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Determining an Operation Sequence for Proactive Islanding of the Power Grid

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***Abstract*—Proactively splitting the power grid into smaller self-adequate islands may be necessary to arrest the propagation of cascading disturbances during extreme events. To create multiple islands within a real power network, many transmission lines will need to be disconnected. This work presents two fast heuristic methods for determining the sequence of line switching operations needed for island creation. It is shown that the proposed methods are computationally efficient, minimize line capacity violations, maintain bus voltages within prescribed limits, and outperform a random operation sequence for the IEEE 39-bus test system.**

***Index Terms*—Extreme events, proactive islanding, line outage distribution factor, transmission line switching, resilience**

I. Introduction

The power grid is a critical infrastructure whose availability is instrumental to the normal functioning of modern society. Extreme events like hurricanes, wildfires and coordinated cyber-physical attacks can cause catastrophic and long-lasting damage to the grid, necessitating the formulation of defensive strategies [1], [2]. Prior works suggest that proactively splitting the transmission network into smaller self-adequate islands could be effective in arresting cascading disturbances during a severe event, thereby enhancing resilience [3], [4]. In [3], the authors assess the component failure probabilities due to a weather contingency and isolate the most vulnerable within an island. In [4], a generalized method for proactive islanding in anticipation of extreme events is presented. However, tools to determine the optimal sequence of actions required for successful grid separation remain to be explored.

To create multiple islands within a grid, many transmission lines need to be disconnected. For instance, in [4] it is shown that about 50 lines need to be disconnected for splitting the PJM network into two parts. Evidently, the number of possible switching sequences would be very large and some method for selecting a *good* choice is required. An acceptable operation sequence would maintain load-generation balance, and avoid line overloads and voltage deviations. This sequence determination problem can be formulated as a mathematical optimization, but due to the combinatorial nature of the task, integer decision variables will be needed. Solving a mixed-integer optimization problem for a large transmission network is computationally prohibitive for near-real-time applications. Hence, fast heuristic methods are required. In this context, this work proposes two methods for the sequence formulation task.

It has previously been shown that transmission line switching can reduce generation cost, network losses, and alleviate line congestion. Both exact and heuristic methods have been employed to address this optimal switching problem [5]–[8]. A popular approach involves using line outage distribution factors (LODF) to approximate the changes in real power flows in response to a topology change [7], [8]. LODF-based approximations have also been used for contingency analysis [9]. As LODF calculations depend only on the system topology, this class of methods avoids expensive AC power flow computations. If the network topology changes, then LODFs need to be recomputed. Strategies for speeding up LODF computations have been proposed [10]–[12]. The present work also utilizes LODF computations to approximate how disconnecting one line changes the loading on the others.

The main contribution of this paper is the formulation of fast heuristic methods to determine a sequence of operations needed for separating the bulk power grid into islands. We present two approaches - *a)* in the forward method, the first line switching step is decided at the start; *b)* while in the backward method, the last step is decided first. Numeric tests on a modified IEEE 39-bus test system show that the proposed algorithms are computationally efficient, minimize line overloads, and maintain bus voltages within limits prescribed by ANSI standards [13]. While we show that the determined sequences outperform a randomly chosen sequence of operations, further work will be needed to ascertain what is an *optimal* solution, and how far are the obtained solutions from the optimal. This operation sequence determination problem has not been explored before in existing literature.

The remaining paper is organized in the following manner. Section II describes two heuristic methods for determining the sequence of operations needed to split a power network into multiple islands. Section III illustrates the performance of the proposed methods using case studies on a modified IEEE 39-bus test system. Section IV concludes this work and outlines future research directions. Findings from this work have also been reported in [14].

II. Methodology

As discussed before, proactive islanding can arrest the propagation of cascading disturbances in the power grid during an extreme event, thereby limiting damages. In this section, two heuristic methods for determining the operation sequence needed to create the islands are presented. Standard mathematical notations are used, calligraphic symbols represent sets, lower (upper) case bold letters represent column vectors (matrices). All zero and all one vectors and matrices of appropriate size are denoted by $\mathbf{0}$ and $\mathbf{1}$ respectively.

