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Evaluation of Interconnected Power Systems Controlled Islanding

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Abstract—**Controlled separation of power systems is the last defense line against wide–area blackout. As a special protection scheme, the methodology of system splitting is a comprehensive decision making problem. This paper introduces a novel approach for separation of the integrated power systems into several stable islands. The proposed method combines both the dynamic and static characteristics of interconnected power networks and determines the proper splitting schemes. The presented algorithm searches for proper islanding strategies using the Krylov projection method and a new optimization algorithm to find the proper splitting points such that the total load shedding is minimized. The method reduces the huge initial search space of islanding strategies considering dynamic characteristics of integrated power systems. The method limits search space to only the boundary networks of coherent machines. A spanning tree based breadth first search algorithm is used to find all possible combination of stable islands. The speed of the proposed algorithm is remarkably high and it can be used for real-time splitting of the power systems. The algorithm is applied to IEEE118 bus test system. Results show the effectiveness and capability of the method to determine the fast and accurate proper islanding strategies. The stability of the islands is verified by time domain simulation.**

Index Terms— **Krylov Projection Method, Coherency, Controlled Islanding, Breadth First Search (BFS), Spanning Tree (ST), Boundary Network**

I. INTRODUCTION

POWER system splitting provides the final remedial action against power system major incidence following a severe disturbance. If there is no proper remedial action in time, it may lead to a catastrophic failure and power system blackout [1]. According to the literature, Controlled system islanding is to determine the proper splitting points for separating of the entire power networks into smaller islands when preservation of integrity of power network is inevitable [1]-[3]. If a system is encountered with severe instability problem and emergency control fails to bring the faulted system back to the normal state, an islanding strategy is executed and splits the interconnected power network into several islands by disconnecting the selected transmission lines. To achieve for the proper islanding strategies which satisfy all the steady-state and dynamic constraints within the islands is a complicated scenario. Major effort is needed to determine a splitting scheme with two following important characteristics: the speed and the proper action of separation scenario. The first one is necessary because of the inherent real-time application of islanding strategies and the second is needed to guarantee the stable operation of islands [4]. Although during last decade there were remarkable efforts on controlled islanding of power system, but yet there are some unsolved problems in the area of the system separation. Transient stability, frequency stability within the islands and development of real-time algorithm for proper splitting which includes both static and dynamic constraints of islands, need for depth studies [5].

II. POWER SYSTEM CONTROLLED ISLANDING IN THE LITERATURE

In the articles there are mainly two islanding methodology: Slow coherency theory is a driven force behind the first method. The main advantage of islanding based on slow-coherency and generator grouping techniques is that they consider the dynamic characteristics of power systems. Generators can be grouped according to the dynamic behavior of each generator due to specific disturbance [1], [6] and [7] as well as the nonlinear interaction among them [8].

Slow coherency theory has the following remarkable features [1]:

The coherent groups of generators are almost independent of the size of the disturbance and the coherent groups are independent of the level of detail used in machines modeling.

The first feature provides a theoretical background for islanding approach independent of disturbance, which makes it possible to design a controlled islanding scheme prior to the disturbance. The second feature states that classical generator model can be used in grouping analysis, which may save the computation effort dramatically.

In [1] and [7], slow coherency theory is used to group generators. The interarea oscillations modes are used to identify the coherent machines in a large interconnected power system. In multi-machine power systems, after a disturbance, some generators have the tendency to swing together [8]. Slow coherency theoretically determines the weakest connections in a power system. The slow coherency method also preserves the features of the coherency-based groupings [1]. In some complicated scenarios, it is convenient to consider the nonlinear interactions of interarea modes and their effects on multi-machine clustering. Normal form algorithm is applied to determine the natural groupings which

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are formed by the machines in the power system due to nonlinear interactions [9]. The drawback of this method is that it is time-consuming because of the evaluation of higher order states of the system and its iterative nature. Although the slow–coherency theory provides a good primary feature for power systems islanding, however, the splitting of the integrated power network into several islands may not yet satisfy both the static and dynamic constraints of the islands.

The second important islanding methodology is based on the graph theory. The algorithms based on this method rise from the fact that the interconnected power systems can be represented as a graph. These methods search for possible lines that can be removed from the network to form islands with balanced load-generation. In power systems the number of lines increases with the size of the network and the search space also increases considerably. In [2]-[3] and [10]-[11] an interesting method based on OBDD (ordered binary decision diagram) representation applied as a three-phase method to online search for splitting strategies for large-scale power systems. The splitting strategies introduced in [2]-[3] try to simplify the graph representation of network and divide the problem of huge search space into smaller and aggregated sub-networks. This approach satisfies some kinds of constraints that are called "proper splitting strategies". In addition, the following outstanding remarks are appeared in literature for islanding process based on generator clustering and graph theory.

