

ADAPTIVE CORRECTIVE CONTROL STRATEGIES FOR PREVENTING POWER SYSTEM BLACKOUTS

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Abstract –In order to investigate power system security and design appropriate control strategies, power systems can be conceptually classified into five operational states: Normal, Alert, Emergency, In Extremis, and Restorative. Various preventive and corrective control strategies have been studied to cope with power systems in the different operational states. Our approach primarily focuses on the corrective control strategies for power systems under emergency and in extremis states. In this paper, two corrective control approaches (transmission system reconfiguration and controlled system islanding) have been investigated and new algorithms have been developed. When the system is in the emergency state, two reconfiguration strategies, line switching and bus-bar switching, have been presented to solve the problems of overloads or voltage violations. Furthermore, to prevent a total system black out, a slow coherency grouping based adaptive power system islanding approach using minimal cutsets has been presented to deal with catastrophic events when power system vulnerability analysis indicates that the system is approaching the in extremis state. A controlled under frequency load shedding scheme with the rate of frequency decline is also proposed to balance the real power within each island and aid restoration. The verification of our approach is proven with simulations on a 179-bus, 29-generator WECC system.

Keywords: corrective control strategies, transmission system reconfiguration (TSR), line and bus-bar switching, controlled system islanding (CSI), slow coherency, minimal cutsets, under frequency load shedding (LS)

1 INTRODUCTION

THE bulk power grid is the largest and most complex interconnected network ever devised by man, which makes control of the grid an extremely difficult task. When a severe fault occurs in the power system, it may cause overloads, voltage violations, cascading failures, or even loss of stability so that the system operators must take appropriate corrective control actions. It is well known that transmission system reconfiguration (TSR), including line switching and bus-bar switching, and controlled system islanding (CSI) are two effective corrective control strategies for different system operational states. When the system is in the emergency state, TSR may change the power flow distribution and voltage profiles, and consequently, solve the problems of overloads and voltage violations caused by system faults. However, when the system is being operated

close to its limits, TSR may not successfully relieve all the overloads and voltage violations for some severe faults, as a result the system may lose stability or even catastrophic failures could be caused. More aggressive corrective control strategies, such as generation re-scheduling (GR), load shedding (LS) and/or controlled system islanding (CSI), must be taken to prevent a catastrophic failure. Figure 1 shows the power system operating states and relative corrective control strategies.

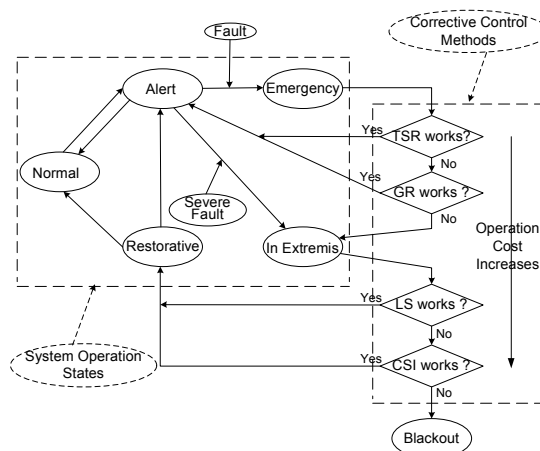


Figure 1: Power system operating states and relative corrective control strategies

Although many studies have been conducted to deal with line and bus-bar switching since this idea was first proposed in early 1980's [1-7], line and bus-bar switching are still not widely employed as effective means of control, due to the reduction in power system security and reliability. Furthermore, the discrete performance of switching actions makes it very difficult to model them and design a systematic search method.

On-line corrective control needs both speed and accuracy. However, it is a dilemma since precise and rapid corrective control is not possible. Any corrective switching algorithm should reduce computation time as much as possible with acceptable accuracy. Line and bus-bar switching is a multi-variable discrete programming problem, which is very hard to solve. Over the past 20 years, the studies of algorithms for line and bus-bar switching focused mainly on the model simplification and search space reduction.

