International Journal of Engineering Research and Development
e-ISSN: 2278-067X, **p**-ISSN : 2278-800X, www.ijerd.com
Volume 5, Issue 2 (December 2012), PP. 64-81

Security Assessment of an Interconnected Power System Considering Voltage Dependent Loads with Dynamic Tap Changer and Exponential Recovery Loads Using Interline Power Flow Controller

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Abstract:- Power system architecture today are being made more complex and they require more sophisticated new technologies or new devices such as Flexible AC Transmission Systems (FACTS). The limiting factor of the stability and the determination of the transfer limits depend on the load-voltage characteristic since load relief due to the load-voltage dependency results in larger transfer limits.This paper deals with the overview of a control strategies for the security assessment of an interconnected power system coordinated with different loads which can be governed by FACTS especially Interline Power Flow Controller (IPFC) devices when the system is approaching an extreme emergency state. IPFC is employed to enhance power system stability in addition to their main function of power flow control. In this method, the island is prevented from the total loss of supply using few FACTS devices. The optimization process is carried out using bacterial foraging optimization algorithm. The optimized result exhibits tremendous improvement in the system performance. when the proposed scheme is adopted in a IEEE 14 bus test system.

Keywords:-Flexible AC Transmission System (FACTS), Interline Power Flow Controller (IPFC), Voltage Dependent Load (VDL) with Dynamic Tap Changer, Exponential Recovery Loads (ERL), Dynamic Security Assessment (DSA).

I. INTRODUCTION

Power system dynamic behaviour analysis requires adequate modelling of various utilities with the consideration of their parameter values that ensure those models with replicate reality. In many cases, the level of approximation is determined by the nature of the study. Load modelling provides an example. It is common for the aggregate behaviour of loads to be represented by a Voltage Dependent Loads with Dynamic Tap Changer and Exponential Recovery. The loads models will be a gross approximation, which provides information about the complex composition of the loads. This deficiency is particularly evident in distribution systems that supply a significant motor load, as the Voltage Dependent Loads with Dynamic Tap Changer and the Exponential Recovery Load model cannot capture the delayed voltage recovery. Design procedure arising from system dynamic behaviour can also be thought of in an optimization framework. However, any the optimization formulation must capture the processes driving dynamics. This class of problem be optimized efficiently using advanced computational procedures is referred as *optimization algorithm*. The classification of models is a decision that should be made based on the knowledge of the actual system composition and the phenomena that are being studied.

In a power system network, there are often multiple loads connected to a single bus, normally the power of individual load is not measured or not available, but the total power transmitted through the bus is measured. In these cases, the loads can be considered as one composite load, which consists of static loads and dynamic or nonlinear loads. In recent years, many techniques have been proposed to model such loads . However, most of them are based on an assumed load equation and the parameters of the equation are estimated through curve fitting. Because of the complexity of modern loads (for example, power electronics loads), the assumed models may not capture power, frequency and voltage phenomena simultaneously and accurately. It is necessary to investigate new load modelling techniques to establish accurate load models for power system stability analysis. When a power system is subjected to large disturbances, such as [1] simultaneous loss of several generating units or major transmission lines, and the vulnerability analysis indicates that the system is approaching a catastrophic failure and more efficient and fast control actions need to be taken to limit the extent of the disturbance.

Even with the FACTS controllers like Static Var Compensators, Unified Power Flow Controllers, Interline Power Flow Controllers trade-offs provides improved damping by optimization or tuning the controller even for small-signal conditions. As a consequence, the performance during the transient period immediately following a large disturbance may be degraded. FACTS devices' output limiters attempt to balance these competing effects. It can be shown that the tuning of these limiter values can be formulated as a bacterial foraging optimization problem. In contrast to design, analysis of system dynamics is more aligned with understanding extremes of system behaviour. The method has two stages. The first stage is to choose the weakest bus. The second stage includes a restoration process. Load restoration depends on the droop characteristic of the generators and maximum power transfer capability of the utilities.

This paper discusses a vision for the solution for the power quality by improving the power system restoration through improved monitoring and control. The demand for larger power transfers over longer-distances, insufficient investment in the transmission system, exacerbated by continued load growth are the trust areas which require continuous reforms to ensure a quality power supply to the consumers. The basic restoration assessment for Voltage Dependent Loads with Dynamic Tap Changer and Exponential Recovery Loads model in the power system network has been carried out and the various control corrective actions using IPFC is considered for the power system security enhancement study.

II. POWER SYSTEM SECURITY ASSESSMENT

Due to the nature of the disturbance and the set up of the power system network, there are two main elements in the Power System Security Assessment namely Static Security Assessment and Dynamic Security Assessment. 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), then this is referred as Static Security Assessment (SSA). Static security is related to an equilibrium point of the system where voltage and thermal limits are observed. It neglects the transient behavior and any other time dependent variations caused by changes in load conditions [2]. If the analysis evaluates the transient performance of the system as it progresses after the disturbance is referred as Dynamic Security Assessment (DSA). Dynamic Security Assessment is an evaluation of the ability of a power system to withstand a defined set of contingencies and to survive in the transition to an acceptable steady-state condition. DSA refers to the analysis required to determine whether the power system can meet the specified reliability and security criteria in both transient and steady-state time frames for all credible contingencies.

In the operating environment, a secure system is one in which operating criteria are given prior important at pre- and post contingency conditions. This implies that analyses must be performed to assess all aspects of security, including the thermal loading of system elements, voltage and frequency variations (both steady state and transient), and all forms of stability. If the system is secured, these oscillations will decay and has to be damped out eventually. Otherwise, the oscillation of the frequency and voltage will grow to the extent of even shutting down the generator. If the system experiences a major disturbance, the oscillation will keep growing to a significant magnitude. The stability is then measured based on the trajectories of the disturbed systems motion related to the region of attraction of the final equilibrium state. For such situations, the accurate modeling of nonlinear system and regressive analysis of the nonlinear system [3] are to be adopted. Due to the tremendous growth in the interconnected Power system network with more complicated load models, increase the possibility of disturbance occurrences and the propagation of the disturbances. So the concept of the preventive (normal), emergency, and restorative operating states and their associated controls are to be adopted effectively.

2.1. Off-Line DSA

In the 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 the off-line Dynamic stability analysis is used to determine limits of power transfers across the important system interfaces. Since the analysis is performed off-line there is no severe restriction on computation time and therefore detailed analysis can be done for a wide range of conditions and contingencies [4]. 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

The simulation results 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 for 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 [5].

III. MATHEMATICAL MODEL OF A POWER SYSTEM

The dynamic behavior of multi-machine power system is described by the detailed modeling of all the elements of the power system [5].

