems and the efficacy of the procedure in determining the grouping. To verify the applicability and validity of the procedure, the scheme is tested on a 179-bus, 29-generator test system.

Two kinds of tests are conducted to verify the slow coherency based grouping. In the first set of tests, the validity and the efficacy of the procedure are tested for two different disturbances conducted by removing different transmission lines. The results of this analysis clearly indicate that the grouping obtained is not very sensitive to the disturbance location. The inherent structural characteristic of the system determines the slow coherency behavior and other important parameters related to topological ability to form islands, and load-generation imbalance results in the formation of either two or three islands. The basic configuration of the islands does not change when different lines are removed. The location of the islands does depend on the existing system conditions prior to the disturbance. The out-of-step operation following the disturbance splits the system into islands one location at a time as the disturbance propagates through the system. This has been clearly established using the R-Rdot relay plots.

In the second set of tests, the grouping is verified for changes in operating condition due to random load changes. In this case, once the grouping is determined, the automatic islanding program determines the cut sets to form the appropriate islands. The results indicate that the change in operating condition will affect the grouping of generators because of the loosely coherent machines. We *do* observe a change in the configuration of the islands formed. However, it should be noted that the islands formed are quite similar, and the method accurately captures the weak connections.

An added issue of great significance is that even though the grouping in the slow coherency approach is done using a linearized model of only the electromechanical model of the system, it accurately captures the gross dynamic behavior of the detailed nonlinear model as shown by the rotor angle curves obtained from nonlinear time domain simulation using detailed models. These curves clearly indicate that the machines that are grouped based on slow coherency are coherent even in the nonlinear simulations.

Plots of the rate of change of impedance also verify that the islands determined by the automatic islanding program can be formed using the proposed R-Rdot out of step relays.

Future work needs to be done on the verification of the scheme with more simulation cases.

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