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An alternative framework for implementing generator coherency prediction and islanding detection scheme considering critical contingency in an interconnected power grid

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ABSTRACT

Formulation of faster frameworks for swift detection of coherent generators in a power system operating under a severe disturbance has been a serious issue for the effective operation of modern power grids. Providing an efficient solution to this problem becomes more compounded when combining the issue of island formation during the disturbance. This paper, therefore, focuses on proffering an alternative but simple approach to coherent generator identification as well as detecting islands in an interconnected power system operating under severe disturbances. The practical 330-kV network of the Nigerian power system and the standard IEEE 30-bus system are used as case studies to test the effectiveness of the suggested approach in this paper. Based on the structural topology of the network, the critical transmission element where the effect of the disturbance is most severe is first determined. The approach is then used to determine the coherency threshold for identifying similarities in the network rotor angles. The normalized bus coherency matrix based on the Euclidean distances for all rotor angles is then determined considering the increasing oscillations in the systems' stability parameters. The symmetrical component matrix is then extracted from the normalized bus coherency machine matrix, which is explored to determine a threshold value for identifying coherent pairs of generators. The N-1 contingency analysis with distinct coherent groups is created and the results before and after the implementation of coherency analysis and islanding scheme are presented. The results revealed an effective generation-to-load matching with four islands formation within the Nigerian system and three island formation within the IEEE 30-bus network. The results obtained when compared with the existing results show that the suggested approach is able to predict the coherent groups of generators as well as identifying the island formed faster and effectively to avoid voltage collapse in the practical power systems.

Keywords: Coherency identification, Coherent generators, Controlled islanding, Euclidian distances, Electrical topology.

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1. INTRODUCTION

As the interconnections associated with modern power systems increase, the probability of a power system losing its harmonious operation also increases with the occurrence power system disturbance (Aghamohammadi and Tabandeh, 2016; Jafarzadeh et al., 2021; Jin et al., 2019; Liu et al., 2009). The discordant operation of the power system network in this context can therefore be referred to as a situation when power system can no longer deliver adequate power to the end-user of the power system, a situation characterized by a partial or total collapse in systems voltage at various buses if not all the buses on the network (Samuel et al., 2017). Identification of coherentgenerators during island formation is a part of the solutions produced from a transient stability study which is aimed at sustaining continues delivery of power to the end users of a power system amidst of severe system disturbance capable of causing a total loss of power transfer. The GCA problem in particular deals with devising a means to locating and grouping machines having similar behaviour to energize smaller portions (islands) of the power grid (Kundur, 2013).

Two essential methods for identifying groups of coherent machines have been identified in the open literature (Aghamohammadi and Tabandeh, 2016; Arefi and Chowdhury, 2019; Arrieta Paternina et al., 2018). The first method is called the state measurement method while the second method is termed model-driven method otherwise known as slow coherency method. The state measurement method involves measuring state variables of the machines and analyzing their dynamics for similarity, which can be obtained either through simulations or in real-time. The model-driven method or slow coherency largely rests on the notion that coherency is closely related to the nature of fault and the locality of the power system disturbance. The slow coherency method can easily be achieved by dividing the system into two portions such that a reduced model is produced for the areas less prone to system disturbances while analysis is then carried out within the portions reported to experience disturbance. This method, however, gives no consideration to the system dynamics and thus, makes the state measurement method to be more popular amongst researchers (El-Arini and Fathy, 2011).

Generally, the importance of generator coherency studies includes but not limited to real-time power system operations and planning and systems security. It is used in overall improvement of a power grid's stability under disturbance, (Amjady and Majedi, 2007). One other importance of generator coherency analysis it is mostly required in implementing protection schemes for protecting groups of generators that may oscillate against each other (Zare et al., 2018) during disturbances. Providing a quick solution to coherent groups of generators during a severe disturbance becomes a complex task when islanding formation within the system is involved. In an attempt to solve this problem, several methodologies have been adopted, in the open literature, to address coherency identification by various researchers. For instance, Jabari et al. (2017) showed that the GCA problem is a solution to a much larger problem, the problem of islanding with severe disturbances prevalent in a power system. In recent years, the development of Phasor Management Units (PMU) for collecting and analyzing the magnitude and direction of phasor quantities in real-time has become more popular for predict machines rotor angle as well as identify coherent machines (Heidary et al., 2014; Aghamohammadi and Tabandeh, 2016).

Although the active stream of research in the area of coherency prediction considering islanding formation has received a lot of attention in the past (Jabari et al., 2017; Jin et al., 2019; Lin et al., 2018; Soni et al., 2018), there are several bottlenecks associated with the approaches proposed for solving the problem. First, most existing methods have lots of assumptions associated with their formulations. The main reason for this is to reduce the complexity of the solution, which may eventually render the inference obtained from the results baseless. Second, it is usually believed that the number of coherent groups identified is always equal to the number of number of islands present in a given network. These challenges become more compounded when considering a larger practical power network. Therefore, one of the contributions offered by this paper is that, it does not depend on any assumption for providing an efficient solution to the problem. The suggested approach mainly depends on the network topology, which is non-iterative-based approach for identifying the strength of the network. This helps in predicting the location of the most severe faults within the network. Another contribution is that the notion that the number of coherent groups in the network is always equal to the number of islands is not assumed but investigated in this paper.

This paper, therefore, proposes a scheme which relies solely on rotor angles in producing a number of coherent groups "inherent" to the analyzed power grid through a calculated coherency threshold obtained from the rotor angles which is unlike some coherency analysis scheme that require a number of coherent groups to be specified prior to coherency analysis.

The remainders of the paper ae sectioned as follows: section 2 present the mathematical background to the problem. Section 3 presents a brief introduction of the Nigerian network used as the case study to test the effectiveness of the suggested approach. The results obtained as well as the discussions of the results are presented in section 4 while the study is concluded in section 5.

