Fast Network Restoration by Partitioning of Parallel Black Start Zones

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Abstract: The restoration of large electrical power systems after a blackout is often a challenging task. A typical restoration process includes the partitioning of the power systems into subsystems and the successive booting of large non-black start (NBS) units by black start (BS) units. A proper partitioning of the starting zone can reduce the restoration time significantly.

This paper investigates a novel network partitioning algorithm to improve the restoration time and ratio of generation and load in each subsystem. The proposed algorithm consists of three stages. In the first stage, the number of subsystems is determined by the number of available BS units and their electrical distance. In the second stage, NBS units are assigned to each subsystem in the way that the rebooting time difference among subsystems is minimized. In the third stage, the substations are assigned to one of the subsystems to achieve the optimal ratio of generation and load in each subsystem.

With the proposed algorithm the switching transient and steady state over-voltages at the receiving end of unload lines are kept within acceptable ranges and the self-excitation phenomenon does not occur in the subsystems. Furthermore, the start-up sequence of NBS units in each subsystem is determined simultaneously. The proposed algorithm is flexible and can be adjusted very easily according to the real status of the power system. The validity and performance of the proposed approach is demonstrated through simulations using a New England 39 Nodes network and a real network from south China.

1. Introduction

With the development of the modern societies, power supply reliability becomes one of the most important issues for today's network operators. A power system blackout can cause serious consequences such as paralysis of social life and industry collapse. Recent power system blackouts (for instance, the Northeast America blackout in 2003 [1], the power system collapse in Japan caused by an earthquake in 2011 [2] and the Northern, Eastern and Northeast India power system blackout in July 2012 [3]) have demonstrated that an efficient power system restoration plan is of utmost importance for reducing the economical impacts.

General challenges and guidelines for a network restoration process are discussed in [4, 5, 6, 7, 8]. Power system restoration subdivides into build-up and build-down strategies [9, 10], and has to consider aspects such as the start-up sequence of the thermal units, over-voltage problem caused by self-excitation and energizing unload transmission lines, skeleton transmission network restoration, frequency control during the load restoration, and cold load pick up. Additionally, the restoration process depends on the status of the power system, the size of the network, the location of the BS units, and the network topology.

Rule based expert systems are a popular approach for the creation of restoration plans [11, 12, 13, 14]. The expert systems may utilize knowledge of human experts and combine expert knowledge with optimization to achieve run-time flexibility.

In order to achieve even better restoration results, evolutionary algorithms have been recently used to optimize the complex restoration process. Thereby, multiple aspects of a restoration procedure have been investigated. In [15] the maximal load restoration has been approached by a parallel genetic algorithm (GA). The BS unit placement has been optimized regarding restoration efficiency in [16] and [17]. Restoration under a high number of renewables has been investigated in [18].

An important aspect of our approach is the optimized network subdivision to allow BS units to provide cranking power to NBS units in a sequence that minimizes the overall restoration time. Close to our approach comes the method using the ordered binary decision diagram (OBDD) for automatic power system subdivision in [19]. However, in the publication only a simplified power plant booting model is utilized which is not considering start-up time limits. Additionally, the boot sequence in each of the subsystems is neglected. In [20], the authors partition the grid to ensure that each subsystem is observable by considering the location of online Wide Area Monitoring (WAMS). However, the status and characteristics of the generators in grid are not considered which play a key role for the power system restoration.

In this paper, following assumptions are made:

1. The network has more than one BS unit that can be started in parallel;
2. The subsystems can be synchronized because of synchronizing switches and synchronization controls of BS units;
3. The ICT infrastructure is available to coordinate all considered BS/NBS units;
4. The ICT infrastructure is capable to coordinate the black start procedure in parallel;
5. A generation unit is defined as BS unit when it can satisfy the following requirements.
   - It can start without need for external power supply for the cranking power demand;
   - It can control frequency and balance active power during the entire restoration process;
   - It can adjust the busbar voltage by controlling the reactive output.

   A renewable energy source (RES) such as wind and solar, equipped with storage can be considered as a BS unit depending on the state of charge (SOC) of storage.
6. A generation unit is defined as a NBS unit when it can only be booted with cranking power from other generation unit. However, a NBS unit can be regarded as a BS unit when it can operate with full load rejection after black out. Full load rejection means that a NBS unit disconnects from grid but it can still run at very low load for a while. During this time, the generation unit can reconnect to grid without cranking power.

7. A NBS unit can be a conventional thermal power station, but also a RES without storage. The available power of RES without storage could be limited to the minimum of the forecast-values.

This paper proposes a novel network partitioning method based on the influence area of generators. The influence area of a generator is defined as the region, in which self-excitation cannot occur and steady state/switching transient over-voltage for unload lines lie within acceptable ranges. The boundary of the subsystem is confined by the influence area of generators in each subsystem. Moreover, the proposed algorithm consists of three stages. In the first stage, the number of subsystems is determined by using a fuzzy classification algorithm according to the electric connection between BS units. The primitive subsystems include only BS units. In the second stage, the NBS units are assigned to each primitive subsystem to achieve a minimal restoration time. The generator start-up sequence in each subsystem can be determined simultaneously. The task of the third stage is to assign the substations to each subsystem so that the ratio of generation and load in each subsystem is optimal.

The paper is organized as follows: Section 2 introduces the definition of the influence area of a generator. Section 3 provides the mathematical approach of the network restoration process. Section 4 explains the proposed algorithm step by step for the network partitioning. Section 5 presents the simulation results for the IEEE 39 nodes grid and a real network in south China. Finally, section 6 gives the conclusion of this paper.

