

Optimal Reactive Power Compensation in Transmission Networks By TCSC Using Particle Swarm Optimization

Subhash Shankar Zope¹, Dr. R. P. Singh²

^{1,2}Computer Science and Engineering

^{1,2}Sri Satya Sai University of Technology & Medical Sciences

^{1,2}Opposite OILFED, Bhopal Indore Highway, Pachama, Sehore (India) 466001

Abstract: Increased demand for electrical energy and free market economies for electricity exchange, have pushed power suppliers to pay a great attention to quality and cost of the latter, especially in transmission networks. To reduce power losses due to the high level of the reactive currents transit and improve the voltage profile in transmission systems, shunt capacitor banks are widely used. The problem to be solved is to find the capacitors optimal number, sizes and locations so that they maximize the cost reduction. This paper is constructed as a function of active and reactive power loss reduction. To solve this constrained non-linear problem, a heuristic technique, based on the sensitivity factors of the system power losses, has been proposed. The optimal location TCSC is studied on the basis of Particle Swarm Optimization (PSO) to minimize network losses. Validation of the proposed implementation is done on the IEEE-14 and IEEE-30 bus systems.

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I. Introduction

The FACTS by means of the acronym "Flexible Alternating Current Transmission System" are devices that by means of the activation of semiconductor elements of power, allow to improve the capacity of power transfer between a point of consumption and one of generation, for this purpose the variables of the system influenced by the flexible compensators are, the voltages of the nodes, the series impedances of the lines or the phase angles. In any case it is translated. In a control of active and reactive power flows, although the one of more interest usually is the decrease of the reactive one. Characteristically the FACTS present advantages over traditional methods of control reagents in power systems, by the ability to intermittent in short and repetitive time periods that are mainly dependent on the variability of the system demand [1]. When the network is disturbed (Short circuit, loss of a load or a group, opening of a line, etc.), the difference between the mechanical and electrical powers leads to an acceleration or deceleration which may lead to the loss of synchronism of one or more generation groups. The rotor angles oscillate until the adjustment systems protection in order to restore the march in synchronism and lead the network to a state of stable operation. However, the demand for electricity varies constantly over the course of a schedules, weather conditions, other criteria are also taken into account such as holiday periods, holidays, weekends, holidays and events that (strikes, sporting events, etc.). For this purpose the design of the electrical system has been made in such a way that an entire inseparable chain is integrated beginning with: production, transport and distribution to consumers. You cannot store large quantities of energy in electrical form, it is the problem is forced to produce the same quantity of electricity that must be consumed; we also know that the production groups have certain technical limitations which must not be exceeded which leads us to another problem too complicated one can translate it mathematically a non-linear problem [2]. Therefore, the economic distribution of electric power produced by power stations at particular marginal cost; has become the object of research and studies over the years. This process has been under study since 1928 due to its great importance in electric power; the numerous publications on this subject are clear proof. Several methods and algorithms have been applied to solve this problem achieving better results. Early research has neglected losses in lines subsequently several improvements of the original proposal have been developed by introducing the losses as well as the operating limits of the production groups. Arriving at their final shapes; algorithms based on marginal costs take into account:

- Fuel costs and their efficiencies.
- Operating and maintenance costs.
- Operating limits and operating areas prohibited.
- Unit response gradients.
- Transmission losses (penalty factors).
- Reserve constraints.

These algorithms prove their efficiencies and provide better results, but another result is the time factor. Thanks to the development of "smart grids", a transition has been made towards a market more dynamic, fast and efficient. Recently, the techniques of neural networks are beginning to be used in different fields of study of electrical networks, including forecasts of consumption, load distribution and Economic Dispatch. The use of the method of

neural networks makes it possible to avoid the disadvantages encountered by classical methods and more precisely lost time; as well as this method is convenient to take into account the various non-linear and random factors.

1.1 Control of Transits

In a mesh interconnection network, the distribution of energy transits depends essentially:

- Location of loads.
- The location of production groups in operation.
- Cross-border trade.
- Location of reactive energy compensation means.
- Impedances of the transport structures.