In [1] authors directly focused on islanding cutsets, or grouping the load buses to corresponding generator area in order to find islanding cutsets using graph theory. Once the generator grouping is determined, an automatic islanding program determines the cutsets to form the appropriate islands. [1] In [4], based on generator grouping, the problem of islanding is converted into searching the minimal cutsets to construct the islands with the minimal net flow. The weak point of recent islanding algorithms based on graph theory is that the methods can only consider static constraints of the network; furthermore a huge search space which is time consuming is required. The reduction of generation-load imbalance in each island reduces the amount of under-frequency load shedding after islanding. It also makes it easier for the islands to be capable of matching the generation and loads within the prescribed frequency limit [12] – [13].

In the literature, generator coherency has been typically obtained at a specific operating point. In [14] a new approach is presented using the continuation method to trace the loci of the coherency indices of the slow modes in the system with respect to variation in system conditions. With their efforts the updated coherency information between generators can be obtained. Reference [15] proposes a new system splitting scheme based on the identification of controlling group. Compared with the conventional coherent splitting scheme, this method is much more effective under complicated oscillation scenarios. The controlling group not only provides sufficient information for the splitting surface determination, but also can be used to combine the system splitting with other emergency control methods. In [16] an approach which illustrates wide-area generators speed measurement combined with Fourier analysis is proposed. This method can be used to determine coherent generator groups and is suited for applications based on communication and GPS technology. Furthermore the method is exclusively based on the generators speed variation which is straightforward and has a well established accessibility at the generators shaft.

Reference [17] describes the use of Krylov subspace methods in the model reduction of power systems. Additionally, a connection between the Krylov subspace model order reduction and coherency in power systems is proposed, aiming at retaining some physical relationship between the reduced and the original system. In [18] authors develop a combined graph-theoretic-algebraic approach to detect island formation in power networks under multiple line outages. The proposed approach detects the island formation and identifies the subset of outaged lines that is the causal factor. The objective of [19] is to develop an adaptive controlled islanding as a component of emergency power system control strategies. System separation includes two primary aspects: where to island? and when to island? Paper [19] seeks to address the "when to island" aspect which assisted by a decision tree (DT) approach. The design of an intentional controlled islanding strategy must be inherently predictive in nature, as well as reliable. In [20] an algorithm is presented that monitors the synchronous stability of the system at a global level using the Prony method. This algorithm is used to detect local out-of-step conditions in order to decide when controlled islanding should be initiated. The boundaries of the islands are derived from the groups of slow coherent generators.

This paper presents an algorithm based on combination of both static and dynamic characteristics of the interconnected power systems to determine the proper islanding strategies. The proposed method combines the characteristics of the dynamic structure of power systems and load-generation balance within the islands. The new splitting algorithm based on Krylov subspace method is used to calculate the interarea modes of the system as well as to cluster the network machines and buses in different coherent groups as primary islanding strategy. In the second step of the splitting strategy a novel approach with minimum spanning tree based breadth first search algorithm is proposed to balance and minimize the net flow between the islands tie lines. The proposed approach can find the proper splitting strategies very fast and accurate. The algorithm can overcome to huge search space of the islanding schemes and it can be implemented for real-time separation of interconnected power systems.

III. KRYLOV PROJECTION METHOD AND ITS APPLICATION IN SELECTIVE MODAL ANALYSIS

In this section the mathematical description of Krylov projection method and its connection between slow modes selection is presented.

There are many approaches to calculate a set of selective modes of the system in a dynamic system [21]-[22]. A coherency-based grouping approach requires the states to be coherent with respect to a selected set of modes σ of the system. This approach allows coherency to be examined in terms of the rows of an eigenvector matrix V which can be used to find coherent groups of states. In a real power system the dimension of the dynamic order of the system may be reach the order of several thousands of state variables. In some application we need to determine only a small window of the frequency scan of the system modes around prespesified frequencies.

It is well-known that the interarea modes of a power system varies from 0 – 1 Hz in frequency domain and the typical damping ratio for interarea modes is below 10%. There have been some fine recent developments on the area of large scale matrix computations. A set of classical methods known as Krylov subspace methods (Arnoldi 1951 and lanczas 1950) have been found to be suitable for sparse matrix computation. The Arnoldi method is a powerful extension of subspace iteration method and is the tool used to find the *k* eigenpairs of a matrix simultaneously [23]-[24].

