Controlled Islanding Using Transmission Switching and Load Shedding for Enhancing Power Grid Resilience

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Abstract

A controlled splitting strategy is proposed as the last resort to determine the splitting points of an interconnected power system before occurring a critical transition. The proposed strategy is expressed as a mixed-integer formulation with considering the slow coherency of synchronous generators. In the proposed integer programming formulation, each coherent group of generators is located in an individual island. This grouping constraint may assure the synchronism of generators after islanding. Each island contains a coherent group of generators and its boundary is determined with the aim of achieving minimum load shedding. Two artificial DC load flow algorithms are proposed to model grouping and connectivity constraints. In addition to operational limits, a switching constraint and a frequency stability constraint are proposed to limit the number of line switchings and assure the stability of resulted islands, respectively. The proposed mixed integer model is solved using Benders Decomposition (BD) technique. Using BD technique, the CPU time of computation is reduced significantly. The proposed splitting strategy is simulated over the IEEE 30-Bus and IEEE 118-Bus test grids. Transient stability simulations are done to validate the accuracy of the proposed method.

Keywords: Controlled islanding, transmission switching, load shedding, resilience, Benders decomposition

Nomenclature

$P^0_{G_i}$ Initial generation of node i

$P^0_{L_i}$ Initial load at node i

α_i Weighting factor for load shedding at bus i

$\Delta P^+_{G_i}$ Generation increment of i^{th} generator after islanding

$\Delta P^-_{G_i}$ Generation decrement of i^{th} generator after islanding

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ΔP_G^{k+} Total generation increment at k^{th} island

ΔP_G^{k-} Total generation decrement at k^{th} island

ΔP_{im}^{k} Total possible power imbalance at k^{th} island

ΔP_{L_i} Load curtailment at i^{th} load point after islanding

ΔP_L^k Total load shed at k^{th} island

δ_i Voltage angle of i^{th} node in power balance constraint

Ω^l Set of all transmission lines

Ω_k^d Set of load points in k^{th} island

Ω_k^g Set of generator nodes in k^{th} island

$\overline{U}_{ij}$ A fixed value of Binary variable U_{ij} .

$\{\bullet\}^s$ Subscript of artificial variables in connectivity constraint

$\{\bullet\}^{max}$ Subscript for maximum of a variable

$\{\bullet\}^c$ Subscript of artificial variables in grouping constraint

cte A constant value

f_0 Nominal frequency

G_{ij}, B_{ij} Real and imaginary parts of ij element in admittance matrix

H_k Equivalent inertia constant of generators in k^{th} island

$J(i)$ Set of nodes connected to node i by a transmission corridor

M An arbitrary large number

N Number of buses

N_k^g Number of generators in k^{th} island

N_{is} Number of islands(i.e. coherent groups)

N_{line} Number of transmission lines

N_{pq} Number of load points

N_{pv} Number of voltage controlled nodes

N_{sw} Number of allowable line switchings

P_{ij} Active power flow from node i to node j

U_{ij} Binary variable showing the switching of line between node i and j.

x_{ij} Reactance between nodes i and j

1. Introduction

1.1. Background and literature review

An important element of each self-healing scheme in power systems is the network reconfiguration to minimize the system vulnerability and to facilitate the restoration process to stop the spread of cascading failures [1, 2] .
Enhancing the resilience of power system to rare events such as uncontrolled islanding is an important requirement in power system operation and control. Self healing schemes have been recently developed in large scale power systems[1]. One of major phenomena, during a partial or wide-spread cascading failure is the formation of unplanned electric islands. Many blackouts would have been mitigated if the suitable controlled splitting strategy had been executed in time[3, 4]. Controlled islanding refers to the intentional splitting of an interconnected power system into stable isolated islands before experiencing a critical transition or blackout[5]. Two major issues must be considered in each controlled islanding strategy: a) the time of islanding and b) the splitting points. Many approaches have been proposed to determine the number and locations of islands such as slow coherency concept [6, 7, 8, 9], optimization-based approaches [10, 11, 12, 13, 14] and fuzzy-based algorithms [15]. In [6, 7], a singular perturbation technique is developed to divide the state variables of system into slow and fast states. The slow states represent groups with the slow coherency. In [8, 9], an integrated algorithm has been utilized to identify a cutset for large scale power system. The large scale power system is presented as a graph and a simplification technique is developed to reduce the complexity of system. In [10], the combination of spectral clustering and distributed optimization technique has been utilized for power system partitioning. In [11, 12, 13], evolutionary algorithms including particle swarm optimization, genetic algorithm, and tabu search have been utilized to solve the MINLP model of controlled islanding. In [14], a MILP stochastic programming model has been proposed to optimize islanding operations plan under severe multiple contingencies.
Graph theory is an efficient searching method for reducing the searching space of splitting scenarios[16, 17, 18]. In [16], using wide area measurement system the boundaries of islands are obtained by the weighted time varying graph structure of the network. In [17], the constrained spectral clustering is used to fine islanding boundary with minimal power flow disruption. In [18], the coherent islands are determined using synchrophasor data based on graph modeling. In [19] a combination of graph theory and optimization has been utilized to minimize the real and reactive power imbalance at the resulted islands.
All steady state constraints in each islanding strategy including power balance constraint, slow coherency constraint(i.e. grouping constraint), and connectivity constraint can be merged in a Mixed Integer Linear Programming (MILP) model. Unlike the graph-based splitting strategies, in MILP-based partitioning strategy it is possible to optimize an objective function(e.g. load shedding), while satisfying the related constraints.
In [1] the islanding strategy and adaptive under frequency load shedding have been utilized for self healing in power systems.
However the conventional MINLP-based and MILP-based splitting strategies suffer from two disadvantages including the CPU time of calculation and ignoring the stability considerations. In this paper, BD technique is utilized to solve the proposed MILP

formulation. A switching constraint is proposed to speed up the algorithm and reduce the searching space of splitting strategies. Also a new constraint is proposed to improve the frequency stability of the network after partitioning. In this paper, the prediction of islanding is done using the energy based approach proposed in [20]. It is noted that the present paper is focused on the " where to island" issue of splitting strategy. In other words it is assumed that making decision about the timing of islanding(i.e. "when to island" issue) is the task of another program such as methods proposed in [20, 21].

1.2. Contributions

The contributions of this paper are as follows.

1.2.1. ***Decomposition Based MILP Formulation***

A MILP formulation is developed to seek the optimal splitting strategy using BD technique. The proposed MILP formulation is solved using BD technique in which the original MILP problem is separated into a relaxed MILP master problem and one LP sub-problem.

1.2.2. ***Switching Constraint***

The splitting problem of a large power system has generally a huge searching space(e.g. for IEEE 118-bus network with 186 lines, there are 2^{186} possible (but not practical) choices for system splitting. In this paper a switching constraint is proposed to limit the number of line switchings(i.e. opening points). This constraint reduces the searching space of splitting strategies significantly.

1.2.3. ***Linear Algorithms to Check Separation and Connectivity***

Before running Decomposition-based MILP formulation the coherent generators are determined using coherency technique. During running MILP formulation and to assure the synchronism of generators in each island, it is required to keep each group of coherent generators in a same island. In this paper the inter-connectivity of each island and the physical separation of non-coherent groups of generators are satisfied using a set of linear equations.