These transits of energy constitute a flow from the stations where customers are connected; it borrows the lines and the transport cables in distributing in proportion to the inverse of their impedance. What is, in a way, a preference marked for the "shortest path". This flow of energy is materialized by the current crosses the structures. The higher the energy flow, the more current currents will be strong. These intensities may increase, particularly when a structure is triggered by a defect. Indeed, the transit initially supported by this structure will be referred to the neighbour's structures; it is the phenomenon of transfer of charge.

The regulation of transits is ensured by playing mainly on two parameters:

Topology of the Network: By adapting the operating diagrams, the dispatcher modifies the impedances of the different meshes of the network (creation of long queues to increase the impedance of the network or, on the contrary, works in order to reduce it) and plays on the distribution of production sources.

Production Programs: By adapting the production programs of the groups, the dispatcher plays on the distribution of sources of production versus loads. In the ultimate situation, the last resort is to act on the charges by shedding customers. For a given topology, it is possible to evaluate, using the driving and simulation tools, the transits in each of the works according to the adopted production plan and the location charges. In the same way, it is possible to calculate the impact of the triggering of a transport structure or production, on the value of transits in the remaining works [3] [4].

II. State Of The Art

A very large part of the losses of power in the electrical networks are attributed to those of distribution. Out of all the power conveyed by distribution networks, power losses are estimated at 14%. The level of these losses combined with the deregulation of the electricity market has prompted the distribution companies to give serious consideration to the problem of losses in distribution networks in order to increase power transmission before thinking about Invest in the construction of new lines. For a given line configuration and given that the active power demand is incompressible, the reduction of voltage drops and that of power losses can only be achieved by reducing the transit of the strong reactive components of the line current. For this purpose reactive energy compensation is recommended and one of the most indicated means is the application of shunt capacitor batteries which is the subject of the present disclosure. However, it is not enough to place batteries of capacitors to say that the problem posed (circulation of strong reactive currents) is solved. The optimization of the reactive energy compensation is to be understood as the choice of the powers of the capacitor banks, their locations and even the time during which they will remain in line if it is an adaptive compensation. Of course, these choices must be made so that there is the least power loss in line and an improvement in the voltage profile while having a positive economic return. The choices of the objective function are dictated by the concern to take into account both the electrical and economic aspects of the problem. The objective function on which all the authors who have dealt with the problem of optimization of reactive energy compensation is the so-called economic return function (saving function). However, since the installation of the capacitor banks reduces not only the active losses but also the losses of reactive power then, unlike all the authors who have dealt with the problem that is research concern, this paper will introduce into the objective function the reduction of reactive power losses. The objective is therefore to determine the powers of the batteries and their locations in order to minimize power losses, improve the voltage profile and thereby increase the transmission capacity of these lines. Since the problem of optimizing the reactive energy compensation cannot be separated from the power flow then the solution of the latter will be studied. A significant number of works have addressed the problem of optimizing the reactive energy compensation in distribution lines, i.e. determining capacitor bank sizes and their locations to reduce power losses in the line. Methods can be classified into four categories: analytics, numerical programming, heuristics, and intelligence and meta-heuristics.

III. Analytical Methods

The pioneer in the field is Cook [5]. In 1959, he studied the effects of capacitors on power losses in a radial distribution network where the charges are uniformly distributed. It considered the reduction of power losses as an objective function by considering a periodic reactive charging cycle. Cook then developed a network of convenient curves to determine the most economical power of the capacitor bank and the location of the capacitor bank on the line. The development of methods has led researchers to become increasingly interested in the optimization of reactive energy compensation. Therefore, they have developed numerical methods for the analysis of the electrical network. Duran [6] in 1968 used a dynamic programming approach to solve the problem of reactive energy compensation in

distribution networks where charges are discrete. The method evaluates the desirability of placing a capacitor bank or not at the different nodes of the network. It then uses the following objective function and exploits the fact that it is Markovian. In 1983, Ponnaivaikko and Prakasa Rao [7] presented a method for determining the optimum powers of fixed and switchable capacitor banks to be placed on a distribution network by a so-called local variation method. In this method, changes are made to the size of the battery placed at any node "i" by keeping the rest of the batteries unchanged and checking whether this change improves the objective function and whether the solution satisfies the constraints. If this is the case, the solution is retained and the second battery is switched to the last installed battery.