A. Scalar Arnoldi method

Given an $n \times n$ matrix of A, a vector v and an integer $m \le n$, the scalar Arnoldi method computes simultaneous a set of orthonormal vectors $\{v_1, v_2, ..., v_{m+1}\}$ and an $m \times m$ Hessenberg matrix H_m such that $V_m{}^T A V_m = H_m$ with $V_m = \{v_1, v_2, ..., v_m\}$. The vectors $\{v_1, v_2, ..., v_m\}$ form an arthonormal basis of Krylov subspace as follow:

$$K_m(A, v_1) = span\{v_1, Av_1, ..., A^{m-1}v_1\} \tag{1}$$

which is the mth Krylov subspace corresponding to A and v_1, Furthermore:

$$AV_m = V_m H_m + H_{m+1,m} V_{m+1} e_m{}^T \tag{2}$$

where e_m is the last column of the $m \times m$ identity matrix. Methods which use linear combination of vectors in this space to extract spectral information are called Krylov subspace methods or projection methods [17]-[25].

The orthonormal basis yields a projection matrix and a relationship that is often referred as the Arnoldi decomposition. The eigenvalues and eigenvectors of the projection matrix are then used as an approximation to the eigenvalues and eigenvectors of A. However, in order to get an acceptable approximation to the eigenpairs, m must typically be large. This is not always possible because of storage constraints and orthogonally issues. To overcome these difficulties a Restarted Arnoldi Method (RAM) can be used. The restarted Arnoldi method maintains a modest value for $m << n$ where each restart either implicitly or explicitly modifies the starting vector v_1 for the next iteration so that a better approximation is obtained. This creates a sequence of Krylov subspaces that hopefully converge to an invariant subspace containing the desired eigenvectors.

B. Block Arnoldi method

The block Arnoldi method is the generalized of the scalar Arnoldi method. Starting with a block vector V_1 of norm unity, the block Arnoldi method constructs a set of block vectors $\{V_1, V_2, ..., V_{m+1}\}$ such that if $U_m = (V_1, V_2, ..., V_m)$, then $U_m^T U = I_{mp \times mp}$, and $U_m^T A U_m$ is an upper block Hessenberg matrix $H_m = (H_{ij})$. Furthermore $AU_m - U_m H_m = V_{m+1} H_{m+1,m} E_m^T$, where E_m is the last p columns of the $mp \times mp$ identity matrix.

The benefits of a block routine include the ability to compute multiple or clustered eigenvalues more efficiently than an unblocked routine.

The selection of the slowest modes results slow coherent groups such that the islands of the system are partitioned along the weakest boundaries. In this paper application of the block Arnoldi method for calculation of some selective eigenvalues to determine coherent states is presented.

In this approach, disturbance is modeled as initial condition. Therefore, a linear system may be modeled as:

$$\dot{X} = AX \,, \quad X(0) = 0 \tag{3}$$

where the state *x* is an *n*-vector.

According to equation (4) suppose that σ is the selected set of modes of the system:

$$\sigma = \{\lambda_1, \lambda_2, ..., \lambda_r\} \tag{4}$$

where λ_i is an eigenvalue of A associated with a dominant mode extracted by the method.

IV. KRYLOV PROJECTION BASED MODEL REDUCTION AND COHERENCY

The mechanism of the Krylov subspace model reduction dictates that the states of the unreduced system are restricted to the subspace V as deduced from equation (5)

$$X = V\overline{X} \tag{5}$$

Which $\overline{X}$ is the reduced model of X that retains the desired eigenvalues of the original system. Therefore, the rows of V may be a good indication about the relative movement of the states of the unreduced system. Note, however, equation (5) does not imply that the actual trajectories lie on subspace V, instead if the trajectories lie on this subspace, then the output of the reduced system matches the output of the unreduced system. From (5)

$$x_i - x_j = (V(i,:) - V(j,:))\overline{X} \tag{6}$$

According to reference (13), the states i and j are coherent if the difference between X_i and X_j in (6) is small. A possible criterion to determine the "closeness" of X_i and X_j is the angle θ between rows $V(i,:)$ and $V(j,:)$ defined as follow:

$$\cos\,\theta = \frac{V(j,:)V(i,:)^T}{\|V(j,:)\|_2 \, \|V(i,:)\|_2} \tag{7}$$

Therefore X_i and X_j are coherent if the angle θ is less than a pre-specified tolerance. Let Π be the angle matrix between each two i and j vectors and defined as [8]

$$\Pi(i,j)=\arccos\left(\frac{V(j,:)V(i,:)^T}{\|V(j,:)\|_2\|V(i,:)\|_2}\right) \tag{8}$$