1.3. Paper organization

The rest of this paper is organized as follows. In section II the details of the MILP-based splitting strategy are described. Also the proposed Artificial DC Load Flow (ADCLF) algorithms are described in this section. The formulation of the BD-based procedure to solve the splitting strategy is discussed in Section III. The results of applying the proposed method over IEEE-30 bus and IEEE-118 bus test systems are given in Section IV. Finally, the conclusions are provided in section V.

2. MILP-based islanding strategy

The overall structure of the proposed scheme has been illustrated in Fig. 1. The coherent groups of generators are determined using slow coherency technique based on the phasor measurement data. This study could be done offline. After deciding to split, the proposed MILP is solved and the obtained strategy is executed.

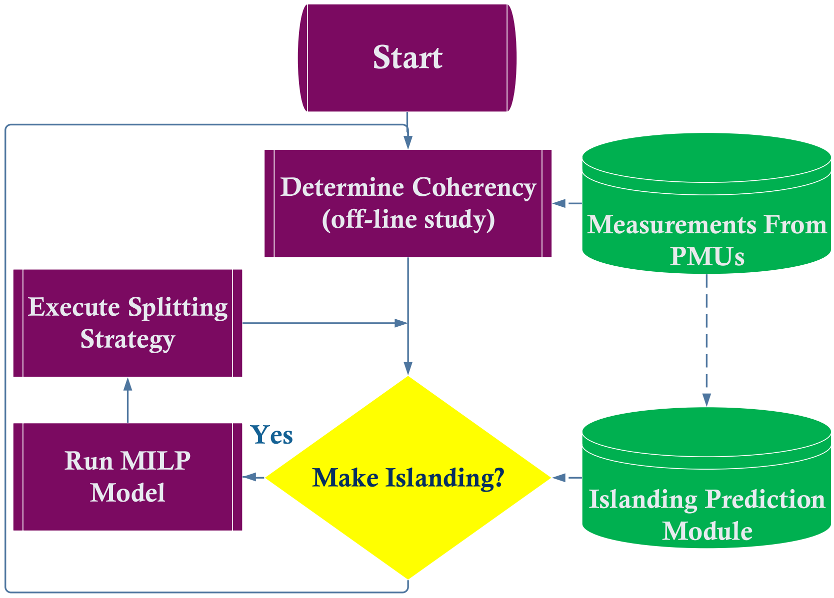


Figure 1: Overall structure of the proposed scheme

In this paper all constraints of islanding problem are combined in a MILP model to obtain the stable islands with minimum load shedding. The objective function is expressed as follows:

$$\textbf{Min} \;\; OF = \sum_{i=1}^{N_{pq}} [\alpha_i \Delta P_{L_i}] \tag{1}$$

where the weighting factor α_i is used to consider the priority of different loads. Different constraints are defined to achieve the stable islands as follows.

2.1. ***Power balance constraint***

The power balance constraint could be modeled using AC or DC power flow equations. DC power flow results in a more computationally favorable MILP problem assuming that reactive power balance is satisfied locally after network splitting. In this paper the active power balance constraint at each node in each island is expressed by a DC load flow formulation as follows.

$$\sum_{j\in J(i)} P_{ij} = [P^0_{Gi} + \Delta P^+_{Gi} - \Delta P^-_{Gi} - (P^0_{Li} - \Delta P_{Li})] \quad \forall i \in N \tag{2}$$

For each transmission line, ij, the power flow is expressed as follows.

$$P^f_{ij} = \frac{\delta_i - \delta_j}{x_{ij}} \tag{3}$$

$$-M(1-U_{ij}) \leq P_{ij} - P^f_{ij} \leq M(1-U_{ij}) \tag{4}$$

$$-P^{max}_{ij} U_{ij} \leq P_{ij} \leq P^{max}_{ij} U_{ij} \tag{5}$$

where (4) and (5) are proposed to linearize the term $P_{ij} = U_{ij} P_{ij}^{f}$.
The generation increment could be provided by the ramping-up of running generators or fast start units. Without loss of generality, the limits of generation change and load shedding are expressed as follows.

$$0 \leq \Delta P_{Gi}^{+} \leq \Delta P_{Gi}^{max+} \tag{6}$$
$$0 \leq \Delta P_{Gi}^{-} \leq \Delta P_{Gi}^{max-} \tag{7}$$
$$0 \leq \Delta P_{Li} \leq \Delta P_{Li}^{max} \tag{8}$$

In this paper it is assumed that in each island one generator is selected as the regulating generator with the capability of fast generation change. Hydro and fast start gas turbine generating units are suitable candidates as the regulating generators.

2.2. ***Grouping Constraint***

The grouping constraint is considered to ensure the synchronism of generators in each island. By splitting the network along the boundaries of these groups, subject to providing minimum load and generation imbalance, the resulted islands are less likely to lose their stability [7]. Coherency of two synchronous machines refers to the consistency of their rotor angle trajectories. Using slow coherency based islanding, the coherent generators are located in the same island. Therefore, the number of required islands are assumed equal to the number of coherent groups of generators. The main advantage of coherency-based islanding is that the resulted grouping of generators does not depend significantly on initial conditions, size of the disturbance and the details of generator's model.
In this paper, before running the MILP splitting strategy the coherent generators are determined using slow coherency technique as proposed in [7]. The set of coherent generators are then used as the input of MILP splitting strategy. The coherent generators must be grouped in a same island via the MILP formulation. Also asynchronous groups of generators must be separated. This requirement is called the grouping constraint which is formulated using a linear ADCLF algorithm as given in (9)-(11).

$$P_{ij}^{fc} = \frac{\theta_i^c - \theta_j^c}{x_{ij}^c} \tag{9}$$
$$-M \times U_{ij} \leq P_{ij}^{c} \leq M \times U_{ij} \tag{10}$$
$$-M(1 - U_{ij}) \leq P_{ij}^{c} - P_{ij}^{fc} \leq M(1 - U_{ij}) \tag{11}$$

The ADCLF algorithm satisfies the physical separation of non-coherent islands by the following settings.

$$P_{ij}^{c} = 0 \qquad \forall ij \in \Omega^{l} \tag{12}$$
$$\theta_i^c = cte_k \qquad \forall i \in \Omega_k^{g} \tag{13}$$
$$cte_1 \neq cte_2 \neq ... \neq cte_{N_{is}} \tag{14}$$

It is noted that this formulation is used just for checking the topological separation of non-coherent generators. According to (13) the artificial voltage angles of generators in each island(e.g. island k) are fixed at a similar constant value (e.g. cte_k). Also the artificial voltage angles of load points in each island are assumed as variables. According to (13) the artificial voltage angles of islands must be set at different values. Indeed this assumption allows the ADCLF to make power flow across the transmission lines. However according to (12) all power flows across the transmission lines are fixed at zero. *Zero load flow for all transmission lines is achieved if and only if there is no physical path between different islands.* According to (13) and (15) a zero line flow is occurred either when there is no connection (i.e. $x_{ij} \Rightarrow \infty$) or when the angle difference across the line is zero(i.e. $\theta_i^c = \theta_j^c$). Therefore when the nodes i and j belong to different islands the zero power flow will assure the dis-connectivity of the related islands.

$$P_{ij}^c = 0 \begin{cases} \theta_i^c = \theta_j^c & \text{nodes i and j are in same island} \\ U_{ij} = 0 & \text{no connection between i and j} \end{cases} \tag{15}$$