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

$$\frac{d\delta_0}{dt}=\omega_0 \tag{2}$$

The general relation for dynamic behavior of a multi-machine power system used for both dynamic and transient security assessment be represented as

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

Where i = 1,2,…………….. N_g. M_i, D_i are the inertia and damping constant of the i_{th} generation; 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 Conductance and Susceptance of the admittance matrix of the of the reduced system, X'_{di} is the transient reactance of the i_{th} generator; N_g is the number of synchronous generator in the system. Modification of equ (3) for dynamic security assessment could result as

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

3. 1. Modelling of Dynamic Loads

A load can be mathematically represented with the relationship between power and voltage where the power is either active or reactive and the output from the model. The voltage (magnitude and/or frequency) is the input to the model. The load can be a static or dynamic load or a combination of both. Load models are used for analyzing power system security problems, such as steady state stability, transient stability, long term stability and voltage control. According to the power voltage equation, power system loads are divided into constant-impedance, constant power and constant current loads. A considerable amount of loads in power systems are induction motors and as several induction motors are connected to a busbar and it may be modelled as a single motor, parameters of which are obtained from the parameters of all motors and is referred as dynamic load modelling. [6].

The dynamic load model describes the time dependence as well as the voltage dependence of the load. The characteristic of a bus load depends on the load composition, which means that the aggregated load characteristics for the bus load must be found. These load parameters can be derived by field measurement based method which is based on direct measurement at a bus, during system disturbances or planned system disturbances, where voltage, frequency, active power and reactive power are measured. Then a method, such as the *Least Square Method* is used to derive parameters to the aggregated load model.

Field Measurement Based Method is a simple Straightaway approach to derive a model. Unless the load composition is analysed in detail and unless buses having loads of fairly different compositions are measured there will not be performance analysis of the system and can even be extrapolated to different conditions. Spontaneous load variations are included in the load model, especially during long term measurements. Traditionally, lumped feeder loads are represented as static composite load models on the basis of constant impedance, constant current or constant power contributions. Models resulted in a classical dynamic model that was however still treated as linear in its voltage and frequency dependence of active and reactive powers [7]

IV. MATHEMATICAL MODEL OF DYNAMIC LOAD

The General form of Load Modelling equation can be written as, [8]

$$\dot{x} = a(x, v) \tag{5}$$

$$P_H = b_p(x, v) \tag{6}$$

$$Q_H = b_p(x, v) \tag{7}$$

$$P_H = b_p(x(\infty), v) \tag{8}$$

Where b_p $x(\infty)$ solve $x = 0$, i.e. $a(x, v) = 0$ for static load characteristic and,

$$P_H = b_p(x(0), v) \tag{9}$$

Where P_H is a Active power consumption model, x (0) is the value of the state when the initial change occurs. Dynamic load model with exponential recovery had also been proposed in [8], a differential equation that defines the behaviour of simple dynamic load model based on the response to a voltage step is given by [9].

$$T_p P_H + P_H = P_s(V) + k_p(V)\dot{V} \tag{10}$$

Where

$$K_p(V) = T_p P_t(v)\dot{v}$$

This equation can be written in first-order form as

$$P_H = \frac{\dot{X}_p}{T_p} + P_t(V) \tag{11}$$

$$\dot{X}_p = P_s(V) - P_L \tag{12}$$

Where T_p is a Active load recovery time, $P_t(v)$ is a Transient part of active power consumption, X_P is a state variable, $P_S(V)$ is the static load function . Using this form of differential equation, for active as well as reactive powers, the system voltage can be determined after the disturbance [9].

4.1.1. Voltage Dependent Loads with Dynamic Tap Changer

Voltage Dependent Loads with Dynamic Tap Changer are nonlinear load model which represents the power relationship to voltage as an exponential equation. The transformer model consists of an ideal circuit with tap ratio *n*, hence the voltage on the secondary winding is *vs = v/n*. The voltage control is obtained by means of a quasi-integral anti-windup regulator The load powers P_H and Q_H are preceded as negative power as these powers are absorbed from the bus, as follows:

$$-P_H = P_O\left(V/n\right)^{\gamma p} \tag{13}$$

$$-Q_H = Q_O\left(V/n\right)^{\gamma q} \tag{14}$$

and the differential equation is

$$\dot{m} = K_d\, n + K_i \left({}^{V}\!/_{n} - V^{ref} \right) \quad (15)$$

Where K_d is the Anti-windup regulator deviation K_i is the Anti-windup regulator gain. The reference voltage sign is negative due to the characteristic of the stable equilibrium point. If voltage dependent loads with embedded dynamic tap changer are initialized after the power flow analysis, the powers p_0 and q_0 are computed based on the constant PQ load powers p_{L0} and q_{L0} as (17and18) and the state variable *n* and the voltage reference v^{ref} are initialized as follows

$$-m_o = V_o \quad (16)$$

$$V^{ref} = 1 + {}^{K_d}\!/_{K_i}\; V_o$$

Where v_0 is the initial voltage of the load bus The parameters of this model are γ_p, γ_q, and the values of the active and reactive power, *Po* and Q_o, at the initial conditions. Common values for the exponents of the model for different load components γ_p and γ_q are (0, 1, 2). Equations can be directly included in the formulation of power flow analysis; where the γ_p and γ_q the active and reactive power exponent. The units of P_0 and Q_0 depend on the status parameter k. If k=1, the Voltage Dependent Loads with Dynamic Tap Changer is initialized after the power flow analysis, and $P_0$and Q_0 are in percentage of the PQ load power connected at the Voltage Dependent Loads with Dynamic Tap Changer bus.

$$P_0 = {}^{K_P}\!/_{100}\; P_L \quad (17)$$

$$Q_0 = {}^{K_Q}\!/_{100}\; Q_L \quad (18)$$

Where K_P and K_Q are Active and Reactive power rating of the loads

4.2.1. Exponential recovery load

A nonlinear load model which represents the power relationship to voltage as an exponential equation as

$$\dot{x_p} = -\frac{x_p}{T_p} + p_s - p_t \quad (19)$$

$$-P_H = \frac{x_p}{T_p} + p_t$$

Where p_s and p_t are the static and transient real power absorptions, which depends on the load voltage

$$-P_s = P_o \left({}^{V}\!/_{V_0} \right)^{\gamma s} \quad (20)$$

$$-P_t = P_o \left({}^{V}\!/_{V_0} \right)^{\gamma t}$$

where γt is a static active power exponent, γs is a dynamic active power exponent β_s is a static reactive power exponent, β_t is a dynamic reactive power exponent, of the load models, V is the actual voltage and V_o is the nominal voltage. Note that constant power, constant current and constant impedance are special cases of the exponential model.

