A Case Study of Power System Restoration Problem Using Quantum Inspired Differential Evolutionary Algorithm

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Abstract: The modern power system grid is stable and interruptions are rare. However, a grid collapse can occur due to natural causes or mal-operation of protective equipment or operator mistakes. Grid collapse normally manifests as blackout with generators and lines tripped or brownouts with islands formed with some generation and with power quality issues. If a grid collapse occurs, the visualization of the grid with modern SCADA and advanced communication is the first step followed by offline study for restoration planning using optimal methods, skeleton grid formation, step-by-step generation, and load resumption. In this study, visualization of the grid for connectedness and optimal restoration planning using Quantum-inspired Differential Evolutionary Programming (QED) are discussed with a case study.

Keywords: Black Out; Brown Out; Quantum-inspired Differential Evolutionary Programming; Microgrid; Black Start; Non-Black Start; Hot Start Time; Cold Start Time; Independent System Operator; Visualization; Mixed Integer Linear Programming; Permutation-Based Power System Restoration model

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1. Introduction

The modern electricity grid is made up of bulk generation, large step up and step down transformer stations, transmission lines, renewable energy sources and micro grids which can operate in a grid-connected and isolated fashion. The grid is normally very stable with standby generation and redundant lines alleviate any congestion problems. However, grid collapses occur rarely due to an outage of generators, tripping of transformers and lines due to permanent or temporary faults or mal-operation of relays and mal-operation by operators. If such interruptions occur, the effects are colossal causing monitory loses to both the supplier and the consumer with political fallouts and disrupting essential services. The normalization usually takes a few hours to a few days. The three Stages of power system restoration are assessment of the post-fault status of the grid, Planning, and formation of the skeleton grid covering Black Start (BS) and Non-Black Start (NBS) generators and step-by-step resumption of generation and load. In this paper, the first two stages are discussed with a case study. The generators in the grid are of two types namely, Black Start (BS) and Non-Black Start (NBS) generators; the formers do not need startup supply from the grid and the latter need grid supply support for their startup. The NBS generators have what is known as hot start time; if a grid collapse occurs and the generator is isolated from the grid, the load can be resumed with the designed ramp rate if the generator is loaded before the elapse of the hot start time. After elapse of the hot start time, the generator can only be started with a cold startup which takes many hours and even days to start generation. The renewable sources with battery backup and with a margin of the depth of charge are considered as BS generators.

1.1Connectedness of Power systems

Literature survey: The Wide Area island detection systems are used to monitor the voltage, voltage phase angle and frequency at buses and give early warning signals indicating the possible collapse of the system. In [3} Rue Sun et.al discuss the detection of islanding contingency using topology and decision tree. In [2], and [1] methods of detection of islanding contingency using change in phase angle and change in frequency are discussed. In a grid connected microgrid in addition to voltage and frequency change methods, Active Method and Passive Methods are also used[1]. In the active method, the current wave is slightly distorted in the Point of Common Coupling(PCC) and the output response of the MG is observed. The frequency drift and reactive var export can detect islanding inception. However these methods require a long detection time (e.g.2.0s) and may be unsuccessful in multiple inverter case due to different frequency bias besides introducing power quality issues. The passive method is based on the comparison of variables

prior to and after an islanding operation. If the variables like magnitude, phase angle, frequency and/or harmonics satisfy the islanding condition then the islanding is detected. However this method may fail if the load matches the generation in the Micro grid since variation in the variables cannot be detected. Also any fault occurring in the MG will distort the detection method and may mal-operate. The literature deal with islanding contingency and can fail sometimes as discussed. The post-fault islanding if any should be known to the system operator and the computer for planning the restoration. The generating stations, substations, lines, transformers and major components of the grid are monitored using state of the art SCADA and communication devices at the Load Dispatch Centre (LDC) of the Independent System Operator (ISO). These systems use redundant and fast SCADA and communications (like fiber optical systems) devices, so that the data are received with less

latency with seconds update time at the control center. The status of the grid with islands if any

formed (connectedness) should be evident to the system operator and the computer system so that actions needed may be taken fast. The circuit breakers which have tripped are indicated with a different color in the grid display and the islands formed are shown with different colors for easy identification by the operator. In a classical grid, this information is needed to plan restoration procedure using optimal methods; in the micro grid environment these are needed also to alter the relay setting since the performance of these relays with the grid is different due to large fault currents than with isolated environment with less fault currents. Hence, determination of the connectedness is very important. In this paper, the determination of the connectedness is discussed in Section 2 using the fusion theory of graphics in the MATLAB environment. 1.2 Power System Restoration. This refers to the skeleton grid formation covering the BS and NBS generator buses at the same time resuming possible load as per priority with available generation capacity. The BS generator is started first and then the sequence of NBS generator buses which are to be energized and the path between the adjacent members of the sequence are optimally chosen taking care of security due to overvoltage (Ferranti effect) and resuming priority loads as permitted by the generators online. The overvoltage that occurs at the other end the line being charged depends on the line charging capacitance for which the line constant B (susceptance) of the line is taken as a measure. High priority loads are assigned a value namely $I = 1$, the medium priority load is assigned a value I_{21}=0.5 and the low priority loads are assigned a value of I=0.1. A modified Dijkstra's algorithm is used to find the shortest optimal path with a new index instead of the edge weight in the original algorithm. Based on the power system topology model and load importance degree, a new index P_s is proposed. P_s is defined as $P_{s3}=\sum W/\sum L$ where $\sum W$ is the summation of weights of edges in the path. $\sum L$ is the summation of load importance degree of all load nodes along a path. The edge weight W is B of the line. The operation time for reaching an NBS bus from the beginning (i.e. from the BS bus) is calculated. Suppose this time for reaching the i_{th} bus is T

and the hot start time of the generator is T_{hi}, this generator can be put into service at time T_{si} if $T_{hsi}>T$. The rate of increase of the generation is determined by the ramp rate. In this method of finding the optimal path, the time war generation schedule of the generator is also arrived at. The theory of finding the connectedness and optimal path are discussed briefly in Section 2 and Section 3 and a case study for the 39 bus 10 generator IEEE system is made in the MATLAB environment.