2.3. ***Connectivity Constraint***

Here to check inter-connectivity of each island, the ADCLF algorithm is used as a fast and non-iterative alternative for graph-based methods such as Breadth-Birst Search (BFS) or Depth First Search(DFS) algorithms. It is noted that using the grouping constraint the physical separation of non-coherent generators is satisfied. However the connectivity of coherent generators in each island is assured using connectivity constraint. Assume that the adjacency matrix of a sub-graph(i.e. the graph of a coherent group) is known. This is a N_k^g-by-N_k^g sparse matrix in which the nonzero entries indicate the presence of an edge. First of all, one node is assumed as a slack generator. All other generator nodes(i.e. $N_k^g - 1$ nodes) are assumed as load points with a small and nonzero demand value(e.g. 0.1^{pu}). Also a small reactance is assigned to each edge or transmission line (e.g. 0.01^{pu}). The resulted network is now an electrical network with $N_k^g - 1$ load points and a single slack node. These settings are chosen to assure the feasibility of the proposed ADCLF algorithm. It should be noted that no limit has been imposed on voltage angles and line flows in the proposed ADCLF. Therefore, the proposed ADCLF only consists of independent linear equations. Therefore, if the original graph is connected then the ADCLF algorithm has a feasible solution. All the inputs and outputs of the proposed ADCLF are artificial data without conflicting with the main DC power balance constraint of the islanding strategy.
The ADCLF algorithm is formulated as follows.

$$\sum_{j \in J(i)} P_{ij}^{s,k} = P_{Gi}^{s,k} - P_{Li}^{s,k} \qquad \forall i \in \Omega_k^g, \quad k = 1, ..., N_{is} \tag{16}$$

$$P_{ij}^{fs,k} = \frac{\theta_i^{s,k} - \theta_j^{s,k}}{x_{ij}^{s,k}} \tag{17}$$

$$-M \times U_{ij} \leq P_{ij}^{s,k} \leq M \times U_{ij} \tag{18}$$

$$-M(1 - U_{ij}) \leq P_{ij}^{s,k} - P_{ij}^{fs,k} \leq M(1 - U_{ij}) \tag{19}$$

This ADCLF algorithm will assure the connectivity of each island(i.e. $k = 1, ..., N_{is}$) using the following settings.

$$P_{Gi}^{s,k} = \begin{cases} \geq 0 & \text{at a slack node p in } k^{th}\text{island} \\ 0 & \text{at all generators except p in } k^{th}\text{island} \end{cases} \tag{20}$$

$$P_{di}^{s,k} = \begin{cases} 0 & \text{at node p in } k^{th}\text{island} \\ D_i^{s,k} & \text{at all generators except p in } k^{th}\text{island} \end{cases} \tag{21}$$

where $D_i^{s,k}$ is a small and constant demand value at related nodes.

2.4. Switching Constraint

The splitting problem of a large power system has generally a huge searching space. In this paper a switching constraint is proposed to limit the number of line switchings(i.e. opening points). This constraint reduces the searching space of splitting strategies, significantly. This switching constraint could be formulated as given in (22).

$$\sum_{ij \in \Omega_l} U_{ij} \geq (N_{line} - N_{line}^{sw}) \tag{22}$$

A lower number of line switchings results in easier restoration process. Total number of transmission lines between approximate boundaries of coherent groups may be assumed as the maximum number of allowable line switchings.
Here, for better convergence of BD algorithm(i.e. to limit the searching space of splitting strategies) and minimizing the number of line switchings, another term is added to the main objective function as follows.

$$Min \;\; OF = \sum_{i=1}^{N_{pq}} [\alpha_i \Delta P_{L_i}] - \sum_{\forall ij \in \Omega^l} [\gamma_{ij} U_{ij}] \tag{23}$$

In this paper the cost of load shedding at all load buses is assumed as $\alpha_i = 1$. The weighting factor of switching constraint is fixed at a small value (e.g. $\gamma_{ij} = 0.001$) to avoid sacrifice of load for minimizing number of line switchings.

2.5. Frequency Stability Consideration

In this paper a constraint is proposed to promote the frequency stability of each resulted island. Due to inherent delay in execution of load shedding and generation change it is expected to have a specific power imbalance in each island for a short time. The resulted power imbalance must be limited to avoid severe frequency decline. In this paper the maximum allowable power imbalance during such short time is constrained according to the maximum allowable rate of change of frequency. This issue is formulated as follows.

$$\Delta P_{im}^{k} = [\Delta P_{L}^{k} + \Delta P_{G}^{k+} - \Delta P_{G}^{k-}] \tag{24}$$

$$\Delta P_{im}^{k} \leq \frac{2 * H_k}{f_0} (df/dt)^{max} \tag{25}$$

where

$$\Delta P_{L}^{k} = \sum_{i \in \Omega_k^d} \Delta P_{Li} \tag{26}$$

$$\Delta P_{G}^{k+} = \sum_{i \in \Omega_k^g} \Delta P_{Gi}^{+} \tag{27}$$

$$\Delta P_{G}^{k-} = \sum_{i \in \Omega_k^g} \Delta P_{Gi}^{-} \tag{28}$$

According to this constraint islands with lower inertia constants experience lower power imbalance. Using the slow coherency technique, the set of coherent generators is determined. The equivalent inertia time constant of each island will be the summation of the inertia constants of coherent generators in that island. The upper limit of the rate of change of frequency is determined using off-line stability simulations. In this paper the maximum rate of change of frequency is assumed equal to 1 Hz/sec.

3. Benders Decomposition for MILP solution

In this section, the formulation of BD technique for the MILP problem is presented. The MILP problem is solved in two stages including a relaxed MILP as the master problem and one LP sub-problem. The master problem aims to determine splitting points that satisfy grouping constraint. The sub-problem seeks solution with minimum load shedding by satisfying connectivity constraint, frequency stability constraint, and generators' limits.

3.1. Master Problem

The master problem which is a relaxed MILP problem is introduced as follows.

$$\underset{U}{Min}\, Z \tag{29}$$

$$Z \geq -\sum_{ij} \gamma_{ij} U_{ij} \tag{30}$$

$$\sum_{ij} U_{ij} \geq (N_{line} - N_{line}^{sw}) \tag{31}$$

The load flow equations to check the grouping constraint are included in master problem as follows.

$$(9) - (14) \tag{32}$$

Based on the Lagrange multipliers(i.e. the Lagrange multiplier of equality constraint: $U_{ij} = \overline{U}_{ij}$) the set of Benders cuts are defined as follows.

$$\textbf{Benders Cuts:} Z \geq W(\overline{U}_{ij}) + \sum_{ij} \lambda_{ij}(U_{ij} - \overline{U}_{ij}) \tag{33}$$

where the $\overline{U}_{ij}$ is obtained from the previous iteration of master problem. The sub-problem is a linear formulation which is solved by fixing the value of U_{ij} at $\overline{U}_{ij}$.