Similar equation holds for the reactive power

$$\dot{x_q} = -\frac{x_q}{T_q} + q_s - q_t \quad (21)$$

$$-Q_H = \frac{x_q}{T_q} + q_t$$

$$-Q_s = Q_o \left({}^{V}\!/_{V_0} \right)^{\beta s} \quad (22)$$

$$-Q_t = Q_o \left({}^{V}\!/_{V_0} \right)^{\beta t}$$

Where q_s is the Static reactive load power as a function of bus voltage magnitude and q_s is the Dynamic reactive load power as a function of bus voltage magnitude. The power flow solution and the PQ load data are used for determining the value of p_o, Q_o, and V_o. In particular p_o and Q_o are determined as below. A PQ load is required to initialize the Exponential recovery load bus.

$$P_0 = {}^{K_P}\!/_{100}\; P_L \quad (23)$$

$$Q_0 = {}^{K_Q}\!/_{100}\; Q_L \quad (24)$$

The parameters of the load can be defined based on the PQ load powers P_{L0} and Q_{L0}:

$$g = \frac{g}{100}\frac{P_{L0}}{v_0^2}, \quad I_p = \frac{I_p}{100}\frac{P_{L0}}{v_0}, \qquad P_m = \frac{P_m}{100} P_{L0}$$

$$b = \frac{b}{100}\frac{Q_{L0}}{v_0^2}, \quad I_q = \frac{I_q}{100}\frac{Q_{L0}}{v_0}, \qquad Q_m = \frac{Q_m}{100} Q_{L0}$$

in this case initial voltage V_0 is also not known, thus the following equation is used.

$$-P_H = g v^2 + I_p v + P_m \quad (25)$$

$$-Q_H = bv^2 + I_q v + Q_m \tag{26}$$

The parameters are constants and indicate the nominal power is divided into constant power, constant current and constant impedance [10]

4.2. Identification of Model Parameters.

$$P_H = \left[1 + K_p(V-1)\right].(1-P_{drop}) + P_{dyn}.(G.V^2 - 1) \tag{27}$$

$$Q_H = \left[1 + K_q(V-1)\right].(1-Q_{drop}) + Q_{dyn}.(B.V^2 - 1) \tag{28}$$

Considering the model given by equation (27), the nonlinear relationship between the measured signals, active power P, voltage V at the load bus, the estimated conductance G, and the parameters K_P, P_{drop} and P_{dyn} can be simplified by re-parameterization, and the model can be written as a linear regression equation

$$P_H = \left[x(1) + x(2).(V-1)\right] + P_{dyn}.(G.V^2 - 1) \tag{29}$$

Where

$$x(1) = (1 - P_{drop})$$

$$x(2) = x(1).K_p$$

$$z(t) = \gamma^T(t).\theta_p \tag{30}$$

$$\theta_p = (x(1).x(2).P_{dyn}) \tag{31}$$

The Least Squares method has then been used for the identification [10]. The objective is to obtain the best estimates for the parameter vector θ_P, which minimizes the difference between the estimated active power and the simulated one (as a quadratic criterion). With the given equation (27) the same procedure is applied for the parameter identification for the reactive load using equation (28). The augmented objective functions to be minimized using a least square criterion which is given by equation (31). The final parameters are determined directly from the expressions given in (29) and (30) The least squares method is used to minimize the function (30) and to obtain the best estimates for the parameter vector θp.

$$L(\theta_p) = \sum_{k=1}^{N}\left(P_{simulated}\left(t_K, \theta_p\right) - P_{measured}\left(t_K, \theta_p\right)\right)^2 \tag{32}$$

The same procedure is repeated for the reactive powers also. The optimum solution represents the of the global minimum of the objective function, i.e. the best estimates for the model. However, the nonlinear model parameters can be estimated accurately by an iterative approach whose algorithm is as follows:

* An initial estimate *Xo* for the parameters is selected;

* The best fit is then determined by using the initial estimate *Xo*; the best estimates are compared with the initial estimates, and it is determined whether the fit improves or not. The direction and magnitude of the adjustment depend on the fitting algorithm [10].

V. OPERATION AND MATHEMATICAL MODEL OF INTERLINE POWER FLOW CONTROLLER UNIT

The development of FACTS-devices [11-12] in ensuring high reliability as well as high efficiency with the modern power electronic components has elaborated the usage in various applications in the power system network. Voltage Source Converters (VSC) provides a free controllable voltage in magnitude and phase due to pulse width modulation of the IGBTs or IGCTs. High modulation frequencies allow to get low harmonics in the output signal and even to compensate disturbances coming from the network. The disadvantage is that with an increasing switching frequency, the losses are increasing as well. Therefore special designs of the converters are required to compensate this. Among various FACTS devices like SVC, SSSC, TCPS, UPFC it has been proven that even for multiline control IPFC contributes a lot [13]. So in this case study IPFC has been considered.

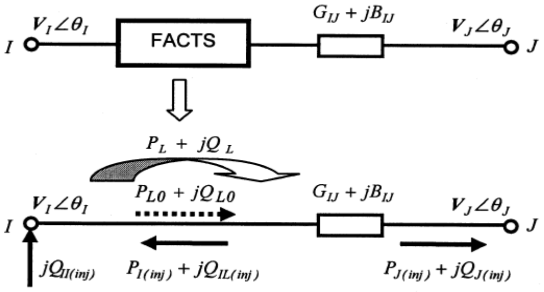


Fig.1 .Power- injection model of FACTS device for power flow

5.1. Steady state representation and load flow model of Interline Power Flow Controller (IPFC)

When the power flows of two lines to be controlled, an Interline Power Flow Controller (IPFC) which consists of two series VSCs whose DC capacitors are coupled can be used. This allows active power to circulate between the VSCs. Fig.2 (a, b) shows the principle configuration of an IPFC. With this configuration two lines can be controlled simultaneously to optimize the network utilization. In general, due to its complex setup, specific application cases need to be identified [14-15].