1.2.1 Literature Review and the limitations of the existing state of the art methods for restoration:

In the two-step method based restoration model [19], the generation capability curve is quasi-concave in nature and therefore optimization methods cannot be applied directly. Therefore, the generator capability curve is split into two concave segments and the problem becomes mixed integer quadratically constrained programming. The problem nature is step-by-step concave optimization problem and the optimization process ends at a specified period T. One implicit assumption is that the cranking period *T* of each unit must be an integral multiple of fixed time interval *t* and this condition is rarely satisfied in a practical power system. This is a limitation of this method. *c*

The MILP-based restoration model [13] is based on the two-step method with the introduction of binary and linear decision variables. It becomes a MILP (Mixed Integer Linear Programming) optimization problem with time horizon broken into fixed time intervals that can be represented as [t, 2t......., nt]. At each interval dividing point, a solution is obtained indicating which NBS unit is on. Then a transmission path and the operation time T *starting* from black-start unit to the NBS unit is found out. If T_{oo} is larger than the time interval, the corresponding modified constraint is added to the MILP and the MILP is resolved again. The constraint of transmission path not only increases computational burden but also the solution may not be globally optimal.

In the DP-based restoration model [20], the radial system configuration is assumed and the objective function is to minimize the unserved system energy. The whole restoration process is divided into stages represented by fixed time intervals. The final strategy provides a step-by-step operation of the sequence of feeders. The DP model is constrained by high dimensionality and consequent computation time increase. This method is not used for any practical power system. In all the above three methods, the entire restoration region is divided into fixed time intervals (Figure 1.), where the starting time of an NBS unit is one-time point belonging to the integer set [t,2t,3t, ...nt]. If the time interval to bring an NBS generator is less than t, then the generator has to wait till time t, which affects restoration efficiency. If the time interval is more than t, the corresponding constraint is to be added and this increases computational burden. In the smart grid environment, power system restoration plan with a flexible timeline (Figure 2.) is needed to improve reliability and efficiency in an automated way. Such flexibility is provided by Permutation-Based Power System Restoration model (PPSRM)[7]. The PPSRM method uses the restored load per unit time as the objective function subject to generation and startup constraints. The selection of optimal path is similar to the classical traveling salesperson problem taking into consideration the line charging capacitance and the load priorities in the buses to be energized and uses a modified Dijkstra's method. This method is used in this study.

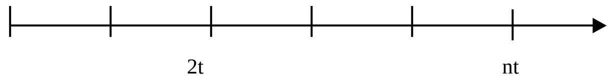


Figure1. Restoration timeline of fixed time interval.

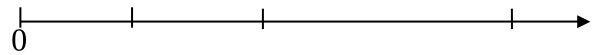


Figure2. Restoration timeline of flexible time interval.

2. Detection of Connectedness of a Smart grid Electrical Network For System Operation

During a large scale power system disturbance, hundreds or thousands of signals may be received simultaneously at the control centre and the operator has to see and analyze the CB positions to come to conclusions like how many islands have been formed for planning restoration. This process is very time consuming and with more parallel operators who may come to conflicting conclusions, further precious time is lost in normalization of the grid. This motivated the author to do research on the determination of islands formed using graph theoretical method. If a grid disintegrates into islands, the short circuit current in the island is less than the short circuit current when the grid is fully integrated. Hence the setting of the protective relays has to be changed either remotely through communication channels or manually in the site. Hence, determination of the connectedness is necessary for the following purposes.

- Planning the restoration process
- revision of relay settings of the protective relays

2.1. Graphics

2.1.1. Adjacency Matrix:

The adjacency matrix of a graph *G* with *n* vertices and no parallel edges is an *n* by *n* symmetric binary Matrix $X=[x_i]$ defined over the ring of integers such that $x_{ij}=1$, if there is edge between *i* and j_{th} vertices and x=0 if there is no edge between them. In the case of power system connectedness, no self-loops and no parallel edges are assumed. For connectedness purpose the parallel edges (line) are considered as one edge as connectivity or no connectivity is the only $_{ij}$ concern. Hence, in our case the following will be observed in the adjacency matrix:

1. The entries along the principal diagonal are all 0's
2. The matrix is symmetrical.

2.1.2. Connectedness:

A graph is connected if we can reach any vertex from any other vertex. A graph *G* is said to be connected if there is at least one path between every pair of vertices in the graph. Otherwise, the graph is disconnected. A disconnected graph consists of two or more connected graphs.

2.1.3. Fusion:

A pair of vertices *a*, *b* are said to be fused (merged) if the two vertices are replaced by a single new vertex.

2.1.4. Algorithm: Connectedness and components

The algorithm for finding connectedness is shown in Fig.3. We start with some vertex in the graph and fuse all vertices that are adjacent to it. Then we take the fused vertex and again fuse with it all those vertices that are adjacent to it now. This process of fusion is repeated until no more vertices can be fused. This indicates that a connected component has been "fused" to a single vertex. If this exhausts every vertex in the graph, the graph is connected. Otherwise, we start with a new vertex and continue the fusing operation. The fused vertices form one island and the number of fused vertices indicates the number of islands to which the grid has disintegrated.

2.1.5. Single Line Diagram(SLD):

The SLD display of the grid is formed using a MATLAB plot function. The islands and their components are available from the connectedness algorithm. For easy perception of the grid islands, different coloring is allotted to each island.

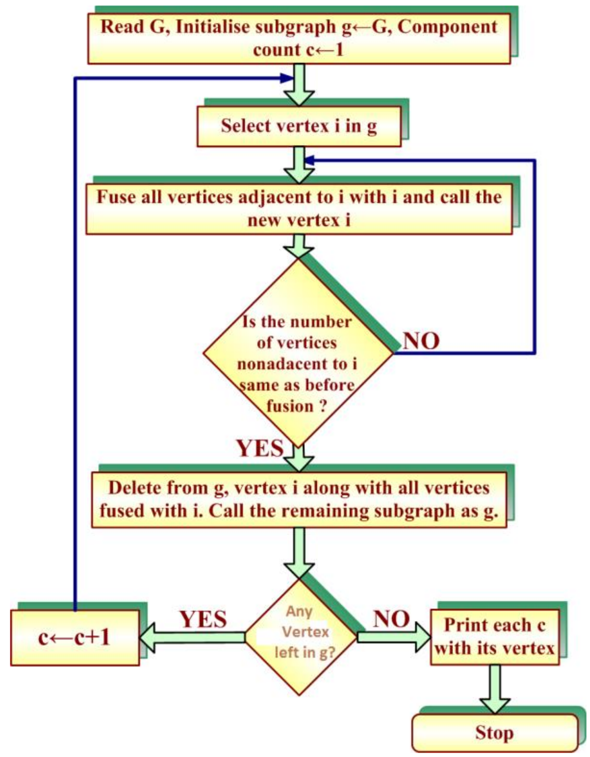


Figure 3. Algorithm for finding connectedness.

