Self-Healing Strategy for Dynamic Security Assessment and Power System Restoration

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Abstract: *This paper presents a self-healing strategy based methodology for power system dynamic security assessment and to restore the power system to its normal operating conditions. A Self-Healing approach is trained to determine the performance indices, which allows the classification of the operative system state security. The load flow inputs are compared by signals then indicates the disturbance severity and its ability to re- establish an acceptable equilibrium point. In this self-healing approach, the system is adoptively divided into islands with consideration of quick restoration. Then load shedding scheme is tested for IEEE 14-bus system. The dynamic security assessment and Islanding results are provided to highlight the overall accuracy and suitability of the approach.*

Keywords: *Self-Healing, Islanding, Dynamic Security Assessment, Load shedding, Power System Restoration.*

1. Introduction

Security assessment is an important studies carried out in an energy management system to determine the security and stability of the system under unfrozen contingencies. In an analysis performed to determine whether, and what extent the power system is safe without violating from serious interference to its operation. A system said to be secure if there is no violation of operating limit of power system components. Security assessment can be classified into three types namely, steady state, Dynamic state and Transient state respectively. All the three need to be performed on-line, with dynamic security being more complex and difficult than steady state and transient security [1-4] The former characterize the steady state behavior of the system under an outage, while transient security deals with transient disturbance upto 2sec. whereas dynamic security assessment deals with long-term behavior of the system of few seconds to minutes that is from the time system is transient secure to the time of system reaches steady state[5] Which first classifies on operating state as steady state secure or steady state insecure. The second stage classifies the steady state secure states as transiently secure or transiently insecure. The third stage classifies the steady state security and transient secure state into dynamically secure or insecure. Generally any deregulation problem introduces several new economic objectives for operation. As power transactions increase, weak connections, unexpected events, and hidden failures in protection systems, human errors and other reasons may cause the system to lose balance and even lead to catastrophic failures. The complexity of the power system network is increasing. Dynamic Security Assessment (DSA) generally needs detailed modeling of power system. That is detailed model of synchronous machine, exciter, stabilizing networks, governor's and turbines are required for DSA [13].Generator ranking usually done for rescheduling to improve the system security [2].

A system is said to transiently stable if the clearing time of fault is less than the critical clearing time. The critical clearing time is a complex function of pre-fault conditions, its location, types and protective relaying strategy. The likelihood of blackouts has been increasing because of various physical and economic factors. These include, the demand for larger power transfers over longer distances, insufficient investment in the transmission system, exacerbated by continued load growth, huge swings in power flow patterns from one day to the next that render classic off-line planning studies ineffective. These factors result in larger operational footprints and greater demands on the operator to deal with smaller error margins and shorter decision times. These circumstances have created a less reliable operating environment by pushing power systems close to their physical limits. Such an environment requires more intensive on-line analyses to better -coordinate controls. Wide-Area Monitoring and control tools, e.g., Phasor Measurement Units (PMU) and Flexible AC Transmission System (FACTS) devices, and distributed generation and storage devices are the primary technologies used to address such problems. A self-healing concept is expected to respond to threats, material failures, and other destabilizing influences by preventing the spread of disturbances [5]. This requires the following capabilities, timely recognition of impending problems redeployment of resources to minimize adverse impacts, a fast and coordinated response for evolving disturbances, minimization of loss of service under any circumstances, minimization of time to reconfigure and restore service

This paper presents a logic of designing a self-healing strategy after large disturbances. When a power system is subjected to large disturbances, such as simultaneous loss in power generation by several generating units or major failure in power transfer through transmission lines, and the vulnerability analysis indicates that the system is approaching a catastrophic failure, control actions need to be taken to limit the extent of the disturbance. In this approach, the system is separated into smaller islands at a slightly reduced capacity. The basis for forming the islands is to minimize the generation-load imbalance in each island, thereby facilitating the restoration process. Then, by exploring with a sophisticatedly designed load shedding scheme based on the rate of frequency decline, the extent of the disruption is limited and are able to restore the system rapidly. The method has two stages. In the first stage a load shedding is adopted. The second stage includes a restoration process [6]. Load restoration depends on the droop characteristic of the generators and maximum power capability of the generators.

2. Dynamic Security Assessment

Most commonly, contingencies result in relay operations that are designed to protect the system from faults or abnormal conditions. Typical relay operations result in the loss of a line, transformer, generator, or major load. When changes occur, the various components of the power system respond and hopefully reach a new equilibrium condition that is acceptable according to some criteria. Mathematical analysis of these responses and new equilibrium condition is called Security Analysis. Due to the nature of the disturbance and the set up of the power system network, there are two main elements to power system security assessment, static security assessment and dynamic security assessment [7]. Static security assessment is usually performed prior to dynamic security assessment. If the analysis evaluates only the expected post disturbance equilibrium condition (steady-state operating point), this is called Static Security Assessment (SSA). Static Security Assessment also applies the assumption that the transition to new operating conditions has taken place. Its main objective is to ensure that the operating conditions are met in the new operation conditions. Static Security Assessment basically ignores the dynamics of the system and synchronization of the power system network during the process of transiting into post fault condition state remains unknown. This level of assessment will only be able to give a rough estimation of the post contingency stability. It also made a dangerous assumption that the system remains stable in the event of fault.