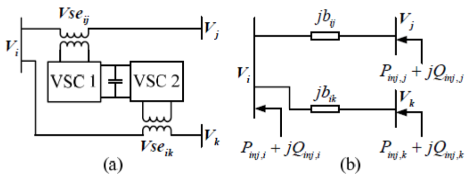


Fig.2. (a) Schematic representation of an IPFC with two voltage source converters (b) Power injection model of IPFC

In this circuit,
the complex Controllable series injected voltage is $V_{sem} = V_{sem} \angle \theta_{sem}$
Series transformer impedance $Z_{sem} = R_{sem} + jX_{sem}$
the complex bus voltage at buses s_m and r_m be $V_{rm} = V_{sm} \angle \theta_{rm}$ and
$V_{sm} = V_{sm} \angle \theta_{sm}$, $Z_{tm} = R_{tm} + jX_{tm}$ and B_{tm} represent the line series impedance and line charging susceptance, respectively [16-17], while m is the line number (m = 1,2….). From Fig (4), for one of the lines, the relations can be derived as follows

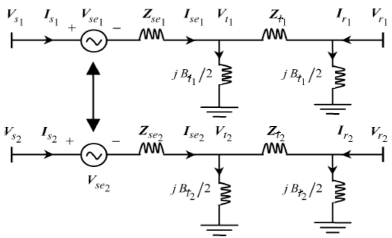


Fig.3. Equivalent circuit of IPFC with two voltage source converters

$$V_{sm} = V_{sm} + I_{sm} Z_{sem} + V_{tm} \tag{33}$$

$$I_{sm} = \frac{(V_{tm} - V_{rm})}{Z_{tm}} + j\frac{B_{tm}}{2} V_{tm} \tag{34}$$

V_{tm} and I_{sm} can be expressed according to V_{rm} and I_{rm} as

$$V_{tm} = \left(1 + j\frac{B_{tm}}{2} Z_{tm}\right) V_{tm} - I_{rm} Z_{tm} \tag{35}$$

$$I_{sm} = \left(jB_{tm} - j\frac{B_{tm}^2}{4} Z_{tm}\right) V_{tm} - \left(1 + \frac{B_{tm}}{4} Z_{tm}\right) I_{rm} \tag{36}$$

From eqn. (33-36) I_{sm} and I_{rm} can be expressed in terms of V_{sm}, V_{rm}, and V_{sem} I_{sm} and I_{rm}

$$I_{sm} = \left(A + \frac{SE}{L}\right) V_{rm} + \frac{E}{L} V_{sm} - \frac{E}{L} V_{sem} \tag{37}$$

$$I_{rm} = \frac{S}{L} V_{rm} - \frac{1}{L} V_{sm} + \frac{1}{L} V_{sem} \quad (38)$$

Where

$$A = \left(j B_{t_m} - Z_{t_m} \frac{B^2{}_{t\,m}}{4} \right) \quad E = \left(1 + jZ_{t_m} - \frac{B_{t\,m}}{4} \right)$$

$$S = \left(Z_{se_m} A - E \right), \quad L = \left(Z_{se_m} E + Z_{t_m} \right),$$

Where V_{sm}, I_{sm}, V_{rm}, I_{rm}, and V_{tm} are the complex bus voltages and currents at the corresponding buses s_m and r_m respectively. As IPFC neither absorbs nor injects active power with respect to the AC system [18], the active power exchange between or among the converters via the dc link is zero, and if the resistances of series transformers are neglected, the equation can be written as

$$P_c = \sum_m P_{d_m} = 0 \quad (39)$$

Where

P_{dm} = Real (V_{sem} I_{sm}).

P_{dm} is a active power exchange on the DC link, V_{sem} is the series injected voltage and I_{sm} complex bus current at bus_{sm}.

Thus, the power balance equations are as follows

$$P_{gm} + P_{inj,m} - P_{im} - P_{tm} = 0 \quad (40)$$

$$Q_{gm} + Q_{inj,m} - Q_{im} - Q_{tm} = 0 \quad (41)$$

Where P_{gm} and Q_{gm} are generations active and reactive powers, P_{lm} and Q_{lm} are load active and reactive powers. $P_{t,m}$ and $Q_{t,m,}$ are conventional transmitted active and reactive powers at the bus m = " *i*" and " *j*".

1. Real power loss

This objective consists to minimise the real power loss P_L in the transmission lines that can be expressed as,

$$P_L = \sum_{k=1}^{Ns} P_K \quad (42)$$

where Ns number of buses; Vk <$\propto_k$ and Vh < $\propto_h$ respectively voltages at bus k and h, Y_{kh} and θ_{kh} respectively modulus and argument of the k_h-t_h element of the nodal admittance matrix Y.

2. Voltage deviation

This objective is to minimize the deviation in voltage magnitude at load buses that can be expressed as,

$$V_D = \sum_{i=1}^{NL} |V_i - V_i^{ref}| \quad (43)$$

where NL number of load buses; ref V_i prespecified reference value of the voltage magnitude at the *i-th* load bus, ref V_i is usually set to be 1.0 p.u.

VI. BACTERIAL FORAGING OPTIMIZATION ALGORITHM

For over the last five decades, optimization algorithms like Genetic Algorithms (GAs), Evolutionary Programming (EP), Evolutionary Strategies (ES) which had drawn their inspiration from evolution and natural genetics have been dominating the realm of optimization algorithms. Recently natural swarm inspired algorithms like Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) have found their way into this domain and proved their effectiveness. Bacterial Foraging Optimization Algorithm (BFOA) [21] was proposed by Passion is inspired by the social foraging behavior of *Escherichia coli.* Application of group foraging strategy of a swarm of *E-.coli* bacteria in multi-optimal function optimization is the key idea of the new algorithm [22]. Bacteria search for nutrients in a manner to maximize energy obtained per unit time. Individual bacterium also communicates with others by sending signals. A bacterium takes foraging decisions after considering two previous factors.

The process, in which a bacterium moves by taking small steps while searching for nutrients, is called chemo taxis and key idea of BFOA is mimicking chemotactic movement of virtual bacteria in the problem search space. The control of these bacteria that dictates how foraging should proceed and can be subdivided into four sections namely Chemotaxis, Swarming, Reproduction, Elimination and Dispersal. These operations among the bacteria are used for searching the total solution space.

6.1. Chemotactic Step

This process is achieved through swimming and tumbling via Flagella. Depending upon the rotation of Flagella in each bacterium, it decides whether it should move in a predefined direction (swimming) or altogether in different directions (tumbling). In BFO algorithm, one moving unit length with random directions represents "tumbling," and one moving unit length with the same direction relative to the final step represents "swimming." The chemotactic step consists of one tumbling along with another tumbling, or one tumbling along with one swimming. This movement is can be described as

$$\theta^i(j+1,k,l) = \theta^i(j,l,l) + C(i) \frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \quad (44)$$

Where C (i) denotes step size ; Δ(i) Random vector ; Δ^T(i)Transpose of vector Δ(i).