2.2. Case Study

A 10 Generator, 39 bus IEEE Power system with 46 lines is used for this purpose (Table A1, Table A2 and Table A3 in Appendix). The study was carried out in MATLAB R2014a environment. The islanded condition of the grid is simulated by setting the Line Status=0 (line is in OFF condition) in the power system database (Table A1 in the Appendix). For example a two island system is created by simulating open condition for lines <25>-<26>, <17>-<18>,<4>-<14>, <13>-<14>, In this study up to five islands are simulated and the working of the algorithm is verified. The expression <bus> denotes the bus number.

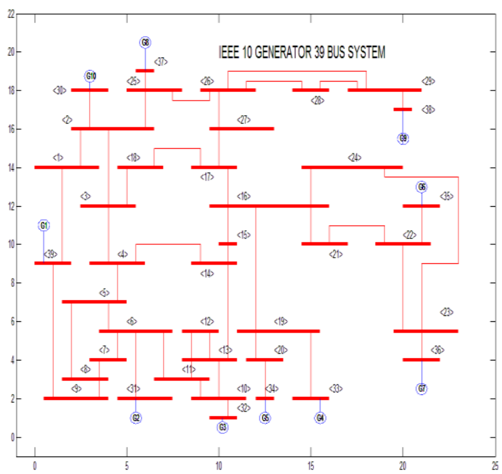
2.2.1. Formation of Adjacency matrix:

The *B* value is used to find the Adjacency Matrix. The diagonal elements are 0. The *B* for the nonexistent edges is taken as 999999(a large number) for the purpose of analysis and the adjacent matrix values for the existing line are the actual values. With these values substituted for B's, the *W* matrix is formed. From this matrix W, the matrix G with 0 or 1 as elements is formed. Corresponding to the values of 999999 and 0 in W, 0 is filled in the G matrix; other elements are 1. The fusing is done with operations on matrix G as discussed in 2.1.4. Once the connectedness and the components are known we can plot the SLD.

2.2.2. Simulation and plotting of the SLD:
The plot and text utilities of the MATLAB are used to construct the network display using the attributes like coordinates, the island to which a bus or line belongs and the line ON/OFF information. The following cases were simulated and the working of the algorithm verified:

a) *With no island formed:* All lines are in service. This condition is simulated by setting **LINE STATUS=1 for all lines in Table.A1. All buses are interconnected and are shown in blue color.** (Figure 4)

Figure 4. SLD OF THE IEEE 39 BUS POWER SYSTEM WITH NO ISLANDING



Island = [1 2 3 4 5 6 7 8 9 11 10 12 13 18 17 16 15 14 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39]

b) *With two islands formed:* Lines <25>-<26>, <17>-<18>,<4>-<14>, <13>-<14> are open . This condition is simulated by making **LINE STATUS=0 for lines 30,25,8 and 18 in Table A1.**

Islands = [1 2 3 4 5 6 7 8 9 11 10 12 13 18 25 30 31 32 37 39]
[14 15 16 17 19 20 21 22 23 24 27 26 28 29 33 34 35 36 38]

c) *With 3 islands formed:* Lines <25>-<26>, <17>-<18>,<4>-<14>, <13>-<14>,<16>-<17> are open.This condition is simulated by making **LINE STATUS=0 for lines 30,25,8,18 and 21in Table 1.**

Islands = [1 2 3 4 5 6 7 8 9 11 10 12 13 18 25 30 31 32 37 39]
[14 15 16 19 20 21 22 23 24 33 34 35 36]
[17 27 26 28 29 38]

d) *With four islands formed:* Lines <25>-<26>, <17>-<18>, <4>-<14>, <13>-<14>, <16>-<17>, <16>-<24>, <16>-<21> are open .This condition is simulated by making **LINE STATUS=0 for lines 30,25,8,18,21,24 and 23 in Table A1.**

Islands = [1 2 3 4 5 6 7 8 9 11 10 12 13 18 25 30 31 32 37 39]
[14 15 16 19 20 33 34]
[17 27 26 28 29 38]
[21 22 23 24 35 36]

e) *With five islands formed:* Lines <25>-<26>, <17>-<18>, <4>-<14>, <13>-<14>, <16>-<17>, <16>-<24>, <16>-<21>, <6>-<11> are open. This condition is simulated by making **LINE STATUS=0 for lines 30,25,8,18,21,24, 23 and 12 in Table A1.** The buses in the five islands formed are shown in blue, magenta, sky blue, red and black colors (Figure 5).

Islands = [1 2 3 4 5 6 7 8 9 18 25 30 31 37 39]
[10 11 12 13 32]
[14 15 16 19 20 33 34]
[17 27 26 28 29 38]
[21 22 23 24 35 36]

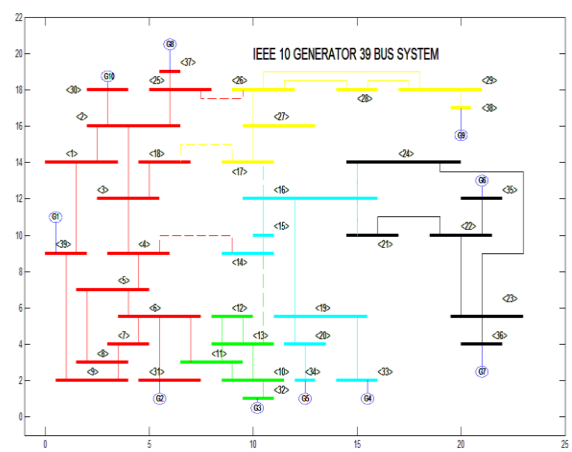


Figure 5. SLD OF THE IEEE 39 SYSTEM WITH FIVE ISLANDS.