2. INFLUENCE AREA OF GENERATORS

Since the occurrence of self-excitation and over-voltage phenomena is related to the lengths of transmission lines, the influence area can be asymmetric and depend on the real network conditions such as line type, reactive compensation equipments, etc. In this paper, software ”Digsilent PowerFactory” is used to conduct the simulations. The electromagnetic transient simulation (EMT) has typically a time scale of several milliseconds. Over this time period, the speed of the rotor can be assumed constant due to the inertia of the turbine and generator. As switching transient over-voltage is a short term phenomenon, the EMT is conducted to calculate the over-voltage. Moreover, the electromechanical transient simulation (RMS) has a longer time scale and the rotor speed will vary and interact with the electromagnetic changes. In this paper, generator self-excitation phenomenon is checked by RMS simulation. For steady state over-voltage, load flow calcualtion is executed.

Before introducing the network restoration approach, the switching transient over-voltage, steady state over-voltage and self-excitation which are used to define the influence area of generators are presented. To compute the maximal lengths for transmission lines allowing for over-voltage free operation, voltage profiles under no-load conditions have to be considered. The over-voltage free distance could be longer if the grid is equipped with automatic voltage regulator (AVR). In order to calculate conservative results, the AVR or other voltage control devices are not considered.

In addition, running EMT, RMS simulations and load flow calculation in a real black start process is unrealistic. In praxis, all possible restoration paths from BS/NBS units have to be analyzed ex-ante by EMT, RMS simulations and load flow calculation. In this way, a look-up table which lists all possible restoration paths during the black start procedure can be generated. Moreover, alternative thumb rules are extracted that can be used for decision making.

2.1. Switching transient over-voltage

In the initial restoration phases, BS units have to re-energize the restoration paths to send cranking power to NBS units. The switching transient over-voltage is caused by the oscillation between the inductive and capacitive components by re-energizing unload restoration paths which consists of transformers and overhead lines or cables. Paper [21] deduces a formula to calculate the maximal switching transient over-voltage and indicates that the maximal switching transient over-voltage is related to the length of line, line parameters, resonance frequency and so on.

2.2. Steady state over-voltage

For transmission lines with the length l, receiving voltage V_R and the propagation constant γ, the voltage profile is [22]:

$$V = \frac{V_R}{2} e^{\gamma l} + \frac{V_R}{2} e^{-\gamma l}. \tag{1}$$

Since the resistance of transmission lines is much smaller than the reactance, the transmission lines can be seen as lossless. For lossless lines, $\gamma = j\beta$, where β is the phase constant. Through this simplification, Eq. 1 can be modified as:

$$V_R = \frac{V}{\cos(\beta l)}. \tag{2}$$

V_R is the steady state over-voltage at the end of unload line. The maximal transmission line length can be calculated as:

$$l = \frac{\arccos(V V_R^{-1})}{\beta}. \tag{3}$$

In this work, the voltage at the end of the unload transmission line should be within 0.9 pu to 1.1 pu.

2.3. Generator self-excitation

Generator self-excitation is caused by parametric oscillations between the synchronous generator (direct-and quadrature-axis x_d, x_q reactance) and the capacitive load [23]. Since long unload transmission line can be regarded as capacitive load, the generator self-excitation has to be checked when a BS unit re-energizes a long unload transmission line.To avoid the self-excitation phenomenon, the maximal line length l can be calculated according to [24] as:

$$K S_G < l Q_c. \tag{4}$$

$$l < \frac{K \cdot S_G}{Q_c}. \tag{5}$$

In Eq. 4, the parameter K is the ratio of the short-circuit current to the rated current of synchronous machine, S_G is the rated apparent power of the synchronous machine and Q_c represents the capacitive reactance of the transmission line per kilometer.

3. Modeling the Temporal Boot Sequence of Power Plants

The overall restoration time of a power grid should be modeled considering the temporal booting procedures of the power plants. In order to simplify the analysis, the following assumptions are made:

1. the maximal output of BS/NBS units is assumed to be 90% of rated power due to reserve power for frequency and voltage control;
2. the time for restoration of subsystems depends mainly on starting process of NBS units which is illustrated in Fig. 1;
3. the active output of BS unit is fast enough to balance the load fluctuation in subsystem.

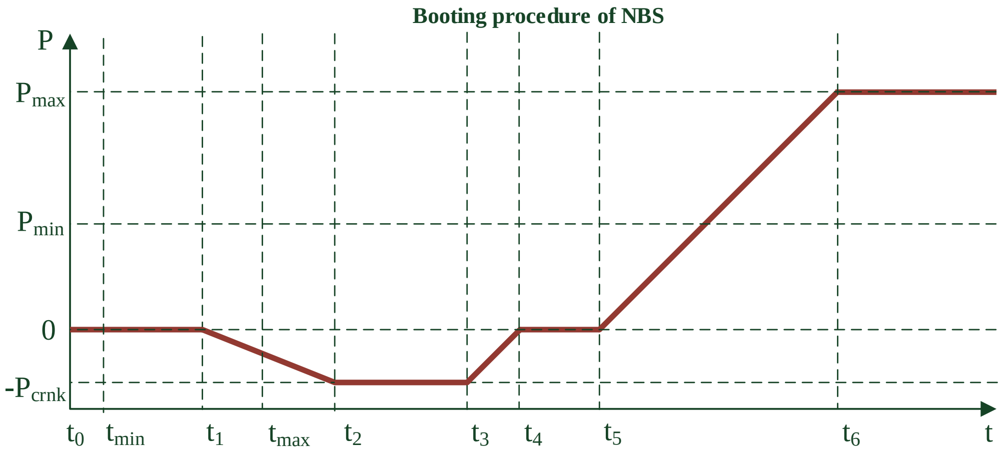

Fig. 1: Temporal model of booting procedure of a non-black start unit

The booting procedure (Fig. 1) of a NBS unit is modeled as follows:

1. Within the interval between t_1 and t_2, a NBS unit starts to receive cranking power from the BS unit.
2. After t_2, the NBS unit starts consuming a constant amount of cranking power from the grid between t_2 and t_3. The time t_{tmax} identifies the latest time when a NBS can start receiving cranking power without delaying the booting procedure. Should the grid not be able to provide the cranking power within t_{max}, several penalty hours are added to t_3 e.g. the cooled boiler. During this period the NBS unit is still consuming the full cranking power.
3. At t_3 the NBS unit starts producing its own power and energizing the ancillary devices. Normally, the NBS unit picks up its own ancillary devices after resynchronisation when its output is stable. To simplify the mathematical model, we assumed that the NBS unit restores its own cranking power before resynchronisation. The cranking power which is originally provided from other online generation units is substituted. This phenomenon is represented by the high power increasing rate between t_3 and t_4 in Fig. 1. However, during this period the output of the NBS unit still equals zero.