3.2. Sub-Problem

Based on a pre-determined value of binary variables(i.e. $\overline{U}_{ij}$) the linear sub-problem is defined as follows.

$$\textbf{Min} \;\; W = \sum_{i=1}^{N_{pq}} [\alpha_i \Delta P_{L_i}] + M \sum_{k=1}^{N_{is}} r_i^{s,k} + M \sum_{i} (\Delta P_{Gi}^{s+} + \Delta P_{Gi}^{s-}) \tag{34}$$

where the second and third terms have been added to the original objective function to handle any infeasibility caused by the connectivity constraints, generators' limits, and frequency stability constraint. To magnify the impact of each infeasibility on objective function (34), it is required to set the value of weighting factor M at a large value (i.e. $M = 100$). The set of DC load flow to model the power balance equation at each node is included in sub-problem as follows.

$$(3) - (8) \tag{35}$$

However, constraint (2) is modified as follows:

$$\sum_{j \in J(i)} P_{ij} = P_{Gi}^0 + \Delta P_{Gi}^+ - \Delta P_{Gi}^- + \Delta P_{Gi}^{s+} - \Delta P_{Gi}^{s-} - (P_{Li}^0 - \Delta P_{Li}) \quad \forall i \in N \tag{36}$$

where the positive variables ΔP_{Gi}^{s+} and ΔP_{Gi}^{s-} are introduced to handle any infeasibility due to generators' limits or frequency stability constraint.

The constraint given by (16) must be modified as follows.

$$\sum_{j \in J(i)} P_{ij}^{s,k} = P_{Gi}^{s,k} - P_{Li}^{s,k} + r_i^{s,k} \qquad \forall i \in \Omega_k^g \quad and \quad k = 1, ..., N_{is} \tag{37}$$

where the new positive variable $r_i^{s,k}$ is included to remove any infeasibility of subproblem due to connectivity constraint. It is noted that the non-zero value of $r_i^{s,k}$ confirms the infeasibility of subproblem. Other connectivity and frequency stability constraints are included as follows.

$$(17) - (21) \tag{38}$$

$$(24) - (28) \tag{39}$$

4. Simulation Results

In this section the proposed MILP-based splitting strategy is simulated for two IEEE 30-Bus and IEEE 118-Bus test systems. The data of these test systems can be found in [22]. The coherency of generators is determined using slow coherency technique. The obtained coherent groups of generators are then passed to the MILP splitting strategy. The results of the proposed splitting strategy including the total load shedding, number of line switchings and computational CPU time are presented.
It is assumed that all loads are available to be shed up to their maximum values. For the sake of simplicity it is assumed that all load points have the same priority for shedding. Time domain simulations are carried out to validate the accuracy of the proposed method. All simulations have been done on a PC with Intel Corei5 3.2 GHz CPU, and 4 GB RAM.

4.1. IEEE 30-Bus Test Grid

This test case has 6 synchronous machines with 24 load points. The dynamic data are as given in [22]. All generators are equipped with IEEEG1 Automatic Voltage Regulator. All loads have been considered as constant power. Using the slow coherency technique two coherent generator groups are formed including group 1 : $(G1, G2)$ and group 2: $(G13, G22, G23, G27)$. Therefore two different islands are assumed. Generators at nodes 1 and 13 are assumed as slack nodes for fast generation change after splitting in islands 1 and 2, respectively.
The proposed MILP strategy is verified for a typical islanding strategy. The base-case reactance of line 13-12 is $x_{12-13} = 25.515^{\Omega}$. Suppose that this impedance is related to a double circuit line or a parallel transmission line. Assume that one circuit of transmission lines between bus 12 and bus 13 is unavailable due to maintenance. Therefore the reactance will be twice the base case reactance(i.e. $x_{12-13} = 51.03^{\Omega}$). At this situation a delayed three phase short circuit is occurred at bus 6 at $t = 1^{sec}$ and is cleared at $t = 1.480^{sec}$ with tripping line $6 - 9$. The rotor angle trajectories of synchronous machines with respect to reference machine(i.e. G1) and the frequency of both islands without executing the splitting strategy have been illustrated in Fig. 4a and Fig. 4b, respectively. It can bee seen that the coherent generators in second island (i.e. G13,G22,G23,G27) are separating electrically from the first group(i.e. G1,G2) . The generator at bus 13 will experience the pole slip. By tripping this generator using the out-of-step relay the electrical frequency of the network will reduce to $0.955 f_0$ and this frequency decline cause the tripping of other generators. To stop this process the proposed partitioning strategy is executed 7 cycles after fault clearing. Results of the proposed splitting strategy over the IEEE 30-bus test grid using the full MIP and BD-based models have been given in Table 1. The convergence rate of the proposed BD algorithm has been shown in Fig. 2.
The obtained splitting boundary using the BD-based algorithm has been illustrated in Fig. 3. The rotor angle trajectories of synchronous machines and the frequency of both islands after executing the BD-based splitting strategy have been illustrated in Fig. 5a and Fig. 5b, respectively. It can be seen that the splitting strategy maintain the stability of the system. According to Table 1 the CPU time of BD-based MILP model(i.e. 0.343 sec) is significantly lower than the CPU time of full MIP model.

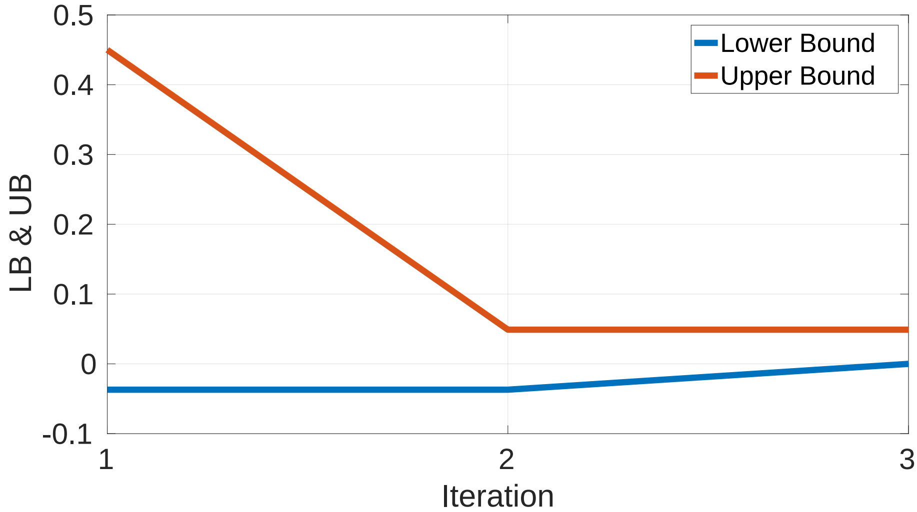


Figure 2: Convergence rate of the proposed algorithm for 30-bus test system

Table 1: Results of Islanding strategy for IEEE-30 bus grid

	Proposed BD-based Algorithm
CPU Time	0.343 sec
Switching Lines	4-12 , 6-9, 6-10,27-28
Cost Function	8.6 MW ($\Delta P_{L_{30}} = 8.6^{MW}$)
Generation Change	($\Delta P^{-}_{G_1} = 16^{MW}$) ($\Delta P^{+}_{G_{13}} = 7.4^{MW}$)
	Proposed MIP-based Algorithm
CPU Time	0.745 sec
Switching Lines	4-12 , 6-9, 6-10,27-28
Cost Function	8.6 MW ($\Delta P_{L_{12}} = 0.4^{MW}$) $\Delta P_{L_{15}} = 8.2^{MW}$)
Generation Change	($\Delta P^{-}_{G_1} = 16^{MW}$), ($\Delta P^{+}_{G_{13}} = 7.4^{MW}$)