If the analysis evaluates the transient performance of the system as it progresses after the disturbance, this is called **Dynamic Security Assessment** (DSA). Dynamic Security Assessment is an evaluation of the ability of a certain power system to withstand a defined set of contingencies and to survive the transition to an acceptable steady-state condition. DSA is required due to the constant variation of loads and change in the behaviour of the power system. Gradual changes such as load variations over the day are normal and can be anticipated to some extent. In the event of unexpected loss of a generating plant due to equipment failure, there will be a large impact on both the user and the supplier. These disruptive changes will cause the system variables such as frequency and voltage to oscillate regardless of how small the disturbance is. If the system is secured, these oscillations will decay and be damped out eventually. Otherwise, the oscillation of the frequency and voltage will grow to the extent of shutting down the generator.

Very early power systems were often separate and isolated regions of generators and loads. As systems became larger and more interconnected, the possibility of disturbances propagating long distances increased. The concept of the preventive (normal), emergency, and restorative operating states and their associated controls were introduced for reliable operation of power system (Fig. 1) [2].

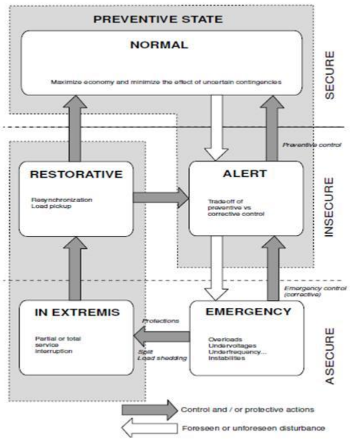

Figure 1: **The operating states and transitions for power systems**

a) Off-Line DSA

In off-line DSA analysis, detailed time-domain stability analysis is performed for all credible contingencies and a variety of operating conditions. In most cases, this off-line analysis is used to determine limits of power transfers across important system interfaces. These limits then are used in an operating environment that is hopefully not significantly different from those conditions considered. Since the analysis is performed off-line, there is not a severe restriction on computation time and therefore detailed analysis can be done for a wide range of conditions and contingencies. These studies include numerical integration of the models for a certain proposed power transfer condition and for a list of contingencies typically defined by a faulted location and specified fault-clearing time (based on known relay settings).The trajectories of the simulation are analyzed to find if voltage transients are acceptable, and to verify whether the transient stability is maintained during the specified fault-clearing time.

If the results for one level of power transfer are acceptable for all credible contingencies, the level of proposed power transfer is increased and the analysis is repeated. This process continues until the level of power transfer reaches a point where the system cannot survive all of the credible contingencies. The maximum allowable transfer level is then fixed at the last acceptable level, or reduced by some small amount to provide a margin that would account for changes in conditions when the actual limit is in force.

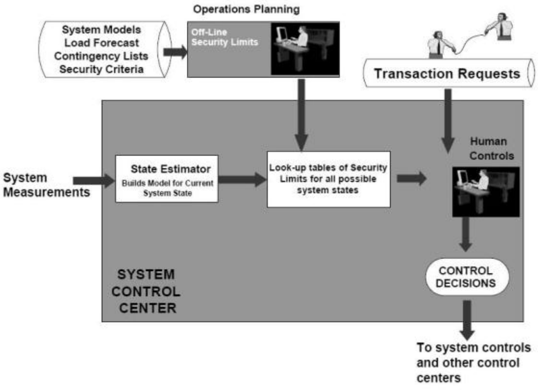

Figure 2: **Traditional Off-line Security Assessment**

b) On-Line DSA

On-line DSA is used to supplement (or update) off-line DSA to consider current operating conditions. A basic on-line DSA framework includes essentially two steps. The first involves a rapid screening process to limit the number of contingencies that must be evaluated in detail. This rapid screening process might consist of some direct method that avoids long numerical integration times. In addition to giving fast stability evaluation, these methods inherently include a mechanism for assessing the severity of a contingency. That is, if a system is determined to be stable, the direct methods also provide an indication of ‘‘how stable’’ the system is. This indication usually takes the form of an ‘energy margin’. On-line dynamic security assessment (DSA) is a promising solution.

Network topology and operating conditions are modeled in real-time as seen by the operator in the control center. System security and limits are calculated using this data Results more accurately characterize the existing system conditions than the off-line planning cases allow the operator to evaluate the impact of certain operating decisions with changing operating conditions[8]. Enhances the decision making capability of an operator and significantly reduces the risk of cascading blackouts by more accurately evaluating limits.

With the increase in transactions on the bulk power system there is a critical need to determine transient security in an on-line setting and also perform preventive or corrective control if the analysis indicates that the system is insecure.

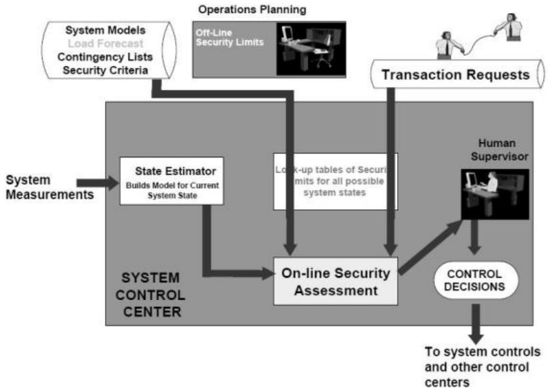

Figure 3: **Traditional On-line Security Assessment**

In recent years, the industry has seen the development of large generation projects at concentrated areas of available fuel supplies .The stability properties of the system have been drastically altered, while the new ‘‘nonutility’’ plants are not cognizant of their impact on system stability. In this environment, stability issues may and will affect available transfer capability. Stability problems may not happen frequently, but their impact, when they do happen, can be enormous. Most of the time, off-line studies are performed to determine conservative limits.