2. THEORETICAL BACKGROUND OF THE SUGGESTED COHERENCY AND ISLANDING DETECTION SCHEMES

In the presence of a severe system disturbance, the power compensation devices may not be sufficient to maintain an acceptable level of voltage within the power system(Xu, 2012). One reasonable method of overcoming this challenge is, therefore, to divide the power grid into smaller portions by opening strategic tie-lines. The resultant portion of the divided power grid is referred to as "Island". The formation of these islands amidst severe disturbance is carried out in such a way that each resulting island maintains continuous operation by its own set of loads which are energized by a group of generators running at approximately the same speed. These groups of generators are called 'coherent generators' in the system (Sun et al., 2003). Two machines are said to be coherent when some similarity can be established between their dynamic states with rotor angles being the most commonly used state variable. This is because instability in rotor angle translates to instability of all other variables of the power system (Rogers, 2000). The rotor angle is usually estimated by solving the swing equation numerically using Runge-Kutta method (Padhi and Mishra, 2015), which describes the interdependence of a machines input mechanical energy and the position of a machines rotor angle with respect to the synchronous rotating reference frame.

$$M\frac{d^2\delta}{dt^2} = P_m - P_e \quad (1)$$

where M represents the inertia coefficient, δ is the rotor angle, P_m is the mechanical power and P_e is the electrical power.

The study carried out by researchers shows that the aim of coherency analysis is to group machines having similar swings when instability is prevalent in a power grid. This similar swing can easily be assessed using similarity of rotor angles between two machines. For example, based on the Euclidean distance measure, the similarity of rotor angle deviation between two buses i and j can be expressed as

$$MC_{ij[t_k,t_k+\Delta t_k]} = \sum_{m=1}^{N}\sqrt{\left[\left(\delta(t)_m^i - \delta(t)_1^i\right) - \left(\delta(t)_m^j - \delta(t)_1^j\right)\right]^2} \quad (2)$$

where the MC_{ij} is defined as the measure of deviation in rotor angle similarity for machines i and j collected between time interval $t_k, t_k + \Delta t$ after a system disturbance. In Equation (2), δ_m^i and δ_m^j represent the rotor angles of generators i and j associated with the sampling point m, δ_1^i and δ_1^j are the generator rotor angles associated with buses i and j at sampling point $m = 1$ and N is the total sampling points under consideration. Thus, the more δ^i and δ^j have dissimilarities, the more MC_{ij} tends to zero. In a similar manner, the measure of deviation in the rotor speed similarity between machines i and j can easily be expressed as

$$SR_{ij[t_k,t_k+\Delta t_k]} = \sum_{m=1}^{N}\sqrt{\left[\left(SR(t)_m^i - SR(t)_1^i\right) - \left(SR(t)_m^j - SR(t)_1^j\right)\right]^2} \quad (3)$$

Thus, in general, for a typical n-machine power system, according to Equation (2), the coherency matrix, whose entries represent the measure of similarity for all possible combinations of two machine rotor angles and rotor speed, can be expressed compactly by Equations(4) and (5) respectively as

$$MC = \begin{bmatrix} MC_{11} & MC_{12} & MC_{13} & \cdots & MC_{1N} \\ MC_{21} & MC_{22} & MC_{23} & \cdots & MC_{2N} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ MC_{(N-1)1} & MC_{(N-1)2} & MC_{(N-1)3} & \cdots & MC_{(N-1)N} \\ MC_{N1} & MC_{N2} & MC_{N3} & \cdots & MC_{NN} \end{bmatrix} \quad (4)$$

$$SR = \begin{bmatrix} SR_{11} & SR_{12} & SR_{13} & \cdots & SR_{1N} \\ SR_{21} & SR_{22} & SR_{23} & \cdots & SR_{2N} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ SR_{(N-1)1} & SR_{(N-1)2} & SR_{(N-1)3} & \cdots & SR_{(N-1)N} \\ SR_{N1} & SR_{N2} & SR_{N3} & \cdots & SR_{NN} \end{bmatrix} \quad (5)$$

Generally, the elements of the coherency matrix MC can be easily normalized such that their values are found between 0 and 1. These normalized values are obtained using

$$V_{ij,factor} = \frac{max(MC_{ij}) - (MC_{ij})}{max(MC_{ij}) - min(MC_{ij})} \quad (6)$$

where MC_{ij} is the element of network generator coherency matrix formulated in Equation (4), $max(MC_{ij})$ represents the maximum value of the MC_{ij} elements and $min(MC_{ij})$ indicates the minimum value of the elements of $[MC_{ij}]$. Consequently, the factorized coherency matrix can, therefore, be formulated as

$$V_{factor} = \begin{bmatrix} V_{11factor} & V_{12factor} & V_{13factor} & \cdots & V_{1Nfactor} \\ V_{21factor} & V_{22factor} & V_{23factor} & \cdots & V_{2Nfactor} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ V_{(N-1)1factor} & V_{(N-1)2factor} & V_{(N-1)3factor} & \cdots & V_{(N-1)Nfactor} \\ V_{N1factor} & V_{N2factor} & V_{N3factor} & \cdots & V_{NNfactor} \end{bmatrix} \quad (7)$$

However, the Euclidean distance measure for two time-series data having exactly the same values is zero and thus, the diagonal entries of matrix $[V_{ij,factor}]$ can be set to zero as

$$V_{factor} = \begin{bmatrix} 0 & V_{12factor} & V_{13factor} & \cdots & V_{1Nfactor} \\ V_{21factor} & 0 & V_{23factor} & \cdots & V_{2Nfactor} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ V_{(N-1)1factor} & V_{(N-1)2factor} & V_{(N-1)3factor} & \cdots & V_{(N-1)Nfactor} \\ V_{N1factor} & V_{N2factor} & V_{N3factor} & \cdots & 0 \end{bmatrix} \quad (8)$$