Rinker and these teams [8] in 1988, proposed a method for the optimal placement of capacitor banks in distribution networks. They set up for this purpose recorders to determine the average consumption of a week this average week is used to determine the best reactive energy compensation scheme. They then try a combination of fixed and / or switchable batteries in one or more nodes of the network and determine the reduction of power losses. If the batteries give results in agreement with the five best combinations retained during the recordings, they are retained as a solution of the problem.

Baran and Wu [9] in 1988, presented a method for solving the problem of placing capacitor banks in distribution networks. In this problem, the locations of the batteries, their sizes, their types, the stresses of the voltage and the variations of the load are taken into account. The problem is considered to be a non-linear programming problem where load flow is explicitly represented.

To solve this problem, it is broken down into a slave problem and a master problem. They exploit for this purpose the property of optimization where:

$$\min_{e \in E, u \in U} f(u, e) = \min_{e \in R} \{ \inf_{u \in U} f(e, u) \} \quad (1)$$

The calculation of the power flow first concerned the transmission or transmission networks. Newtonian methods were then developed to solve the problem of power flow in the latter. Among these methods are the Newton-Raphson method [10] and the fast decoupled Newton-Raphson method [11]. Attempts have been made to apply these methods to the distribution networks but, since they diverge in the majority of cases due to the characteristics of these networks, the configuration of which is radial, a large number of nodes and Branch, and especially since the R/X ratios of the latter are very high. The topology of distribution networks has been exploited for some authors to develop the technique of double-scanning of the line (backward / forward sweep technique). In recent decades particular interest has been given to the distribution networks and to the calculation of the power flow which produces a literature review of the methods developed for this purpose will be given in the paragraph that follows.

IV. Literature Review

In recent decades, a number of techniques have been developed to resolve the issue of power flow in distribution networks. Since it is not possible to give all the work carried out in this direction, it will be sufficient to describe some of them only. Among the authors who dealt with this problem is Goswami [12] in 1991 gave a solution of power flow in radial and weakly meshed distribution networks. When the network is meshed, the meshes are broken and fictitious nodes are created, these nodes whose number of loops and the power flowing there are negative. The model of load considered is the model with constant impedance. In [13] Das in 1995 proposed a method for solving recursive relations, a function of the tensions based on scanning up and down the line. Abdul Rahman [14] in 1995 also proposed an iterative method. It uses the fundamental principles of theory of equivalent circuits of Thevenin, to determine the factors of stability of the tension whose determination requires the knowledge of the tensions of the nodes therefore the solution of the flow of charge. Haque in [15] in 1996 proposed an iterative method that applies both to radial networks and to weakly meshed networks. It then converts the network if it is meshed, into a radial network by breaking the meshes thus creating fictive nodes whose number is equal to that of the loops and where the powers which circulate there are negative. Then, it determines the tensions of the nodes and their phases at the origin by sweeping the line up and down. It initializes the tensions of all nodes to that of the source whose relative value is equal to one. Thukaram in [16] presented a formulation and algorithm to solve the problem of power flow, for large three-phase lines. The solution technique is based on sweeping up and down the line. Gosh [17] in 1999 which will give a method involving the evaluation of simple algebraic expression. The method that it proposes is iterative and or at the first iteration the tensions of the nodes are initialized to 1 in relative value. It then calculates the load currents and the branch currents as a result of which it determines the voltages of the nodes. Mok in [18] in 2000 examined the effects of different load models the convergence of the power flow method. The technique on which it was developed has been implemented and presented as a software called "distriflow" capable of performing power flux analysis for a radial distribution network of any number of busbars. Haque [19] in 2000 developed a method for calculating power flow in distribution networks where multiple sources operate. The method of solution is identical to that given in reference [15]. It considers, for the solution, of problem, that the network is single source. The rest of the sources are simulated by an injection of power at the points of their connections (negative powers). Aravindhababu [20] in 2001 also proposed an iterative method in which the tensions of the nodes are assumed to be equal to that of the voltage source (1 pu). He first gave the shape of the branch-to-node incidence matrix, then he calculated the branch currents and the node tensions. As a criterion of convergence, he proposed the difference between the tensions of two successive iterations. Augugliaro and Dusonchet [21] in 2001 used an iterative method of scanning the line up and down with the convergence of the load flow calculation algorithm. To accelerate the convergence, they choose values for the initial voltages of values close to their final values. This choice makes it possible to reduce the number