3. Mathematical Model of Dynamic Security Assessment

The dynamic behavior of multi-machine power system is described by the detailed modeling of all the elements of the power system [8].

$$M\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} + P_{ei} = P_{mi} \quad (1)$$

$$\frac{d\delta_0}{dt} = \omega_0 \quad (2)$$

$$P_{ei} = E_i \sum_{i=1}^{N_j} E_j \left[G_{ij}\cos(\delta_0 - \delta_1) + B_{ij}\sin(\delta_i - \bar{\delta j})\right] \quad (3)$$

Where i= 1,2,…………….. N_g, D_i are the inertia and damping constant of the Ith generator; P_{mi} mechanical input to the i_{th} generator; E_j is the EMF behind X'_{di} of the i_{th} generator; G_{ij}, B_{ij} are the real and imaginary parts of the admittance matrix of the of the redused system, X'_{dt} is the transient reactance of the i_{th} generator; N_g is the number of synchronous generator in the system. Eq (3) provide’s the general relation for dynamic behavior of a multi-machine power system used for both dynamic and transint security assessment. Modification of Eq(3) for dynamic security assessment could result as

$$\frac{Md^2\delta}{dt^2} = P_{mi} - P_{ei} = P_m - P_{\max,i} \quad (4)$$

4. Islanding Control

In this process the time-scale method is employed for determining the groups of the generators with coherency. This method considers the structured characteristic of the various generators and finds the strong and weak couplings. Through the selection of the time-scale option, the coherent group of generators can be obtained on any power systems and an automatic islanding program is also developed.

a. Islanding

In determining the islands, the inherent structured characteristic of the system should be considered. In addition, the choice of these islands should not be disturbance dependant. The time-scale method employed is on the application of the singular protection method in power systems [7, 9]. This method assumes the state variable of the n th order septum and are divided into x slow states, y and (n-x) fast stated f, in which the x slowest states represent x groups with coherency. The use provides the estimate for the number of groups. However, the automatic islanding program take into account the mismatch between generation, load and availability of tie lines to form islands and approximately combined groups when islands cannot be formed. For a time-scale method both linearized and non-linear power system models can be used. The basic classical second-order electromechanical model of an n-machine power system was adopted [8].

$$\delta_j = \Omega\,(N_j - 1) \tag{5}$$

$$2H_j N_j = -A_j (N_j - 1) + (P_{mj} - P_{ej}) \quad j = 1,2,\ldots n \tag{6}$$

Where,

N_j= speed of machine j , in p. u.

Ω = base frequency, in radians per second

δ_j = rotor angle of machine j in radians.

P_{mj} = mechanical input power of machine j , in p. u.

P_{ej}= electrical input power of machine j , in p. u.

H_j = inertia constant of machine j , in per seconds.

D_j = damping constant of machine j , in per seconds.

An automatic islanding program based on description method [2] was developed in order to search for the optimum cut sets after the grouping of information is done. The optimum cut set is obtained considering the least generation-load imbalance. The approach begins with the characterization of the network structure or connectivity using the adjacent link table data structure [7], then through a series of reduction processes, the program forms a small network and performs an exhaustive search on its to get all the possible cut sets.

With the information of the coherent groups of generators and the exact locations of where to form the islands, is deployed to form the islands [5,10]. The relay used for islanding requires the local measurements and makes tripping decision using settings based on various offline contingency simulations. It shows much better performance than the conventional out of step relay, which is actually the impedance relay. Besides the impedance, the new relay uses the information of the rate of change of the impedance or resistance and gets better results in practice. Different switching lines make sure different corrective control actions are taken based on the level of the seriousness of the disturbance. When a fault trajectory enters into the range defined by the switching lines, the tripping action will takes place.

5. Load Shedding and Restoration

a. Load Shedding

Load shedding is an emergency control operation and various load shedding schemes have been used in the industry. Most of these are based on the frequency decline in the system. By considering only one factor, namely the frequency, in these schemes the results were less accurate. Any part of a power system will begin to deteriorate if there is an excess of load over available generation. The prime movers and their associated generators begin to slow down as they attempt to carry the excess load. Tie-lines to other parts of the system, or to other power systems across a power pool, attempt to supply the excess load. This combination of events can cause the tie-lines to open from overload or the various parts of the systems to separate due to power swings and resulting instability.

The result may be one or more electrically isolated islands in which load may exceed the available generation. Further, the drop in frequency may endanger generation itself. While a hydro-electric plant is relatively unaffected by even a ten percent reduction in frequency, a thermal generating plant is quite sensitive to even a five percent reduction. Power output of a thermal plant depends to a great extent on its motor driven auxiliaries such as boiler feed water pumps, coal pulverizing and feeding equipment, and draft fans. As system frequency decreases, the power output to the auxiliaries begins to fall off rapidly which in turn further reduces the energy input to the turbine generator.

The situation thus has a cascading effect with a loss of frequency leading to a loss of power which can cause the frequency to deteriorate further and the entire plant is soon in serious trouble. An additional major concern is the possible damage to the steam turbines due to prolonged operation at reduced frequency during this severe overload condition. To prevent the complete collapse of the island, under frequency relays are used to automatically drop load in accordance with a predetermined schedule to balance the load to the available generation in the affected area. Such action must be taken promptly and must be of sufficient magnitude to conserve essential load and enable the remainder of the system to recover from the under frequency condition. Also, by preventing a major shutdown, restoration of the entire system to normal operation is greatly facilitated and expedited. Where individual operating utility companies are interconnected, resulting in a power pool, it is essential that system planning and operating procedures be coordinated to provide a uniform automatic load shedding scheme.

Although the earlier schemes were considerably successful, they lacked efficiency. They shed excessive load which was undesirable as it caused inconvenience to the customers. Improvements on these traditional schemes led to the development of load shedding techniques based on the frequency as well as the rate of change of frequency. This led to better estimates of the load to be shed thereby improving accuracy. The measurement and recording equipments for analysis have undergone developments. Usually, Phasor Measurement Units, PMU are used for measuring the real time data. The load shedding is on a priority basis, which means shedding less important loads, while expensive industrial loads are still in service. Thus the economic aspect plays an important part in load shedding schemes.