Thus, for a 4-machine power grid, as an example, the factorized bus coherency matrix is expressed as

$$V_{factor} = \begin{bmatrix} 0 & V_{12factor} & V_{13factor} & V_{14factor} \\ V_{21factor} & 0 & V_{23factor} & V_{24factor} \\ V_{31factor} & V_{32factor} & 0 & V_{34factor} \\ V_{41factor} & V_{42factor} & V_{43factor} & 0 \end{bmatrix} \quad (9)$$

The geometric mean of all distinct non-zero entries of the factorized bus coherency matrix can be defined as

$$\varepsilon = \sqrt[k]{\prod_{i=1}(Q_i)} \quad (10)$$

where k represents the number of all distinct non-zero entries of the factorized coherency matrix given inEquation (9) and Q_i represents the i^{th} distinct non-zero entries of the factorized coherency matrix.

The factorized bus coherency matrix is symmetrical about its main diagonal and as such only the elements above or below the main diagonal elements of the matrix are required for the computation of the geometric mean. It worth stating that the factorized bus coherency matrix formulated in Equation (9) is symmetrical about the main diagonal. Consequently, only the elements above the main diagonal elements are stored in the computer memory which eventually leads to a significant saving in computer memory and reduces the time complexity associated with the computations. For example, the geometric mean of the distinct non-zero entries of the factorized bus coherency matrix, for a simple 4-bus system, given in Equation (9) is estimated from

$$\varepsilon = \sqrt[6]{V_{12factor}V_{13factor}V_{14factor}V_{23factor}V_{24factor}V_{34factor}} \quad (11)$$

Thus, coherency between any two machines $i\&j$ over time interval $[t_k, t_k + \Delta t]$is established if

$$V_{factor} < \varepsilon \quad (12)$$

After coherency analysis is completed, searches for the feasibility of forming islands with the identified coherent groups begin. This is because a coherent machine may be separated from its coherent counterpart due to its location on the grid (topology constraint) hence such machines are to be place in its own coherent group. The consequence of this new coherent group is an additional island. The author of reference (Chow and Sanchez-Gasca, 2019) shows that the solutions to the islanding increases as the complexity of the power system also increase. The authors highlighted that island can be formed by taking into account the power imbalance in the proposed islands such that load shedding is as minimal as possible. Thus, in this paper, islands are formed based on power-balance and topology constraints such that load shedding is completely avoided in the suggested islands. Tie-lines to be opened for islanding are selected such that the anticipated generation by coherent groups are enough to cater for the loads allocated to the proposed island Following coherency analysis between time interval $[t_k, t_k + \Delta t]$, islanding is therefore implemented at time $(t_k + \Delta t)$.

3. CASE STUDIES

In order to demonstrate the effectiveness of the proposed methodology in this paper, Nigerian 28-bus system and IEEE 30-bus network are used. A brief description of each network is presented in this section while the results obtained are presented in the section that follows.

The Nigerian 330-kV network, operating at 50Hz, is used as a case study for testing the effectiveness of the approach suggested in this paper. The one-line diagram for the network under consideration is shown in Fig. 1. It consists of seven number of generators. The machines are set to trip on over frequency or under frequency in accordance to the frequency limits chosen in the Nigerian grid code under reference(Nigerian Electricity Regulatory Commission (NERC), 2010) which states that it is considered expedient to disconnect machines which have violated upper speed limit of 51.75Hz and 47.5Hz under extreme fault conditions.

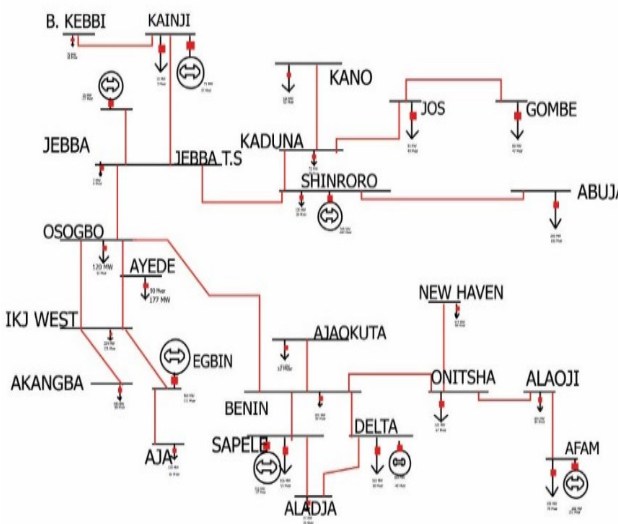

Fig. 1. Single line diagram of Nigerian 330-kV Network from reference (Ayodele et al., 2015)

The standard IEEE 30-bus network used as the second test case in this paper is adapted from (Dabbagchi and Christie, 1993) as shown in the appendix. It consists of 6 generators, 24 load points and 41 transmission lines.

4. RESULTS AND DISCUSSION

4.1Numerical Illustration with the Nigerian 28-bus Network

The simulation results obtained using 330-kV Nigerian grid system, considering various contingency scenarios are presented in the subsections that follows. Recently, a novel approach of Coupling Strength Index method, which is mainly dependent on the structural interconnectivity of various network elements, is proposed by Alayande et al. (2020). The approach is completely non-iterative and has the capability of detecting swiftly the critical transmission lines whose outage could cause total blackout within the network. This coupling strength approach is explored in this paper to quickly identify the most critical line within the network under consideration. Based on the strength of coupling of the network transmission lines, B.Kebbi-Kainji line is identified as the most critical line and its influence in determining the sets of coherent groups of generator within the system is investigated. Under this scenario, the number of coherent groups of the network generator when the system is subjected to severe disturbance conditions based on the identified critical lines are determined. The predicted coherent groups of generators are then explored to identify the number of islands formed within the system. The simulation results obtained using 330-kV Nigerian grid system, considering various contingency scenarios are presented in the subsections that follows.