of iterations and thus the computation time to reach the solution. Moreover, the authors in question determine the topology of the network by using the incidence matrix branches to nodes whose generic elements are equal to zero and one. Mekhamer in [22] in 2002 used the equations developed by Baran and Wu [23] for each node of the line but with different procedures. In this method, the lateral branches are considered concentrated loads on the main line.

After that, it calculates the voltages of the nodes of the latter which it uses to calculate the tensions of the nodes of the lateral branches. Afsari [24] in 2002, used a method of scanning the uphill line. It first evaluates the tensions of the terminal nodes, which it takes as initial voltages at the first iteration. As a criterion of convergence, it considers the difference between tensions obtained during two successive iterations. Ranjan and Das [25, 26] in 2002 and 2003 used the fundamental principles of the theory of electrical circuits and developed an algorithm to determine the nodes after each branch automatically. However, in their methods, only the effective values of the node voltages are determined based on the algebraic equations they have given. As a criterion of convergence they considered the difference between the active and reactive powers that calculate during two successive iterations. Ranjan and Das [26] in 2003, in their method of optimizing the distribution network configuration and determining the optimal location of a transformation post, have given a solution to the problem of power flow similar to that of the Reference [25]. This method, based on the theory of electrical circuits, has been modified to incorporate different models of the load. Hamouda [27] in 2011, presented an iterative method based on the laws of electrical circuits and which allows the evaluation of tensions and their phases at the origin. Also, it proposes an algorithm to define the nodes after each branch, knowing the source and receiver nodes of each branch of the line. The speed of convergence was improved by a suitable selection of the initial voltages. Because our concern is the optimization of reactive energy in distribution networks that cannot be carried out without first solving the problem of load flow, we will address in this chapter the solution of this problem. We begin by modeling the problem and giving a method of recognizing the configuration of the line to finally test and validate the program developed for this purpose.

V. Thyristor Controlled Series Compensator (TCSC)

This device is widely used for the control of flow of power in the transmission lines through a series compensation. The function of a TCSC, is to modify the impedance of the line, inserting capacitors or inductances in series with the circuit to modify the power flow. The capacitive compensation is the most used, because it helps to verify the natural inductive effects of the transmission lines. The advantage of the TCSC over conventional stabilizers is that these latter use devices with mechanical drives, which over time and use tend to wear out and suffer breakdowns, whereas the TCSC when using static drive devices based on Thyristors do not have this problem due to mechanical stress [28]. For the modeling of a TCSC in a transmission line, the simplified PI model is taken from the line and in series to the line impedance, a XTCSC variable reactance is placed, representing the inductive or capacitive capacitance that the compensator has over the Line as shown in figure 1.

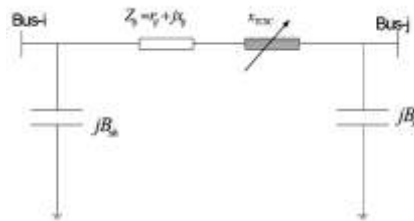


Fig. 1. Diagram of a Transmission Line Compensated with a TCSC [29]

5.1 TCSC Modeling

During the steady state, the compensator can freely change between reactance values according to its control. To avoid over-compensation of the line, limits are recommended for the reactance oscillation, given by the equation (2).

$$-0,8 X_L \leq X_{TCSC} \leq 0,2 X_L p. u. \tag{2}$$

The proposed limit vary among different research works, but a tendency of capacitive factor greater than 50% of reactance of the line and inductive factor less than 25% of the inductance of the line is maintained.

In order to be used in a power flow, the model must be in a line impedance with the built-in transformer reactance, in order to obtain the scheme shown in Figure 2, in this figure the reactance variations introduced by the compensator are expressed through the variation equation (2).