However, most of these studies only considered the

MW overload problem and ignored the voltage violation problem which sometimes is more severe and needs more attention. Although the algorithm developed in [7] could solve both overload and voltage violation problems, it was computationally burdensome and infeasible for practical power systems. In addition, these studies either only took into account the line switching or only dealt with very simple bus-bar switching. However, in practice, the bus-bar switching in substations is more complicated by involving several breaker switching actions and is preferred to line switching because it will cause smaller disturbances in power systems.

When the systems are being operated close to their limits, weak connections, unexpected events, hidden failures in protection system, human errors, and a host of other reasons may cause the system to lose stability and even lead to catastrophic failure. Furthermore, it has been observed that, following large disturbances, groups of generators tend to swing together. Attention has thus been drawn to the stability of inter-area oscillations between groups of machines. These oscillations are lower in frequency than the local oscillations between machines that are electrically close. As a result, there is a separation in time scale between these two phenomena. Besides, several comprehensive software packages for computing these low frequencies in large power systems are available to analyze the participation of the machines in these oscillations.

In the literature, there are some other approaches for the detection of islanding [10]. However, for better system islanding, the dynamic characteristics of the system, namely dynamics of generators and loads, should be considered. Slow coherency approach of generator grouping, which is widely studied in the literature, provides the potential for capturing the movement of generators between groups under disturbance. Therefore, in this approach, we use the slow coherency as our grouping technique.

Based on slow coherency, the generators in the system have been divided into several groups. For two interconnected generator groups, [8] and [11] present an islanding method by constructing a small sub-network using the center bus, which is one of the buses in the group boundary. This sub-network is referred to as the interface network. A brute force search is then conducted on the interface network to determine the cutsets where the islands are formed. For each island candidate, the total load and generation are calculated, and the island with minimum load-generation imbalance is picked up as the optimal cutset if no other criteria have been considered. However, this approach involves more computational effort. Furthermore, it is system-specific. For some systems, it returns fairly good results, but not for others. In this paper, a new slow coherency grouping based approach by using minimal cutsets is presented to solve this type of problem.

Minimal cutsets have been widely investigated in communication, network topology, and network (par-

ticularly, power systems) reliability analysis (maximum flow and connectivity) [12], [13]. As shown in this paper, it also has the potential to determine where to actually island the system.

The paper is organized as follows. In section 2, a new algorithm is developed to find the best line and bus-bar switching action for relieving both overloads and voltage violations. Section 3 presents 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. The controlled system islanding scheme has been developed. A new load shedding scheme has been presented to reduce the real power imbalance in each island. The approach is examined on a 29 Gen-179 Bus system in Section 4 to verify the effectiveness. The conclusions are provided in section 5.

2 SYSTEM RECONFIGURATION

2.1 Line Switching Model

The system model with network modification can be described as

$$(\mathbf{Y} + \Delta\mathbf{Y}) \cdot \mathbf{V} = \mathbf{I} \quad (1)$$

Where, \mathbf{Y} is a sparse network admittance matrix.

$\Delta\mathbf{Y}$ is the modification matrix.

\mathbf{V} and \mathbf{I} are the voltage and current matrices.

The sparse inverse technique is adopted to find the solution after network modification. For fast decoupled power flow, the branch-oriented modification is employed, as shown in (2).

$$\Delta\mathbf{Y} = \mathbf{M} \cdot \delta\mathbf{y} \cdot \mathbf{M}^T = \begin{matrix} f \\ t \end{matrix} \begin{bmatrix} +1 \\ -1 \end{bmatrix} \cdot [\pm\Delta y_{series}] \cdot \begin{bmatrix} +1 & -1 \\ f & t \end{bmatrix} \quad (2)$$

When m branches are modified simultaneously, the diagonal matrix $\delta\mathbf{y}$ is of size $(m \times m)$, and the matrix \mathbf{M} has $2m$ elements with +1 and -1 in corresponding rows.