4.1.1 Contingency Analysis

Under this scenario, a three-phase fault is simulated on the B.Kebbi-Kainji line at 5s and cleared at 7s and the influence of this contingency situation is shown in Fig. 2. Based on the simulation results, Shinroro machine was the first to trip on over frequency at 12.704s, which eventually led to other machines tripping on under frequency (47.5Hz) at 16.767s. This tripping is mainly due to the observed frequency limits violation of the machines as well as the deviations in speed, which consequently leads to frequency instability within the system.

The rotor angles for the first scenario, under consideration, is presented in Fig. 3. It can be seen that thereis a significant increase in rotor angle disturbance with time and thus rotor angle instability is experienced. This further increases the overall systems disturbance in all of the system variables and consequently a total voltage collapse result. This scenario, therefore, is suitable to test the effectiveness of the suggested coherency detection and islanding scheme in preventing a total system collapse as well as preventing the propagation of power system disturbances.

Following the simulation of fault at 5s and clearing of fault by tripping of the B. Kebbi - Kainji Line at 7 s, rotor angle time series data of all the machines generated by Powerworld simulator was therefore collected between 7 to 8.5s from which the factorized coherency matrix presented in Table 1 is formulated for coherency analysis. One of the unique characteristics of the factorized coherency matrix is that it is symmetrical about the main diagonal distinct non-zero elements. As such, only the distinct non-zero elements above or below the main diagonal elements are required for the coherency analysis. The overall advantage is that the computational complexity is reduced and also the memory required for storing the elements is less which makes the application, of the matrix-based method suggested in this paper, to large power systems so attractive.

Based on the results presented in Table 1, a coherency threshold is estimated by evaluating the geometric mean of distinct non-zero entries of the factorized coherency matrix. For this scenario, a coherency threshold is estimated to be $\varepsilon = 0.4083$ which can be established from the Euclidean distance of all pair of machines' time series data. Consequently, the Euclidean pairs of all column data falling below the calculated coherency threshold are deemed as coherent pairs.

By examining the Factorized Coherency Matrix, it can be seen that Kainji (generator 1) belongs to the same coherent group with Jebba (generator 2) and AFAM (generator 6) machines because their values in the factorized coherency entries with Kainji are 0.118928 and 0.231693 respectively and can be seen to be less than the established coherency threshold of 0.4083. Based on the results presented in Table 1, the identified groups of coherent generators are presented in Table 2.

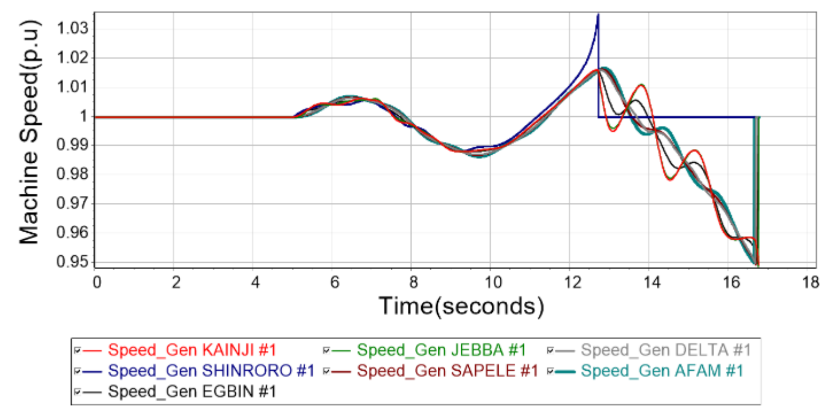

Fig. 2. System collapse induced by fault on the B.Kebbi-Kainji line

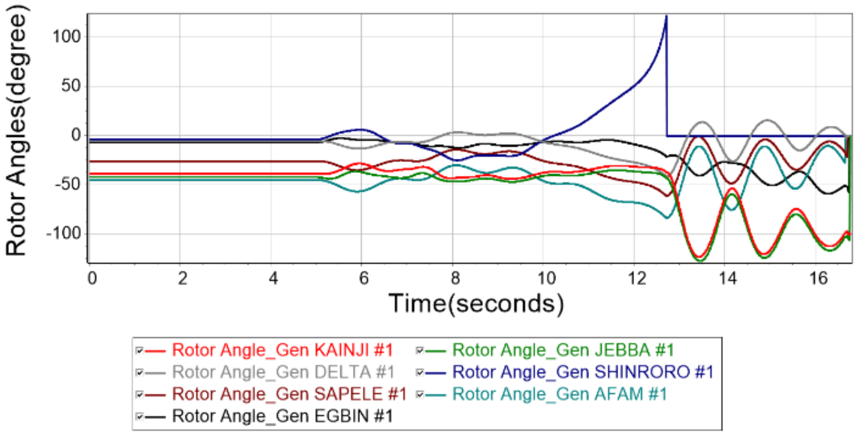

Fig. 3. Waveforms showing rotor angle instability following fault simulation for critical outage case

Table 1. The Factorized Coherency Matrix (FCM) for contingency N-1 scenario with distinct non-zero entries highlighted

	Kainji	Jebba	Delta	Shinroro	Sapele	Afam	Egbin
Kainji	0.000000	0.118928	0.881072	0.492647	0.445001	0.231693	0.662168
Jebba	0.118928	0.000000	1.000000	0.611576	0.563930	0.222988	0.781096
Delta	0.881072	1.000000	0.000000	0.388424	0.436070	0.854956	0.218904
Shinroro	0.492647	0.611576	0.388424	0.000000	0.220257	0.466532	0.169521
Sapele	0.445001	0.563930	0.436070	0.220257	0.000000	0.418886	0.217167
Afam	0.231693	0.222988	0.854956	0.466532	0.418886	0.000000	0.636052
Egbin	0.662168	0.781096	0.218904	0.169521	0.217167	0.636052	0.000000