Thus, the entries of Π determine whether or not two states are coherent. Equation (8) does not distinguish between the modes of the reduced system; it assumes that all modes may be excited. It is possible to eliminate certain high-frequency modes that are of no interest, by ignoring the states of the reduced system that have a relatively small participation on these modes. The small dimension of the reduced system allows a complete eigenvalue analysis in a robust and efficient way. Therefore, the contribution of each state to the modes of the reduced system can be identified through the use of participation factors [25]. Let U and W be the right and left eigenvectors of the reduced system corresponding to an eigenvalue λ. For complex vectors, the magnitude of each entry of U and W are considered. Then, the participation factor of state i to the eigenvalue λ is defined as (9)

$$p=\frac{u_i w_i}{U^T W} \tag{9}$$

The participation factors can be normalized so that the largest one is 1. The modes of interest are isolated (for example, the ones corresponding to the low frequencies) and the participation of each state of the reduced system on a certain mode can be computed from (9). The states that contribute the least to the modes of interest are discarded. This is equivalent to ignoring the corresponding columns of V in equation (8). Then, Π is constructed using the reduced matrix of V [17] - [25].

V. THE PROPOSED METHODOLOGY

Nowadays the real power systems are large interconnected networks, where there are plenty of opportunities for power wheeling and therefore sharing of spinning reserve and unit inertial response. This tends to result in a stiff system, where a large generation-load imbalance must occur before the frequency deviate to any significant level [26]. Unlike a large interconnected power system, frequency stability within islands seems to be more important. When a power system is separated to several smaller islands, even a little imbalance between load and generation may be cause a large frequency deviation. This can be significant from frequency stability and restoration points of view. Minimizing power imbalance between the islands can improve the frequency stability of islands. The proposed algorithm is designed such that preserves the primary dynamic based islanding feature and obtains global minimum load shedding solution.

A connected undirected acyclic graph is called a tree. Spanning Tree (ST) is a tree that is subgraph of G and contains every nodes of *G*. The spanning tree connects all nodes of a network to each other preserving the tree characteristics of the network. It can be started from one nodes of the network and expanded to all nodes to connect all the nodes preserving tree characteristics of the network [27].

The concept of the new proposed algorithm is illustrated in Fig. 2. In the figure, the primary boundaries between each coherent group of generators and buses, which are the result of primary grouping algorithm based on Krylov projection method, are presented. Suppose that area A has common boundaries with area B and C. The passive boundary network between each area with other adjacent area is called boundary network. The lines which connect each area to the others are called boundary lines, and the buses that are connected to these lines are called boundary buses. Each area is connected to the adjacent areas by the boundary lines. All load buses on the trees which originated from boundary buses and expanded to the adjacent areas, while they have no direct connection to a generator bus, are members of boundary network. For example in Fig. 1 the lines and buses which are indicated with dashed lines belong to a boundary network. It should be noticed that boundary network only includes the load buses and there is no generator bus.

The idea is that it is possible to select some buses of the adjacent areas and bring them into the other islands. This is done by directly minimizing of total load–generation imbalance within islands. For each spanning tree originated from boundary buses, all branches of spanning trees are determined and introduced as a candidate case for the adjacent area. In Fig. 1, B1, B3, B8, B11 and B15 buses are adjacent buses. For example if the algorithm determines that B11 should be transferred from area B to area C, and B8 brought to the area A, according to minimum load shedding algorithm, In this situation the lines L7, L8 instead of L1, L2 and L10, L11 instead of L4 should be tripped off respectively. For this case L1, L2 and L4 should be removed from switching lines list and L7, L8, L10 and L11 should be added to new switching lines group to form new islands.

