# Power System Restoration in Smart Grid Environment

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*Abstract*—**This paper reviews the work done in power system restoration and its procedural development throughout the years. The issues during restoration are discussed in details. Network reconfiguration is done to minimize the losses of the line with minimal changes to the present network. Voltage profile is also a major issue during network reconfiguration which is also addressed in this reconfiguration process. The island formation during the restoration process and its issues are discussed in this paper. A suitable method for island formation during system restoration is proposed.**

## I. Introduction

Power system operates with some constraints, which are load constraints and operating constraints. Load constraints concerns that the requirement of the customer load should be met and operating constraints concerns that system itself stays within its stability limits. Normal state is when both the constraints, load constraints and operating constraints are met. Emergency state is noticed by violation of operating constraints. Restorative state is achieved after emergency state with some loss of load and gaining stability in the system[1].

One of the essential process of electric power system is restoration without which we can not go back to normal state from emergency state. The restoration process reverts the process of an outage, by taking back the system to acceptable operating condition after complete or partial blackout. This is previously done by manual operators through utility assisted guidelines[2].

For restoration to start we have to modify the network from the present faulted condition. This modification will reconfigure the network by isolating the faulted line from healthy part of power network.

Sometime normal operating conditions may need a reconfiguration in network. These conditions may arise due to the change in load configurations of the system. Some line may be overloaded due to the change. Now a day, with the increased penetration of distributed generation and renewable energy, the generation also becomes uncertain along with the load. Under these circumstances it is always advised to transfer the load from heavily loaded lines to lightly loaded lines. This helps in improving the voltage profile, as the drop in the heavily loaded line also improves.

## II. Restoration Issue

Primary issue of power system restoration starts before the restoration phase. At emergency state fault is detected in a section of power system and isolated. Due to this isolation load rejection takes place to maintain load generation balance, which tries to match boiler turbine generator output with system load. In steam turbine partial or complete load rejection is done by intercept valve. In hydro system surge tank along with bypass synchronous valves are used for this purpose.

Low frequency isolation scheme is followed for isolating generator when load generation imbalance is there. These isolations give various island which have partial load and generation match. This scheme provides initial power for restoration which reduces the time taken for restoration. It also minimizes the unserved load.

Control separation is separating part of the power system where the load and generation are balance. This is done in real time to transfer load from unbalanced region to a balanced region. Only some internal faults cause external faults due to out of step operation. The out of step area or unbalanced zone may not be same as the initial fault zone. There may be separate zones which may be separated as the desirable zones. This also reduces the unserved energy and improve the restoration duration.

Frequency and voltage level are to be maintained for sustained operation of power system. In normal operating condition automatic control loops take care of the change in frequency. But during restoration perturbation is outside the range of automatic control loop, due to heavy load addition to the system. Hence special techniques are necessary for the control of frequency of the power system.

During restoration there are always a chances of occurrence of high voltage at the end of long lines and underground cables. Some of the over voltage is sustained which is due to charging current of the lightly loaded line. There might be occurrence of transient over voltage due to switching of large line segments or capacitive elements in the network. There are some equipments which are voltage sensitive like power transformers, circuit breakers and surge arresters. So this is a crucial issue during restoration.

Restoration duration estimation is an issue which is estimated by the duration of the availability of generation. Because it is assumed that load can be picked up, as soon as, the generations are available. The time taken for the load pick up is very less as compare to start up time for the generator. But test studies shows that these assumption are not necessary to be true. So power system operation duration is also should be considered along with generation availability duration for exact estimation.

Protection system can be evaluated by its reliability of operation. This can be evaluated by mal operation, undesired tripping, correct operation, zone or reach of operation. Under restoration these operation are crucial as the system is under changing condition. So any wrong tripping may again push the system to emergency state. There are many relay which may affect restoration (viz. synchro-check relay, negative sequence voltage relay, distance relay without potential restraints, differential relay lacking harmonics restraints, etc.)