A. Line Outage Distribution Factor

Network sensitivity factors are widely used in power systems studies to obtain quick estimates of power flow shifts in response to changes in generation or network topology. Closed form expressions for the sensitivity factors are derived using the DC power flow model [15].

Let us consider a power network with $N+1$ buses and L transmission lines. The set of buses is denoted as $\mathcal{N} = \{0, 1, , \dots, N\}$, where bus 0 is the slack bus. The set of lines is given by $\mathcal{L} = \{l_1, l_2, \dots, l_L\}$. Each line l_m is associated with an ordered pair of nodes (i_m, j_m), and it is assumed that real power flow f_{l_m} on line l_m is directed from node i_m to node j_m. The injection shift factor $ISF^{i}_{l_m}$ is the approximate change in f_{l_m} when 1 MW power is injected at some node $i \in \mathcal{N}$ and withdrawn at the slack bus. Under typical DC power flow assumptions and lossless conditions, the formula for the ISF matrix is

$$\mathbf{ISF} = \mathbf{B_d A B^{-1}}$$

Here, $\mathbf{B_d}$ is the $(L \times L)$ branch susceptance matrix, $\mathbf{A}$ is the $(L \times N)$ reduced incidence matrix, and $\mathbf{B}$ is the $(N \times N)$ reduced nodal susceptance matrix. Using the ISF matrix, other sensitivity factors like power transfer distribution factor (PTDF) and LODF can be calculated.

PTDFs describe how line flows change when there is a transaction of Δt MW from node i to j. For line l_m, the approximate change in real power flow would be as follows:

$$\Delta f^{(i,j,\Delta t)}_{l_m} = PTDF^{(i,j)}_{l_m} \times \Delta t \tag{1}$$

Now, the PTDFs may be computed in the following manner.

$$PTDF^{(i,j)}_{l_m} = ISF^{i}_{l_m} - ISF^{j}_{l_m} \tag{2}$$

PTDFs need to be recomputed if the network topology changes. Now, let us consider the impact of an outage on line l_k on f_{l_m}. With the help of LODF, the fraction of pre-outage real power flow on line l_k (between nodes (i_k, j_k), say) redistributed to the remaining lines can be calculated. It can be shown that [12]:

$$LODF^{l_k}_{l_m} = \frac{PTDF^{(i_k,j_k)}_{l_m}}{1 - PTDF^{(i_k,j_k)}_{l_k}} \tag{3}$$

Hence, approximate real power flows in a network following an outage on line l_k may be computed as:

$$\mathbf{f}^{c}_{S} = \mathbf{f}^{0}_{S} + \mathbf{LODF}^{l_k}_{S} \times f^{0}_{k} \tag{4}$$

Here, the superscripts 0 and c are used to denote pre and post-outage conditions respectively. The real power flow on lines in service are stacked in vector $\mathbf{f}_S$ of length $(L-1)$. Pre-outage real power flow on line l_k is given by f^0_k. It must be noted that the values of sensitivity factors depends on the choice of the slack bus. Most power flow solvers used in the industry and academia provide built-in commands for computing PTDF and LODF, once the slack bus is specified.

B. Generalized LODF

With the LODF expression of equation (3), approximate redistribution of real power flow can be calculated for a single line outage. Closed form expressions for computing LODF when multiple transmission lines are disconnected have also been derived [12]. It can be shown that

$$\mathbf{LODF}^{O}_{S} = \mathbf{PTDF}^{O}_{S}(\mathbf{I} - \mathbf{PTDF}^{O}_{O})^{-1} \tag{5}$$

Here, O denotes the set of lines on outage and S is the set of lines remaining in service. Matrix $\mathbf{I}$ is the identity matirx of size $|O| \times |O|$. The PTDF values are calculated for the pre-contingency network topology. Proof of the relationship in equation (5) is available in [10], [12]. Once the Generalized LODF (GLODF) values are calculated, post-contingency approximate real power flow distribution can be computed using the following expression.