4. After t_4, the NBS unit stops consuming the cranking power and adjusts the voltage phase angle to meet synchronization conditions from t_4 to t_5.
5. At t_5, the NBS unit starts injecting its own power into the grid. After grid connection, the output of NBS unit should reach the minimal power P_{min} as soon as possible to ensure stable operation. The NBS unit can only operate between the interval from P_{min} to P_{max}. The output of NBS unit is available as cranking power for other NBS units and can rise until the maximal power output P_{max}, which is defined as 90% of its rated capacity, is reached at t_6.

With this model of the temporal behavior of the subsystem, the objective function is to minimize the total restoration time of the subsystems. With r as the number of subsystems, $i = 1, \ldots, r$ as the subsystem index, and T_i as the duration when subsystem i accomplishes its booting procedure, the goal of minimizing the overall restoration time t_{tot} can be defined as:

$$t_{\text{tot}} = \min(\max_{i} T_i) \tag{6}$$

The calculation of T_i has to consider two situations. If the load is larger than generation in a subsystem, the booting procedure of subsystem is accomplished when the subsystem approaches P_{max} and no additional load can be picked up because of limited generating capacity. If the load is smaller than the generation in the subsystem, the rebooting process of subsystem is accomplished when all the load in this subsystem is restored.

In this paper, the algorithm in [25] is used to calculate T_i. Eq. 6 shows that the overall restoration time equals the booting time of subsystem with longest booting procedure. We do not consider the case that the subsystems with short booting time will support the booting process in the subsystem with long booting time via subsystem resynchronization. According to the experience of restoration process in Northeast America blackout 2003, it can be very difficult to control the frequency and voltage in each subsystem to reach the subsystem synchronization requirements within short time. The proposed algorithm can ensure that the overall power system restoration time is minimized without subsystem resynchronization.

4. Black Start Zone Partitioning–The Approach

The proposed network partitioning algorithm consists of three stages (see Fig. 2). In the first stage, the number of the subsystems is determined according to the electric connections between BS units by using λ-cut algorithm [26] which is one of the fuzzy classification algorithms. The goal of the second stage is to assign the NBS units to the primitive subsystems according to the subsystem restoration time. In the third stage, the substations are assigned to one of the subsystems to achieve the optimal ratio of generation and load in each subsystem.

4.1. First restoration stage (Primitive Subsystem): Determination of number of subsystems

During power system restoration process, the BS units are the key elements. Each subsystem has to have at least one BS unit. The capacity of BS units have impact on the subsystem booting procedure, such as generator start-up sequence and load restoration. If two or more BS units have very close electric distance and the these BS units can be synchronized before sending cranking power to NBS units, we can assign these BS units into one subsystem. So the initial step of subsystem classification is the identification of the number of subsystems. In this paper, the λ-cut

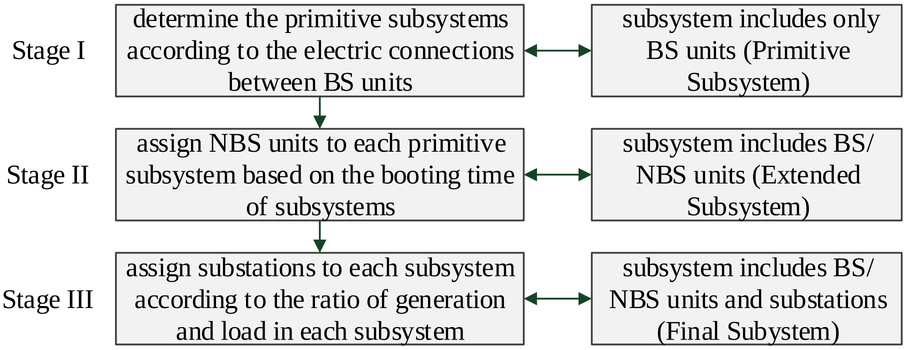

Fig. 2: Three stages of the proposed partitioning algorithm

fuzzy classification algorithm is implemented to partition the power system to subsystems. In [26], this method is presented in detail.

Fig. 3 elaborates the detailed algorithm steps in the first stage as following:

(1) The Dijkstra's algorithm [27] is implemented to find out the shortest line length between BS units.

(2) Since the longer the line length, the weaker electric connection between BS units is, monotone linear decreased membership function is used to normalize the shortest line length between BS units. After normalization, the equivalence fuzzy relation matrix [26] BB with n BS units can be established as follows:

$$BB = \left(\begin{array}{c|cccc} & BS_1 & BS_2 & \cdots & BS_n \\ \hline BS_1 & bb_{11} & bb_{12} & \cdots & bb_{1n} \\ BS_2 & bb_{21} & bb_{22} & \cdots & bb_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ BS_n & bb_{n1} & bb_{n2} & \cdots & bb_{nn} \end{array}\right),$$

with n as number of BS units, bb_{ij}=1, if i = j; $0 < bb_{ij} < 1$, if i $\neq$ j. In this way, the number of primitive subsystems is smaller than the number of BS units. If more than one BS unit is assigned to one subsystem, only one of them is operated as a BS unit and the others in one primitive substation are operated as NBS units.

(3) Since BB matrix is a equivalence fuzzy relation, λ-cut algorithm can be applied to partitioning the grid into primitive subsystems which include only BS units.

4.2. Second restoration stage (Extended Subsystem): assignment of NBS units

After the power system has been partitioned into primitive subsystems according to the electric connections between BS units, the next step is to map NBS units to the primitive subsystems. Fig. 4 indiciates the flow chart of the second restoration stage.