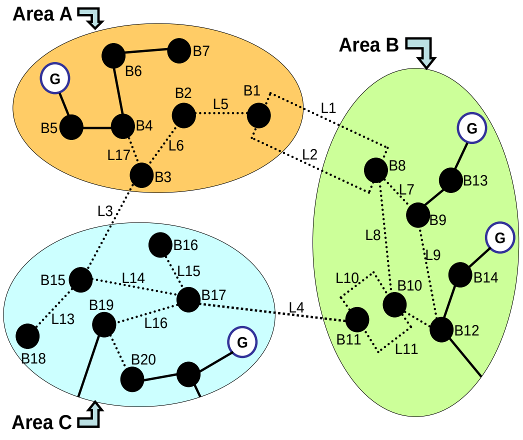

Fig. 1. Concept of the load-generation balancing algorithm

The maximum number of load buses that can be transferred into the adjacent areas called penetration bus and can be selected by the user. In other word the number of nodes in a largest branch of spanning tree among the set of spanning trees is the penetration bus. The upper limit of penetration buses depends on the network structure and number of initial islands and determines by the dimension of electrical distance matrix between each boundary bus and machine bus. This matrix is called the boundary bus electrical distance matrix (BEDM). BEDM is a matrix that determines the electrical distances between each adjacent or boundary bus and each generator in the other islands. It is evident that if the boundary of islands changes due to new algorithm, then the number of tripping lines also may be changed. The maximum acceptable number of new lines within each area that can be tripped off is called maximum cutting line and can be selected by dispatcher.

The flowchart of proposed algorithm is given in Fig. 2. The algorithm starts with one or more of boundary buses and finds all combination of possible spanning trees that are originated from the boundary buses and are expanded into the adjacent areas. In a dynamical-based islanding scenario only a few numbers of primary islands are formed, which in fact depends on the interarea oscillations modes. This implies that the number of boundary buses are little and the initial huge search space is considerably reduced to a very small space. In this case all the combination of spanning trees and their branches can be found directly by the breadth first search algorithm. Therefore, the search is localized only on the load buses associated with the boundary of the coherent groups to be islanded. A spanning tree based breadth first search algorithm is used to determine all possible combinations of buses that can be interchanged between all areas.

The expansion of penetration buses is limited to adjacent areas and it is expected that the search space for power balance is considerably reduced and a direct search can be used to specify the final configuration of islands with minimum total load shedding within islands. There is a relation between penetration bus number, maximum acceptable cutting lines within islands and amount of load shedding after system separation. In general, with the increase of the two parameters the amount of load shedding decreases dramatically and the frequency stability of the islands would be guaranteed.

The value of minimum load shedding for each scenario can be calculated directly as:

$$Min\ LS = \sum_{i=1}^{n-islands} \left| P_{G_{Island}}(i) - P_{L_{Island}}(i) \right| \qquad (10)$$

In equation (10) $P_{G_{Island}}(i)$ and $P_{L_{Island}}(i)$ are total generation and the load of i th island respectively, that are obtained from equations (11) and (12) and LS is the total load shedding of the islanded system.

$$P_{G_{Island}}(i) = \sum_{k=1}^{Island_{Gen}} \left(P_G(k) \right) \qquad (11)$$

$$P_{L_{Island}}(i) = \sum_{h=1}^{Island_{Load}} \left(P_L(h) \right) \qquad (12)$$

where $P_G(k)$ and $P_L(h)$ are the generation of the machine k and load of bus h in each island respectively.

For each splitting pattern and each island the total sum of generation and load is calculated by equations (11) and (12). The generators of each island remain in the same island, and the total generation of each island is constant and does not change with the different load shedding optimization patterns. In the contrary the loads of islands can be varied from primary load to the new load by the buses that are transferred to the other areas.

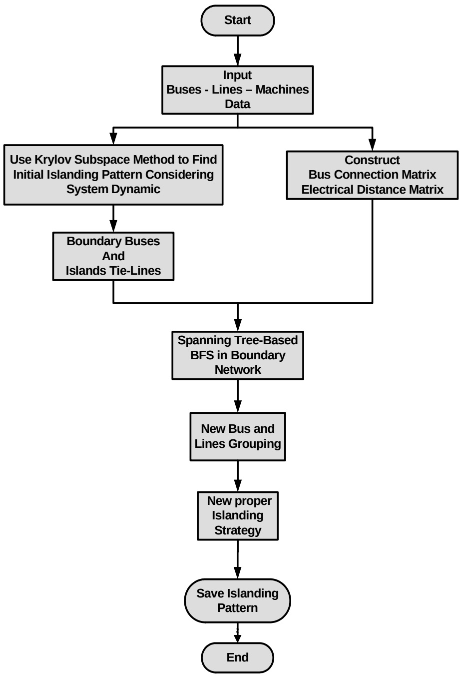

Fig. 2: Proposed islanding Strategy flowchart

VI. SIMULATION AND RESULTS

In this section the main results related to application of the algorithm on IEEE118 BUS test system are presented. The system data of the 118-bus network is given in [11]. There are 118 buses and 19 generators and 186 lines in the system. The generators data are selected according to the typical generator data [11].