By the inverse matrix modification lemma (IMML), we can obtain

$$\mathbf{V} = (\mathbf{Y}^{-1} - \mathbf{Y}^{-1} \cdot \mathbf{M} \cdot \mathbf{C} \cdot \mathbf{M}^T \cdot \mathbf{Y}^{-1}) \cdot \mathbf{I} \quad (3)$$

Where $\mathbf{C} = (\delta\mathbf{y}^{-1} + \mathbf{Z})^{-1}$ and $\mathbf{Z} = \mathbf{M}^T \cdot \mathbf{Y}^{-1} \cdot \mathbf{M}$

Since system solution would already have been obtained by contingency analysis, the post-compensation method should be employed to find the solution after network modification, which is shown as follows:

- (1) Obtain solution: $\hat{\mathbf{V}} = \mathbf{Y}^{-1} \cdot \mathbf{I}$
- (2) Calculate compensation: $\Delta\mathbf{V} = -\mathbf{Y}^{-1} \cdot \mathbf{M} \cdot \mathbf{C} \cdot \mathbf{M}^T \cdot \hat{\mathbf{V}}$
- (3) Perform compensation: $\mathbf{V} = \hat{\mathbf{V}} + \Delta\mathbf{V}$

2.2 General Bus-bar Switching Model

A practical and general bus-bar structure is that each line connected to the bus-bar can be switched onto either of the buses of the bus-bar, as shown in Figure 2. Thus, there are many kinds of switching scenarios when a bus-bar is split.

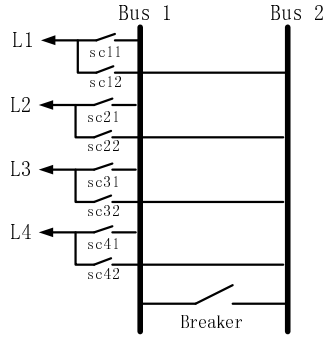
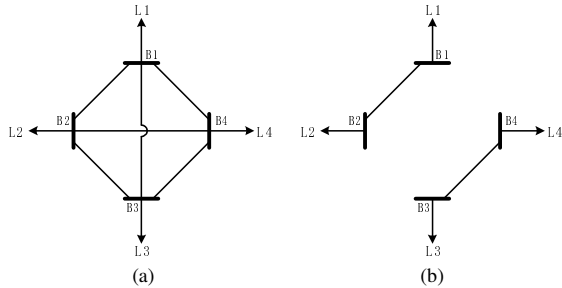


Figure 2: The Structure of a Bus-bar with Four Lines

The process of modeling bus-bar switching is as follows:

- (1) Find all the lines connected to the bus-bar, including loads which are also considered as lines.
- (2) Generate a new node for each line connected to the bus-bar, and the lines are connected to their corresponding nodes.
- (3) Connect every two generated new nodes with a breaker which is modeled as a line with very small impedance such as $1.0e-8$.
- (4) Find all possible results to divide the new nodes into two groups under the constraints of bus-bar switching.
- (5) For each grouping result, disconnect all breaker lines connected to the nodes in the first group except the breaker lines connecting them to each other.
- (6) The breaker line switching can be modeled as line switching as described above.

The model diagrams of a bus-bar with four lines connected to it are shown in Figure 3.



(a) Model of the Bus-bar with Four Lines
(b) Switching Action with the Lines L1 and L2 on One Bus-bar and Lines L3 and L4 on the Other Bus-bar

Figure 3: Model Diagrams of a Bus-bar with Four Branches

2.3 Proposed Line and bus-bar Switching Algorithm

Fast Decoupled Power Flow (FDPF) is employed to obtain voltage and reactive power information. In order to get a tradeoff between the accuracy and computation speed, the convergence criteria for FDPF are set as the iteration tolerance being less than 5MW for real power and 5 MVar for reactive power and the iteration count being not more than 3.

The switching actions are compared by their Performance Index of Security Margin (PISM) which is defined as follows:

$$PISM = \min \left\{ \min_i \left(\frac{|S_{i_{max}}| - |S_i|}{S_{BASE}} \right), 100 * \min_j [\min(|V_{j_{max}}| - |V_j|, |V_j| - |V_{j_{min}}|)] \right\} \quad (5)$$

Where, $|S_{i_{max}}|$ and $|S_i|$ are the rated maximal and actual apparent power in MVA on line i , respectively.