(4) The shortest path between primitive subsystems and NBS units is defined as the shortest path between BS units in the primitive subsystems and NBS units. After identifying the shortest line length between primitive subsystems and NBS units, the connection matrix BNB can be formed as

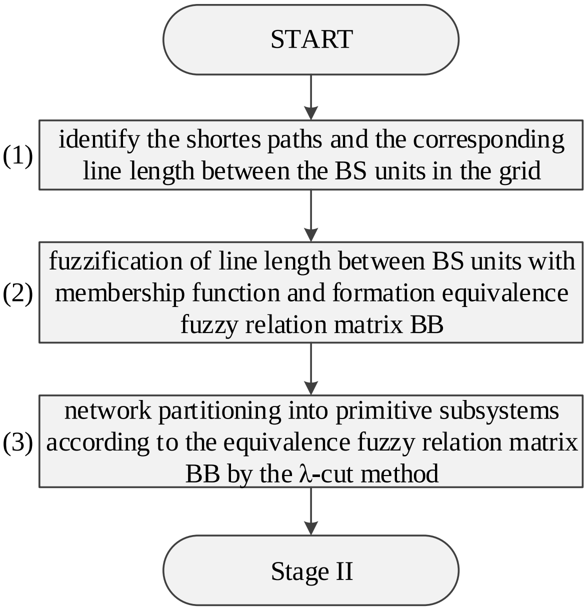

Fig. 3: Network partitioning algorithm (stage I)

follows:

$$BNB = \left(\begin{array}{c|cccc} & NBS_1 & NBS_2 & \cdots & NBS_m \\ \hline SUB_1 & sn_{11} & sn_{12} & \cdots & sn_{1m} \\ SUB_2 & sn_{21} & sn_{22} & \cdots & sn_{2m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ SUB_t & sn_{t1} & sn_{t2} & \cdots & sn_{tm} \end{array}\right)$$

with NBS_j as j_{th} NBS unit, $1 \leq j \leq m$, m as number of NBS unit, SUB_i as i_{th} primitive subsystem $1 \leq i \leq t$, t as number of primitive subsystems, t $\leq$ n, sn_{ij} as the shortest line length between i_{th} primitive subsystem and j_{th} NBS unit.

(5) The operation constraints including the switching transient over-voltage, steady state over-voltage, and self-excitation are checked when BS units re-energize the unload restoration path between primitive subsystems and NBS units.

(6) The elements sn_{ij} in matrix BNB set to -1, if one of the operation constraints in step 5 can not be satisfied.

(7) The smallest value in each column of matrix BNB sets to one (except elements with value -1), while the other elements set to zero. If more than one elements in the column have equal minimal values, one of them is selected randomly to set one, the others set to zero.

$$sn_{ij} = \begin{cases} 1 & \text{if } sn_{ij} = \min_{i=1}^{t} sn_{ij}, 1 \leq j \leq m \\ 0 & \text{if } sn_{ij} > \min_{i=1}^{t} sn_{ij}, 1 \leq j \leq m \end{cases} \tag{7}$$

If element sn_{ij} in Eq. 7 equals one, means that the j_{th} NBS unit is assigned to i_{th} primitive subsystem.

(8) After assigning NBS units to each subsystem, algorithm proposed in [25] is implemented to calculate the optimal generator start-up sequence and restoration time in each subsystem. If the primitive subsystem does not have enough power to reboot NBS units, the restoration time sets to infinite.

(9) The maximal restoration time difference Δt among subsystems is calculated by subtraction of the maximal and minimal restoration time.

(10) In order to minimize the Δt, one NBS unit in the subsystem which has longest restoration time should be selected and reassigned to the subsystem which has shortest restoration time. The NBS unit which can reduce Δt most efficiently is selected for reassignment. After NBS unit reassignment, the graphic connectivity is checked. If the new Δt is smaller than in the previous step, the algorithm continues, otherwise, the algorithm is convergent and proceeds to the next stage.

4.3. Third restoration stage (Final Subsystem): assignment of substations

The main task of third restoration stage is to assign the substations to each subsystem to achieve the optimal ratio of generation and load in each subsystem. Fig. 5 shows the flow chart of the third restoration stage.

(11) The shortest path between subsystems and substations is defined as the shortest path between BS/NBS units in subsystem and substations. After identifying the shortest paths between subsystems and substations, the connection matrix SBB can be formed as follows:

$$SBB = \left(\begin{array}{c|cccc} & S_1 & S_2 & \cdots & S_q \\ \hline SUB_1 & ss_{11} & ss_{12} & \cdots & ss_{1q} \\ SUB_2 & ss_{21} & ss_{22} & \cdots & ss_{2q} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ SUB_t & ss_{t1} & ss_{t2} & \cdots & ss_{tq} \end{array}\right)$$

with S_r as r_{th} substation $1 \leq r \leq q$, q as number of substations, ss_{ir} as the shortest line length between i_{th} subsystem and r_{th} substation.

(12) The operation constraints including the switching transient over-voltage, steady state over-voltage, and self-excitation are checked when the BS/NBS units in subsystem re-energize the unload restoration path between subsystems and substations.

(13) The element ss_{ir} in matrix SBB sets to -1, if the operation constraints can not be satisfied.

(14) The smallest value in the column of matrix SBB sets to one (except the element with value -1), while the other elements set to zero. If more than one elements in the column have equal minimal values, one of them is selected randomly to set one.

$$ss_{ir} = \begin{cases} 1 & \text{if } ss_{ir} = \min_{i=1}^{t} sn_{ir}, 1 \leq r \leq q \\ 0 & \text{if } ss_{ir} > \min_{i=1}^{t} sn_{ir}, 1 \leq r \leq q \end{cases} \tag{8}$$

If element ss_{ir} in Eq. 8 equals one, means that the r_{th} substation is assigned to i_{th} subsystem.