## III. RESTORATION OVERVIEW

In late 80s a task force was assigned for the restoration plans for different type of systems having different generation.They survey for different cases and gave report on restoration process followed on different system.Thermal based generation restoration plan is seen to be subdivided into sectionalize, restart, reintegration, load pick-up, interconnection. Hydro-thermal system have one benefit of absorbing charging current by large hydro plants which give system the capability to energize the entire system. The high receiving end voltage is controlled by manually keeping the voltage regulator of hydro much below normal. Some common concern in all the system are immediate resupply of station service, switching operation time consideration, thermal unit constraints, receiving end high voltage, frequency response of sudden load pick up, power factor and coincident demand factors [2]. Normal steps involved in restoration planning is given in a flow chart of figure-1.

The same year second task force report is submitted which considered some bulk power disturbances. The report listed major problems during restoration. They are listed below [3].

- Reactive power balance
- Load generation balance
- Load and generation co-ordination
- Monitor and control
- Protective system
- Energy storage
- system restoration plan

Due to the problems faced in restoration, analytical approach is proposed. The analytical approach start with measuring present condition of the network. These measurements are filtered and state estimation is done to get network topology. We also need to model the external network to process the system. This is done in the modeling phase. This model is then analyzed/optimized. The analysis involves solving of multi-objective, multi stage, large-scale, combinatorial, nonlinear problem(e.g. load flow, optimal power flow). The analysis
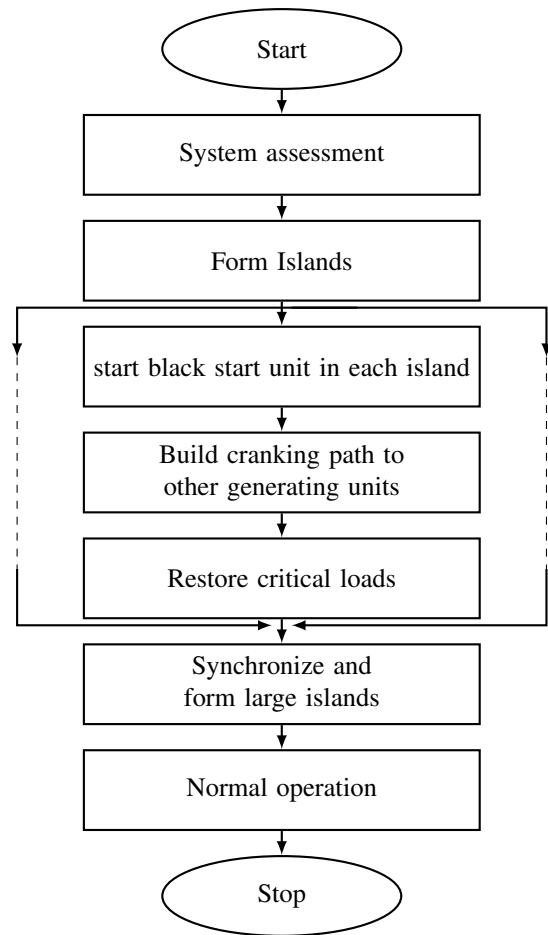


Fig. 1: Steps involved in system restoration

gives data for synthesis of the network. In synthesis switching sequence, load pickup sequence, generation and load schedule are decided [4].

In following years, review of past disturbance reported by federal power commission(24 cases in 1960s) and North American Electric Reliability Council(42 cases in 1980s) indicates each case is somewhat different restoration problem. These problems can be divided into several groups[5]. These group are similar to the task force report with some addition.

A hierarchical approach is developed in early 90s for restoration control problem. It listed some objectives and its constraints in different layer of control. Here three control level are discussed viz. adaptive control, optimizing control and direct control. In adaptive control the objective is minimization of restoration time subject to constraints global connectivity, and global voltage & current. Optimizing level of control, maximize load allocation and minimize control action are the objectives subject to voltage and current of each system island. Direct control has the same objectives as optimizing control with constraints for local connectivity with local voltage & current constraints [6].

## IV. RESTORATION TECHNIQUE

From the years of experience some expert systems are developed for the restoration task. There they consider the switching condition of the system before fault. Then identifying the fault point from a SCADA system tried to restore maximum load as fast as possible. The expert systems developed some methods for zone restoration, group restoration to aid the system operator. At this stage cost of software, implementation of knowledge representation, accuracy and performance evaluation come into picture[1]. Some rules are defined to achieve the goals and subgoals. It has given an methodology rather than structure or procedure of power system.