$$\mathbf{f}^{c}_{S} = \mathbf{f}^{0}_{s} + \mathbf{LODF}^{O}_{S} \times \mathbf{f}^{0}_{O} \tag{6}$$

C. LODF-based Forward-Approach

We propose heuristic methods for formulating the operation sequence needed to separate a transmission network into islands. It is assumed that at the initial stage, generation dispatch and load-shedding needed to establish power balance in the intended islands will be executed. Once the new operating conditions are realized, sequential line disconnections can start. It is further supposed that the lines are to be disconnected one at a time to limit system shock, and there will be sufficient delay between consecutive switching actions so that the system can reach a steady state before the next line is disconnected. Dynamic performance has not been considered by the proposed methods, with the assumption that minimizing line congestions will avoid voltage violations and hidden failures, and offer operators adequate opportunity to maintain system stability using power systems stabilizers, voltage regulators, etc. Of course, the heuristic methods could also be used to screen initial candidate sequences, and the optimal operation plan may be chosen after performing dynamic simulation studies. The possibility of component failures during the line switching operations has not been studied herein.

If n transmission lines need to be disconnected to realize the intended islands, then the number of possible switching sequences becomes $n!$, and any brute-force method would have to check $n \times n!$ power flow cases for possible constraint violations. Needless to say, this would be computationally prohibitive. Using LODFs to approximate changes in real power flows due to changes in grid topology, we formulate a greedy approach that, at each stage, chooses to disconnect the line that produces the least loading on the five highest loaded lines in the post-disconnection topology. The loading on the heaviest lines is minimized so that other parts of the network can be better utilized.

We start with the topology where all branches in the cut-set are connected and disconnect one line at a time. This forward-approach method is summarized in algorithm 1. Of course, if the computation budget allows, accurate line loadings could be

Algorithm 1 LODF-based forward approach

Start
$\mathcal{T} \leftarrow$ Initial network topology
$k \leftarrow 1$
Perform the generation redispatch and load-shedding required to establish load-generation balance in the intended islands. Compute power flows on all transmission lines.
Determine the cut-set of lines to be disconnected. Denote it by $\mathcal{L}_{cut}$. Let $|\mathcal{L}_{cut}| = n$.
Initialize an empty sequence $\{L'_j\}_{j=1:n}$ which will store the chosen switching sequence.
while $\mathcal{L}_{cut}$ is non-empty **do**
    Calculate LODF matrix for topology $\mathcal{T}$.
    for $i = (1 : n - k + 1)$ **do**
        Compute approximate real power flows when the i-th element of $\mathcal{L}_{cut}$ is disconnected using equation (4).
        Calculate line loadings.
        $S_i \leftarrow$ sum of loading on the five most heavily loaded lines.
    $l \leftarrow \mathcal{L}_{cut}(i)$ for which S_i is minimum.
    $L'_k \leftarrow l$
    $k \leftarrow k + 1$
    Disconnect line l. $\mathcal{T} \leftarrow$ updated topology.
    Remove l from $\mathcal{L}_{cut}$.
End
Output: Sequence L'.

computed using AC power flow. The number of power flow cases to be solved would be $\frac{n(n+1)}{2} - 1$, which is significantly lower than $n!$.

D. GLODF-based Backward Approach

It may be argued that it is critical to ensure that there are no overloads or voltage violations during the later steps of the switching sequence when the system is already weakened. Considering this, we propose a heuristic backward-approach method, as outlined in algorithm 2. Here, we start with the topology where $(n-1)$ branches in the cut-set have been disconnected. The number of such possible topologies is n, and approximate power flow redistributions are computed for each combination of $(n-1)$ branch disconnections from the cut-set. The candidate which minimizes loading on the five most heavily loaded branches is selected for the $n-$th switching step. Next, the selection process is repeated for topologies with $(n-2)$ line disconnections and so on and so forth. Again, if computation budget allows, exact line loadings could be calculated by solving AC power flow cases.