S_{BASE} is the system MVA base.

$V_{j_{max}}$, $V_{j_{min}}$ and $|V_j|$ are the rated maximal, minimal and actual voltage magnitude at bus j , respectively.

$i=1, \dots, n, j=1, \dots, m$. n and m are the line number and bus number of the system.

The proposed line and bus-bar switching algorithm has been presented in detail in [15].

3 SLOW COHERENCY GROUPING BASED ISLANDING AND ADAPTIVE LOAD SHEDDING

3.1 Slow Coherency Grouping Based Islanding

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 [9], 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.

Therefore, slow coherency can be used to determine generator grouping based on system dynamic characteristics. However, actual boundary buses need to be determined in order to form the islands. In other words, not only system dynamic characteristic is needed, but also system topology.

Power systems are composed of buses and transmission lines connecting them. Therefore, it is very convenient to consider a power system network as a directed graph with different weights at vertices.

One of the most important requirements for islanding is to minimize the real power imbalance within the islands to benefit the restoration. After an island is formed, the imbalance between the real power supply and load demand is usually calculated by computing all the generator vertices and load vertices [8], which needs much computation. An alternative approach is to consider the branches connecting this island with other islands instead of browsing all vertices within this island. This intuitively makes sense, because most of the time, the number of lines tripped is limited in order to form an island.

The power flows in the transmission line also contain information of the distribution of the generators throughout the system. Once the island is formed, the net flow in the lines tripped indicates exactly how different the real generation and load is within the island (assume that the losses can be ignored).

Therefore, a systematic approach has been developed to form the islands, such that each island only includes

one generator group, and each island satisfies the optimized real power imbalance requirement, as well as other criteria to aid the restoration. It is composed of four main components.

1. Network reduction;
2. Generate modified Breath-First-Search (BFS) tree with no offspring in sink vertex;
3. With BFS flag, Depth-First-Search (DFS) will be conducted to enumerate all possible minimal cutsets.

Islanding criteria will be applied to select the optimal minimal cutsets. Two comprehensive islanding methods, aggregated islanding method and trial-error iterations tuning method, have also been developed to deal with large systems which have many islands. [10]

3.2 Adaptive Load Shedding

Controlled islanding divides the power system into islands. Some of these islands are load rich and others may be generation rich. Generally, in a load rich island, the situation is more severe. The system frequency will drop because of the generation shortage. If the frequency falls below a certain set point (e.g., 57.5 Hz), the generation protection system will begin operation and trip the generator, further reducing the generation in the island and making the system frequency decline even further. In the worst case, the entire island may blackout.

A threshold value (M_0) is defined in each island, such that, if the rate of frequency decline after islanding at one load exceeds M_0 , a new load shedding scheme will be deployed. Otherwise, a conventional load shedding scheme will be deployed. The value of M_0 can be obtained based on the equation as follows,

$$M_0 = \frac{60 \times P_{L\Delta}}{2 \sum H_i}, \text{ where } P_{L\Delta} = 0.3 \times P_{sys} \quad (6)$$

Where H_i is the inertia of i^{th} generator within the island. P_{sys} is system MVA. $P_{L\Delta}$ is the minimum load deficit that could drive the system frequency down to 57Hz, which is the minimal operational frequency. [11]

4 RESULTS FROM SAMPLE SYSTEM

The algorithms are implemented with MATLAB and tested on the WECC 179-bus system [8].

4.1 Line and Bus-bar Switching

The outage of line 170-171 is selected to be analyzed. The contingency analysis results are shown in Table 1.