Table 2. Coherency analysis results based on the FCM for critical outage case

Machine number	Machine name	Coherent machines combination	Calculated coherency threshold	Fault location	Time interval (s)	Simulation period (s)
1	Kainji	1, 2 and 6	0.4083	B. Kebbi – Kainji line	7.0 - 8.5	5.0 – 7.0
2	Jebba	1, 2 and 6				
3	Delta	3, 4 and 7				
4	Shinroro	3, 4, 5 and 7				
5	Sapele	4, 5 and7				
6	Afam	1, 2 and 6				
7	Egbin	3, 4, 5 and 7				

Constructed on the Coherency Analysis results presented in Table 2, the coherent machines combination column shows the machines having at least one machine number in common. From these results, it can be seen that two coherent groups can easily be identified when a faults occurs on the line connecting B.Kebbi bus and Kainji bus. Group 1 consists of Kainji, Jebba and Afam machines with the associated machine numbers 1, 2 and 6 respectively. Coherent group 2 comprises of Delta, Shiroro, Sapele and Egbin machines whose associated machine numbers are 3, 4, 5 and 7.

Fig. 4 shows the identification of island within the system under consideration with a special interest on scenario 1. The balance between the power generation and load demand within the encircled regions is kept constant.The tie-lines required to be opened for the formation of islands are identified by a red asterisk as shown in Fig. 4. Although Kainji, Jebba and Afam belong to the same coherent group as predicted by the coherency analysis scheme, it can be seen in Fig. 4 that Afam is separated from its coherent group by the machines in the identified coherent group 2 (Delta, Shiroro, Sapele &Egbin).

Based on the results presented in Fig. 4, the Shiroro machine has no tie-line connecting it to its identified counterparts, which implies that the Shiroromachine is placed in its own island. The boundaries drawn around the coherent groups contain load buses that meet the power-balance constraints. Therefore, the load demands are allocated to the islands based on their proximity to the machines as well as the power-balance constraint. Consequently, this reveals that the tie-lines to be opened for island formation are Jebba T.S - Osogbo line, Jebba - T.S-Shiroro line &Alaoji - Afam line as shown in Fig. 5. The groups of islands formed are therefore identified to be group1 with its associated generators to comprises Kanji &Jebba, group 2 which consists of only Afam generator bus, group 3 with only Shiroro generator bus and group 4 with Delta, Sapele &Egbin generator buses as shown in Fig. 5

and Table 3. The implication of this result is that the number of identified coherent generators is not always the same as that of the number of the island formed within the system under consideration. This notion could be misleading most especially when dealing with large practical power systems and therefore should be totally ignored.

The implementation of islanding scheme by opening of the identified tie-lines, Jebba T.S - Osogbo line, Jebba T.S-Shiroro line &Alaoji - Afam line at 8.5s of the island simulation ultimately produced four islands as seen in Fig. 5.

This is because 8.5s is ending time of the collected rotor time series data. This clearly revealed the effectiveness of the coherency and islanding schemes, suggested in this study, in minimizing disturbances that could lead to total collapse of the network in the power system variables. The generation-to-load matching problem implemented for the identified islands are presented in Table 3. The waveforms for the rotor angles of the four identified island groups are shown in Fig. 6. It can be seen that the four distinct plots shown also agree with that of the proposed coherency and islanding detection schemes.

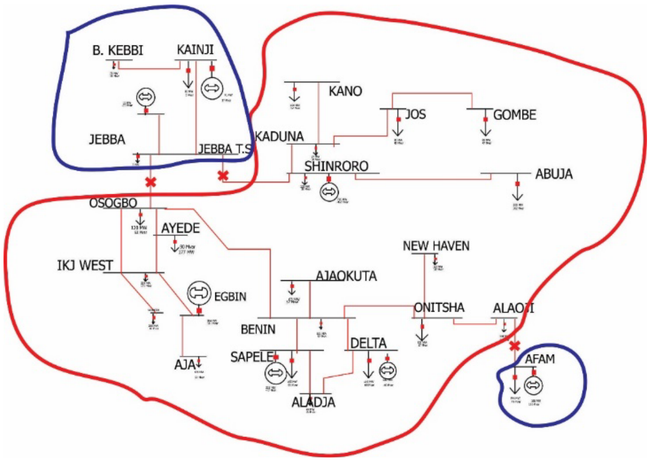

Fig. 4. Detection of Island formation within Nigerian grid considering critical line outage

Table 3. Generation-to-load matching implemented for the identified islands considering critical outage

Identified number of islands	Identified coherent generators within identified islands	Total power generation prior to system disturbance (MW)	Load buses allocated to the identified island (MW)	Total demand (MW)
1	Kainji&Jebba	85.9400	Kainji, JebbaT.S	17.44
2	Afam	166.07	Afam	155
3	Shinroro	765.4	Kaduna, Kano, Gombe, Jos, Abuja, Shinroro	740
4	Delta, Sapele &Egbin.	1872.41	Ikeja West, Akangba, Ayede, Benin, Onitsha, Osogbo, Aja, New Haven, Delta, Sapele, Ajaokuta, Aladja, Alaoji	1843.88