f) *With random line outage:* Lines <4>-<14>,<13>-<15> open, No islands formed. This condition is simulated by making **LINE STATUS=0 for lines 8 and 18 in Table A1.** The buses are shown in blue colour(Figure 6)

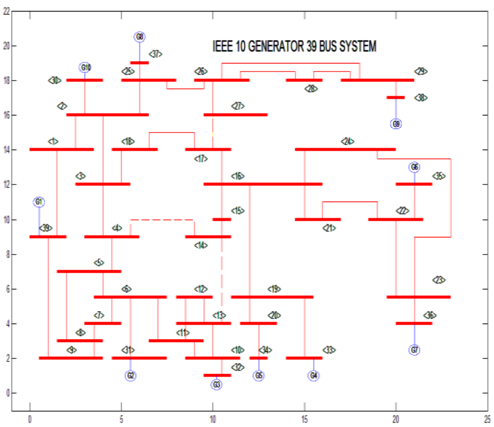


Figure 6. SLD OF THE IEEE 39 SYSTEM WITH RANDOM TRIFPPINGS.WITH NO ISLANDS FORMED

3. Permutation-Based Power System Restoration Model (PPSRM)

3.1. PPSRM

By utilizing the PPSRM method [7], the power system restoration problem becomes a permutation-based optimization problem similar to the classical travelling salesman problem. The block diagram showing the various modules are shown in the Fig.7. It is assumed that there are a total of *n* generators and m NBS generator (*n*>*m*). The input to the transmission path search module is the sequence of generators to start. For example, this sequence could be a member of the initial population S in section 3.12. There are *m* restoration stages and in each restoration stage, the optimal restoration path *P* is found. Here *i* is one of the restored node and *j* is the node of the target NBS generator. An operation-time-calculation module computes generator startup time T_s, stage restoration time T_{stage} and T_{ij} time from beginning to until the last warm start up generator is ready to reach maximum generation power. Here T_s=[T_{s1}, T_{s2},........., T_{sn}] and T represents unit i start up time and T_{stage}=[$_{stage1}$,T_{stage2},.........,$T_{stagemsi}$] and $T_{stagejtotal}$ represents jth restoration time.

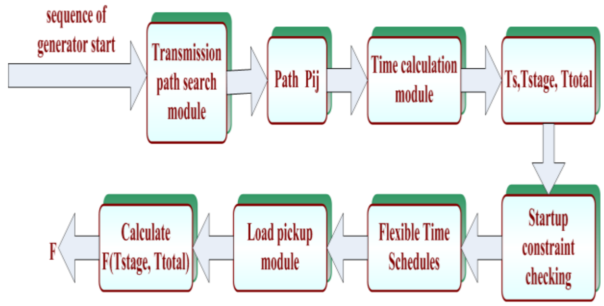


Figure 7. Block Diagram of Permutation Based Power System Restoration Model.

T_s and T are sent to start up constraint checking module to decide whether the generator could start up within the hot startup time. Then a flexible time schedule is provided depending upon the load pickup module. Finally, the objective function F(T_{stage}, T_{total}) indicating restored load per unit time is calculated and it is used as the evaluation function in the optimization process.

3.2. Generator Characteristics

Let For BS or NBS generator i,T_{si}=starting time, T_{ci}=cranking time, R_t=ramp rate. P_m=maximum power, P_{geni}=generator power,; P_{crankj}=cranking power for j th generator, t =time instant. The equations for P_{geni} and P_{geni} are given below and the graphical characteristics in shown in Fig.8

$$\begin{aligned} \text{Pgeni(t)} &= 0 \; if \;\; t < T_{si} + T_{ci} \\ &= R_i(t - T_{si} - T_{ci}) \;\; if \; T_{si} + T_{ci} \le t \le T_{si} + T_{ci} + T_{mi} \\ &= P_{mi} \; if \; T_{si} + T_{ci} + T_{mi} < t \qquad (1) \end{aligned}$$

$$\text{Pcrankj} = P_{rj} \; if \; t \ge T_{sj} = 0 \;\; if \; 0 \le t < T_{sj} \qquad (2)$$

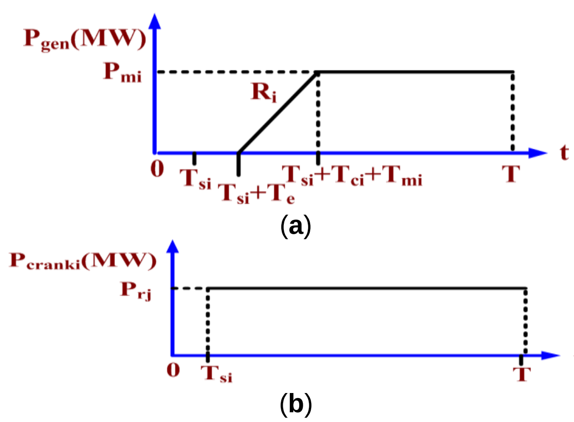


Figure 8. Characteristics (a) Startup characteristics of a BS or NBS generator, (b)Characteristics of NBS generator Cranking power.

3.3. Power system topology model

The line charging capacitance value is used as edge weight in the power system topology model which can then be formulated as an undirected weighted graph G=(V, E, W) where V={*V* the set of nodes representing electric power station or transformer station; E={(i,j)} edges represent high voltage transmission lines. For each edge, there is a positive route cost *W* which accounts for line charging capacitance. For disconnected lines, $W_{ijij,}$ is set as infinity. Traditionally, the optimal path from node *i* to node *j* is the minimum cost path searched by using the Dijkstra method [3,4]. In the method under consideration load importance is also taken into account [7]. The three predetermined values for the load importance are I_1=1 for high priority load like hospitals, *I*=0.5 for some industries and *I*=0.1 for other loads. Based on the power system topology model and load importance degree, a new index P_{3s} has been proposed. P_s is defined as *P*=∑W/∑L where ∑W is the summation of weights of edges in the path. ∑L is the summation of load importance degree of all load nodes along a path.

3.4. The modified Dijkstra method

Step 1: *V* indicates all the nodes in the graph. Initially, *S* contains only source node V_s. Initially, S={V_0}. *U*=*V*-*S* which contains all nodes except *V*.
Step 2: Calculate all P_s from node V_0 to every node V_{u0} in *U*. Choose node *k* from *U*, ensuring minimum P_s of the path from node *V*.
Step 3: Add V_k in *S* and regard V_{k0} to V_k as the middle node and modify P_{s20} of every node in *U*. If *P* of a path node V_0 to V_u (across node V_k) is smaller than P_s, of the pre-calculated *P* of the path from node V_0 to V_u (not across node V_k), P_s of the node from node *V* is modified based on the new path.
Step 4: Repeat Steps 2 and 3 until all nodes are contained in s
.