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        ┌─────────────────────────┐
        │     fault detection     │
        └─────────────────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │  Isolating fault element │
        └─────────────────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │  searching and energizing │
        │   path of blackout areas  │
        └─────────────────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │ Calculate capacity margins │
        └─────────────────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │  Forming Heuristic problem │
        └─────────────────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │    Switching operation    │
        │    planning from result   │
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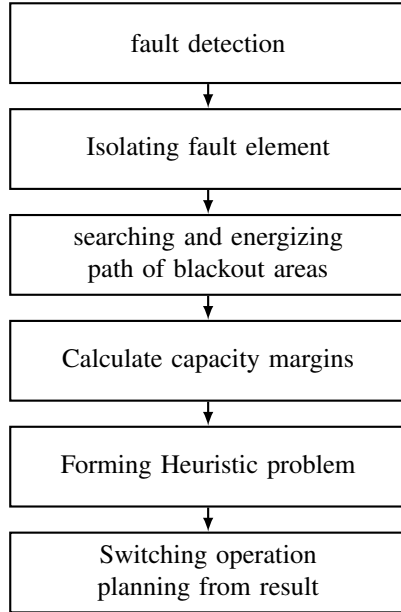
Fig. 2: Hybrid system for power system restoration

Later artificial intelligence techniques are developed for the restoration process. In 1996 a group of researcher in Fuji Electric Corporate R & D, Ltd proposed a hybrid system using both genetic algorithm(GA) and expert system. In this method GA is used to identify the part of out of service area when the total capacity is not enough for the whole load to be supplied[7].

Genetic algorithm and expert system take a further step ahead when GA is used for planning & restoration and the expert system is used for preparation of data concern. The expert system gather data of alarm information, diagnosing fault elements, searching for blackout areas, energizing plant, calculating capacity margin and encoding of the string GA can handle. GA does the optimization for the reconfiguration of the blackout areas. The expert system then again decode the final chosen string from GA for use [8]. The various step involved are given in flow chart figure-2.

Other artificial intelligence techniques are also investigated during this period. Artificial neural network and pattern recognition methods are evaluated for the power system restoration. These methods have their short coming that it needs large time

and huge data for training the network. This method is also not same for all the networks. Different data sets have to be developed for training different systems [9].

Loop control scheme is proposed in 2001. It increases the reliability and implementation of distribution automation. It utilizes the auto re-closure schemes of the circuit breakers. It has a line breaker and a tie breaker. The co-ordination of breaker is done by a microprocessor. The restoration process do not need any optimization process. it detects the fault and restores the system by opening the faulted line and feeding the healthy part by re-closing the tie line breaker [10].

In the year 2008, dynamic programming approach is formulated for restoration problem. Using dynamic programming the objective function may be of many different types where the time required by the percentage of power system feeders to be restored or the time required to energize the key feeders of the system can be taken as objective. Unserved energy of the system can also be taken as an objective, which is given by $U_E = \sum_{i=1}^{n} P_i t_i$, where $P_i$ is the expected load on the $i^{th}$ feeder, $t_i$ the restoration time of the $i^{th}$ load, N is the total no of feeders or substations. The constraints of optimization are power balance $P_G \geq P_L$ and frequency range $f_{min} \leq f \leq f_{max}$ [11].

Now procedures are developed to restore power system using automation. This improves power system reliability. The restoration scheme however is controlled and managed by automatic control system. These automatic control system detect faults, isolate the faulted section and restore service for the non faulted section which is disconnected from the fault. These automatic control system are of two major types depending on their communication capabilities. One with only local information where as the other type has well developed communication link, so as to gather more data for optimized output [12].

Network reconfiguration is the method of changing the status of sensationalizing switches to reduce power loss and providing power for out of service areas. This method is easy to develop in a computer based algorithm for increasing the efficiency of power system.The algorithm of this method for radial network is given in figure-4 [13].This method can be modified to get the desired result for meshed network with variable generation.