(15) The network connectivity within the subsystems is checked.

(16) After initial assignment of substations, each subsystem includes BS units, NBS units and substations. The difference between generation capabilities and load in each subsystem (ΔA=GenCap-Load) can be calculated. The positive ΔA means that generator capability is larger than total load size in subsystem, while the negative ΔA means that there is no sufficient generator capability to restore all load in the subsystem.

(17) The reassignment process of the subsystem begins with the subsystem with highest absolute

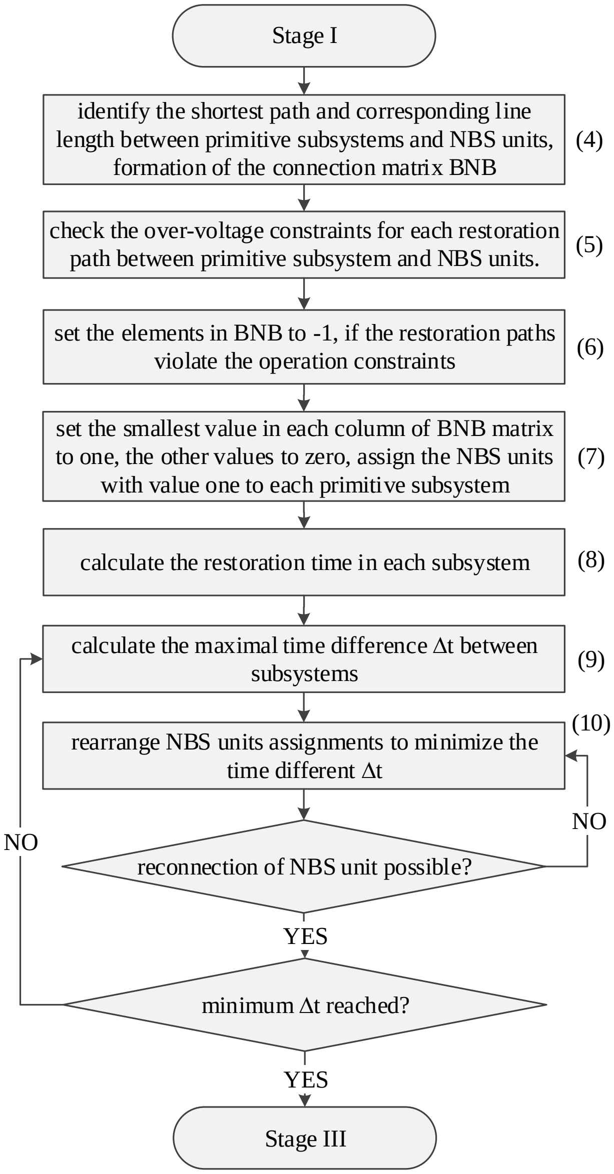

Fig. 4: Network partitioning algorithm (stage II)

value of $|\ \Delta A\ |$ and this subsystem is defined as object subsystem. If the object subsystem has a positive ΔA, one of the substations in neighborhood subsystems should be reassigned to object subsystem. All the substations which have direct connection to the object subsystem are regarded as candidate substations. On the other hand, if the object subsystem has a negative ΔA, one of the substations in the object subsystem should be reassigned to neighborhood subsystems. All substations which have direct connection to neighborhood subsystems are regarded as candidate substations. The candidate substation which can reduce $|\ \Delta A\ |$ most efficiently is selected for re-assignment. After substation reassignments, the subsystem connectivity is checked. If the absolute vale of $|\ \Delta A\ |$ is larger than in the previous step, this substation reassignment is invalid and the candidate substation with second highest ranking value is selected to conduct substation reassignment again. If there is no valid substation reassignment for the subsystem with highest absolute value of $|\Delta A|$ or no improvement of $|\Delta A|$ for ten iterations, the subsystem with second highest value of $|\Delta A|$ begins the substation reassignment procedure. The entire algorithm terminates after all values of $|\Delta A|$ remain unchanged for ten iterations.

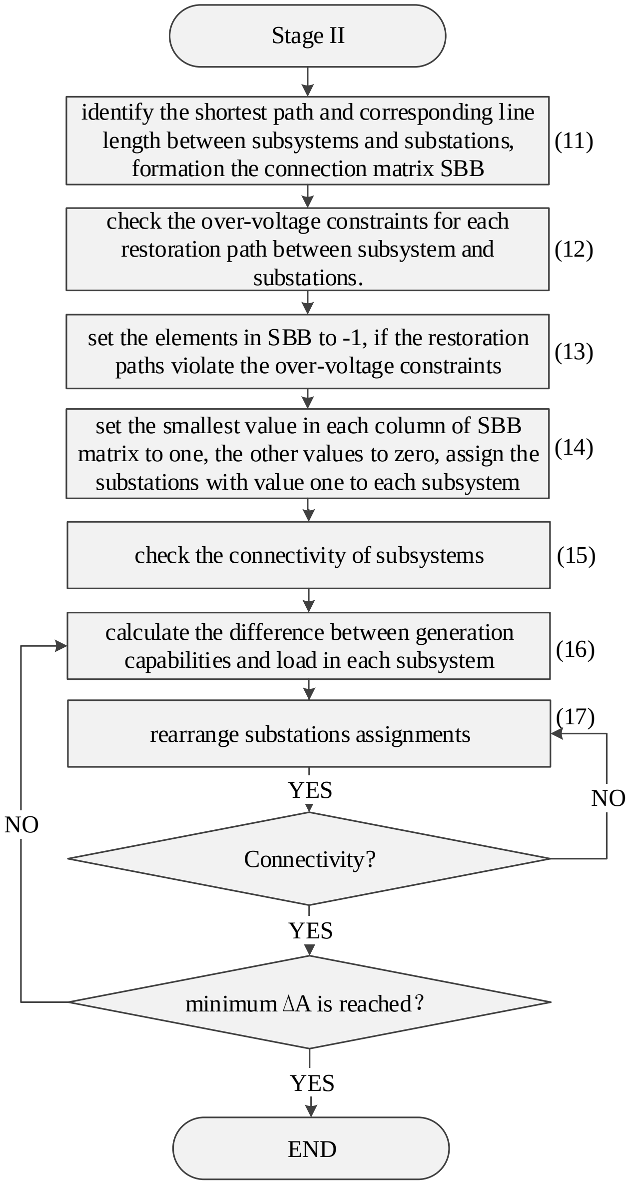

Fig. 5: Network partitioning algorithm (stage III)