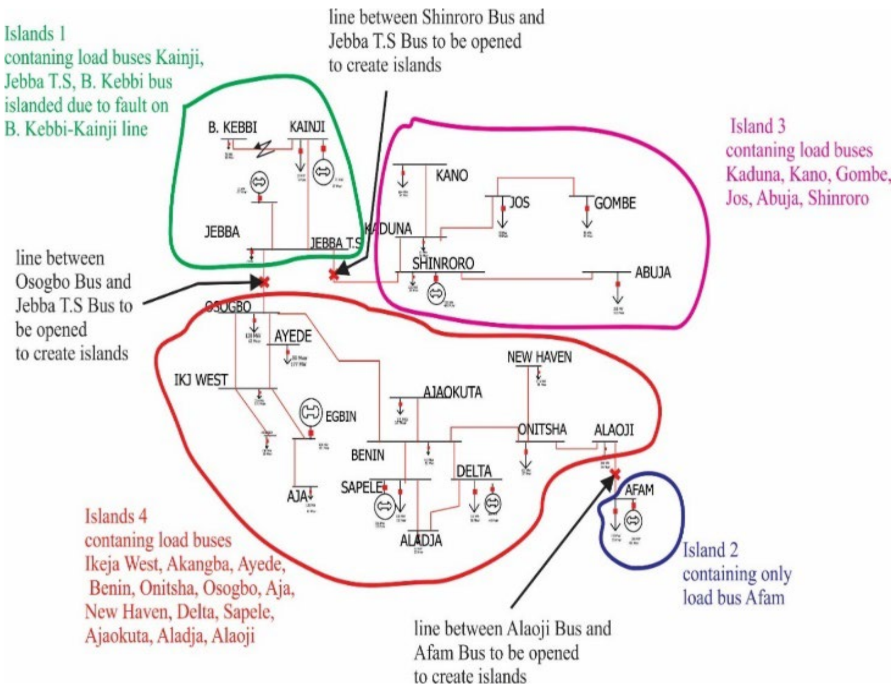

Fig. 5. Final Islanding solution for Nigerian grid network considering critical outage scenario

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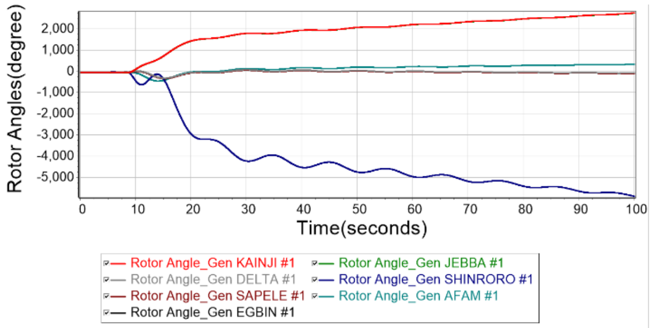

Fig. 6. Machine rotor angles after implementing islanding scheme for critical outage scenario

After the implementation of the overall coherency analysis and islanding scheme, it is observed that none of the machines violates frequency limits as all the rotor angles are well stabilized and the generator speeds are, therefore, able to stabilize over time as shown in Fig. 7. It can be seen that all the generators are in synchronism. In other words, none of the generators is out of phase from each other and hence, generation-to-load matching is achieved and voltage collapse is completely eliminated.

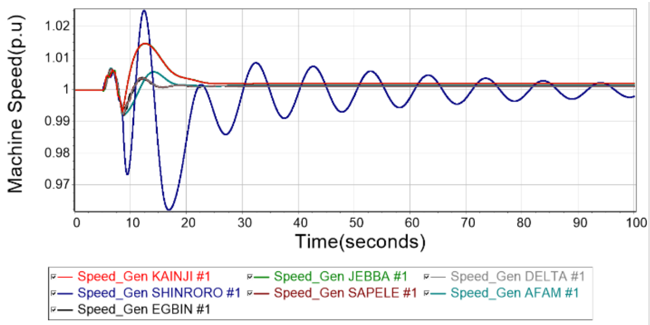

Fig. 7. Machine speeds after implementing the islanding scheme for critical outage

4.2 Numerical Results with the Standard IEEE 30-bus Network

As explained in the previous numerical illustration, the critical transmission line is first identified using the CSI approach. Based on the CSI results using the standard IEEE 30-bus system, the line connecting the generator and load bus located at buses 5 and 7 (Fieldale-Blaine) respectively is identified as the most critical transmission line within the system. This line is subjected to a three-phase fault for 15-18 s with the line tripped at both ends for the post-fault contingency conditions. In these situations, the presence of electromechanical oscillations is seen on the machine speed plots as shown in Fig. 8.

It can be observed that there is a decline in machine speed for the Fieldale machine when compared with the other machines on the grid. The effect of these severe disturbances on the bus voltages, which resulted to a poor quality of bus voltages within the standard IEEE 30-bus system can be seen in Fig. 9.

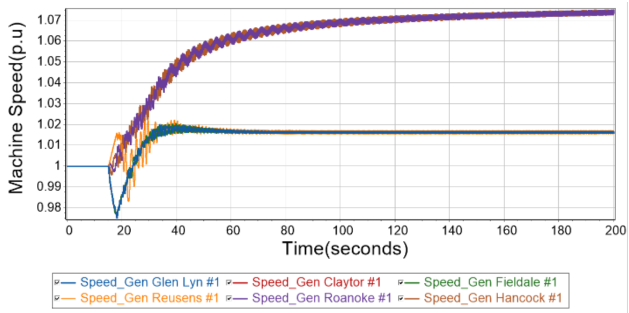

Fig. 8. Effect of critical line outage on machine speeds in the IEEE 30-bus system

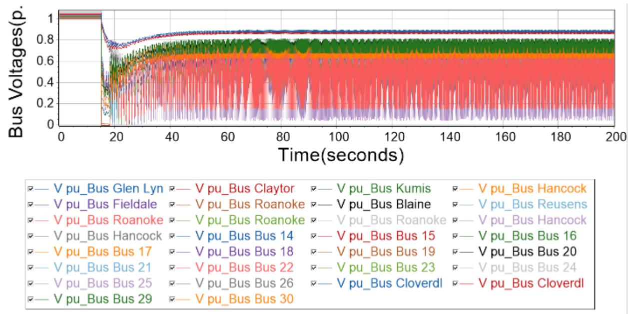

Fig. 9. Poor voltage quality due to critical line outage in the IEEE 30-bus

The deviation experienced by the rotor angles of the machines is shown in Fig. 10. It can be observed that the system is severely disturbed and loss of synchronism has occurred thus making the grid ready for coherency and islanding implementations.