III. Numeric Results

We illustrate the performance of the proposed sequence determination methods with case-studies on the modified IEEE 39-bus 10-machine test system shown in fig. 1 [16]. All computations are performed on a 3.6 GHz Intel Core i7-4790 CPU with 16 GB RAM. MATPOWER is used for analyzing the electrical performance of the test system [17].

Algorithm 2 GLODF-based backward-approach

Start
$k \leftarrow 1$
Perform the generation redispatch and load-shedding required to establish load-generation balance in the intended islands. Compute power flows on all transmission lines.
Determine the cut-set of lines to be disconnected. Denote it by $\mathcal{L}_{cut}$. Let $|\mathcal{L}_{cut}| = n$.
Initialize an empty sequence $\{L'_j\}_{j=1:n}$ which will store the chosen switching sequence.
$\mathcal{T} \leftarrow$ Network topology with all lines in $\mathcal{L}_{cut}$ disconnected.
while $\mathcal{L}_{cut}$ is non-empty **do**
    for $i = (1 : n - k + 1)$ **do**
        $\mathcal{O} \leftarrow \mathcal{L}_{cut} \setminus \mathcal{L}_{cut}(i)$.
        In topology $\mathcal{T}$, connect $\mathcal{L}_{cut}(i)$ and compute GLODF for outages on elements of $\mathcal{O}$ using equation (5).
        Compute approximate real power flow distributions using equation (6).
        $S_i \leftarrow$ sum of loading on the five most highly loaded lines.
    $l \leftarrow \mathcal{L}_{cut}(i)$ for which S_i is minimum.
    $L'_{n-k+1} \leftarrow l$
    $k \leftarrow k + 1$
    Connect line l. $\mathcal{T} \leftarrow$ updated topology.
    Remove l from $\mathcal{L}_{cut}$.
End
Output: Sequence L'.

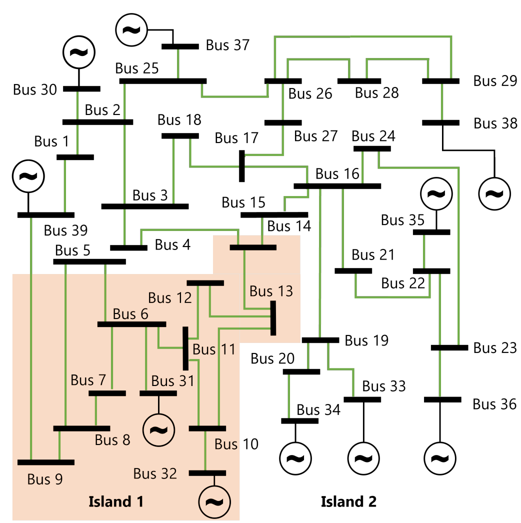

Fig. 1: Modified IEEE 39-bus test case

A. Experiment Setup

The network in fig. 1 is to be split into two islands; disconnecting five transmission lines on the boundary. These lines are: $\mathcal{L}_{cut} := \{(4,14),(5,6),(5,8),(9,39),(14,15)\}$. Island 1 (shown in color in fig. 1) has 780 MW load, and 1371 MW generation capacity. Island 2 has 4690 MW load,