Usually, a step wise approach is incorporated for any scheme. The total amount of load to be shed is divided in discrete steps which are shed as per the decline of frequency. For example, when the frequency decreases to the first pick up point a certain predefined percentage of the total load is shed. If there is a further decay in frequency and it reaches the second pickup point, another fixed percentage of the remaining load is shed. This process goes on further till the frequency increases above its lower limit. Increasing the number of steps reduces the transients in the systems. The amount of load to be shed in each step is an important factor for the efficiency of the scheme. By reducing the load in each step the possibility of over shedding is reduced.

b. Load Shedding Techniques

Different methods for load shedding have been developed by many researchers[11-17]. Currently there are various load shedding techniques used in the power industry worldwide. These conventional load shedding schemes are discussed first and latter includes a discussion on under frequency and under voltage load shedding techniques which are proposed by researchers and are yet to be incorporated by the power industry. Industry Techniques for Load Shedding, some of the conventional industry practices for load shedding [11] has definite load shedding requirements. The load serving members must install under frequency relays which trip around 56% of the total load in case of an automatic load shedding scheme. It has nine steps for load shedding. The pickup frequencies are 59.7 Hz for the first step and 59.1 Hz for the last step. The frequency steps, time and the amount of load to be shed is in the table 1. The steps from A to F follow the shedding of load as per a downfall in the frequency. The steps L, M and n are peculiar since they indicate load shedding during a frequency rise. The purpose of this is to avoid stagnation of frequency at a value lower than the nominal. Thus if the frequency rises to 59.4 Hz and continues to remain in the vicinity for more than 10 seconds, 5% of the remaining load is shed so that the frequency increases and reaches the required nominal value. The effectiveness of this scheme is tested every five years by the a specific Stability Working Group (SWG). Based on this scheme certain frequency targets are established. The frequency must remain above 57 Hz and should recover above 58 Hz in 12 seconds. In addition, the frequency must not exceed 61.8 Hz due to excessive load shedding.

Another scheme which can be implemented incorporates both automatic as well as manual load shedding. If the frequency goes lower than 59.5 Hz, the status of the generators is noted. If sufficient load has not been shed further steps of load shedding are undertaken. The immediate action on account of a decision to shed load is to inform the power sector participants regarding the suspension of the hour ahead or the day ahead markets due

***Table 1:* Steps performed for load shedding steps**

Under Frequency Load Shedding Step	Frequency (hertz)	Time Delay (seconds)	Amount of load to be shed (% of the total load)	Cumulative Amount of load (%)
A	59.7	0.28		9
B	59.4	0.28	7	16
C	59.1	0.28	7	23
D	58.8	0.28	6	29
E	58.5	0.28	5	34
F	58.2	0.28	7	41
L	59.4	10	5	46
M	59.7	12	5	51
N	59.1	8	5	56

Another stepwise load shedding procedure can also be adopted. In this, the generator protection is also considered when establishing the frequency set points and the amount of load to be shed at each step. The generator protection relay is set to trip the generators after the last load shedding step. The scheme has the following requirements. They have three basic load shedding steps as shown in table 2. The number of load shedding steps can be more than three provided the above schedule is maintained. This scheme is a distributed scheme as it sheds loads from distributed locations as opposed to centralized schemes. The loads tripped by this scheme are manually restored.

***Table 2:* Alternative approach to perform load shedding**

Amount of load to be shed (% of total load)	**Frequency set points (Hertz)**
10%	59.3
20%	58.9
30%	58.5

Time delay settings are applied to the under frequency relays with a delay of 0.1 seconds. These relays are required to maintain ± 0.2 Hz stability in set point and ± 0.1 seconds in time delay. The styles and manufacturing of these relays is required to be identical to obtain approximately similar response rates. An Under frequency load shedding database can also be maintained with the informations related to the load shed at each step, the total number of steps and records every load shedding event.

Under voltage load shedding scheme[15] have also been developed to protect their system against fast and slow voltage instability. The scheme has been designed for two voltage instability scenarios. The first one is associated with the transient instability of the induction motors within the first 0-20 seconds. The second one is up to several minutes. This collapse may be caused due to the distribution regulators trying to restore voltages at the unit substation loads. According to the topology of the system the Imported Contingency Load Shedding Scheme (ICLSS) has been developed. This scheme uses distribution SCADA computers and consists of PLCs. The Albuquerque area system has been used for testing this method. Thirteen load shedding steps were required to correct the frequency deviation.

Another load shedding scheme based on under frequency relays can be performed in three steps. In case the frequency decline cannot be curbed in three steps, additional shedding steps are carried out. Other actions may include opening lines, creating islands. These actions are carried out once the frequency drops below 58.7 Hz. The scheme is inherently automatic but in case it fails to achieve successful frequency restoration, manual load shedding is incorporated.

Besides the above various load shedding schemes, certain techniques are also employed [12] having three steps in load shedding. In the first step, up to 10% of the load but no more than 15% is required to be shed. In the second step up to 20% of the load but no more than 25% is required to be shed. The third step requires up to 30% but not more than 45% of the existing load to be shed. This scheme is based on the decline of frequency and sheds load as the frequency decreases below its nominal value. The proportion of the load selected for shedding is based on the average of three months of load data and is annually updated. The first three steps of load shedding are set up at three manned substation or substations with remote supervisory control. The amount of load seems to be lesser when the load to be shed is evenly distributed over the system. A new eleven step scheme has been recently suggested. An automatic under frequency load shedding scheme is used [12] to minimize the load to be shed based on the severity of load unbalance and the availability of spinning reserves. It is based on the declining average system frequency.