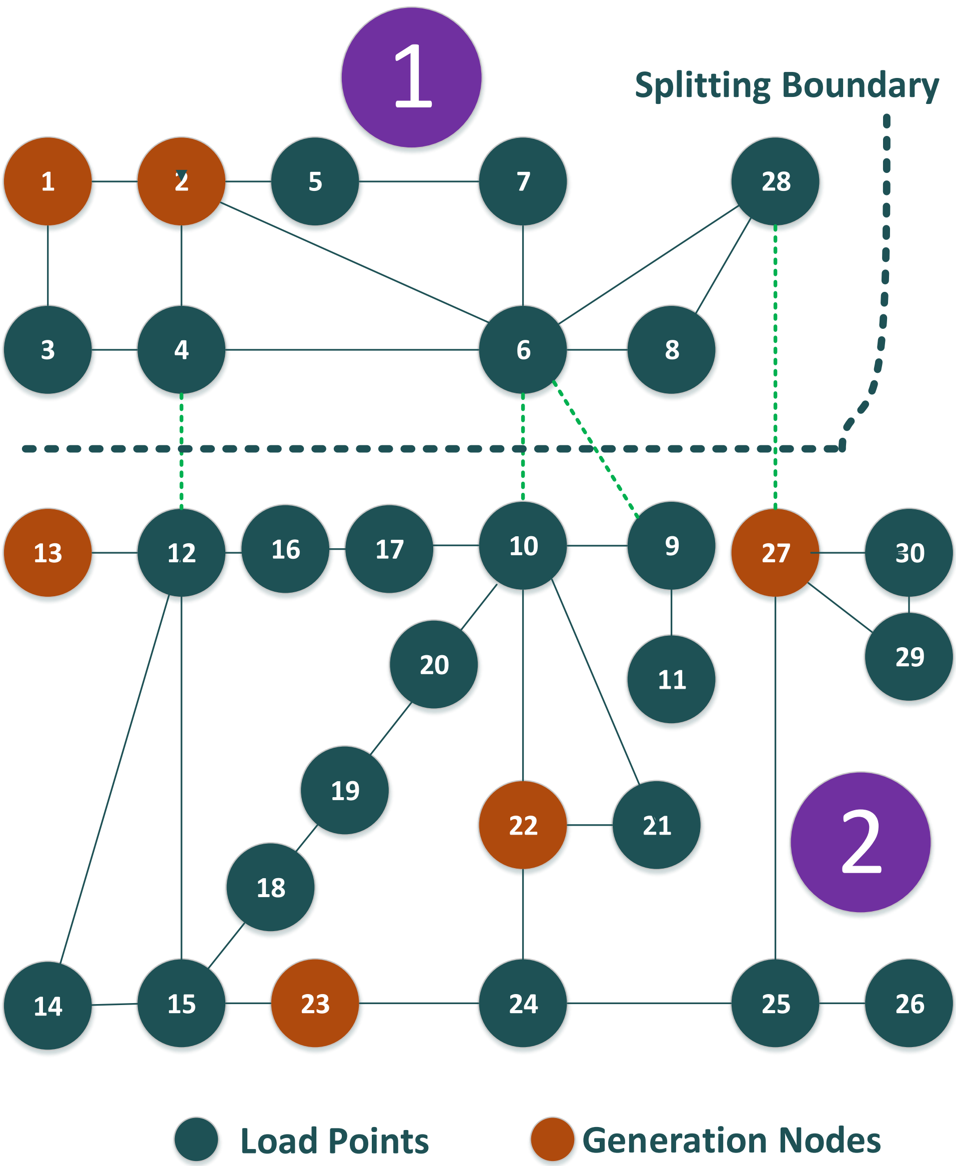
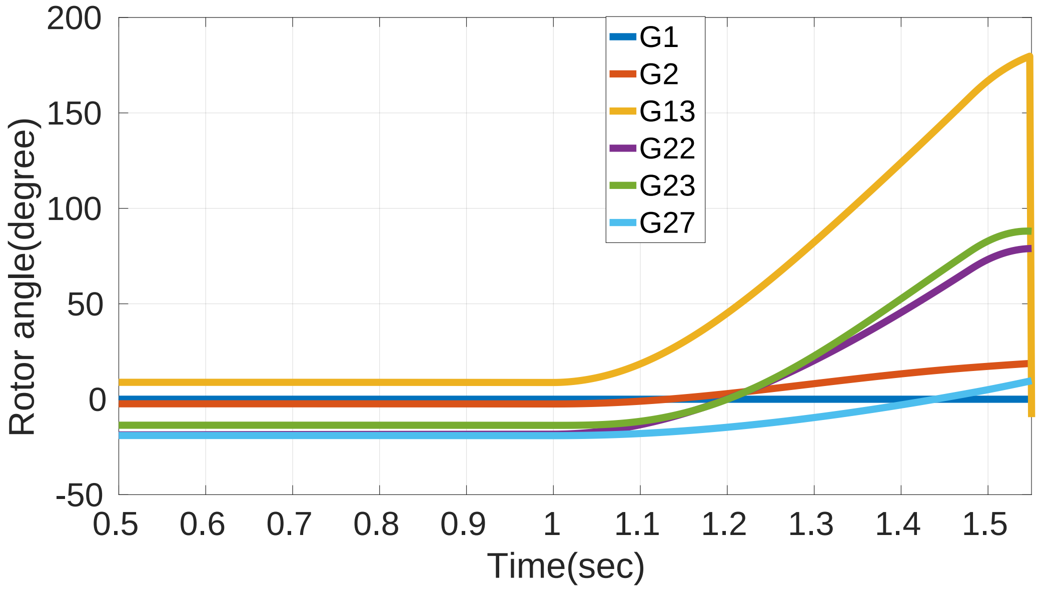
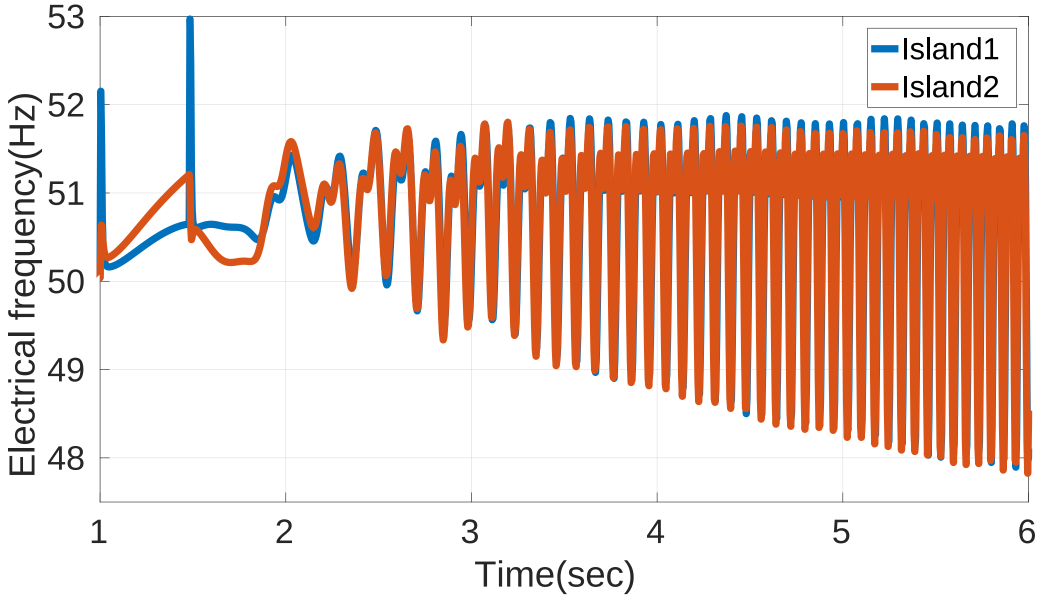