3.5. Operation Time Calculation Module

In a power system of M NBS generators, there will be M stages in the restoration process. The stage time is calculated by adding the operation time for charging all lines in the stage; in this work, the charging time per line is assumed as 2 minutes. Ts1=Tstage1, Ts2=Ts1+Tstage2 etc. The first stage is from a BS bus to a first NBS bus and the operating time of the lines in the first stage path *T* is calculated. For the second and subsequent stages, the time is calculated taking care to avoid counting in the common path with the earlier stages. Finally, T_{s1},............T_{stagem}] and the corresponding T_s=[T_{s1}, T_{s2}, ..., *T*] are obtained and these are used in objective function calculation. T_{total}

3.6. Startup Constraints Checking Module

T_s and T_{total} are sent into the startup constraint checking module to decide which generator can start within the hot startup time limit T_{hi}. *T* is the maximum hot startup time limit of unit *i*. In this module, the unit can only start if the inequality T_{si} <T_{hi} is satisfied or it fails.

3.7. Load Pickup Module

The load should be equal to generation every minute as shown below; the restored load nodes are determined from high priority to lower priority in every restoration stage T_{stagei}

$$\sum_{k=1}^{m} \int_{T_{stagek}}^{T_{total}} P_{loadk}(t)\, dt = \sum_{i=1}^{n} \int_{T_{si}}^{T_{total}} P_{geni}(t)\, dt - \sum_{j=1}^{m} \int_{T_{si}}^{T_{total}} P_{crankj}(t)\, dt \qquad (3)$$

3.8. Permutation-Based Optimization Problem

The solution x of the problem is the startup sequence of NBS generators, which determine $T_{si,}$ T_{stage}, and T_{total}. The objective function is to maximize the restored load per unit time during T_{total}. The optimization problem can be formulated as

$$Max\ F\big(T_{stage}(x), T_{total}(x)\big) \qquad (4)$$

subject to hot startup time limitation, cranking power requirements and power balance.

3.8.1. Objective function:

The maximization of restored load per unit time is preferred to maximize the restoration efficiency. T_{stagej} is the j_{th} restoration stage time period, T_{total} is a total restoration, and P represents the restored load at stage i.

$$F\big(T_{stage}, T_{total}\big) = \frac{\sum_{i=1}^{m} \int_{T_{stagei}}^{T_{total}} P_{loadi}(t)dt}{T_{total}} \qquad (5)$$

3.8.2. Constraints:

The generator hot startup time constraint is T_{si}<T_{hi} , where i=1,2,...........m
The generator cranking power requirement is

$$\sum_{i=1}^{Gn}\int_{0}^{T_{stagek}} P_{geni}(t)dt - \sum_{j=1}^{Gm}\int_{0}^{T_{stagek}} P_{crankj}(t)\,dt > 0 \quad (6)$$

$$k \in [1,2,\ldots\ldots\ldots m]$$

The power balance is given by

$$\sum_{k=1}^{m}\int_{T_{stagek}}^{T_{total}} P_{loadk}(t)dt = \sum_{i=1}^{n}\int_{T_{si}}^{T_{total}} P_{geni}(t)dt - \sum_{j=1}^{m}\int_{T_{sj}}^{T_{total}} P_{crankj}(t)dt \quad (7)$$

This constraint has established that the available generation must be equal to restored load. The input to the PPSRM module namely the sequence of generator startup forms the important set of input to the optimization module. This sequence of generators is determined using quantum inspired, Quantum Differential Evolutionary algorithm which has been found best for global optimization.

3.9. Quantum-Inspired Differential Evolutionary Algorithm

3.9.1. QDE Algorithm [7]

Power system restoration becomes a permutation based combinatorial problem similar to travelling salesperson problem which is a classical NP-hard problem. According to literature, even though the existing meta heuristic algorithm can solve, the problem, the solutions depend on the parameters chosen and the computation time is also more. Hence the QDE (Quantum Differential Evolutionary) algorithm has been discussed as a problem solver for such problem for its population diversity and quick convergence [21] and [7].

In the QDE Algorithm a quantum chromosome individual is represented as

$Q_i = [\theta_{i1}, \theta_{i2}, \ldots\ldots\ldots\ldots, \theta]$ (8)

where $\theta_{ijin} \in [0, pi/2]$ is the quantum rotating angle. The observation operator and update operator are applied on quantum rotating angle directly

3.9.2. Observation Operator

Under the algorithm, once Q_i is given, $P_i = [\cos\theta_{i1}, \cos\theta_{i2}, \ldots\ldots\ldots\ldots, \cos\theta]$ is determined. The two empty arrays first() and last() are initialized. A random number $\mu \in [0, 1]$ is then generated and if $\mu > \cos\theta_{i1in}$, "1" is put into the last(). Another μ is generated for the second-bit operation and if $\mu < \cos\theta$,"2" is put into first (). After all Q-bits operation, first () and last () are determined. The sequence chromosomes S_i is obtained by combining first () and last ().

3.9.3. Update Operator (based on DE mechanism proposed by Storn and Price [17])

Suppose the population at generation *t* of *m* size is $Q_t = [Q_{1t}, Q_{2t}, \ldots\ldots Q_{mt}]$, each individual is $Q_{int} = [\theta_{i1t}, \theta_{i2t}, \ldots\ldots\ldots\ldots \theta]$. For each individual, mutation, crossover, and selection operation are applied successively.