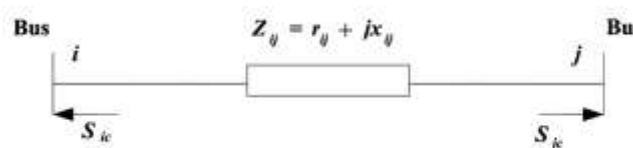


Fig. 2. TCSC Power Injection Model [29]

$$\Delta y_{i,j} = y'_j - y_{i,j} = (G'_{i,j} + jB'_{i,j}) - (G_{i,j} + jB_{i,j}) \tag{3}$$

Where

$$G_{i,j} + jB_{i,j} = \frac{1}{Z_{i,j}} \quad (4)$$

$$G_{i,j} = \frac{r_{i,j}}{r_{i,j}^2 + x_{i,j}^2}, G_{i,j} = \frac{-x_{i,j}}{r_{i,j}^2 + x_{i,j}^2} \quad (5)$$

$$G'_{i,j} = \frac{r_{i,j}}{r_{i,j}^2 + (x_{i,j} + x_{TCSC})^2}, G'_{i,j} = \frac{-(x_{i,j} + x_{TCSC})}{r_{i,j}^2 + (x_{i,j} + x_{TCSC})^2} \quad (6)$$

In function (3) it is stated that in fact there is a variation of admittances by the presence of the compensator, so that the admittances matrix will also be affected in the mean indicating (7).

$$Y'_{BUS} = Y_{BUS} + \begin{bmatrix} 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & \Delta y_{i,j} & 0 & \dots & 0 & -\Delta y_{i,j} & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & -\Delta y_{i,j} & 0 & \dots & 0 & \Delta y_{i,j} & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ & Col - i & \dots & Col - j & & & \end{bmatrix} \begin{matrix} \text{Fila} - i \\ \text{Fila} - j \end{matrix} \quad (7)$$

In terms of power flows between bars, the equations denoting power with the addition of the compensator can be written for active and reactive power flow, applying the admittance variation produced by the compensator series so that they are obtained [30, 31]:

$$P_{ijrCSC} = V_i^2 G'_{i,j} - V_i V_j [G'_{i,j} \cos(\delta_{ij}) - B'_{i,j} \sin(\delta_{ij})] \quad (8)$$

$$Q_{ijrCSC} = -V_i^2 (B'_{ij} + B_{sh}) + V_i V_j [G'_{ij} \sin(\delta_{ij}) - B'_{ij} \cos(\delta_{ij})] \quad (9)$$

5.2 Algorithm for TCSC

For the case of the compensator algorithms, two considerations are necessary for its modelling and simulation, the modelling translates into defining the variations that introduce the compensators and for the simulation to be considered, if this value will be subject to changes according to the method of Solution of power flows, as the iterative method evolves. The "modTCSC" function adjusts the admittance matrix as presented in the upper section, in a magnitude as a function of the same serial admittance of the branch, and may have an inductive or capacitive behaviour.