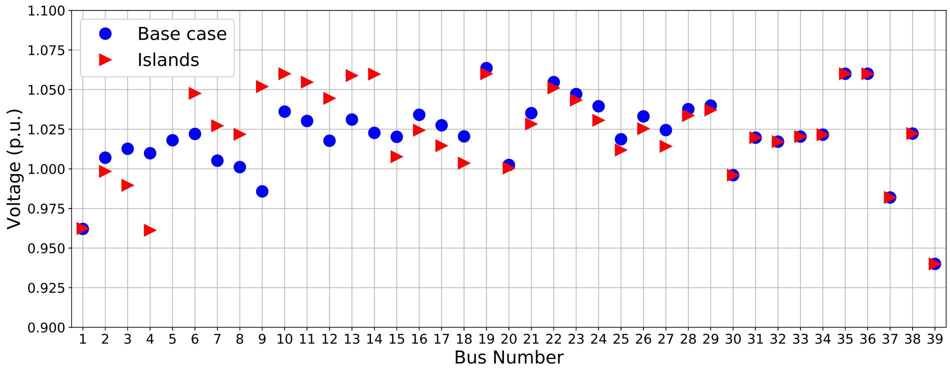

Fig. 2: Bus voltages before and after separation into islands

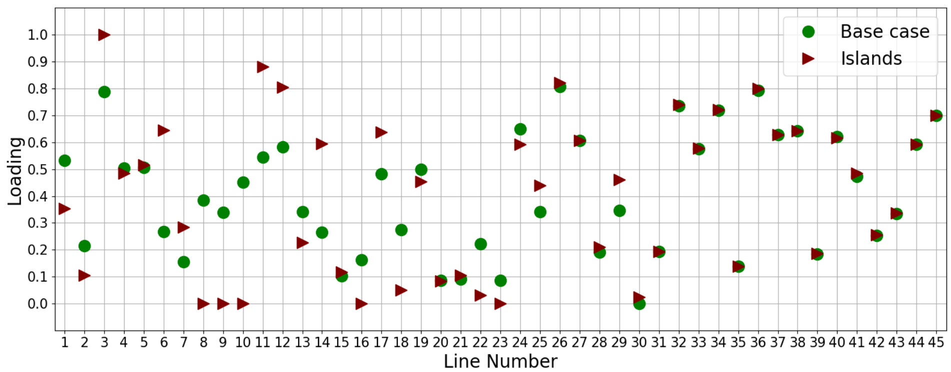

Fig. 3: Line loading before and after separation into islands

TABLE I: Operation Sequences Determined by Various Methods

Method	Line Switching Sequence
Random Sequence	$(4, 14), (14, 15), (5, 6), (5, 8), (9, 39)$
Forward-Approach	$(9, 39), (14, 15), (5, 6), (5, 8), (4, 14)$
Backward-Approach	$(14, 15), (5, 8), (5, 6), (9, 39), (4, 14)$

TABLE II: Violations Observed for Various Switching Sequences

Method	No. of Overloads	No. of Overvoltages
Random Sequence	5	8
Forward-Approach	0	10
Backward-Approach	0	8

and 6031 MW generation capacity. Bus 31 and 39 are assigned as the slack buses in islands 1 and 2 respectively. Before network splitting, losses in the network are minimized by redispatching generation (solving AC-OPF with identical cost parameteres for all generators). As the defensive islanding approach is expected to be deployed only when extreme events are expected, the grid may face emergency operating conditions.

The bus voltages and line loadings in the redispatched network before and after islanding are shown in fig. 2 and fig. 3 respectively. Some bus voltages in island 1 are slightly higher than 1.05 p.u. which can be remedied by voltage regulators. Line $(3, 4)$ is loaded to capacity as after islanding, the entire load at bus 4 is being supplied by this line. To alleviate the overload at line $(3, 4)$, some load at bus 4 may be shed.

B. Operation Sequence

The switching sequence for network separation is determined using algorithms 1 and 2, and the electric performance of the topologies at each step are checked using steady-state AC power flow. Buses 31 and 39 are both assigned as slack buses with equal participation. The operation sequences obtained are compared to a randomly generated sequence of disconnections, as listed in table I. It can be seen that the last step determined by both the forward and backward approach-based methods is the same.

The voltages computed at non-generator buses in the network for each step in the switching sequences are shown in fig. 4-6. Note that voltages at buses 19 and 22 were slightly higher than 1.05 p.u. in the base case itself. It can be seen that in the forward-approach method, the voltage at bus 9 is higher than 1.05 p.u. during steps 1 and 2. For the backward-approach method, there is no overvoltage at bus 9.