4.4. Iteration Process: Determination of λ value

In order to get optimal value of λ in λ-cut algorithm, the iteration process in Fig. 6 has to be conducted. The λ value should be iterated from the smallest value, which makes all elements in BB matrix equal one, to largest value one. When the updated λ value leads to different number of primitive subsystems, Stage II and III should be re-calculated. All the partitioning results, restoration time and ΔA calculated by different λ values should be saved in set L^e. The best partitioning result among set L^e is select as final result. However, this step is only necessary if a global optimal solution is looked for. In practical usage thumb rules could be used to calculate λ value.

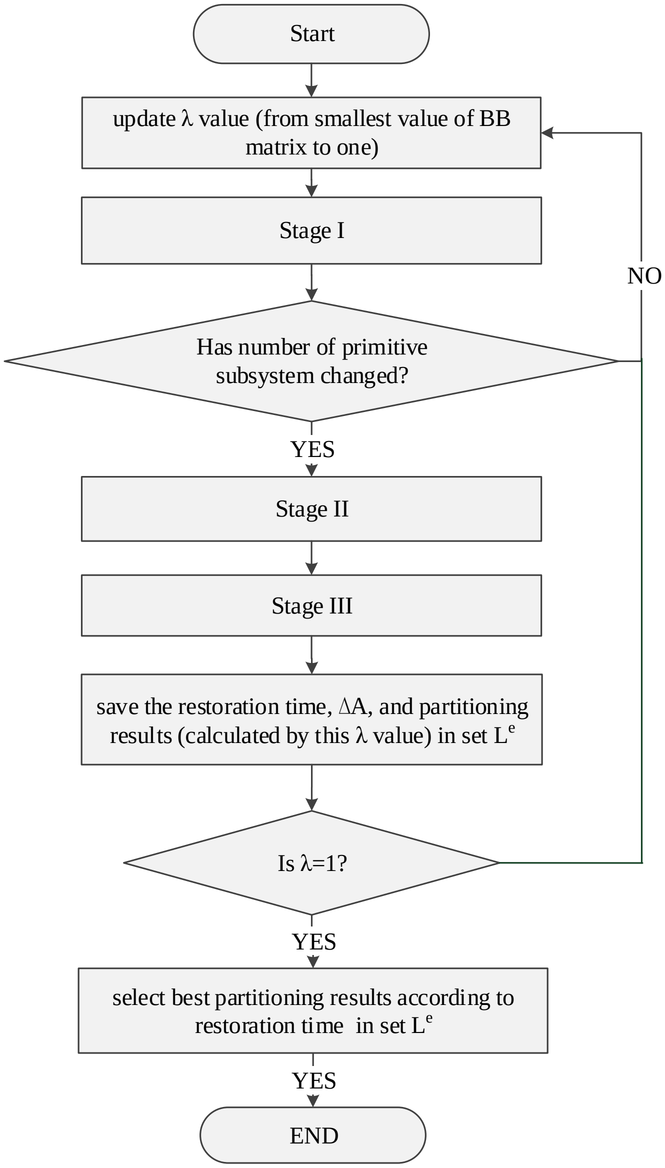

Fig. 6: Determination of λ value

5. Experiments and Results

In order to demonstrate the proposed method, the New England 39 nodes network [20] and a real network from southern part of China have been used.

Case A: The New England 39 network

Fig. 7 shows the topology of the IEEE New England 39 nodes which includes 10 generators and 29 substations. Generators in bus bar 4, 7, 8, and 10 are the BS units, while the other generators are NBS units. The detailed network partitioning steps are described as follows:

Subsystem Formation

Tab. 1 shows the shortest line length between BS units. The monotone decreased membership function is used to normalize the value of line length in Tab. 1.

Table 1 Shortest line length between BS units(km)

G4-G7	G4-G8	G4-G10	G7-G8	G7-G10	G8-G10
99	110	97	141	128	49

After normalization of the data in Tab. 1, Eq. 9 shows values of matrix BB.

$$BB = \left(\begin{array}{c|cccc} & G4 & G7 & G8 & G10 \\ \hline G4 & 1 & 0.4885 & 0.384 & 0.5075 \\ G7 & 0.4885 & 1 & 0.0895 & 0.213 \\ G8 & 0.384 & 0.0895 & 1 & 0.9635 \\ G10 & 0.5075 & 0.213 & 0.9635 & 1 \end{array}\right) \tag{9}$$

By chosing λ=0.97, Eq. 10 can be derived.

$$BB(\lambda = 0.97) = \left(\begin{array}{c|cccc} & G4 & G7 & G8 & G10 \\ \hline G4 & 1 & 0 & 0 & 0 \\ G7 & 0 & 1 & 0 & 0 \\ G8 & 0 & 0 & 1 & 0 \\ G10 & 0 & 0 & 0 & 1 \end{array}\right) \tag{10}$$

There are four different columns/rows in BB(λ=0.97) matrix, which means that each BS forms a primitive subsystem.

Since each primitive subsystem has only one BS unit, the shortest paths between primitive subsystems and NBS units are represented by the shortest paths between BS units in primitive subsystem and NBS units. Tab. 2 shows the shortest paths between BS units and NBS units.