6.2. Swarming Step

A group of *E.coli* cells arrange themselves in a traveling ring by moving up the nutrient gradient when placed amidst a semisolid matrix with a single nutrient chemo-effecter. The cells when stimulated by a high level of *succinct*, release an attractant *aspirate*, which helps them to aggregate into groups and thus move as concentric patterns of swarms with high bacterial density. The mathematical representation for *E.coli* swarming can be represented by

$$J_{cc}\ (\theta, P(j,k,l)) = \sum_{i=1}^{s} J_{cc}{}^{i}\left(\theta, \theta^{i}(j,k,l)\right)$$

$$= \sum_{i=1}^{s}\left[-d_{attract}\exp(-w_{attract})\sum_{m=1}^{p}\left(\theta^{m}-\theta_{m}^{i}\right)^{2}\right] + \sum_{i=1}^{s}\left[-h_{repelent}\,exp(-w_{repelent})\sum_{m=1}^{p}(\theta^{m}-\theta_{m}^{i})^{2}\right] \quad (45)$$

Where

J_{CC} - Relative distance of each bacterium from the fittest bacterium

S - Number of bacteria

P - Number of Parameters to be optimized

θ^m - Position of the fittest bacteria

$d_{attract}$, $w_{attract}$, $h_{repelent}$, are the coefficients representing the swarming behavior of the bacteria.

6.3. Reproduction

The least healthy bacteria eventually die while each of the healthier bacteria asexually split into two bacteria, which are then placed in the same location. This keeps the swarm size constant. For bacterial, a reproduction step takes place after all chemotactic steps.

$$J^{i}{}_{health} = \sum_{j=1}^{N_c+1} J(i, j, k, l) \quad (46)$$

For keep a constant population size, bacteria with the highest J_{health} values die. The remaining bacteria are allowed to split into two bacteria in the same place.

6.4. Elimination and Dispersal

In the evolutionary process, elimination and dispersal events can occur such that bacteria in a region are killed or a group is dispersed into a new part of the environment due to some influence. They have the effect of possibly destroying chemotactic progress, but they also have the effect of assisting in chemotaxis, since dispersal may place bacteria near good food sources. In BFOA, bacteria are eliminated with a probability of P_{ed}. In order to keeping the number of bacteria in the population constant, if a bacterium is eliminated; simply disperse one to a random location on the optimization domain [23-24].

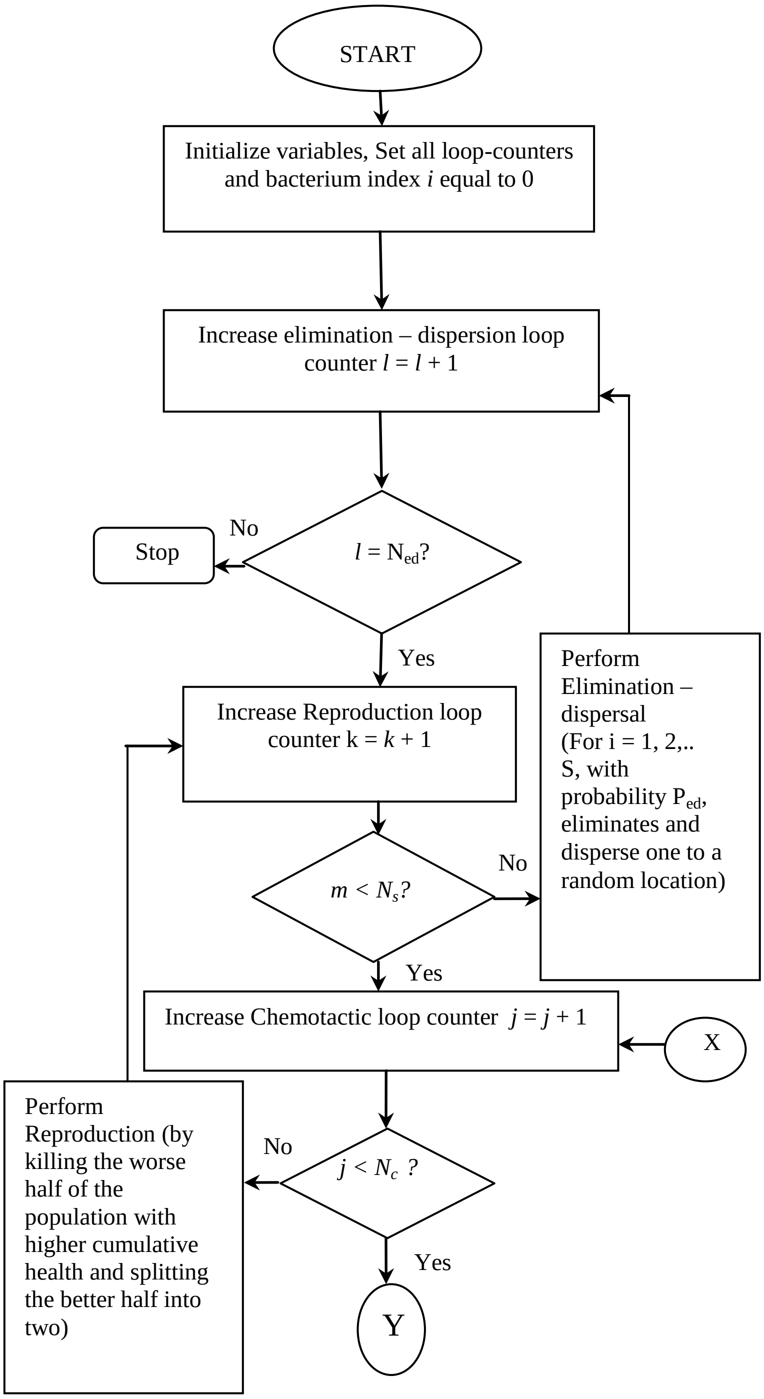
Problem Formulation

$Min\ J = k_2\, p_i^{2} + k_1\, p_i + k_0$ (47)

Subject to:

$P_{\min} \le P \le P_{\max}$; $Q_{\min} \le Q \le Q_{\max}$; $V_{\min} \le V \le V_{\max}$

Where k_0, k_1, k_2 are cost coefficients


START
Initialize variables, Set all loop-counters and bacterium index *i* equal to 0
Increase elimination – dispersion loop counter *l* = *l* + 1
No
Stop
$l = N_{ed}$?
Yes
Perform Elimination – dispersal (For i = 1, 2,.. S, with probability P_{ed}, eliminates and disperse one to a random location)
Increase Reproduction loop counter k = *k* + 1
No
$m < N_s$?
Yes
Increase Chemotactic loop counter $j = j + 1$
X
Perform Reproduction (by killing the worse half of the population with higher cumulative health and splitting the better half into two)
No
$j < N_c$?
Yes
Y