Overloaded Line	Line Flow	Line Rating	Amount of Overload
Line 168-169	1818.60 MVA	1700 MVA	118.60 MVA
Voltage Violation	Bus Voltage	Voltage Limits	Amount of Violation
Bus 84	1.0612 pu	$V_{max} = 1.06$ pu	+0.00121 pu

Table 1: Contingency Analysis Results for Outage of Line 170-171

90 lines are selected as line switching candidates and 10 bus-bars are selected as bus-bar switching candidates. The output results of the line and bus-bar switching program are as follows:

- Overloads and voltage violation have been relieved by bus-bar switching.
- The recommended best switched bus-bar is bus-bar 83.
- The recommended best switching action is that lines 83-94, 83-98, 83-172, and load 83 are switched on one split bus and lines 83-89 and 83-168 are switched on the other split bus.
- The minimal PISM of the system is 0.1369.
- The CPU time is 5.09 seconds.

The power flow results are shown in TABLE II and the system diagram for the switching action is shown in Figure 4. (The directions of power flow are shown by arrows)

Overloaded Line	Line Flow	Line Rating	Security Margin
Line 168-169	1574.34 MVA	1700 MVA	125.66 MVA
Voltage Concern	Bus Voltage	Voltage Limits	Security Margin
Bus 84	1.05863 pu	$V_{max} = 1.06$ pu	0.00147 pu

Table 2: Power Flow Results after Switching Action

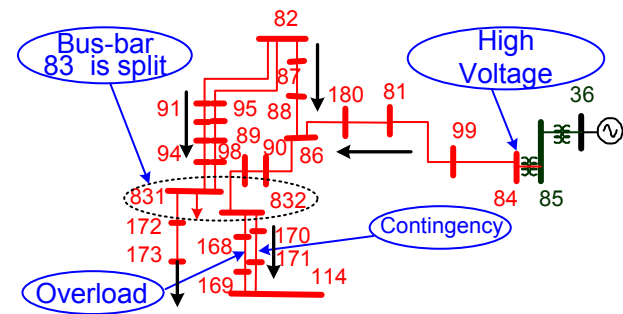


Figure 4: System Diagram of the Interesting Part of the WECC 179-bus System

4.2 Grouping Result for the Base Case

In this section we will demonstrate the advantage of proposed controlled system islanding on this test system. Four generator groups have been calculated by using the DYNRED package [14]. To apply a larger disturbance to force the system into the emergency state, Lines 83-168, 83-170, and 83-172 have been removed [8]. Transient simulation shows that the system will not be stable under this disturbance. Therefore, system islanding should be applied to separate the system into smaller islands.

To develop a better understanding of the proposed approach, the minimal cutsets between the South Island and the rest of the system are first determined. Once the minimal cutset of the south island are found, we can

continue to find other islands by removing the south island from the network and treating the rest of the network as the whole network.

A recursive function with BFS tree flag based DFS searching technique enumerates all the possible minimal cutsets with different real power imbalance with each island.

For the purpose of comparison, we have applied the same contingency as in the Test Case for Set 1 Case 3 in [8], which actually cuts the WECC system from the West. According to the method mentioned in Section 3, in order to handle the system with more than two islands, either Tuning Trial-Error or Aggregated Island approach may be used to form the island in a systematic manner. In this case, the Aggregated Island approach is applied to island the system into two subsystems (one load rich, another is generation rich), along with the contingency. Once this is done, the Trial-Error approach is conducted in the aggregated load rich island to form two islands out of it.

	Generator (Bus No.)	Cutset (Bus No.)	Inertia (S)	Net Flow (MW)	TI (MW/S)
Island 1	15, 103, 148,	132 119	966.66	-2084.46	-2.1563
	13, 43, 144,	134 119			
	149, 140, 40,	14 29			
	138, 47				
Island 2		168 83	343.39	-2022.24	-5.8891
		170 83			
	112, 116, 118	172 83			
		119 132			
		119 134			

Table 3: Detail information of two islands in South.

Table 3 illustrates the detailed information of these two islands. The last column intuitively gives the idea of how fast the rotor angle of generators on average in this island will move once the island is actually formed. It is expected that the TI values for island 1 and 2 will be the same. However, depending on the topology of this real case, these values are not the same, while they are as close as possible.

4.3 Transient Simulations

To verify the advantages of the new islanding approach, time domain simulation has been conducted.

As mentioned above, three 500kV transmission lines (83-168, 83-170, 83-172) are tripped at time 0 s, the path from north to south along west thus has been disconnected.