Figure 3: The resulted islands for IEEE 30-bus test system

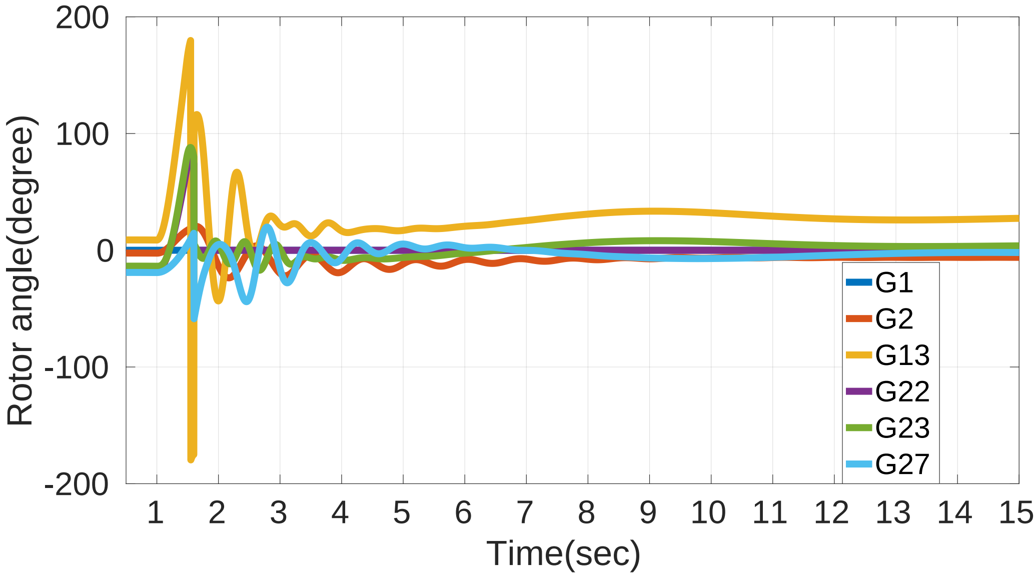


(a) Rotor angles

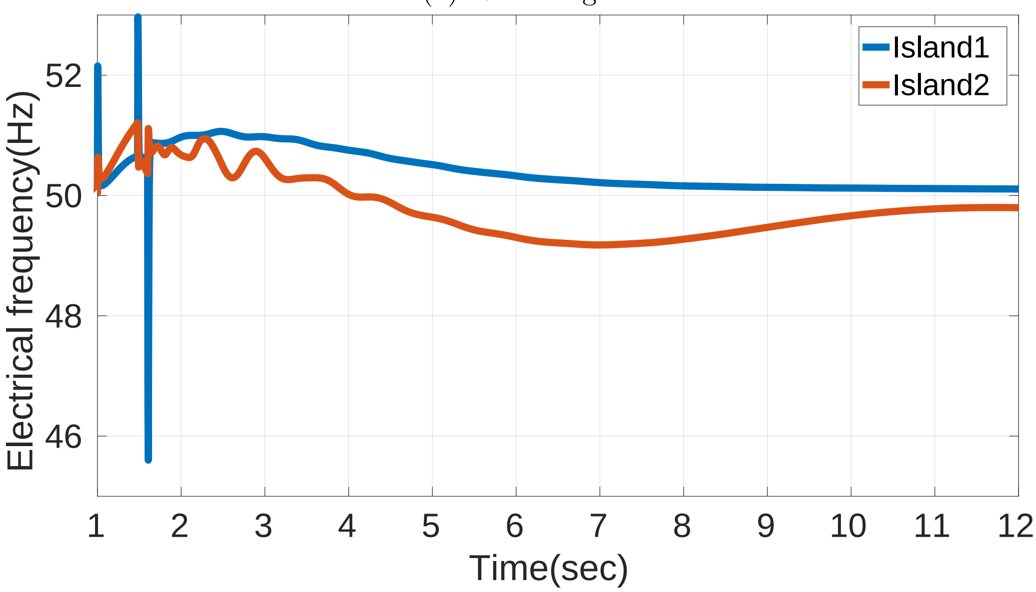


(b) Electrical frequency

Figure 4: Time simulation for IEEE 30-bus system without executing the splitting strategy



(a) Rotor angle



(b) Electrical frequency

Figure 5: Time simulation for IEEE 30-bus system with executing the splitting strategy

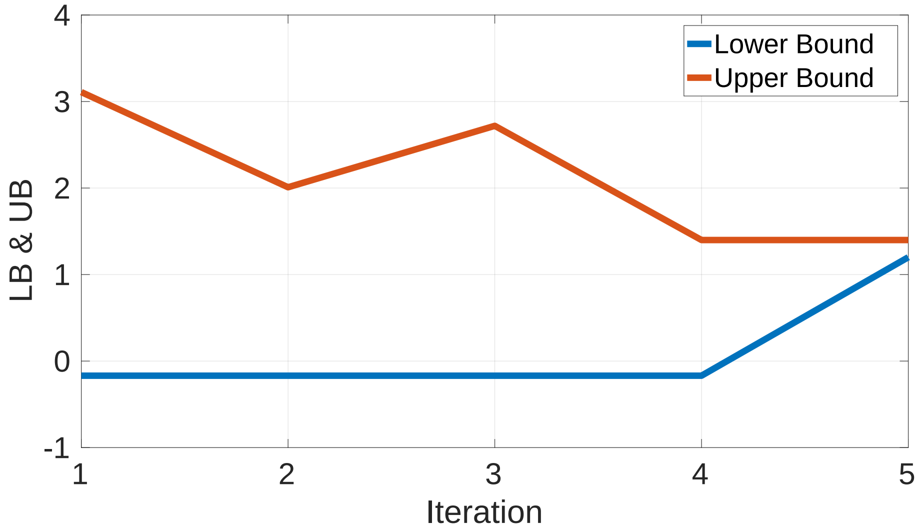


Figure 6: Convergence rate of the proposed algorithm for 118-bus test system

4.2. IEEE 118-Bus test grid

The IEEE-118 bus test grid has 19 synchronous generators. The utilized static and dynamic data are as given in [22]. Using the slow coherency technique, three coherent groups are formed as given in Table 2. All synchronous generators are equipped with IEEEG1 automatic voltage regulator and a standard governor. It is assumed that a delayed three phase short circuit fault is occurred at bus 30 of transmission lines 26-30 at $t = 1^{sec}$ and is cleared at $t = 1.540^{sec}$. Following this fault the generators G10 will be out-of-step. By tripping the generator G10 as a large unit, the network experiences a severe frequency decline causing the outage of other generators.

The results of applying the proposed splitting strategy over the IEEE 118-Bus system have been given in Table 3 for BD-based and full MIP models. Generators G10, G69, and G89 are considered as regulating units for increasing or decreasing generation after islanding. The convergence rate of the proposed BD algorithm has been shown in Fig. 6.