Table I shows the primary grouping of test system according to Krylov projection method that splits the entire power network into three coherent group considering interarea modes. The grouping may be extended to the buses, so that buses with angles coherent with generators angles may be grouped with the generators, into system coherency partitions. It should be mentioned that the number of initial islands can be varied based on degree of coherency. Typically the ranges of interarea modes vary from 0.1 Hz to 1 Hz [28]. Furthermore if damping effects of the system elements is negligible, the coefficient of the damping for the selected modes will be zero which is the characteristics of interarea modes. For example in the IEEE 118 BUS system the slow or interarea modes of the system which are found by Arnold method are equal to ten slow modes. In Table II the interarea modes of the test system around 0.5 Hz bias frequency are indicated. From the theoretical and mathematical points of view the number of islands can be less or more than the base case. It mostly depends on the degree of coherency, operational conditions as well as system structure, switching lines availability, blackstart capability within the islands and so on. From the above discussion it is possible to split the test system to less and more islands from base case.

TABLE I
PRIMARY SEPARATION OF TEST SYSTEM INTO TWO ISLANDS

Machines	Island Buses	Splitting Points
Gen1-Gen5	B40-…-B39, B72, B113, B114, B115, B117	B68-B65, B69-B47, B69-B49, B72-B71 B70-B24 B34-B43 B37-B40 B38-B65 B39-B40
Gen6-Gen12	B40-…-B68	
Gen13-Gen19	Other	

TABLE II
INTERAREA MODES OF THE TEST SYSTEM

Mode No	Eigen Value	Frequency (Hz)	Damping
1	-0.1278+3.202i	0.507	0.0399
2	-0.1073+2.994i	0.477	0.0358
3	-0.1278+3.202i	0.602	0.0305
4	-0.1154+3.784i	0.390	0.0337
5	-0.0846+2.512i	0.648	0.0252
6	-0.1028+4.072i	0.315	0.0332
7	-0.0658+1.981i	0.788	0.0209
8	-0.0811+1.653i	0.263	0.0490
9	-0.0782+1.622i	0.258	0.0482
10	-.07843+1.421i	0.226	0.0551

By implementation of the proposed method all initially formed islands are stable and the minimum possible load shedding is obtained.

In Fig. 3 the values of load-generation imbalance with respect to maximum number of penetration bus and maximum cutting lines for the three area case is indicated. In this case the minimum load shedding is obtained when maximum penetration bus is 6 and maximum cutting line is 3 respectively. In this figure the flat surface shows the value of load shedding at base case and the lower one indicates the minimum load shedding with respect to the maximum number of penetration bus and acceptable cutting line.

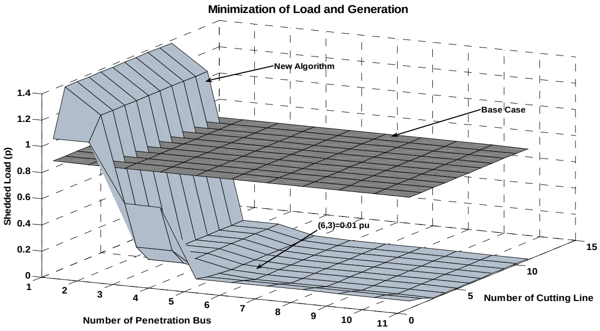

Fig. 3. Load-generation balancing for three areas

Fig. 3 shows that the value of load shedding depends on the number of transferred load buses. From Fig. 3 it can be seen that according to primary islanding strategy and without implementation of the new algorithm, 0.85 pu of the total 38.61 pu load should be shedded which is 2.2 % of total load. Application of the new algorithm decreases the amount of total load shedding to 0.01 pu which is only 0.03 % of total system load.

VII. VERIFICATION OF CONTROLLED SYSTEM ISLANDING

For the verification of the effectiveness of the presented method a solid three phase fault is occurred on the bus 37 of line B37- B40 at t=1.0 second and is cleared after 0.25 second by removing the faulted line. Time domain simulation shows that the interconnected power system is unstable if there is no corrective control action. To prevent from wide-area blackout and catastrophic failure, automatic islanding strategy should be executed as soon as possible. Detection or prediction of loss of synchronism is performed by stability assessment program, which indicates the stable or unstable conditions of the system for a given fault. For this fault, the power system is transiently unstable and islanding strategy should be executed.