A similar scheme is incorporated which has established a five stage load shedding scheme with the first pick up frequency of 49.5 Hz (on a 50 Hz system) and the pickup frequency of the last stage is 47.7 Hz. An efficient under frequency load shedding scheme [14] is reviewed with the operating guidelines for every five years. The total load it sheds is up to 25% of the system load. Similar to the basic under frequency scheme it constitutes of three steps. It's pickup frequency for step one is 59.3 Hz as shown in table 3.

Table 3: **Frequency threshold with Load Shedding Scheme**

Frequency Threshold	**Load Relief**
59.3 Hz	5% of the System Load (Total 5%)
58.9 Hz	An additional 10% of the System Load (Total 15%)
58.5 Hz	An additional 10% of the System Load (Total 25%)

An intelligent adaptive load shedding scheme proposed [16] divides the system into small islands when a catastrophic disturbance strikes it. Further, an adaptive load shedding scheme is applied to it based on the rate of change of frequency decline. Under frequency load shedding mainly sets up relays to detect frequency changes in the system. As soon as the frequency drops below a certain value a certain amount of load drops, if the frequency drops further, again a certain amount of load is dropped. This goes on for a couple of steps. The amount of load to be shed and the location of the load to be shed are predetermined.

Terzija [13] had developed under frequency load shedding in two stages. During the first stage the frequency and rate of frequency changes of the system are estimated by non-recursive Newton-type algorithm. In the second algorithm, the magnitude of the disturbance is estimated using the simple generator swing equation.

In another approach Thalassinakis et al [17] have developed a method which uses the Monte Carlo simulation approach for the settings of load shedding under frequency relays and selection of appropriate spinning reserve for an autonomous power system. The settings of the under frequency relays are based on the four parameters; the under frequency level, rate of change of frequency, the time delay and the amount of load to be shed. Three sets of system indices are defined. These sets are for the purpose of comparisons between load shedding strategies. The three aspects of the power systems that were developed in the simulation were, Operation of the power system as performed by the control centre. Primary regulation of the generating units may not be sufficient to control the various parameters after the failure of a generating unit has occurred. Secondary regulation utilizes the spinning reserves. Three different cases of comparing the spinning reserves with the load mismatch are considered. One, when the spinning reserve is sufficient or greater. Thus the load can be restored immediately. Second, when the spinning reserve is slightly insufficient and the rapid generating units will require a certain amount of time to be started. Thus it will be 10-20 minutes before the load can be completely restored. Third, the spinning reserves are insufficient and there are not enough rapid generating units thus implying that the load will not be restored for a considerably long period of time.

c. Load Restoration

Power system restoration is a unique event. However, there are certain goals, steps and aspects that are common to all restoration procedures. Fig. 4 shows all the aspects of power system restoration. They involve almost all aspects of power system operation. If a load shedding program has been successfully implemented, the system frequency will stabilize and then recover to 50 Hz. This recovery is assisted by governor action on available spinning reserve generation, or by the addition of other generation to the system. The recovery of system frequency to normal is likely to be quite slow and may extend over a period of several minutes. When 50 Hz operation has been restored to an island, then interconnecting tie lines with other systems or portions of systems can be synchronized and closed in. As the system frequency approaches the normal 50 Hz, a frequency relay can be used to automatically begin the restoration of the load that has been shed.

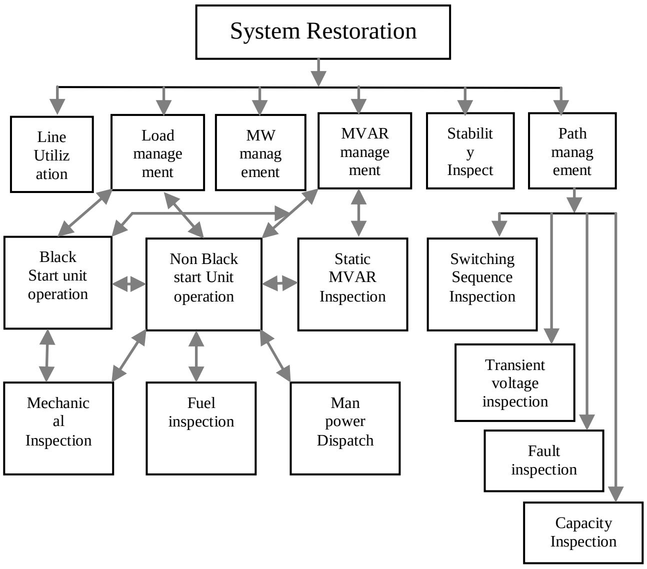

Figure 4 Power System Restoration Aspects

The amount of load that can be restored is determined by the ability of the system to serve it. The criterion is that the available generation must always exceed the amount of load being restored so that the system frequency will continue to recover towards 50 Hz. Any serious decrease in system frequency at this point could lead to undesirable load shedding repetition, which could start a system oscillation between shedding and restoration. This would be a highly undesirable condition. The availability of generation, either locally or through system interconnections, determines whether or not the shed load can be successfully restored. Therefore, a load restoration program usually incorporates time delay, which is related to the amount of time required to add generation or to close tie-lines during emergency conditions. Also, both the time delay and the restoration frequency set points should be staggered so that the entire load is not reconnected at the same time.