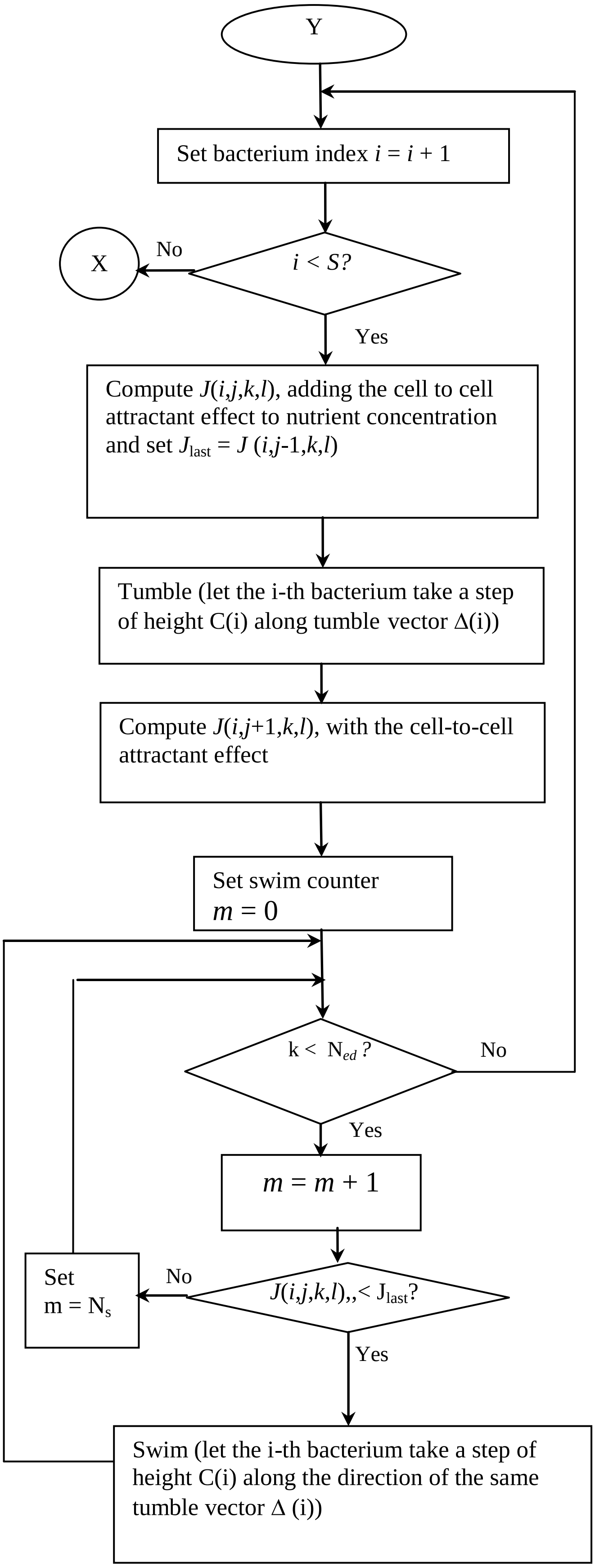


Fig. 4 Flowchart of the Bacterial Foraging Algorithm

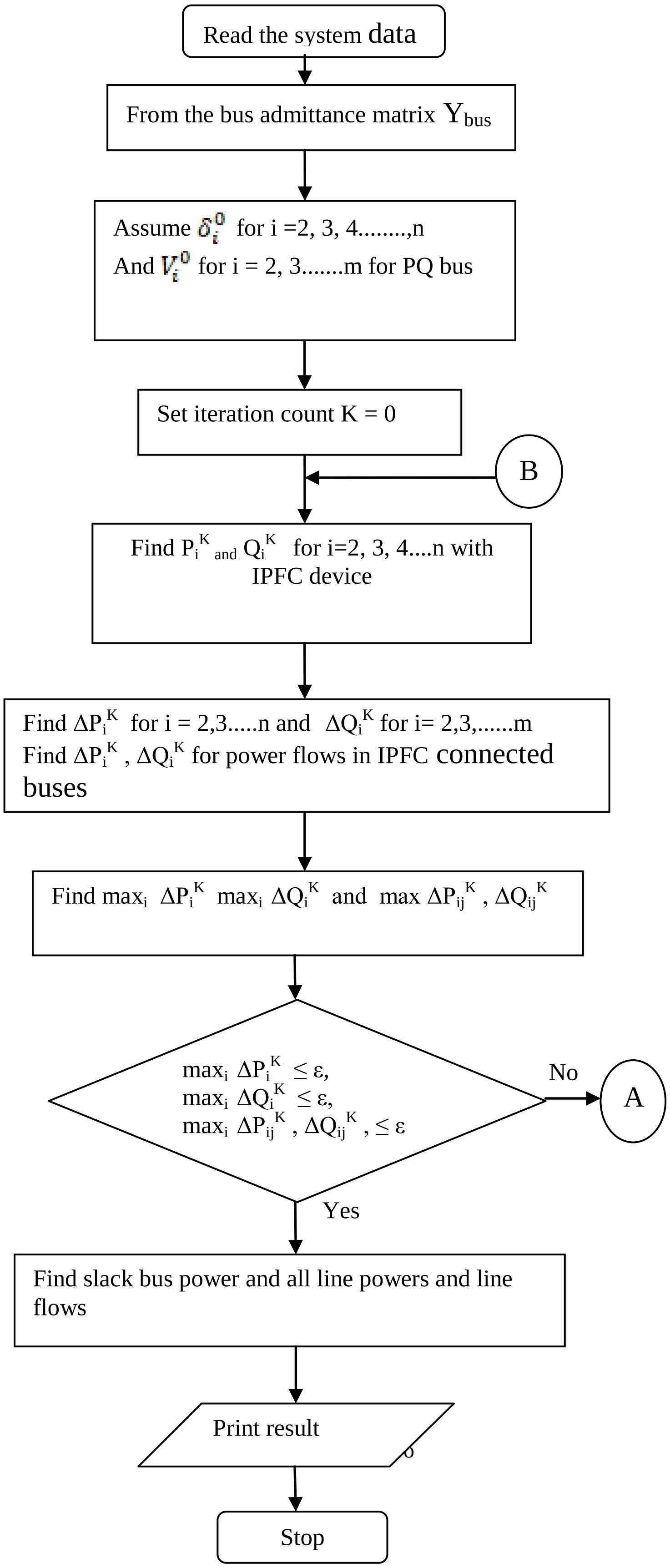
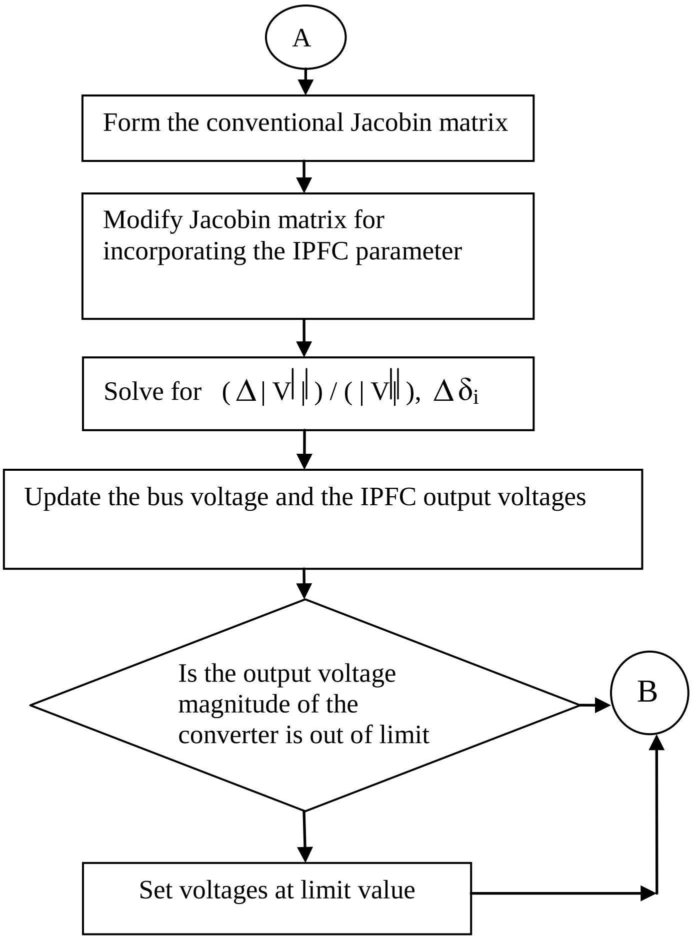