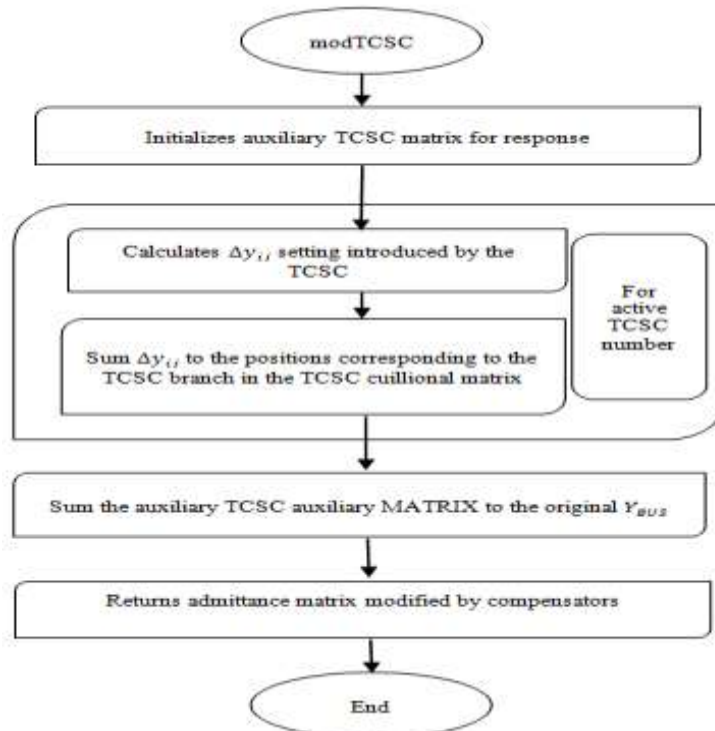


Fig. 2. Algorithm for TCSC

The algorithm of modifications introduced by TCSC receives, an information matrix of TCSC, the system admittance matrix without TCSC, a TCSC location vector, and the dimensions of the admittance matrix. The second condition mentioned above is related to the place that will be given to the compensator in the program to calculate power flow, this place should be in accordance with the variables that modify the compensator. In this case, the TCSC

changes the serial admittance of a branch of the system, so its location must go after the admittance matrix is computed without compensators and it does not depend of any parameter that changes during the iterations as the voltage, it is not necessary to place it within the loop of the iterative method.

In order to avoid that the "modTCSC" function is called without active TCSC, a conditional is placed that allows to start the function only on the test of active compensators, this conditional is used for the three types of compensators treated in this document and use a column to State of operation in each compensator that marks with one the operation and with zero the non-operation of a compensator in an extension or bar.

VI. Formulation of The Problem

Power losses, low power factor and degradation of the voltage profile are the result of strong current flow in power systems. These phenomena are more pronounced in distribution networks where the branch currents are stronger compared to those circulating in the transport networks. This state has paid great attention to the distribution networks and the strong currents circulating there in order to limit their intensities and thus improve the quality of energy supplied to consumers. The limitation cannot be done, if the network is not reconfigured, by acting on the reactive components of the branch currents then, the most indicated means is the installation of batteries of shunts capacitors. The installation of capacitor banks must be done rationally, i.e. in such a way that the quality of the energy is improved without, however, making major investments which would increase the energy consumption. The problem is therefore to decide the number of batteries, their powers and their locations which would make an objective function "F" maximum. This objective therefore makes the problem of reactive energy compensation an optimization problem. However, owed to the discrete nature of the battery sizes and their locations, this problem is non-linear with constraints. It is generally modelled as follows:

$$\begin{cases} \max f(x, u) \text{ subject to:} \\ x_{min} \leq x \leq x_{max} \\ u_{min} \leq u \leq u_{max} \\ g(x) \geq 0 \end{cases} \quad (10)$$

Where,

f : is the objective function to maximize.

g : is the equality constraint. It is the set of equations of the power flow

x : is the control variable vector

u : is the state variable vector.

6.1 Objective Function

The choice of the objective function is dictated by the concern to take into account at the same time the economic aspect and the electrical aspect of the problem. The objective function on which all the authors who have dealt with the problem of optimization of reactive energy compensation is the so-called "economic return" function or cost reduction noted as " ΔS ". Mathematical expression is given by:

$$\Delta S = k_p \Delta P - \sum_{i=1}^{nc} K_{ci} Q_{ci} \quad (11)$$

Where,

nc : is the total number of batteries installed.

k_p : is the cost of kW produced (\square /kW).

K_{ci} : is the annual price of kVAr installed depreciation and life included.

Q_{ci} : is the size of the installed battery at node " k ".

ΔP : is the reduction of the active power losses.

6.2 Reduction of Active Power Losses

The reduction of the power losses due to a battery " k " is equal to the difference of the losses of active power in the network before and after the installation of the said capacitor bank. It is given by:

$$\Delta P_k = P_{av_k} - P_{ap_k} \quad (12)$$

Where,

P_{av_k} : are the active power losses in line before compensation.

P_{ap_k} : are active power losses in line after compensation.