3.9.4. Mutation

Classically, one type of mutant vector V_{it} of a target vector *Q* is obtained by adding randomly selected vector Q_{r1t} and a weighted difference vector $F(Q_{r2t} - Q_{r3tit})$, where r1, r2 and r3 and *i* are all distinct random numbers; F is a real number between 0 and 2, which controls the amplification of the differential variation. In this work, Q_{r1t} is replaced by the best individual of the generation *Q*, as used by Jia Hou et.al [17,7].

$$V_i^t = Q_{best}^t + F(Q_{r2}^t - Q_{r3}^t) \quad (9)$$

3.9.5. Crossover

A trial vector *U* is generated by comparing a random number between 0 and 1 with crossover factor CR for each bit U_{itijt} and

$$U_{ij}^t = Q_{ij}^t \;\; if\ (rand < CR)$$
$$= V_{ij}^t \;\; otherwise \quad (10)$$

3.9.6. Selection

The greedy strategy is adopted in the selection operation. If *U* generates a better fitness function value compared with the target vector Q_{itit}, the target vector will be replaced by *U* in the next generation; otherwise, Q_{it} remains unchanged

3.10. Procedure QDE

Begin t←0

Initialise control parameters for DE

Initialise Q_t

Observe Q^t by new observation operator and produce S

Evaluate S^t

Store Q_{bes}^t, SS_{best}^t, S_{best}^t

While (t<max generation) do t←t+1

Update Q^t by using DE algorithm

Observe Q^t

Evaluate S^t by new observation operator and produce S^t

Use insert operator for local search
Store Q_{best}^t, SS_{best}^t, S_{best}^t
use reset operator to modify Q_{best}^t used in DE update process

End

3.11. Case Study

The effectiveness of the algorithm is tested using the IEEE, 10 Generator, 39 bus system with the following parameters:
n=10 generators, operation time for each line=2min(assumed)
N=5 = Population size
F=0.7=mutation amplification factor
CR=0.9

Combinations of the F and CR values in the ranges F=(0.25 ,2.00) and CR=(0.1 ,0.9) were tried and F=0.7 and CR=0.9 yielded best results for this power system.
Tables A1 and A2 contain data for the IEEE, 10 Generator, 39 bus system. Table A3 contains the assumed priority data for the bus loads.
Modules developed in MATLAB R2014a environment were used:
.

3.12. Initial Population

An initial population of chromosomes *theta* as per Section (3.9.1) was generated. By observing this chromosome the random sequence of the NBS generators *SS* is found out. From *SS*, the sequence of buses to which the NBS generators are connected *S* is found out. This sequence of buses is used to find the optimal paths using Modified Dijkstra's Algorithm. The following are a set of results after running the Initial Population module.

$$\text{theta} = \left[\begin{matrix} 1.2798 & 1.4228 & 0.1995 & 1.4347 & 0.9933 & 0.1532 & 0.4375 & 0.8590 & 1.5040 \\ 1.5156 & 0.2476 & 1.5246 & 1.5035 & 0.7624 & 1.2571 & 0.2229 & 0.6625 & 1.4384 \\ 1.2444 & 1.5072 & 1.0300 & 0.0561 & 1.3338 & 1.4671 & 1.0662 & 1.1903 & 1.1673 \\ 0.6161 & 1.0296 & 0.2689 & 1.1091 & 0.0500 & 0.4350 & 0.0725 & 0.1526 & 1.2935 \\ 1.0914 & 0.4981 & 1.4926 & 0.0541 & 0.6892 & 0.5994 & 1.2025 & 1.2491 & 0.2935 \end{matrix}\right.$$

$$SS = \left[\begin{matrix} 1 & 2 & 4 & 5 & 8 & 9 & 3 & 6 & 7 \\ 1 & 3 & 4 & 9 & 2 & 5 & 6 & 7 & 8 \\ 1 & 2 & 3 & 6 & 8 & 4 & 5 & 7 & 9 \\ 9 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 1 & 3 & 7 & 8 & 2 & 4 & 5 & 6 & 9 \end{matrix}\right.$$

$$S = \left[\begin{matrix} 19 & 39 & 31 & 34 & 35 & 38 & 30 & 32 & 36 & 37 \\ 19 & 39 & 32 & 34 & 30 & 31 & 35 & 36 & 37 & 38 \\ 19 & 39 & 31 & 32 & 36 & 38 & 34 & 35 & 37 & 30 \\ 19 & 30 & 39 & 31 & 32 & 34 & 35 & 36 & 37 & 38 \\ 19 & 39 & 32 & 37 & 38 & 31 & 34 & 35 & 36 & 30 \end{matrix}\right.$$

Now there are five individual bus sequence *S* covering the BS generator Bus19 and other nine NBS generator buses. The modified Dijksras' algorithm is used to find the optimal path of the individuals. For example the nine paths for the last individual [19 39 32 37 38 31 34 35 36 30] is as given below:

$$SP = \left[\begin{matrix} 19 & 16 & 17 & 18 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 39 & 0 & 0 \\ 39 & 9 & 8 & 7 & 6 & 5 & 4 & 14 & 13 & 12 & 11 & 10 & 32 & 0 \\ 32 & 10 & 13 & 12 & 11 & 6 & 5 & 4 & 3 & 2 & 25 & 37 & 0 & 0 \\ 37 & 25 & 2 & 3 & 18 & 17 & 27 & 26 & 28 & 29 & 38 & 0 & 0 & 0 \\ 38 & 29 & 28 & 26 & 27 & 17 & 16 & 15 & 14 & 13 & 12 & 11 & 6 & 31 \\ 31 & 6 & 11 & 12 & 13 & 14 & 15 & 16 & 19 & 20 & 34 & 0 & 0 & 0 \\ 34 & 20 & 19 & 16 & 21 & 22 & 35 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 35 & 22 & 23 & 36 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 36 & 23 & 22 & 21 & 16 & 17 & 18 & 3 & 2 & 30 & 0 & 0 & 0 & 0 \end{matrix}\right.$$

The 0's are discarded in the later processing. For example, the path from bus 19 to bus 39 is
19 16 17 18 3 4 5 6 7 8 9 39. The second stage is from bus 39 to bus 32; however, some buses are already covered under stage1 and this has to be taken care of; for all subsequent stages similar consideration is followed. This is done by pruning the SP array and an array SPP is created as below for the last individual:

$$SP = \left[\begin{matrix} 19 & 16 & 17 & 18 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 39 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 4 & 14 & 13 & 12 & 11 & 10 & 32 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 2 & 25 & 37 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 17 & 27 & 26 & 28 & 29 & 38 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 16 & 15 & 0 & 0 & 0 & 0 & 6 & 31 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 20 & 34 & 0 & 0 & 0 \\ 0 & 0 & 0 & 16 & 21 & 22 & 35 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 22 & 23 & 36 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 30 & 0 & 0 & 0 & 0 \end{matrix}\right.$$