Four scenarios have been studied, shows as follows:

1. No self healing strategy;
2. At time 0.087 s, form the islands but without any load shedding scheme installed;
3. At time 0.087 s, form the island with conventional load shedding scheme installed;
4. At time 0.087 s, form the island with new adaptive load shedding scheme installed.

For the sake of comparison, islanding based on experience has been also conducted, such that, after fault

at time 0 s, four lines are tripped to form the island, shows as follows: 139-12, 139-27, 136-16(dct) [11]. Simulation shows that new islanding approach with both conventional and new load shedding scheme has the advantage of shedding less loads than that from islanding based on experience. Due the limited space, those results are not shown in this paper. Furthermore, there is less frequency oscillation detected at Generator 118 when the new islanding approach is applied, compared to islanding based on experience, as shown in Figure 5 and Figure 6.

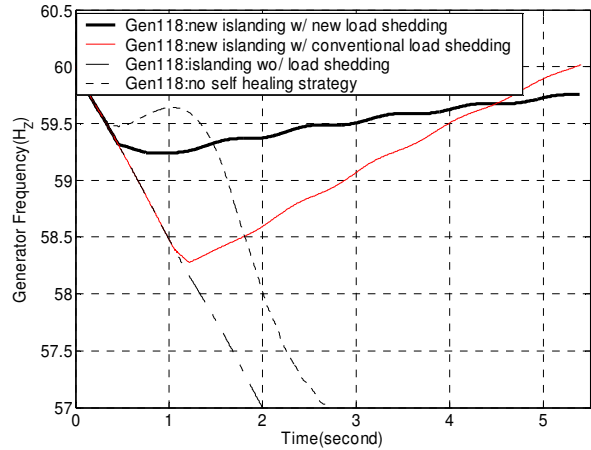


Figure 5: Generator frequency under different scenarios at Generator 118.

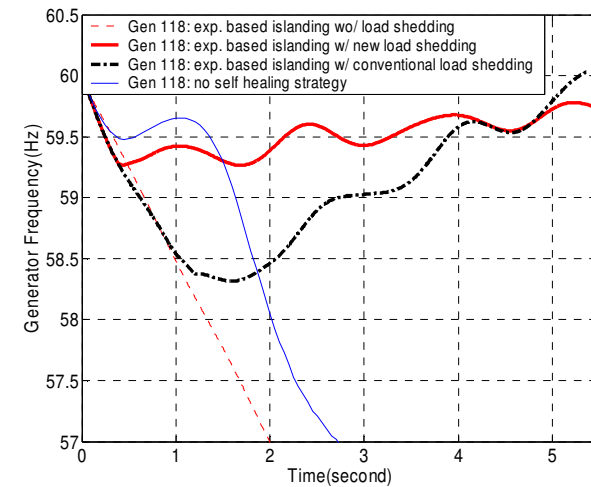


Figure 6: Generator frequency under different scenarios at Generator 118.

5 CONCLUSION

In this paper, two corrective strategies: transmission system reconfiguration (TSR) and controlled system islanding (CSI), have been investigated for preventing power system from blackouts, which present a comprehensive strategy to deal with disturbances with different scales. The most significant contributions may be summarized as follows:

1. A general model for bus-bar switching is proposed, which can deal with any kinds of bus-bar switching scenarios.
2. The idea of evaluating switching actions by maximizing the minimal system security margin is proposed.
3. Based on the FDPF with limited iteration count, a new line and bus-bar algorithm is developed. Simulation results show that the proposed line and bus-bar switching algorithm can effectively solve the problems of overloads and voltage violations and can significantly improve computation speed.
4. A novel controlled system islanding approach based on minimal cutsets has been presented. This method takes advantage of mature techniques in Graph Theory to form the islands.
5. An adaptive load shedding scheme has been developed to reduce real power imbalance after the islands are created by taking the rate of frequency decline into consideration.

In this paper the technique was demonstrated on a moderate sized system representing the WECC. However, the techniques can be applied without loss of generality to realistic systems.

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BIOGRAPHIES

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