Table 2 Shortest line length between BS units and NBS units (km)

NBS / BS	G1	G2	G3	G5	G6	G9
G4	162	118	98	46	76	153
G7	193	149	129	117	51	184
G8	97	108	114	128	118	133
G10	84	95	101	115	105	136

The EMT simulation in PowerFactory yields that the switching transient over-voltage constraint can not be satisfied when G7 sends cranking power to re-energize the unload restoration path to G1. So, the element in the intersection of column G1 and row G7 of the Tab. 3 sets to -1. The smallest value in each column of matrix BNB sets to 1, while the other elements set to 0 (except for the elements with value -1). The initial NBS assignments are shown in Tab. 3.

Table 3 BNB Matrix

	G1	G2	G3	G5	G6	G9	T(min)
Subsystem1(G4)	0	0	1	1	0	0	141
Subsystem2(G7)	-1	0	0	0	1	0	133
Subsystem3(G8)	0	0	0	0	0	1	146
Subsystem4(G10)	1	1	0	0	0	0	144

The NBS units with value 1 are assigned to the subsystem in the same row. For example, G3 and G5 are assigned to subsystem1. So, in subsystem1, there are one BS unit G4, two NBS units G3 and G5. The last column in Tab. 3 indicates the restoration time in each subsystem. The maximal restoration time difference for this assignment is between subsystem3 and subsystem2 with Δt = 13min. The Tab. 3 shows final results as the reassignment of G9 in subsystem3 enlarges the value of Δt.

Substations Assignments

By executing the simulations in Powerfactory, it is checked that all the restoration paths between subsystems and substations satisfy the operation constraints. In initial substation assignments, the substations are assigned to the subsystem with shortest restoration paths. Tab. 4 shows the ΔA values in each iteration.

Table 4: ΔA values in each iteration

Iteration / Subsystem	1	2	3	4&5	6&7	8
Subsystem1(G3,G4,G5)	-84.1	224.5	505.5	5.5	334.5	334.5
Subsystem2(G6,G7)	688.5	379.5	379.5	379.5	50.5	50.5
Subsystem3(G8,G9)	517.5	517.5	236.5	236.5	236.5	78.5
Subsystem4(G1,G2,G10)	-485.8	-485.8	-485.8	14.2	14.2	172.2

From Tab. 4 can be seen that the maximal $\mid \Delta A \mid$ value decreases from 688.5 MW in first iteration to 334.5 MW in sixth iteration. Since there are no valid substation assignments for Subsystem1 after sixth iteration, the maximal $\mid \Delta A \mid$ value remains unchanged. The next step is to reduce the second highest $\mid \Delta A \mid$ value (236.5 MW) in Subsystem3. As ΔA value is Subsystem3 is positive, substations in Subsystem3 should be removed to other subsystems. After two iterations, the second maximal $\mid \Delta A \mid$ value decreases from 236.5 MW to 172.2 MW. The algorithm terminates at eighth iteration, as there is no improvement of $\mid \Delta A \mid$ value for ten iterations. Even though $\mid \Delta A \mid$ does not change between iteration setp 4,5 and iteration 6,7, the topology of subsystem changes by reassigning the connection substations in which there is no load. Fig. 7 shows the final partitioning results.

Case B: China Network

In the China network, generators 11, 13, 47, 54, and 94 are the BS units and the other generators are NBS units. In the first stage, generator 11 and 13 are assigned into one subsystem by choosing $\lambda = 0.98$, which is shown in Eq. 11.

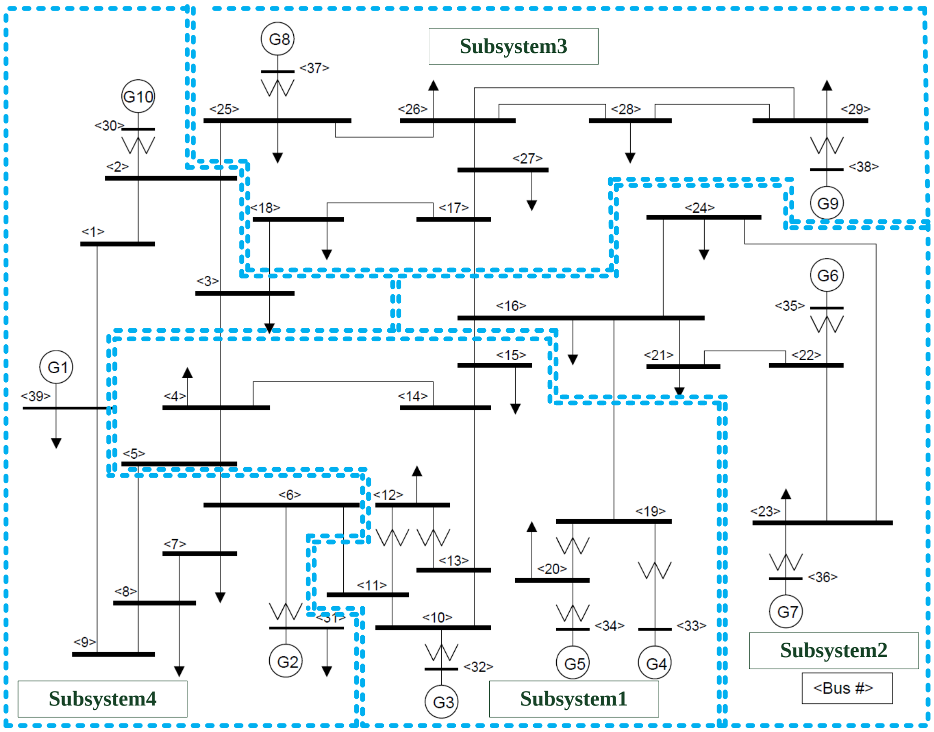

Fig. 7: New England 39 nodes network partitioning result

$$BB(\lambda = 0.98) = \left(\begin{array}{c|ccccc} & G11 & G13 & G47 & G54 & G94 \\ \hline G11 & 1 & 1 & 0 & 0 & 0 \\ G13 & 1 & 1 & 0 & 0 & 0 \\ G47 & 0 & 0 & 1 & 0 & 0 \\ G54 & 0 & 0 & 0 & 1 & 0 \\ G94 & 0 & 0 & 0 & 0 & 1 \end{array}\right) \tag{11}$$

The second stage is to assign each of the NBS units to one of the primitive subsystems. After 3 iteration, the minimal time difference Δt with 34 minutes is reached and Tab. 5 shows the final assignment of NBS units.