6.3 Reduction of Reactive Power Losses

The reduction of the reactive power losses due to a battery installed at node " k " of the distribution line is defined by the difference between the losses before and after the installation of batteries in question of capacitors. It is given by:

$$\Delta Q_k = Q_{av_k} - Q_{ap_k} \quad (13)$$

Where,

Q_{av_k} : are the losses of reactive power in line before compensation.

Q_{ap_k} : are the losses of reactive power in line after compensation.

6.4 Reactive Power Losses

The losses of reactive power in a distribution network line composed of n branches are given by the following formula:

$$Q_{av_k} = \sum_{i=1}^n x_i I_i^2 \quad (14)$$

Where,

x is the reactance of branch i

I_i is the line current of the i^{th} branch.

As with the active power losses, the active and reactive components of the branch current thus allow to write the losses of reactive power as follows:

$$Q_{avk} = \sum_{i=1}^n x_i I_{ai}^2 + \sum_{i=1}^n x_i I_{ri}^2 \quad (15)$$

The losses of reactive power when a capacitor bank is placed on a node k are given by:

$$Q_{apk} = \sum_{i=1}^n x_i I_{ai}^2 + \sum_{i=1}^k x_i (I_{ri} - I_{crk})^2 + \sum_{i=k+1}^n x_i I_{ri}^2 \quad (16)$$

The reduction of reactive power losses by calculating the difference between equation (15) and equation (16), will be equal to:

$$\Delta Q_k = 2I_{crk} \sum_{i=1}^k x_i I_{ri} - I_{crk}^2 \sum_{i=1}^k x_i \quad (17)$$

6.5 Heuristic Method

Heuristic methods are based on experience and practice. They are easy to understand and simple in their implementation. They use sensitivity factors which they incorporate into optimization methods in order to achieve qualitative solutions with small computational efforts. The heuristic methods were first introduced by Civanlar et al. [32] and Taylor et al. [33] to reduce the power losses in the distribution networks by reconfiguration of the latter. Because of the simplicity of the method, Abdel-Salam et al. [34] took up the idea and developed a heuristic method to determine the sensitive nodes where the capacitor banks will be placed. The latter are decided by first finding the branches where the most power losses occur as a result of the reactive charge currents. The node whose reactive load current produces the most reduction in power losses in the branch in question is said to be the most sensitive. Chis et al. [36] have enhanced the reference method [35] by considering that the most sensitive node is the one whose reactive load current produces the most reduction in power losses of the entire network studied. In both of these last two references the objective function considered is the net economic savings function except that in the case of Chis [36], different load levels were considered. Haque [37] in the method he proposed was aimed at minimizing power losses. The candidate nodes for receiving the capacitor banks are identified by installing at each of the nodes of the network taken alone a capacitor bank which minimizes power losses. Once the candidate nodes are determined, the optimum powers of the batteries to be placed there are determined simultaneously in order to avoid overcompensation. Nevertheless, the author considered the powers of the batteries as continuous variables which does not answer the reality of the problem. Mekhamer et al. [38] proposed two heuristic methods to solve the problem of optimization of reactive energy compensation. In the first method which they proposed and all in [37], the sensitive nodes are identified by installing, at each node of the network taken alone, a battery of capacitors which maximizes the reduction of the cost. The most sensitive node is the one that gives the greatest cost reduction. It is therefore selected first to receive the standard battery closest to the optimal battery which maximizes the cost reduction. The second method proposed by the authors is identical to the first one except that in order to select the candidate nodes and to calculate the optimal sizes of the batteries, they consider the reduction of the power losses instead of the reduction of the cost. Hamouda et al. [39] gave a method in which the candidate nodes for receiving the capacitor banks are determined as a function of the effect of the reactive current of the load at each node on the power losses of the whole Network studied. These nodes are ranked in decreasing order according to the effects on power losses. The range node 1 is selected first to obtain a standard size battery, just smaller or just larger than the optimum size battery, depending on the reduction it produces

Since the problem of determining the suitable battery locations has been separated from that of optimum power determination since the locations are determined by the sensitivity factors then the size calculation is generally modeled as follows:

$$\begin{cases} \max \Delta S_k(Q_{ck}) \text{ subject to:} \\ g(Q_{ck}) = 0 \\ Q_{c_{min}} \leq Q_{ck} \leq Q_{c_{max}} \\ V_{min} \leq V_i \leq V_{max} \end{cases} \quad (18)$$