In this array also the zeros are to be discarded. The operation time required for each stage is calculated and for the above SPP the Operation time array is given below:

$$SPPT = \{22 \ 12 \ \ 6 \ 10 \ \ 4 \ \ 4 \ \ 6 \ \ 4 \ \ 2$$

Example: In the first path, SPP (1, :) there are 11 lines and so the operation time is 11*2min=22min; in the second path, there are 6 lines and the operation time is 6*2=12min.
From the SPPT array, the starting time of the generator for the individual starting sequence is easily calculated. For example for the above SPPT, the staring time array for the generators in the buses [19 39 32 37 38 31 34 35 36 30] is given by,

$$T_S = \{0 \ \ 22 \ \ 34 \ \ 40 \ \ 50 \ \ 54 \ \ 58 \ \ 64 \ \ 68 \ \ 70\}$$

The initial population module calls the operation time calculation module which returns the following

SPP, F, Ts, T_{stage}, SPPT, RLT, gensch

Where, F=objective function, RLT=Restored load tabulation, gensch= generator start up schedule, T_{stage} = the stage time. The above are captured for the best value of the objective function namely Fbest. Fig.9 is a plot of the Generation (P_{Gen}) and Load (P_{Load}) schedule for the objective of Fbest drawn from the data in the table RLTbest

thetabest = {1. 5156 0.2476 1.5246 1.5035 0.7624 1.2571 0.2229 0.6625 1.4384

SSbest= 1 3 4 9 2 5 6 7 8

Sbest = {19 39 32 34 30 31 35 36 37 38

$$
SPPbest=\begin{bmatrix}
19 & 16 & 17 & 18 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 39 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 4 & 14 & 13 & 12 & 11 & 10 & 32 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 19 & 20 & 34\\
0 & 0 & 0 & 0 & 0 & 0 & 3 & 2 & 30 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 2 & 25 & 26 & 27 & 0 & 0 & 0 & 0 & 0 & 6 & 31 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 14 & 15 & 16 & 21 & 22 & 35 & 0 & 0 & 0 & 0\\
0 & 22 & 23 & 36 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 25 & 37 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 26 & 28 & 29 & 38 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

Fbest = 202.1550

SPPTbest = {22 12 4 4 8 10 4 2 6

Tsbest = {0 22 34 38 42 50 60 64 66 72

$$
Genschbest(Generator, Ts)=\begin{bmatrix}
19 & 0\\
39 & 22\\
32 & 34\\
0 & 0\\
30 & 42
\end{bmatrix}
$$

The BS generator, Gen at bus 39, Generator at bus 32 and generator at bus 30 are to be started at time= 0, 22,34 and 42 minutes. The other generators cannot be put into service as hot start up times (T_h) are less than the starting time (T_s)

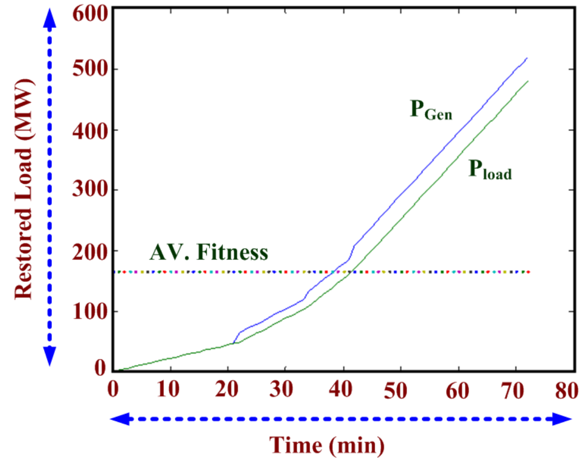


Figure 9. Restoration Schedule with the initial population.

The restoration paths sequence is:

Path 1 = {19 16 17 18 3 4 5 6 7 8 9 39

Path 2 = {4 14 13 12 11 10 32

Path 3 = {19 20 34

Path 4 = {3 2 30

Path 5 = {2 25 26 27 0 0 0 0 0 6 31

Path 6 = {14 15 16 21 22 35

Path 7 = {22 23 36

Path 8 = {25 37

Path 9 = {26 28 29 38

3.13. Update Operation

The initial population *theta* and the global *thetabest* chromosomes are subjected to mutation, crossover and selection operations with the number of generations as the stopping criterion (Section3.9.3 and Section3.10). The results with 20 generations of the population are presented below:

Fbest = 259.6552

Sbest = {19 34 35 36 38 39 31 32 37 30

$$
SPPbest=\begin{bmatrix}
19 & 20 & 34 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 19 & 16 & 21 & 22 & 35 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 22 & 23 & 36 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 16 & 17 & 27 & 26 & 28 & 29 & 38 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 16 & 15 & 14 & 13 & 12 & 11 & 6 & 5 & 8 & 9 & 39\\
0 & 0 & 8 & 7 & 6 & 31 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 13 & 10 & 32 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 5 & 4 & 3 & 2 & 25 & 37 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 2 & 30 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

SPPTbest = {4 8 4 12 20 6 4 10 2

Tsbest = {0 4 12 16 28 48 54 58 68 70

$$\text{genschbest}=\begin{bmatrix}19 & 0\\ 34 & 4\\ 35 & 12\\ 0 & 0\\ 38 & 28\\ 39 & 48\end{bmatrix}$$

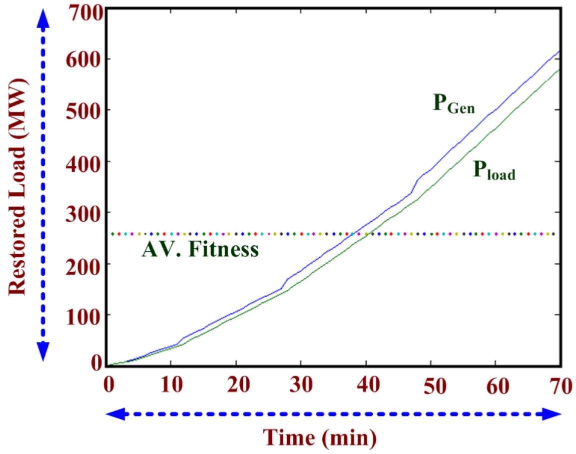


Figure 10. Restoration Schedule after the update operation.