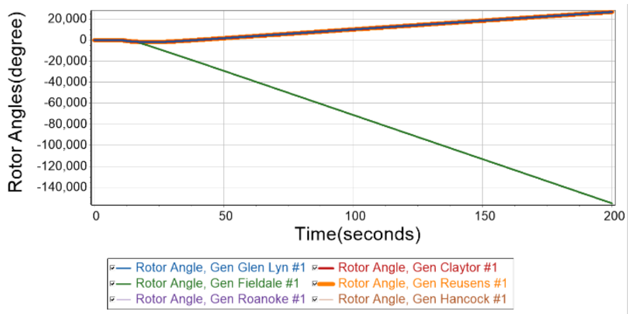

Fig. 10. Loss of synchronism by Fieldale machine during critical outage

The time series data of all the machines generated is collected between 30.5-30.8 s for coherency analysis which produced the FCM as presented in Table 4.

A coherency threshold is therefore computed based on the geometric mean of distinct non-zero entries of the factorized coherency matrix. The estimated coherency threshold found to be 0.094719 from the Euclidean distance of all pair of machines' time series data. The Euclidean pairs of all column data falling below the calculated coherency threshold of 0.094719 are deemed as coherent pairs. As such, 3 coherent groups (Group 1: Roanoke, Hancock;

Group 2: Glen Lyn, Claytor, Fiedale and Group 3: Reusens) are produced based on the results presented in Table 5.

For the real power generation-to-load matching constraint to be satisfied such that the MW generation is kept within each encircled region with load buses allocated to the islands based on their proximity to the machines, some transmission lines need to be opened for the formation of islands solution proposed in Fig. 11, The three identified islands formed within the IEEE 30-bus system are, therefore, presented in Table 6.

It can be seen in the Table abovethat the load exceeds the generation for the Island 1 hence the Load buses 21 and 30 opened at 17.5MW and 10.6MWto reduce the total load in the island 1 to 86.6 MW thus improving the generation-load constraint in island 1.

Table 4. The FCM for contingency N-1 scenario with distinct non-zero entries highlighted

	1-Glen Lyn	2-Claytor	3-Fieldale	4-Reusens	5-Roanoke	6-Hancock
1-Glen Lyn	0.000000	0.000382	0.000804	0.172080	0.999200	0.999160
2-Claytor	0.000382	0.000000	0.000422	0.172470	0.999580	0.999540
3-Fieldale	0.000804	0.000422	0.000000	0.172890	1.000000	0.999960
4-Reusens	0.172080	0.172470	0.172890	0.000000	0.827110	0.827080
5-Roanoke	0.999200	0.999580	1.000000	0.827110	0.000000	0.000976
6-Hancock	0.999160	0.999540	0.999960	0.827080	0.000976	0.000000

Table 5. Coherency analysis results based on the FCM for critical outage case

Machine number	Machine name	Coherent machines combination	Calculated coherency threshold	Fault period	Time interval (s)
1	Glen Lyn	1, 2 and 3	0.094719	15-18 s on Fieldale-Blaine line	30.5-30.8
2	Claytor	1, 2 and 3			
3	Fieldale	1, 2 and 3			
4	Reusens	4			
5	Roanoke	5 and 6			
6	Hancock	5 and 6			

Table 6. Generation-to-load matching for the identified islands considering critical outage

Identified number of islands	Identified coherent generators within identified islands	Total power generation prior to system disturbance (MW)	Load buses allocated to the identified island (MW)	Total demand (MW)
1	Roanoke, Hancock	46.1	Kumis, Roanoke, Hancock, Cloverdl, Buses 14-26, Buses 29 and 30	114.7
2	Glen Lyn, Claytor, Fiedale	221.89	Glen Lyn, Claytor, Fiedale, Blaine	138.5
3	Reusens	30	Reusens	21.5

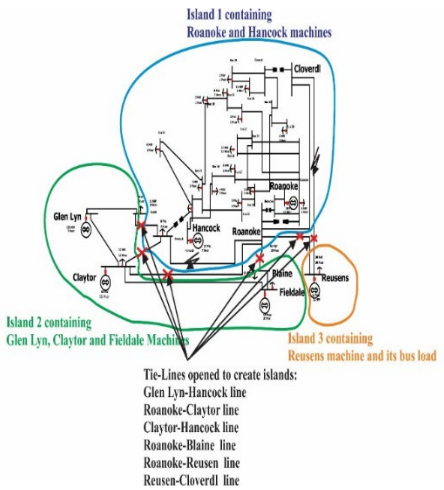

Fig. 11. Proposed islanding scheme for the IEEE 30-bus system

With the implementation of the coherency and islanding scheme at 45s, it can be seen from the plot in Fig. 12 that there is a significant and continuous reduction in electromechanical oscillations of the machine speeds

Also, the rising speed of the Roanoke and Hancock machines can be seen to hold a steady state along with other machines on the network, which suggests a substantial improvement in the frequency stability of all the machines in their respective islands.

The quality of the bus voltages on the network can also be seen to hold a steady state with decreasing oscillation following the implementation of the coherency and islanding scheme as shown in Fig. 13. This evidently shows that some form of voltage stability is experienced on all the buses in the respective islands.

Furthermore, the three groups of rotor angles based on the identified groups of generator coherency and by extension an indication of the islands formed shown in Fig. 14 clearly indicate absence of oscillations in the rotor angles. It can, therefore, be established that rotor angle stability is maintained following the implementation of the coherency and islanding scheme.