The time interval between occurrence of initial fault and execution of islanding scenario depends on the two major factors: 1) the time which is required for detection or prediction of out of step and 2) the time which is needed to find the proper splitting strategy. The total time which is spent to find a proper splitting strategy by the proposed method is below 0.45 second for all cases. It means that we can run the splitting strategy at almost 0.7 second after initial disturbance (fault clearing time + proper splitting strategy search time). The islanding algorithm starts during the occurrence of a disturbance and is executed if the stability assessment program predicts the instability of the integrated power system.

The islanding algorithm is applied to the faulted system after detection of system instability. For example splitting of the integrated power network into three islands two seconds after removing the faulted line is presented in this section in detail. The splitting strategy is executed at t=3.3 second.

It should be noticed that the time for finding set of proper strategies is very critical. If the algorithm finds the proper splitting strategy for a given fault in real-time, the islanding scenario can be implemented by the dispatchers shortly. For the examination of robustness and effectiveness of the new splitting strategy, the strategy is executed two seconds after fault clearing which is a large time window in islanding problem. Results show that the islands formed by the new methodology are stable for all cases.

The schematic illustration of splitting of test power system into three islands by the proposed method is indicated in Fig. 4. In this figure the dashed lines are the disconnected lines which split the network into three stable islands according to new proposed algorithm. The algorithm searches for the stable islanding strategies with both dynamic and static stability constraints. It can be seen that the proposed method is changed some of the selected line as well as boundary buses for splitting of the power network. In this situation the load balancing algorithm works such that the total shedded load is minimized. Based on time domain simulation result shown in Fig. 5, the primary islanding strategy is stable with long-term simulation with a larger frequency deviation. Application of the new algorithm not only reduces the amount of load shedding during system splitting but also creates the islands which satisfy both transient and frequency stability of them.

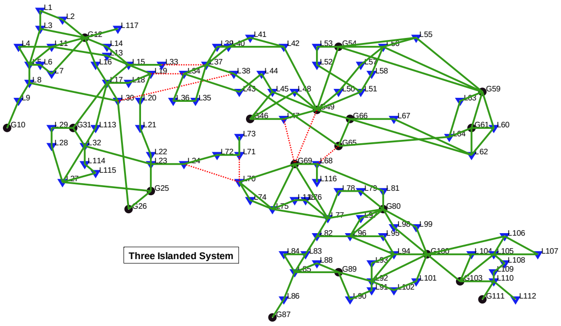

Fig. 4. Splitting of the network into three stable islands (Dashed lines are the disconnected lines to form islands)

For the verification of the effect of the proposed method on the stability of the islands, the splitting strategy according to the proposed method is executed in time domain and is illustrated in Fig. 5. From the figure it is clear that the proposed method is improved the frequency deviation within islands. The figure also indicates that proposed algorithm creates three stable islands in which the frequencies of all islands are within acceptable limits.

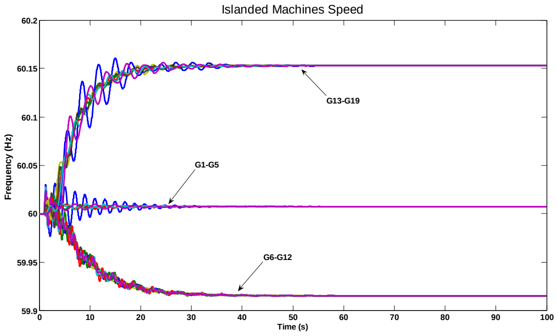

Fig. 5. Machines frequency with load-generation balancing (Three area case)

In Table III the results of the primary separation of interconnected power system and results of splitting of the system with new algorithm, according to degree of coherency of interarea modes into 3, 8 islands are presented. Table III also is summarized and compared the main results of power system splitting based on the primary and proposed algorithms. The automatic islanding program finds the proper islanding strategies for each given fault. From Table III it can be seen that the machines configuration in each islands with respect to primary islanding pattern remains unchanged and only the load buses of the islands may be transferred to the other area, hence the first two columns of Tables III are the same for primary and new splitting case. From the table it can be seen that the number of disconnecting lines is changed in some cases.

The speed of all machines after splitting strategy in a three dimension plot is shown in Fig. 6. This figure provides a good view of the speeds of all machines within the islands. Group 1 contain generator 1-5, and generators 6-14 are in the group 2. Group 3 consists of generators 15 to 19.