## V. SMART GRID RESTORATION

Smart grid can be defined by the quote of Council of European Energy Regulators which says "The smartness of the grid is manifested in making better use of technologies and solutions to intelligently control generation, to better plan and run existing electricity grids, and to enable new energy services and energy efficiency improvements. " Here the author gave focus on "make better use of technology and solution". With the advent of faster communication technology real time control of various system is now catching interest. At this stage we exploit the characteristics of start grid to increase energy efficiency. Some of its function which are associated with the present work are real time data assessment,

distributed generation at load end, and real time control of control equipments.

There is no well defined definition of intelligent electronic devices(IED). So for simplicity we are taking IED is any device with control and communication capability. They might have many functionalities like protection function, metering and data logging. But here only its communication and control are used. Real time data is always available to the control center which is responsible for optimizing the network condition at all time. Any change in the present network condition is sent back to the IED which change the switching condition of the present network at the specific node.

Smart grid of present day must be ready for distributed generation which is at its peak in now a days research and implementation. In this work author has not considered detail modelling of any distributed generation source. It is simply considered as negative load at bus. This is an approximation to ease the calculation and get fast solution. Fast response will give more benefit while optimizing the system for high reliability by reducing the amount of unserved energy.

This increased functionality will lead us to real time monitoring of network condition. Any fault or change in major load will initiate the process of reconfiguration of the network. The proposed algorithm then give us the change in network for the most efficient operation of the system.
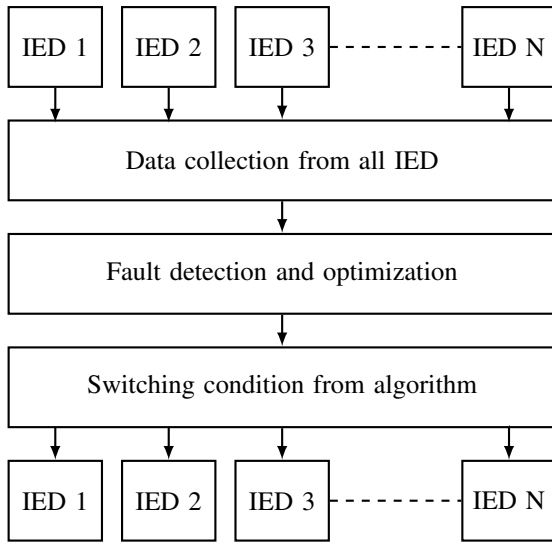


Fig. 3: Smart grid Restoration

## VI. PROBLEM FORMULATION

Traditional GA will not give the optimized result due to its inherent stochastic characteristics. The GA has to be modified which meets our requirement. The no of switching during restoration should be minimized. To meet this requirement we have to constrict the change in switching position to the adjacent sectionalizing switch or maximum by two step. This constraint will help when we reconfigure the system after the fault is cleared. Time requirement for the GA to converge will

also reduce as the solution is of minimal range of the present prefault condition.

There are cost involved in the switching itself. This will also reflect in the time involved for the restoration process. We have to minimize the cost of switching which is also best suited for the modified GA. The constraint on the step in change for reconfiguration will also help in satisfying these objectives.

Above all, the losses in the network should be minimized along with the other objectives. The losses in the system is calculated as per the consideration of radial network. Considering radial network time taken for calculating the load flow and the losses are drastically reduced. The time saving in the loss calculation is due to a back feed algorithm for loss calculation rather than the time consuming detail load flow. Consideration for objectives,

- Loss minimization
- Switching minimization

Objective function:

$$F = min\left\{w_{11}\sum_{i=1}^{n}(1-x_i) + w_{22}\sum_{i=1}^{m}y_i + w_2\sum_{i=1}^{BN}I_i^2r_i\right\}$$
(1)

Here $w_{11}$ gives the cost coefficient for opening a switch, $w_{22}$ gives the cost coefficient for closing a switch and $w_2$ is the cost of coefficient for loss of power in lines. $x_i$, $y_i$ are binary variables for switching operation for opening and closing the switch respectively for $i_th$ switch. $n$ represents the total no of switches in the network, $BN$ represents to total no of branches.