4.3 Comparison of Approaches

This section presents the main differences between the solution provided by the existing methods and the solution provided by the approach suggested in this paper.The results of the study presented by El-Arini and Fathy (2011) are compared with the results obtained in this study. Although, the results obtained using the method proposed by El-Arini and Fathy (2011) also employed the use of Euclidean distance measures as that presented in this study, the Euclidean distance measures are used in (El-Arini and Fathy, 2011) to create initial membership matrix for the Fuzzy C-Means Clustering Algorithm while they are used in this study to determine the coherency threshold between all possible generator pairs. Other notable differences are presented in Table 7.

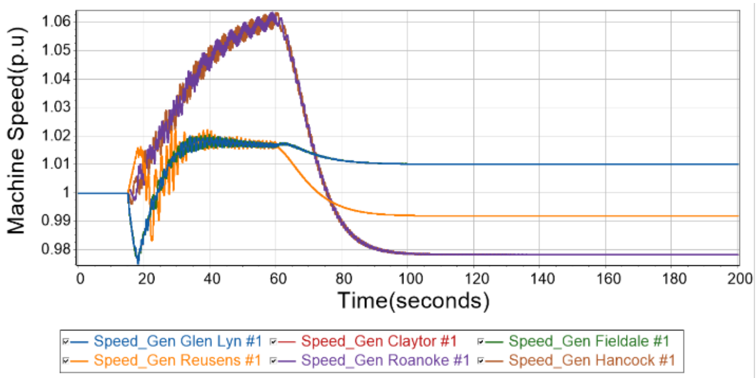

Fig. 12. Machine speeds after the implementation of the islanding scheme for critical outage in the IEEE 30-bus system

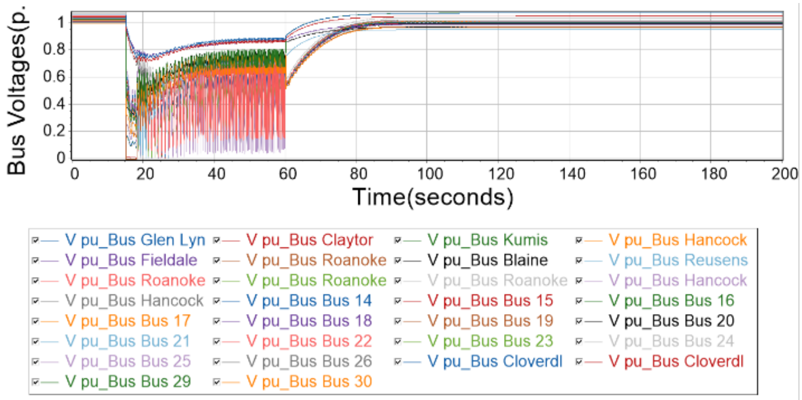

Fig. 13. Waveforms showing the improvement in bus voltages after implementing coherency and islanding scheme

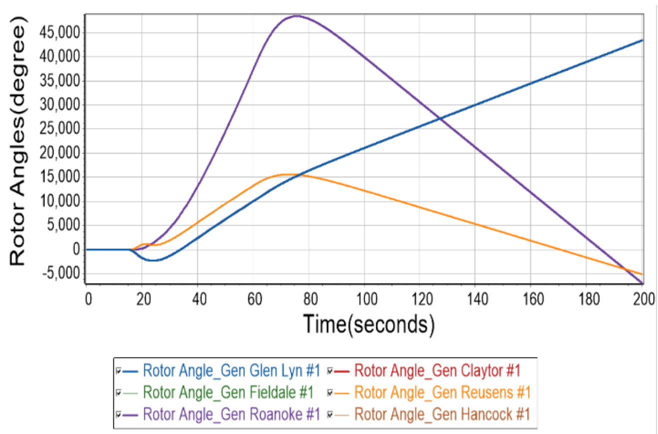

Fig. 14. Rotor angles following the implementation of coherency and islanding scheme for the IEEE 30-bus system

Table 7. Comparism with the existing solution method in reference

Fuzzy C-Means Clustering Algorithm (El-Arini and Fathy, 2011)	Proposed method
Requires the number of coherent groups to be specified prior to coherency analysis	Does not require the number of coherent group to be specified but strictly relies on the rotor angle time series data and topology of the network
The critical line subjected to a three-phase fault is assumed	The most critical line whose outage could cause total blackout in the network is identified through the use of a non-iterative based CSI framework
Does not consider the effect of the contigency on the bus voltages	Considers the influnce of the critical outage on the network bus voltage profile
It is computationally complicated in terms of time and memory space for data storage	The solution is provided within one computational time since iteration is not involved and the sparsity of the network is considered
Coherency analysis is based on an iterative process	The coherency analysis is purely non-iterative in nature

5. CONCLUSION

An easy-to-implement framework, based on the network structural interconnections, for generator coherency analysis in preventing a total power system collapse has been presented in this paper. A coherency threshold is first formulated from the rotor angle after which the scheme is implemented to establish an independent coherent group of machines. The effectiveness of the coherency analysis threshold is improved by considering topology constraints after which islanding based on generation-load constraint is implemented using the results of the coherency analysis scheme. The main contribution offered by the approach suggested in this paper is that the scheme does not require an initial estimate for obtaining the solution coherent groups. Also, the use of iterative-based algorithm is avoided in identifying the critical transmission line whose when outage could make the system to be prone to voltage collapse. The scheme is simple and thus poses less computational burdens. The simulations were carried out in Powerworld whereas the computations for coherency were carried out in MATLAB. The simplicity associated with the approach makes it suitable for providing an effective solution to coherency-based problems as well as island formation analysis in a more complex interconnected power system.

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Appendix

Single-line diagram of the standard IEEE 30-bus system (Dabbagchi and Christie, 1993)