In third stage, the substations are assigned to each subsystem according to the value of ΔA. The final partitioning result is illustrated in Fig. 8.

6. Conclusion

In this paper, a novel network partitioning algorithm based on fuzzy classification has been presented. The goal of the proposed algorithm is to determine the boundary of network subsystems to achieve the overall minimal restoration time and optimal ratio of generation and load in each subsystem. The proposed network partitioning algorithm comprises three stages including primitive subsystem formation (stage I), NBS units assignments (stage II), and substation assignments (stage III) and has the following advantages:

Table 5: NBS assignment

NBS Subsystem	G17	G23	G36	G37	G52	G76
G11,G13	1	1	1	-1	0	1
G47	0	0	-1	-1	1	0
G54	0	-1	-1	1	0	0
G94	0	0	-1	-1	0	0

	G80	G83	G84	G98	Start-up sequence	Restoration time(min)
G11,G13	0	0	0	0	17-23-36-76	169
G47	0	0	0	0	52	179
G54	-1	0	0	0	37	145
G94	1	1	1	1	80-83-98-84	166

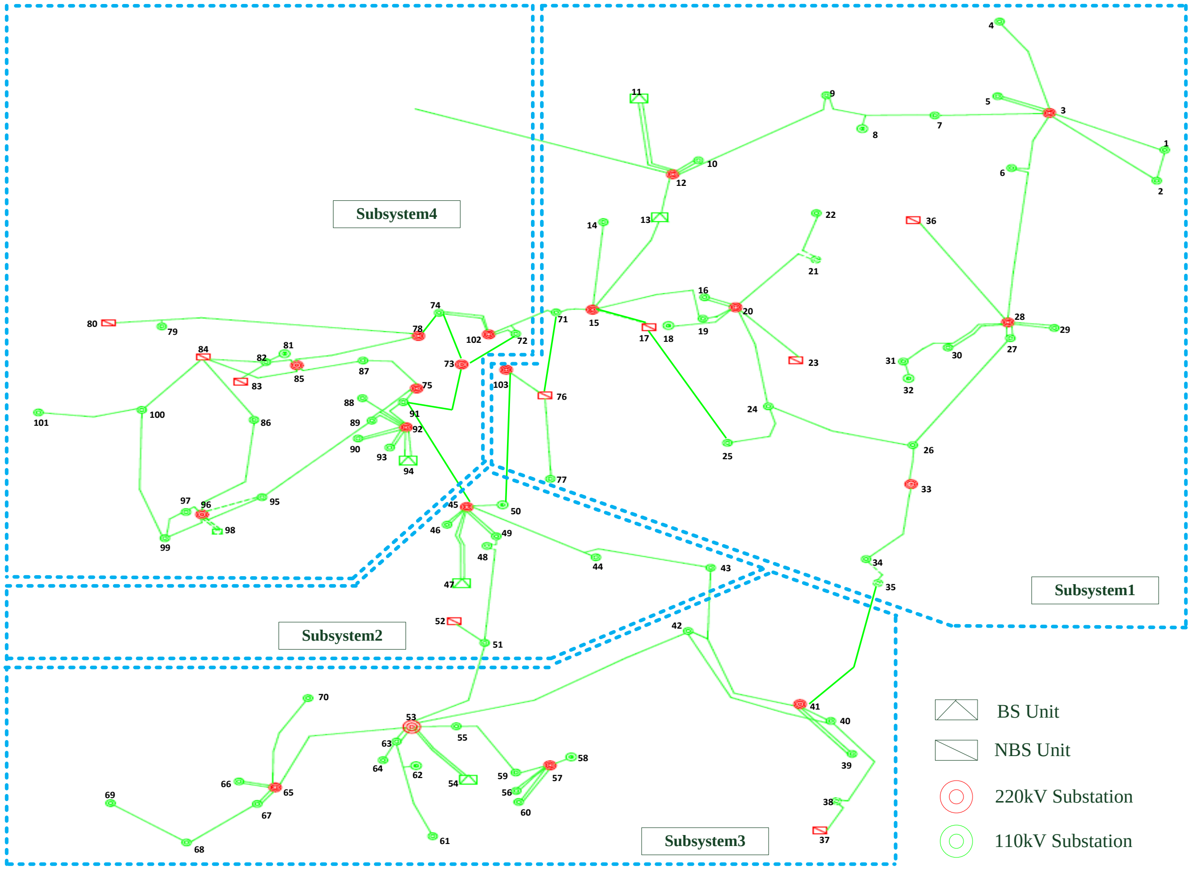

Fig. 8: Partitioning Results for China Grid

- The proposed algorithm is flexible and can be adjusted very easily according to the status of the power system. For example, NBS unit with full load rejection can be regarded as BS unit at the beginning of the restoration process, the proposed algorithm only needs to add this

NBS unit in BB matrix and delete this NBS unit in BNB matrix. The other procedures remain unchanged.

- The proposed algorithm considers the operation constraints during the black start procedure. In each subsystem, the switching transient over-voltage, steady state over-voltage lie in the tolerance range and the self-excitation does not occur when the generators re-energize the unload lines.
- Having determined the boundaries of the subsystem, the generator start-up sequence in each subsystem can be fixed simultaneously.
- The NBS units assignments are oriented by the restoration time in each subsystem by considering the maximal and minimal time interval. The proposed algorithm can achieve near-optimal minimal restoration time.
- Generation and load are evenly distributed among the subsystems which means that maximal load can be restored before subsystem resynchronization.

In future work, the thumb rules to determine the optimal λ value should be extracted. In this way, the calculation speed can be accelerated significantly.

7. Acknowledgement

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