No line was overloaded in both the switching sequences found by the heuristic methods. Average loading on the five highest-loaded lines at each step was similar for both the algorithms. In the random sequence, line $(3, 4)$ was overloaded at steps 2, 3, and 4; and line $(6, 7)$ was overloaded at steps 3 and 4. The number of constraint violations observed for the different switching sequences are summarized in table II.

Hence, we see that the approaches proposed in this work

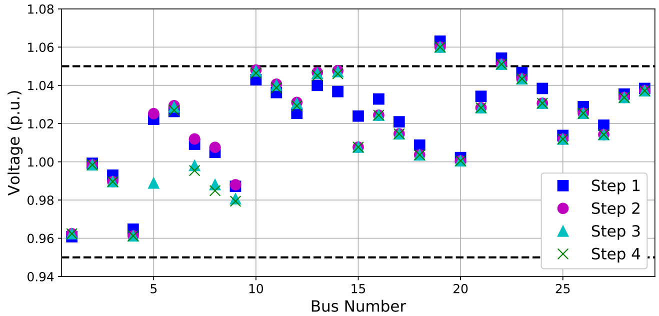

Fig. 4: Voltages at load buses following a random sequence of operations. The black dotted lines correspond to 0.95 and 1.05 p.u..

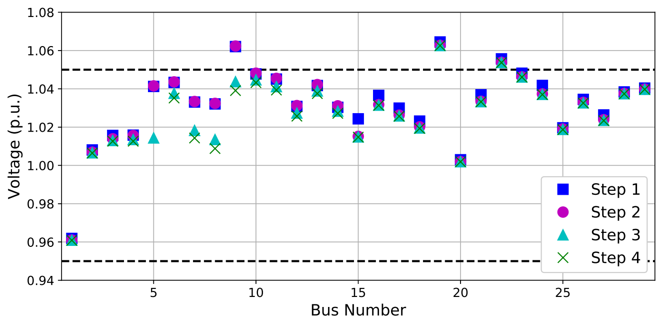

Fig. 5: Voltages at load buses following the operation sequence determined by algorithm 1

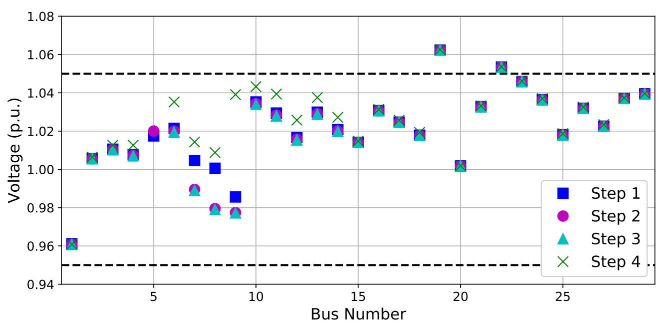

Fig. 6: Voltages at load buses following the operation sequence determined by algorithm 2

show similar performance and can split the network avoiding line overloads and maintaining voltages within limits. For the backward-approach method, fewer overvoltages are recorded. Both methods perform better than a randomly selected sequence of operations.

IV. Conclusion

Proactive islanding can enhance grid resilience by arresting cascading failures during an extreme event. However, existing literature has not explored in what sequence should generator dispatch, load-shedding and line switchings be carried out to split the grid into viable islands. In this work, two methods for choosing an acceptable islanding operation sequence are proposed. It is shown that these methods are computationally efficient, minimize line capacity violations, maintain bus voltages within prescribed limits, and outperform a random operation sequence for case-studies on the IEEE 39-bus test system. Of course, the presented approaches are not without limitations, and further work is needed to rigorously assess the effectiveness of the developed methods.

Tests on a larger system will be needed to check the scalability of the proposed approaches. The possibility of component failures during line switchings should also be accounted for. This paper additionally considers that the generation dispatch and load-shedding required to establish power-balance in the intended islands will be executed before any lines are disconnected. Establishing power balance may be time-consuming due to the ramping constraints on generators, and an operation plan that accounts for redispatch and switching actions at each step can be useful. The authors plan to address these issues in their future work.

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