For the given objective we have some operational constraints as well. The major constraint are the voltage limits of buses, capacity limit and power balance. All the buses in the system must not violate the voltage limit assigned by the utility at all cost. The voltage levels of buses also affect losses in the system so directly affecting the objective of the reconfiguration of the system.

$$min\left\{\sum_{i}^{busNo}(V_i - V_{iref})^2\right\}$$
(2)

Here $V_i$ represents the per unit voltage of $i_{th}$ bus and $V_{iref}$ represents the reference voltage of $i_{th}$ bus.

Capacity limit is the limit put by the utility for the consumption of power. This limit must not be violated in any condition. Power balance constraints are the operating constraints which take care of load and generation matching at all time.

$$P_i^2 + Q_i^2 \leq S_{i,max}^2$$
(3)

Here $P_i$ is the real power consumed at bus $i$, $Q_i$ is the reactive power consumed at bus $i$, $S_{i,max}$ represents the maximum apparent power tapped from $i_{th}$bus

$$\sum S_{generation} = \sum S_{load} + \sum S_{loss}$$
(4)

Here all the variables are apparent power for different buses.

For the system to be reconfigured, we have to calculate the path with minimum losses. But extensive load flow is not advisable for the time constraints. So let us assume a system having radial configuration as always in distribution system environment. Let us take a small system for example.
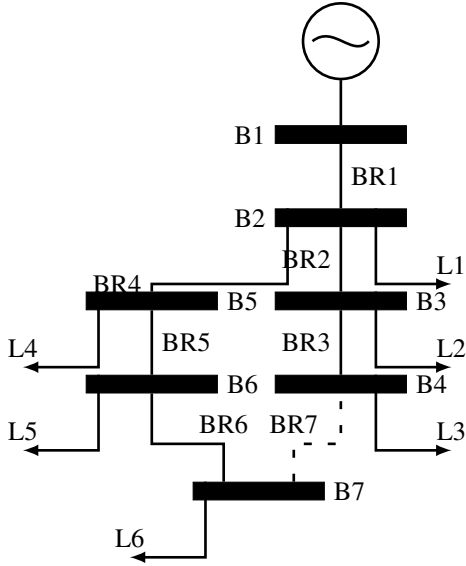


For this small system we will create one connection matrix and one load matrix. System matrix gives that all the diagonal of this matrix is -1, and the branches supplied by the buses will be 1. This means it gives us the data about which branch it is supplied from and which branch it is supplied to i.e. from the first row of the H matrix gives us that branch 1 is supplying to branch 2 and branch 4. Connection matrix is a square matrix of size equal to the no of branches. For this small system given above the connection matrix is given by,

$$H = \begin{bmatrix} -1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

The load matrix is given by the load served by the branch. It gives the branch data from where the load is being served. E.g. load L1 is served by branch 1, so element of 1st row and 1st column should be 1 and rest of the value in that row are zero. Dimension of load matrix depends on no of branches and no of loads. According to this assumptions the load matrix is given by,

$$L = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

For the given system, applying Kirchoff's current law, we can write,

$$H.I_b + L.I_L = 0, \tag{5}$$

where load current can be calculated as,

$$I_{Li} = \frac{P_{Li} - jQ_{Li}}{V_i} \tag{6}$$

Here the most important thing to be noted is the representation of distributed generation in the system. As the grid is getting better communication facilities and increase in the penetration of distributed generation, the proposed algorithm should take that into consideration also. Here the generation in each bus will be represented as negative load. These negative load will produce real and reactive power instead of consuming it. The equation for which remains the same. Branch current

$$I_b = -[H]^{-1}.L.I_L \tag{7}$$

Considering the load current can be negative it is possible that branch current might be negative for some cases where the power is fed back to the network. However least the chance might be this case is also possible. Voltage drop in the branch is given by:

$$\Delta V_i = Z_i.I_{bi} \tag{8}$$

Voltage drop of the branch may show negative values if the load is lower than the generation capability of the bus succeeding it. So the voltage drop is modulus of the above value.

This calculation will go through an iterative process till it is converged. The end result is used to calculate the power loss as follows. Total power loss is:

$$P_{Loss} = \sum \Delta V_i.I_{bi} \tag{9}$$

The same procedure is followed by the different switching configuration to calculate losses in all condition. This algorithm of calculating losses in the line is fast but it only holds for radial configuration. To ensure the radial configuration is maintained we have to change the heuristic algorithm so that there is no loop formed. The heuristic algorithm has to be tweaked so that major changes in the system can be avoided to make it economical. The reconfiguration algorithm is given in figure-4.