Reconnecting loads on a distributed basis also minimizes power swings across the system and thereby minimizes the possibility of initiating a new disturbance. In general, wide frequency fluctuations and the possibility of starting a load shedding/restoration oscillation can be greatly minimized if the amount of load restored per step is small and the spinning reserve generation available is adequate. There should also be adequate time delay provided between load restoration steps to allow the system to stabilize before an additional block of load is picked up. In general, wide frequency fluctuations and the possibility of starting a load shedding/restoration oscillation can be greatly minimized if the amount of load restored per step is small and the spinning reserve generation available is adequate. Horowitz et al [18] suggests spinning reserve availability at least three times the size of the load to be restored at any given step. There should also be adequate time delay provided between load restoration steps to allow the system to stabilize before an additional block of load is picked up.

6. Proposed Load Shedding and Restoration

a. Load Shedding Procedure

Consider a region consists of m generators, the electromechanical equation for the generators can be written as

$$\frac{J_k}{\omega_s}\frac{d\omega_k}{dt} = P_{m,k} - P_{e,k} - P_{d,k}(p.u.) \quad k = 1,\dots,m \tag{7}$$

The electrical power produced by the each generator can be found using the reduction matrix method. The complex produced power for each generator can be of

$$S_g = \quad Diag\{V_g \,.\cdot\, g^{*}\} = [S_1 \cdots S_k \cdots S_m] \tag{8}$$

Therefore, the electrical power needed, $P_{e,k}$, needed in Equation (7) is the real part of S_k as

$P_{e,k}$ = Real $\{S_{e,k}\}$

The damping power for Generator *k* can be obtained from

$$P_{D,k} = D_k\,\omega_k \qquad k = 1, \ldots.., m \tag{9}$$

The produced electric powers of the generators are calculated from the power flow equation at each time step of the differential equations being solved. Also the differential equation corresponds to excitation can be expresses as

$$\frac{d_{E,K}}{dt} = \frac{K_{B,k}}{T_{E,k}}\left(V_{t,k} - V_{ref,k}\right) - \frac{E_k}{T_{E,k}}\; k = 1, \ldots.., m \tag{10}$$

When the region is connected, the input mechanical power of the generators is equal to power associated with the output signal of the governor. However, when the region becomes an island, i.e. is disconnected from the network, it goes into frequency control mode.

In this situation the input mechanical power of the Generator k,$P_{m,k,}$,is considered to be related to the power associated with the governor of Generator *K*, $P_{gov,k}$, by a first order differential equation as:

$$\frac{d_{m,k}}{dt} = \frac{P_{gov,k} - P_{m,k}}{T_{g,k}} \qquad k = 1, \ldots, m \tag{11}$$

For Generator *K* the output power associated with the output signal of the governor, $P_{gov,k}$, is related to the frequency, f_k , the output mechanical power associated with the output signal of the governor , $P_{gov,k}$, needs to be expressed in terms of frequency as

$$P_{gov,k} \quad = \quad \frac{R_k\; P_{\max k} + f_k}{R_k} \qquad k = 1, .., m \tag{12}$$

Consider the case that the region is connected to the main network through a tie line. The region imports electrical power from the main network. If the circuit breaker of the tie-line is tripped, the region in the network then becomes separated from the network. After disconnecting the region from the main network, the region is referred to as the electrical island. As the load is typically less than the generation in the island at the time of separation, the frequency in the island starts to drop.

According to the shedding procedure the loads are shed until the frequency drop is stopped and starts to rise. The shedding procedure is based on a predefined shedding policy. Any policy for load shedding such as prioritized load can be considered in the shedding procedure. Considering the case that the total rated power of the generators in the island can meet the total load in the island, eventually the frequency of the island becomes stable and the region keeps its integrity by initially removing some of the loads in the region and gradually restoring them. Fig. 5 shows the flowchart of shedding process for shedable load *i*.

The frequencies f_{island} and f_{shedi} are the island frequency and shedding frequency of shedable load *i*. The ordering in load shedding (if any) might be coming from a shedding policy set by the utility in the island. When the frequency stabilized, i.e. there is no more reduction in the island frequency, then due to predefined droop characteristic of each generator, the produced power of the generators increase. Thus, the frequency rises.

b. Load Restoration Procedure

In the proposed algorithm for restoration process, the droop characteristics of the generators need to be adjusted so that the rated load is supplied at the frequency which is more than *50 Hz*.