Fig.5. Flowchart for the Proposed Method



VII. RESULTS

The performance analysis of a IEEE 14-bus, 5-generator system coordinated with different types of Dynamic load models without and with IFPC Unit were studied and the optimum utilization requirement with the IPFC device for each load was determined using BFO technique. In this case of study the buses 5 and 14 are connected with VDL and ERL Loads. The system under the study is shown in Fig 6 and 7.

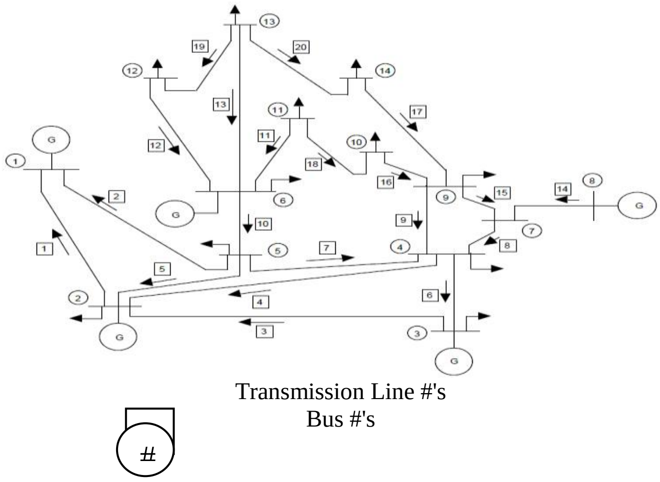
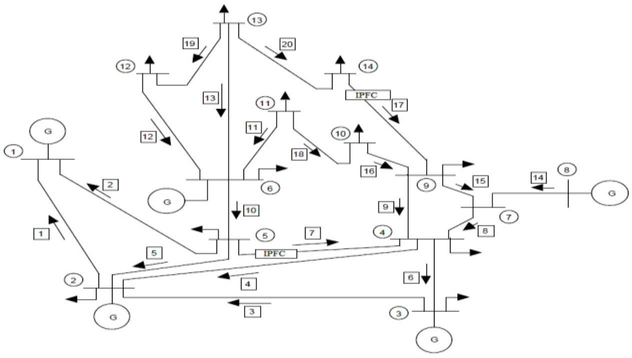


Fig.6. IEEE 14-bus test system one line diagram



Figu.7. IEEE 14-bus test system with IPFC Units

Table.1. Power flow solution for IEEE 14 Bus systems with VDL with Dynamic tap changer Load in bus4, 5 and bus 14.

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.0000	2.3045	-0.4347
2	1.0000	-5.962	0.1830	0.6624
3	0.9800	-14.773	-0.9420	0.3103
4	0.9602	-11.694	-0.4780	0.0390
5	0.9616	-10.009	-0.0760	-0.0160
6	1.0000	-16.570	-0.1208	0.1122
7	0.9766	-15.192	0.0000	0.0000
8	1.0000	-15.191	0.0000	0.1328
9	0.9607	-17.071	-0.3093	-0.1740
10	0.9595	-17.309	-0.0900	-0.0580
11	0.9757	-17.075	-0.0350	-0.0180
12	0.9822	-17.549	-0.0610	-0.0160
13	0.9753	-17.597	-0.1350	-0.0580
14	0.9474	-18.488	-0.1490	-0.0500

Table. 2. Power flow solution for IEEE 14 Bus systems with Exponential Recovery Load in bus 4, 5 and bus 14.

Bus No.	Voltage Magnitude	Voltage Angle	Real Power	Reactive Power
1	1.0300	0.0000	2.3502	-0.4376
2	1.0000	-6.071	0.1830	0.6812
3	0.9800	-14.955	-0.9420	0.3166
4	0.9591	-11.915	-0.4780	0.0390
5	0.9606	-10.222	-0.0760	-0.0160
6	1.0000	-17.105	-0.1454	0.1281
7	0.9747	-15.586	0.0100	0.0100
8	1.0000	-15.890	0.0000	0.1435
9	0.9585	-17.493	-0.3150	-0.1860
10	0.9577	-17.750	-0.0900	-0.0580
11	0.9748	-17.562	-0.0350	-0.0180
12	0.9821	-18.079	-0.0610	-0.0160
13	0.9750	-18.166	-0.1350	-0.0580
14	0.9460	-18.956	-0.1490	0.0500

Table.3. Power flow solution for IEEE 14 Bus systems with Exponential Recovery Loads in Bus4, 5 and Bus 14 with IPFC Unit