The BS generator, Gen at bus 34, Generator at bus 35.Generator at bus 38 and generator at bus 39are to be started at time= 0, 4,12, 28 and 48minutes. The other generators cannot be put into service as hot start up times (T_h) are less than the starting time (T). Figure 10 show the plot of generated MW, load MW and the average fitness. The restoration paths to be followed in sequence are:

Path1 = {19 20 34

Path2 = {19 16 21 22 35

Path3 = {22 23 36

Path4 = {16 17 27 26 28 29 38

Path5 = {16 15 14 13 12 11 6 5 8 9 39

Path6 = {8 7 6 31

Path7 = {13 10 32

Path8 = {5 4 3 2 25 37

Path9 = {2 30

It is seen that there is an improvement in the objective function Fbest from 202.1550 to 259.6552

4. Conclusions

The power System Restoration consists of three stages namely, the post-fault visualization, the planning of the formation of the skeleton grid covering BS and NBS buses and step by step load resumption. The first two are considered in this paper taking into account security and resumption of priority loads during skeleton grid formation. Determination of connectedness is important for the system operator and the Energy Management system to plan the restoration process. Connectedness is also required for revising the settings of the protective relays in islanded condition and back to the normal settings after the restoration of the grid. For determination of connectivity (connectedness) fusion method of graph theory was used.

The existing state of the art power system restoration methods namely, two-step method, MILP based method and DP(Dynamic Programming) Methods have the limitation of fixed restoration stage times, take longer computational time and the solution may not be global. In the RE/smart grid environment a flexible restoration time, diversity in the population and quicker convergence are required and PPSRM with QDE provides such an environment. For the second stage (skeleton grid formation), PPSRM model is used using QED for optimization of generator sequence. The programs are written in MATLAB R2014a environment and were tested using IEEE 39 bus 10 generator system. The connectedness algorithm can support any system provided the status of the circuit breakers is available from SCADA or any sensing system. The PPSRM algorithm can also be applied to any system with suitable F (mutation amplification factor) and CR (crossover factor) which will give best results.

5. Appendix:

Line No.	Line Data					Transformer Tap		LINE STATUS
	From Bus	To Bus	R	X	B	Magnitude	Angle	
1	1	2	0.0035	0.0411	0.6987	0	0	1
2	1	39	0.001	0.025	0.75	0	0	1
3	2	3	0.0013	0.0151	0.2572	0	0	1
4	2	25	0.007	0.0086	0.146	0	0	1
5	3	4	0.0013	0.0213	0.2214	0	0	1
6	3	18	0.0011	0.0133	0.2138	0	0	1
7	4	5	0.0008	0.0128	1.34E-01	0	0	1
8	4	14	0.0008	0.0129	0.1382	0	0	1
9	5	6	0.0002	0.0026	0.0434	0	0	1
10	5	8	0.0008	0.0112	0.1476	0	0	1
11	6	7	0.0006	0.0092	0.113	0	0	1
12	6	11	0.0007	0.0082	0.1389	0	0	1
13	7	8	0.0004	0.0046	0.078	0	0	1
14	8	9	0.0023	0.0363	0.3804	0	0	1
15	9	39	0.001	0.025	1.20E+00	0	0	1
16	10	11	0.0004	0.0043	0.0729	0	0	1
17	10	13	0.0004	0.0043	0.0729	0	0	1
18	13	14	0.0009	0.0101	1.72E-01	0	0	1
19	14	15	0.0018	0.0217	0.366	0	0	1
20	15	16	0.0009	0.0094	0.171	0	0	1
21	16	17	0.0007	0.0089	0.1342	0	0	1
22	16	19	0.0016	0.0195	0.304	0	0	1
23	16	21	0.0008	0.0135	0.2548	0	0	1
24	16	24	0.0003	0.0059	0.068	0	0	1
25	17	18	0.0007	0.0082	0.1319	0	0	1
26	17	27	0.0013	0.0173	0.3216	0	0	1
27	21	22	0.0008	0.014	0.2565	0	0	1
28	22	23	0.0006	0.0096	0.1846	0	0	1
29	23	24	0.0022	0.035	0.361	0	0	1
30	25	26	0.0032	0.0323	0.513	0	0	1
31	26	27	0.0014	0.0147	0.2396	0	0	1
32	26	28	0.0043	0.0474	0.7802	0	0	1
33	26	29	0.0057	0.0625	1.029	0	0	1
34	28	29	0.0014	0.0151	0.249	0	0	1
35	12	11	0.0016	0.0435	1.00E-10	1.006	0	1
36	12	13	0.0016	0.0435	1.00E-10	1.006	0	1
37	6	31	0	0.025	1.00E-10	1.07	0	1
38	10	32	0	0.02	1.00E-10	1.07	0	1
39	19	33	0.0007	0.0142	1.00E-10	1.07	0	1
40	20	34	0.0009	0.018	1.00E-10	1.009	0	1
41	22	35	0	0.0143	1.00E-10	1.025	0	1
42	23	36	0.0005	0.0272	1.00E-10	1	0	1
43	25	37	0.0006	0.0232	1.00E-10	1.025	0	1
44	2	30	0	0.0181	1.00E-10	1.025	0	1
45	29	38	0.0008	0.0156	1.00E-10	1.025	0	1
46	19	20	7	0.0138	1.00E-10	1.06	0	1

Table A2. 39 BUS SYSTEM-Generator Data.

Gen Bus	Tc(min)	Th(min)	Tr(min)	R(MW/hr)	Pr(MW)	Pm(MW)	GEN ID
30	8	60	120	160	15	1040	10
31	4	12	999999	130	8	646	2
32	5	35	999999	165	9	725	3
19	0	999999	0	132	0	652	4
34	3	8	60	124	3	508	5
35	4	15	999999	134	8	687	6
36	3	10	60	128	7	580	7
37	3	8	60	126	6.5	564	8
38	6	40	120	144	10	865	9
39	8	60	120	164	15.5	1100	1

Table A3. Bus Load Priorities (assumed for this study).

Bus No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Load priority	1	1	1	0.1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.1	1	1	1	0.5
Bus No	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	
Load priority	0.5	1	0.5	0.5	0.5	1	0.5	0.1	0.1	1	1	1	1	1	1	1	1	1	1	

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