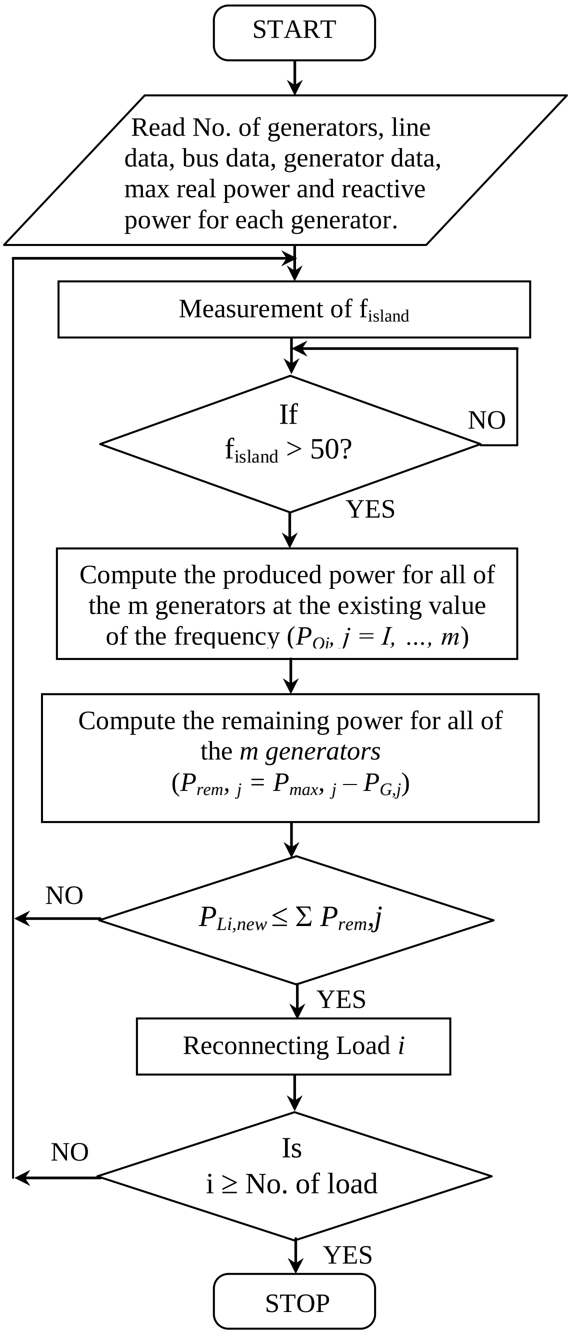

***Figure 6*: The Flowchart for the Restoration Procedure**

The restoration process comes to effect when the frequency goes more than *50 Hz*. In the simulation, at each time step of the restoration process, the produced power of each generator is computed according to the frequency of the island at that step using the droop characteristic of each generator. Then, for each generator the produced power is subtracted from the maximum power of the generator and the result is referred as the remaining power, $P_{rem,1}$, for that generator. The restoration of a specific load will be performed if the power of the of the incoming load, P_L , is less than or equal to the total remaining of the generators. In the real power system the droop characteristic of the generators are to be chosen to be similar or, alternatively, for each load the droop characteristic of all of the generators are provided. Therefore the loads can asses that which time suits it to reconnect to the load. Also the restoration policy may incorporate the prioritized loads in restoration.

7. Simulation Results

Case: 1

The load shedding scheme is tested on a 14-bus, 5-generator system. The following lines are tripped:

1. Bus 6–Bus 5;
2. Bus 9–Bus 4;
3. **3.** Bus 7–Bus 4.

After islanding, the system is divided into two islands shown as in Fig. 7. The bus 1, 2,3,4,5 forms the island which is generation rich.

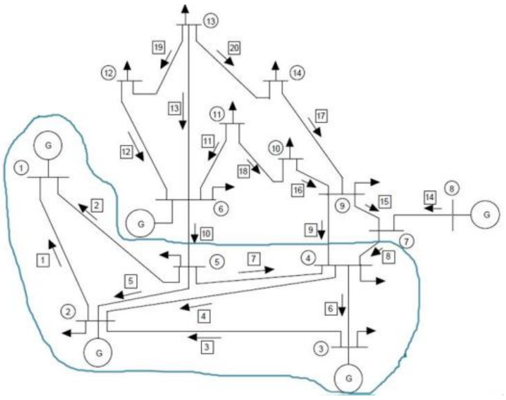

Figure 7 Two islands for IEEE 14 bus system

Table 4: Load flow of IEEE 14 Bus system

No of Iteration 116

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1	0	2.3515	0.2169
2	0.9601	-5.3281	0.1830	-0.5510
3	0.9681	-14.9735	-0.9420	0.4000
4	0.9501	-11.7966	-0.4780	0
5	0.9525	-10.0902	-0.0760	-0.0160
6	1.0168	-16.5429	-0.1120	0.2400
7	0.9871	-15.1529	0	0
8	1.0282	-15.1529	0	0.2400
9	0.9709	-16.9200	-0.2950	-0.1660
10	0.9710	-17.1672	-0.0900	-0.0580
11	0.9898	-16.9818	-0.0350	-0.0180
12	0.9988	-17.4876	-0.0610	-0.0160
13	0.9915	-17.5197	-0.1350	-0.0580
14	0.9605	-18.3375	-0.1490	-0.0500

Frequency of the system 49.9842

Table 5: Load flow for power System Island consists of 3 Generator buses and 2 Load buses

No of Iteration: 31

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0000	0	1.3849	-0.1006
2	0.9810	-3.2879	0.1830	-0.5510
3	0.9972	-11.0980	-0.9420	0.4000
4	0.9868	-6.9533	-0.4780	0
5	0.9891	-5.5758	-0.0760	-0.0160

Governor Output power at the base frequency: 2.5061, 2.5006

Governor Output power after Islanding: 2.5295, 2.5240

Table 6: Generation at the buses after Islanding:

Bus No	P Generated (p.u)
1	2.3200
2	0.4000
3	0
4	0
5	0

Table 7: Load at the Buses after Islanding

Bus No	P Load (p.u)
1	0
2	0.2170
3	0.9420
4	0.4780
5	0.0760

Frequency of the system after Islanding: 50.4675

Governor Output power after Load Restoration: 2.5060, 2.5005

Table 8: Generation at the buses after Load Restoration:

Bus No	P Generated (p.u)
1	1.4840
2	0.2300
3	0
4	0
5	0

Frequency of the system after Load Restoration = 49.9978Hz

Case: 2

The bus 2,3,4,5 forms the island which is Load rich.

Table 9: Load flow for power System Island consists of 2 Generator buses and 2 Load buses.

No of Iteration: 20

Bus No	Voltage magnitude	Voltage angle	Real Power	Reactive Power
1	1.0000	0	1.5512	-0.5165
2	1.0130	-8.3663	-0.9420	0.4000
3	0.9986	-5.0495	-0.4780	0
4	0.9983	-4.2343	-0.0760	-0.0160

Governor Output power at the base frequency: 2.5006, 2.5016.