Bus No.	**IPFC**				**IPFC**				**IPFC**			
	V p.u	**Angle**	**Power at the Bus**		**V p.u**	**Angle**	**Power at the Bus**		**V p.u**	**Angle**	**Power at the Bus**	
			MW	**MVAR**			**MW**	**MVAR**			**MW**	**MVAR**
1	1.0300	0.00	2.3287	-0.1365	1.0300	- 0.00	2.2847	-0.1361	1.0300	0.00	2.3336	-0.1467
2	1.0000	-5.52	0.2475	-0.2012	1.0000	-5.44	0.2473	-0.2391	1.0000	-5.55	0.2476	-0.2364
3	1.0000	-14.38	-0.9420	0.2950	1.0000	-14.12	-0.9420	0.2955	1.0000	-14.29	-0.9420	0.2953
4	1.0000	-11.88	-0.4780	0.0446	1.0000	-11.47	-0.4780	0.0442	1.0000	-11.68	-0.4780	0.0443
5	0.9905	-10.06	-0.0586	0.0236	0.9919	-9.76	-0.0588	0.0238	0.9924	-10.02	-0.0586	0.0237
6	1.0200	-16.51	-0.1454	-0.0303	1.0300	-16.05	-0.1208	0.0193	1.0400	-16.82	-0.1454	0.0291
7	1.0007	-15.35	-0.0100	-0.0100	1.0026	-14.66	0.0000	0.0000	1.0020	-14.89	-0.0100	-0.0100
8	1.0000	-15.34	0.0000	-0.0042	1.0000	-14.65	0.0000	-0.0146	1.0000	-16.57	0.0000	-0.0114
9	0.9923	-17.15	-0.3150	-0.1861	1.9950	-16.38	-0.3093	-0.1740	0.9949	-16.91	-0.3150	-0.1860
10	0.9893	-17.35	-0.0900	-0.0581	0.9933	-16.63	0.0900	-0.0580	0.9951	-16.98	-0.0900	-0.0580
11	1.0008	-17.07	-0.0350	-0.0180	1.0078	-16.47	-0.0350	-0.0180	1.0137	-16.52	-0.0350	-0.0180
12	1.0064	-17.50	-0.0610	-0.0160	1.0163	-17.08	-0.0610	-0.0i60	1.0291	-17.96	-0.0611	-0.0160
13	1.0030	-17.68	0.1350	0.0580	1.0121	-17.32	-0.1350	-0.0580	1.0267	-18.39	-0.1351	-0.0580
14	1.0000	-19.08	-0.0499	-0.0498	1.0000	-17.84	-0.1499	-0.0499	1.0000	-17.58	-0.1490	-0.0495

Table.4. Power flow solution for IEEE 14 Bus systems with VDL with Dynamic Tap Changer Loads in Bus 4, 5 and Bus 14 with IPFC Unit

Bus No	**IPFC**				**IPFC**				**IPFC**			
	V p.u	**Angle**	**Power at the Bus**		**V p.u**	**Angle**	**Power at the Bus**		**V p.u**	**Angle**	**Power at the Bus**	
			MW	**MVAR**			**MW**	**MVAR**			**MW**	**MVAR**
1	1.0300	0.00	2.2837	-0.1303	1.0300	- 0.00	2.2847	-0.1361	1.0300	0.00	2.2885	-0.1404
2	1.0000	-5.41	0.2472	-0.2102	1.0000	-5.44	0.2473	-0.2391	1.0000	-5.44	0.2473	-0.2441
3	1.0000	-14.21	-0.9420	0.2951	1.0000	-14.12	-0.9420	0.2955	1.0000	-14.12	-0.9420	0.2955
4	1.0000	-11.65	-0.4780	0.0444	1.0000	-11.47	-0.4780	0.0442	1.0000	-11.45	-0.4780	0.0442

5	1.0220	-9.84	-0.0588	0.0237	0.9919	-9.76	-0.0588	0.0238	0.9928	-9.81	-0.0588	0.0238
6	1.0200	-16.01	-0.1208	-0.0382	1.0300	-16.05	-0.1208	0.0193	1.0400	-16.32	-0.1208	0.0200
7	1.0019	-14.96	0.0000	0.0000	1.0026	-14.65	0.0000	0.0000	1.0032	-14.52	0.0000	0.0000
8	1.0000	-14.95	0.0000	-0.0109	1.0000	-14.65	0.0000	-0.0146	1.0000	-14.51	0.0000	-0.0181
9	0.9937	-16.73	-0.3093	-0.1740	0.9950	-16.38	-0.3093	-0.1740	0.9962	-16.16	0.3093	-0.1740
10	0.9904	-16.92	-0.0900	-0.0580	0.9933	-16.63	-0.0900	-0.0580	0.9966	-16.49	-0.0900	-0.0580
11	1.0013	-16.60	-0.0350	-0.0180	1.0078	-16.47	-0.0350	-0.0180	1.0142	-16.52	-0.0350	-0.0180
12	1.0064	-17.00	-0.0610	-0.0160	1.0163	-17.08	-0.0610	-0.0i60	1.0292	-17.47	-0.0610	-0.0160
13	1.0030	-17.18	-0.1350	-0.0580	1.0121	-17.32	-0.1350	-0.0580	1.0268	-17.90	-0.1350	-0.0580
14	1.0000	-18.61	-0.0490	-0.0487	1.0000	-17.84	-0.1495	-0.0490	1.0000	-17.11	-0.1490	-0.0495

VIII. CONCLUSION

This paper presents the coordinated emergency control with the usage of FACTS device especially IPFC. It has been found that with the IPFC controller, the risk of load shedding is considerably reduced and can easily be adopted for emergency control. Moreover the result indicate that this comparison method successfully prevent the system from blackout and restore the system faster.

APPENDIX

TABLE. 5 .GENERATOR DATA [25]

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.6. BUS DATA [25]

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	-0.169	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	0.234	0.9420	0.1900	2	0.4	0.00
4.	0.00	0.00	0.478	0.039	3	0.00	0.00

			0	0			
5.	0.00	0.122	0.0760	0.0160	3	0.00	0.00
6.	0.00	0.00	0.1120	0.0750	2	0.24	-0.06
7.	0.00	0.174	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	0.0610	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

* Bus Type: 1) Swing bus, 2) Generator bus (PV bus) and 3) Load bus (PQ bus)

TABLE.7. LINE DATA [25]

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

Table.8. Control Parameters of the Bacterial Foraging Algorithm

S.No.	**Parameters**	**Values**
1	Number of bacteria ,S	45
2	Swimming Length, N_s	4
3	Number of chemotactic steps, N_c	95
4	Number of reproduction steps, N_{re}	4
5	Number of elimination-disperse events, N_{ed}	2
6	Elimination and dispersal Probability, P_{ed}	0.25
7	$w_{attract}$	0.05
8	$w_{repelent}$	12
9	$h_{repelent}$	0.02
10	$d_{attract}$	0.02
11	The run-length unit (i.e., the size of the step taken in each run or tumble), C(i)	0.1

Table.9. IPFC Data [15]

Parameters	**Values (p.u./deg)**
Complex control series injected voltage V_{se1}	0.015
Complex control series injected voltage V_{se2}	0.0216
Phase angle δ_{se1}	349.662
Phase angle δ_{se2}	185.240
DC link capacitance voltage(V_{dc})	2
Q_{inj} (rad)	1.0878

ACKNOWLEDGEMENT

The authors wish to thank the authorities of Annamalai University, Annamalainagar, Tamilnadu, India for the facilities provided to prepare this paper.

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