The obtained results prove the capability and effectiveness of the proposed method, considering both static and dynamic constraints of the power system for islanding scenario with a fast and efficient algorithm. One of the advantages of the proposed method is that it only changes the boundary of the primary islands. In Krylov subspace based islanding the lines that should be removed, are usually interarea tie-lines which probably have more switching problem when they are removed or closed. The new algorithm changes the most of switching lines which are short lines. It may give an easy switching pattern and restoration scenario. The drawback of the method is based on the fact that application of the method may cause sustained overvoltages or undervoltages at the last penetration buses. Also the number of switching lines to form proper splitting points may be increased in general. The capability of the algorithm is that only by changing of some boundary buses it is possible to create stable islands and obtain a better load shedding results.

TABLE III
RESULTS OF COHERENCY-BASED AND NEW ALGORITHM-BASED SPLITTING

N o. of Islands	Island Machines	Island Buses (Base)	Island Buses (New)	Splitting Points (Base)	Splitting Points (New)
3 Islands Case	G1-G5	B40-…-B39, B72, B113, B114, B115, B117	B40-…-B39, B72, B71 , B73, B113, B114, B115, B117	B68-B65, B69-B47, B69-B49, B72-B71 B70-B24 B34-B43 B37-B40 B38-B65 B39-B40	B68-B65, B69-B47, B69-B49, B70-B71 B70-B24 B33-B37 B19-B34 *B30-B38*
	G6-G12	B40-…-B68	B34-…-B68		
	G13-G19	Others	Others		
8 Islands Case	G1-G2	B1-…-B20, B33-…-B39, B30, B113, B117	B1-…-B22, B33-…-B39, B30, B113, B117	B31-B17, B32-B113, B30-B26, B20-B21, B38-B65, B43-B44, B37-B40, B39- B40, B32-B23, B27-B25, B72-B71, B24-B70, B45-B49, B46-B48, B46-B47, B69- B70, B69-B75, B69-B77, B81-B80, B84-B85, B83- B85, B88-B85, B89-B85, B103-B110, B109-B110,	B31-B17, B32-B113, B30-B26, *B22-B23,* B38-B65, *B34-B43,* B37-B40, B39- B40, B32-B23, B27-B25, *B70-B71,* B24-B70, B45-B49, B46-B48, B46-B47, B69- B70, B69-B75, B69-B77, B81-B80, B84-B85, B83- B85, B88-B85, B89-B85, B103-B110, B109-B110,
	G3-G4	B21-…-B26, B72	B23-…-b26, B72, B71, B73		
	G5	B27, B28, B29, B31, B32, B114, B115	B27, B28, B29, B31, B32, B114, B115		
	G6	B44, B45, B46	B43, B44, B45, B46		
	G7-G13	B40-…-B43, B47-…-B69, B81, B116	B40-…-B42, B47-…-B69, B81, B116		
	G15	B85, B86, B87	B85, B86, B87		
	G14,G16 G17,G18	B1, B9, B30, B31, B32, B33, B34, B35, B36, B37,	B1, B9, B30, B31, B32, B33, B34, B35, B36, B37,		
	G19	Others	Others		

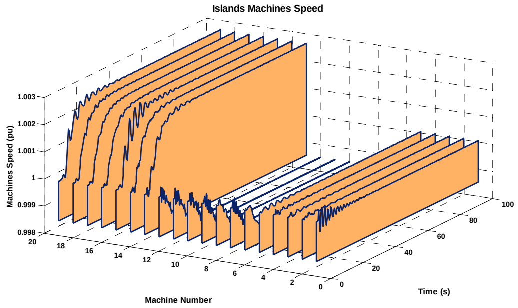

Fig. 6. Machines speed of proper islanded system into three islands

VIII. CONCLUSION

In this paper a novel strategy based on simultaneous application of both static and dynamic characteristics of an interconnected power system is presented for proper islanding of power networks. The methodology calculates the splitting points of the integrated power systems considering the stability of the islands as well as minimum load shedding within the areas. The presented method searches by spanning tree based BFS algorithm in the boundary of primary feature of clustered islands specified by the Krylov projection method. The algorithm determines the best splitting points such that the total shedded load is minimized and stability of the islands is preserved. The proposed approach finds the proper islanding pattern in a very fast and accurate manner. The algorithm can overcome the inherent time-consuming nature of the islanding schemes and is suitable for real-time separation of power systems.

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