Governor Output power after Islanding: 2.4718, 2.4918.

Table 10: Generation at the buses after Islanding:

Bus No	P Generated (p.u)
2	0.4000
3	0
4	0
5	0

Table 11: Load at the buses after Islanding:

Bus No	P Load (p.u)
2	0.2170
3	0.9420
4	0.4780
5	0.0760

Frequency of the system after Islanding: 49.4244Hz

Governor Output power after Load Restoration: 2.5008, 2.5108

Table 12: Load at the buses after Load Restoration:

Bus No	P Load (p.u)
2	0.0564
3	0.2449
4	0.1243
5	0.0198

Frequency of the system after Load Restoration: 50.0034Hz

8. Conclusion

In this paper, a self-healing scheme for large disturbances with concentration on a new load shedding scheme is described. A method is presented for survival of an electrical island when it becomes separated from the main network. The method has two stages. In the first stage a load shedding is adopted. The second stage includes restoration process. Results indicate that using this method successfully prevents the island from blackout and restore the system when it becomes separated from the network. The scheme is tested on the 14-bus sample system and shows very good performance.

9. Appendix

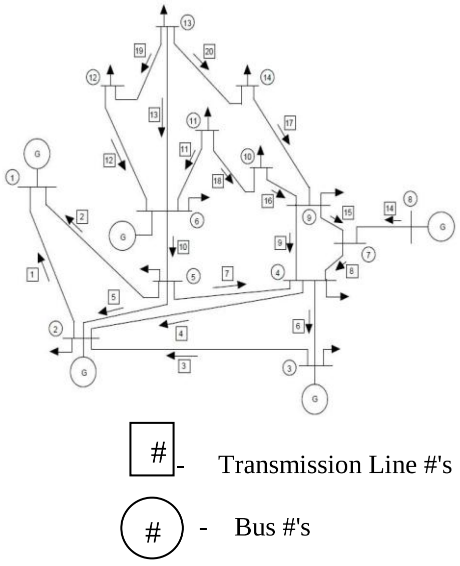

Figure 8: IEEE 14-bus test system one line diagram

Table 13: Generator Data

Generator Bus No.	1	2	3	4	5
MVA	615	60	60	25	25
x_l (p.u.)	0.2396	0.00	0.00	0.134	0.134
r_a (p.u.)	0.00	0.0031	0.0031	0.0014	0.0041
x_d (p.u.)	0.8979	1.05	1.05	1.25	1.25
x'_d (p.u.)	0.2995	0.1850	0.1850	0.232	0.232
x''_d (p.u.)	0.23	0.13	0.13	0.12	0.12
T'_{do}	7.4	6.1	6.1	4.75	4.75
T''_{do}	0.03	0.04	0.04	0.06	0.06
x_q (p.u.)	0.646	0.98	0.98	1.22	1.22
x'_q (p.u.)	0.646	0.36	0.36	0.715	0.715
X''_q (p.u.)	0.4	0.13	0.13	0.12	0.12
T'_{qo}	0.00	0.3	0.3	1.5	1.5
T''_{qo}	0.033	0.099	0.099	0.21	0.21
H	5.148	6.54	6.54	5.06	5.06
D	2	2	2	2	2

Table 14: Bus Data

Bus No.	P Generated (p.u.)	Q Generated (p.u.)	P Load (p.u.)	Q Load (p.u.)	Bus Type*	Q Generated max.(p.u.)	Q Generated min.(p.u.)
1.	2.32	0.00	0.00	0.00	2	10.0	-10.0
2.	0.4	-0.424	0.2170	0.1270	1	0.5	-0.4
3.	0.00	0.00	0.9420	0.1900	2	0.4	0.00
4.	0.00	0.00	0.4780	0.00	3	0.00	0.00
5.	0.00	0.00	0.760	0.0160	3	0.00	0.00
6.	0.00	0.00	0.1120	0.0750	2	0.24	-0.06
7.	0.00	0.00	0.00	0.00	3	0.00	0.00
8.	0.00	0.00	0.00	0.00	2	0.24	-0.06
9.	0.00	0.00	0.2950	0.1660	3	0.00	0.00
10.	0.00	0.00	0.0900	0.0580	3	0.00	0.00
11.	0.00	0.00	0.0350	0.0180	3	0.00	0.00
12.	0.00	0.00	0.610	0.0160	3	0.00	0.00
13.	0.00	0.00	0.1350	0.0580	3	0.00	0.00
14.	0.00	0.00	0.1490	0.0500	3	0.00	0.00

Table 15: Line Data

From Bus	To Bus	Resistance (p.u.)	Reactance (p.u.)	Line charging (p.u.)	Tap ratio
1	2	0.01938	0.05917	0.0528	1
1	5	0.5403	0.22304	0.0492	1
2	3	0.04699	0.19797	0.0438	1
2	4	0.05811	0.17632	0.0374	1
2	5	0.5695	0.17388	0.034	1
3	4	0.6701	0.17103	0.0346	1
4	5	0.01335	0.4211	0.0128	1
4	7	0.00	0.20912	0.00	0.978
4	9	0.00	0.55618	0.00	0.969
5	6	0.00	0.25202	0.00	0.932
6	11	0.099498	0.1989	0.00	1
6	12	0.12291	0.25581	0.00	1
6	13	0.06615	0.13027	0.00	1
7	8	0.00	0.17615	0.00	1
7	9	0.00	0.11001	0.00	1
9	10	0.3181	0.08450	0.00	1
9	14	0.12711	0.27038	0.00	1
10	11	0.08205	0.19207	0.00	1
12	13	0.22092	0.19988	0.00	1
13	14	0.17093	0.34802	0.00	1

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