## VII. NETWORK MODIFICATION

The reconfiguration result from the previous algorithm has to be applied to the network for fast recovery of the system. For the purpose of reconfiguration and restoring the power of the system we have to take some step wise action for normal operation.

Result of the new network proposed will come in the form of switching configuration of each island. For the small test system the result considering fault at branch 3 prefault connection of sectionlizing switches can be given in Table-F. Post fault system configuration can be given in Table-H.

System operator will check the present network switching condition, get the solution from the algorithm and the sequence
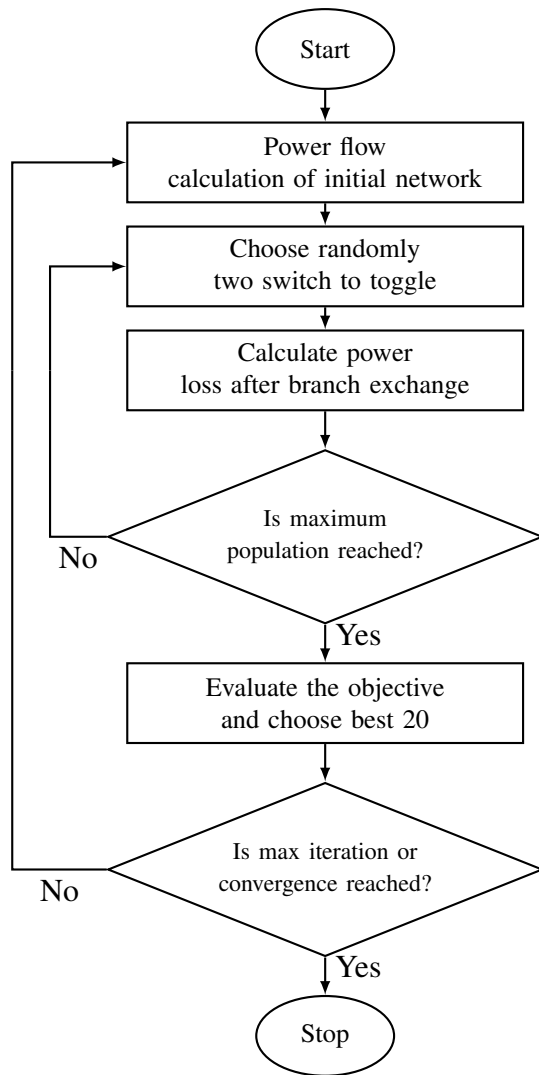
Fig. 4: Heuristic algorithm for network reconfiguration

TABLE I: Prefault switch condition

| Branch no | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| connectivity | 1 | 1 | 1 | 1 | 1 | 1 | 0 |

of switching. These data will help the operator for energizing high priority load and connecting to the lines where generation are present.

Generation and transmission capabilities are again evaluated at this stage. These evaluation will give us the amount of load that can be picked up according to the order of their priorities.

After the fault is cleared system can go back to its normal state with minimum modification as the change in system condition before occurrence of fault and after fault is cleared, be minimal as possible.

TABLE II: Post fault switch condition

| Branch no | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| connectivity | 1 | 1 | 0 | 1 | 1 | 1 | 1 |

## VIII. CONCLUSION

In case of large system the reconfiguration stage is followed by attaching each island formed during restoration. At the time of combining each island, stability issues are more complex than adding a single line to the system. This may take the entire system into the initial stage. The algorithm for the island synchronism is more complex than the present algorithm. The same work can be extended for the system restoration where the primary logic is used for small system. These initial restoration can be done in parallel using this primary algorithm . Then a complex stability study must be done before connecting each island and taking the system to normal condition in its entirety.

This work is a study for the present system restoration procedure and a single island restoration procedure with network reconfiguration considering the distributed generation in the system. The work also proposes the stability issues while considering larger system restoration combining each islands. The complexity of solar and PV generation and its impact at the time of restoration with detail modeling will be added in later work.

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