The obtained splitting boundaries have been depicted in Fig. 9. The rotor angle trajectories of synchronous generators in island 1 have been illustrated in Fig. 7a and Fig. 8a without and with executing the proposed splitting strategy, respectively. Also the frequency of each island without and with executing the splitting strategy has been depicted in Fig. 7b and Fig. 8b, respectively. It can be seen that the obtained strategy will satisfy the frequency stability constraint. According to Table 3 the CPU time of BD-based algorithm is significantly lower than the full MIP model.

5. Conclusion

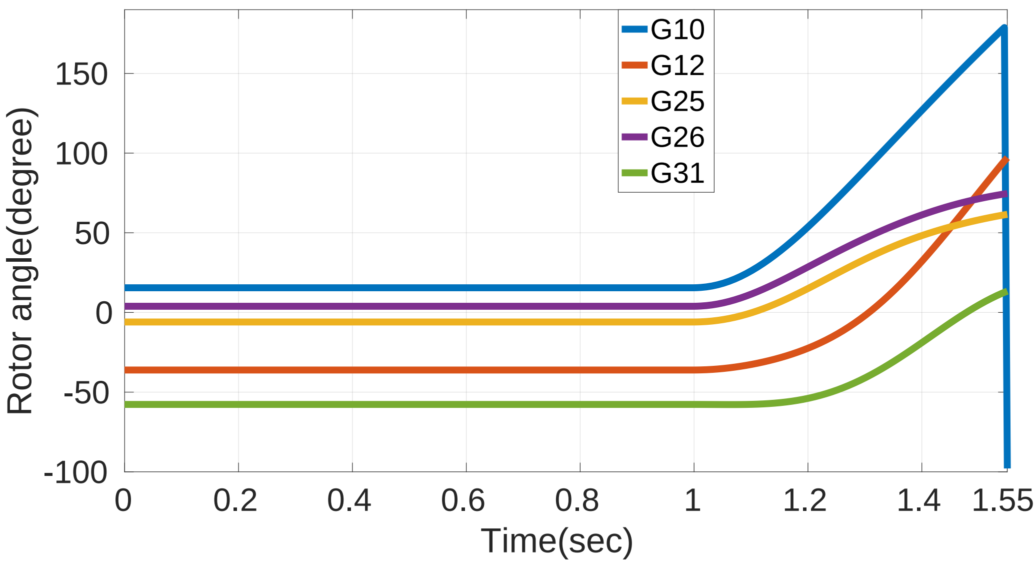
In this paper the splitting strategy was developed as a MILP problem with considering coherency and frequency stability constraints. The proposed linear grouping and connectivity constraints are fast alternatives for DFS and BFS graph-based techniques. The proposed switching constraint reduces the searching space of splitting strategies. Also the BD-based algorithm reduces the CPU time of calculations with respect to the

Table 2: The obtained coherent groups for IEEE 118-bus system

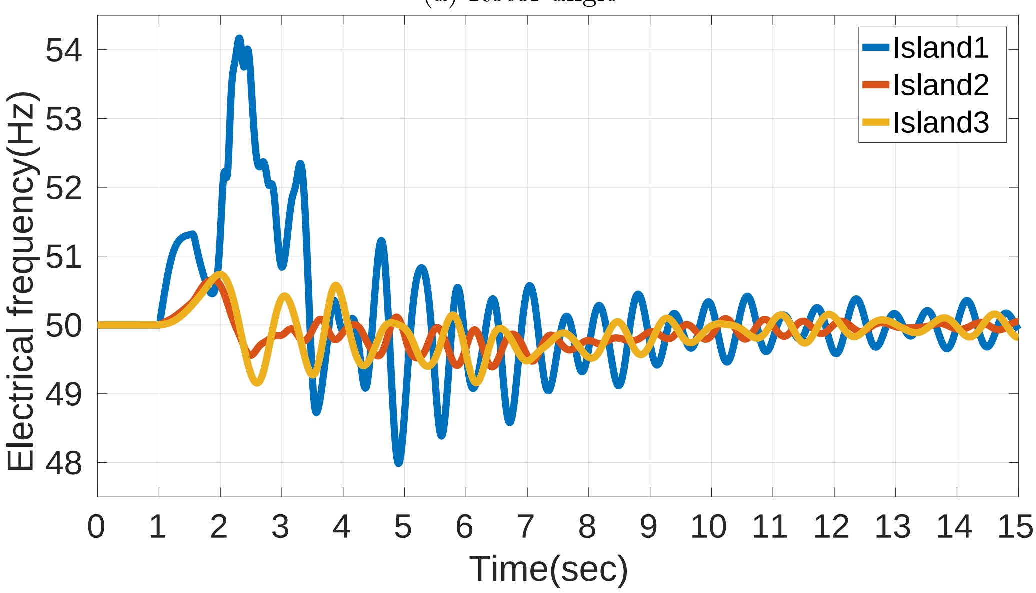
Gen No	Coherent Island		
	Island 1	Island 2	Island 3
10 12 25 26 31	●	-	-
46 49 54 59 61 65 66 69 80	-	●	-
87 89 100 103 111	-	-	●

Table 3: Results of Islanding strategy for IEEE-118 bus grid

	Proposed BD-based Algorithm
CPU Time	3.556 sec
Switching Lines	15-33, 23-24 ,19-34, 30-38 69-77 ,75-77, 76-77,68-81
Cost Function	156.8 MW $(\Delta P_{L55} = 1.8^{MW})$, $(\Delta P_{L60} = 78^{MW})$ $(\Delta P_{L62} = 77^{MW})$
Generation Change	$(\Delta P^{+}_{G69} = 76.2^{MW})$, $(\Delta P^{-}_{G10} = 113^{MW})$ $(\Delta P^{-}_{G89} = 120^{MW})$
	Proposed MIP-based Algorithm
CPU Time	8.672 sec
Switching Lines	23-24 ,34-43,38-65,42-49 77-80,79-80 ,77-82,68-81
Cost Function	169 MW $(\Delta P_{L1} = 43.9^{MW})$, $(\Delta P_{L3} = 23.3^{MW})$, $(\Delta P_{L4} = 12^{MW})$, $(\Delta P_{L6} = 18.8^{MW})$, $(\Delta P_{L42} = 67.9^{MW})$,$(\Delta P_{L117} = 3.1^{MW})$
Generation Change	$(\Delta P^{+}_{G69} = 32^{MW})$, $(\Delta P^{+}_{G10} = 90^{MW})$ $(\Delta P^{-}_{G89} = 291^{MW})$

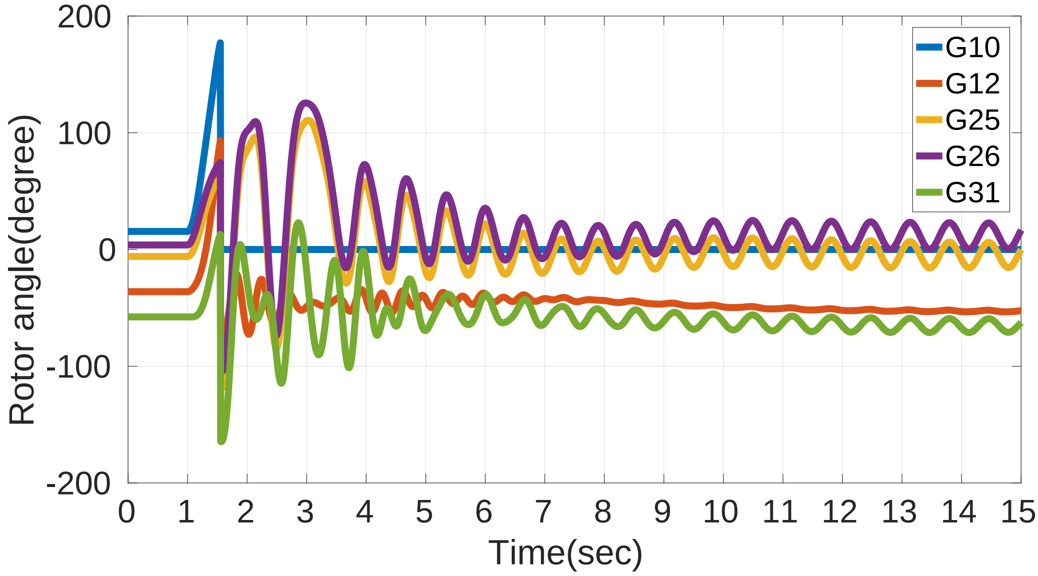


(a) Rotor angle

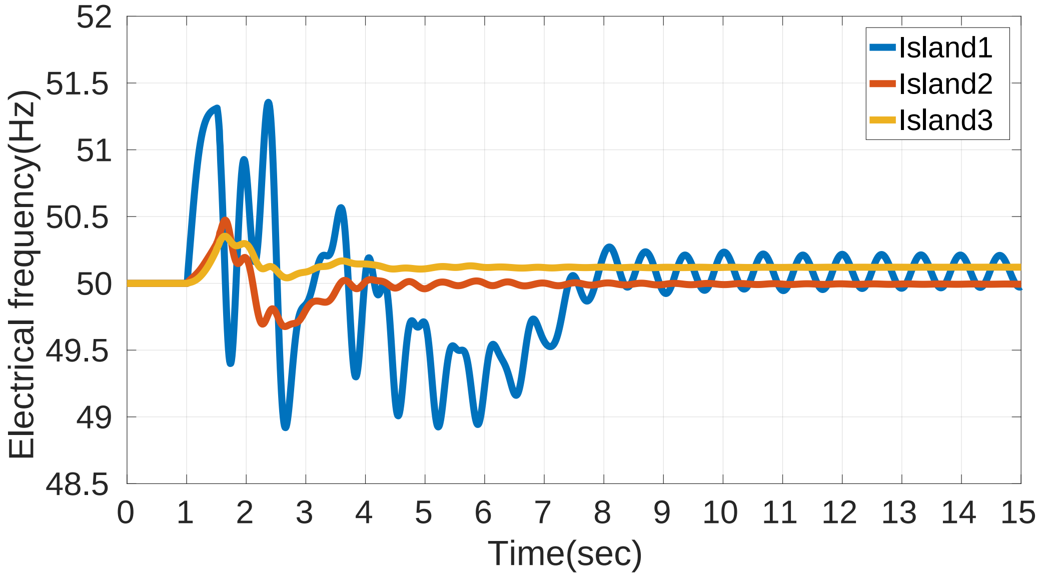


(b) Electrical frequency

Figure 7: Time simulation for IEEE 118-bus system without executing the splitting strategy



(a) Rotor angle



(b) Electrical frequency

Figure 8: Time simulation for IEEE 118-bus system with executing the splitting strategy

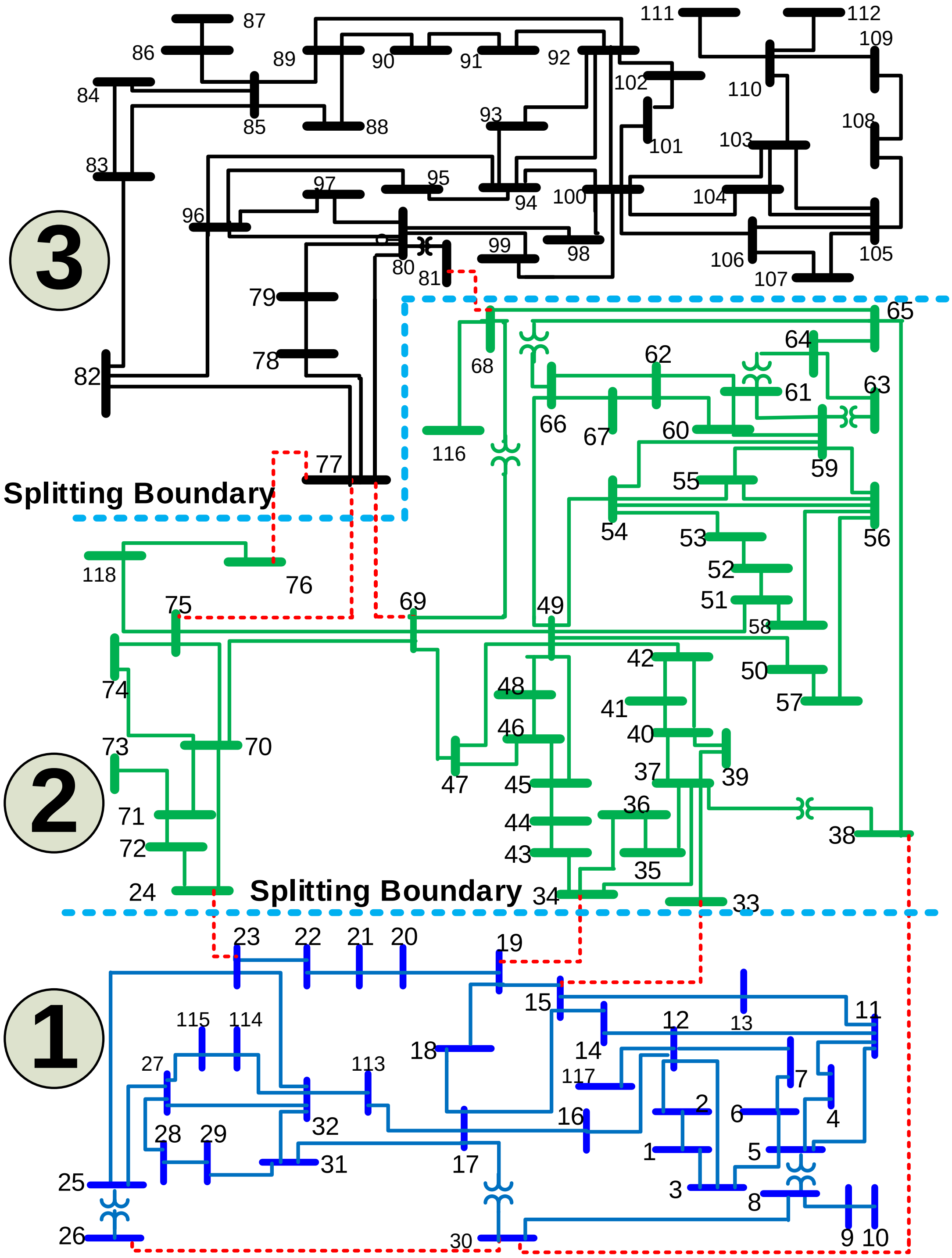


Figure 9: The resulted islands for IEEE 118-bus test system

full MILP-based splitting approach. Using time domain simulations, it was shown that by limiting the maximum allowable power imbalance in each island, the frequency stability is improved. The obtained results validated the efficacy of the proposed decomposition-based partitioning strategy especially for large scale power systems.

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