6.6 New Modeling of the Problem

As stressed by Hamouda et al. [39], the stress imposed on the voltage may not be satisfied if small voltage limits are considered and therefore the problem would be unresolved. Such as the placement of shunted capacitors on a distribution network, where the effect is to increase the voltage which would at most exceed the maximum permissible value. In this case, the network (or branch) is said to be overcompensated and thus the reactive component (I_{ri}) of the branch current becomes positive. To avoid overcompensation, this component of the current d must always be negative or equal to zero.

By substituting the constraint on the tension with that made on the branch current, the new mathematical model of the problem becomes:

$$\begin{cases} \max \Delta S_k(Q_{ck}) \text{ subject to:} \\ g(Q_{ck}) = 0 \\ Q_{c_{min}} \leq Q_{ck} \leq Q_{c_{max}} \\ I_{ri} \leq 0 \quad i = 1, \dots, nj \end{cases} \quad (19)$$

6.7 Optimal Operation of Batteries

The sensitivity of the reduction of the active power losses of the line to each of the reactive components of the charge currents is used to determine the optimum battery locations [38]. This reduction in power losses for a given node "k" is defined as the difference between the power losses before canceling the reactive current of the load at node "k" and after the latter has been canceled. It is given by:

$$\Delta P_k = P_k^{av} - P_k^{ap} \tag{20}$$

The power losses before the cancellation of the reactive current of the load at the node "k" are given by:

$$P_k^{av} = \sum_{i=1}^n r_i I_{ai}^2 + \sum_{i=1}^n r_i I_{ri}^2 \tag{21}$$

The power losses after the cancellation of the reactive current of the load at the node "k" are given by:

$$P_k^{ap} = \sum_{i=1}^n r_i I_{ai}^2 + \sum_{i \in S_k}^k r_i (I_{ri} - I_{Lrk})^2 + \sum_{i=k+1}^n r_i I_{ri}^2 \tag{22}$$

After simplification, the reduction in power losses will have the following expression:

$$\Delta P_k = 2I_{Lrk} \sum_{i \in S_k}^k r_i I_{ri} - I_{Lrk}^2 \sum_{i \in S_k}^k r_i \tag{23}$$

The most sensitive node is one whose reactive charge current produces the greatest reduction in losses. It will then have range 1 and will be considered first to receive a capacitor battery of optimal size.

6.8 Determination of Optimal Sizes

To calculate the optimum sizes of the batteries, the currents they generate are first determined. This current is calculated so as to make the objective function the maximum ΔS_k cost reduction. This current is acquired by undertaking the accompanying condition:

$$\frac{\partial \Delta S}{\partial I_{crk}} = 0 \tag{24}$$

The expression of the current is then given by:

$$I_{crk} = \frac{2k_p \sum_{i \in S_k}^k r_i I_{ri} + 2k_{cm} \sum_{i \in S_k}^k x_i I_{ri} - k_{ck} V_{ck}}{2k_p \sum_{i \in S_k}^k r_i + 2k_{cm} \sum_{i \in S_k}^k x_i} \tag{25}$$

The initial optimum power is calculated by the following expression:

$$Q_{ck} = V_{ck} I_{crk} \tag{26}$$

The maximum value of the cost reduction in this case:

$$\Delta S_{k_{max}} = \frac{[2k_p \sum_{i \in S_k}^k r_i I_{ri} + 2k_{cm} \sum_{i \in S_k}^k x_i I_{ri} - k_{ck} Q_{ck}]^2}{4(k_p \sum_{i \in S_k}^k r_i + k_{cm} \sum_{i \in S_k}^k x_i)} \tag{27}$$

The value of the equivalent power loss reduction is given by:

$$\Delta P_{\Delta S_{max}} = \frac{4k_p^2 (\sum_{i \in S_k}^k r_i I_i)^2 + 4k_{cm} (\sum_{i \in S_k}^k x_i I_i)^2 - (k_{ck} V_{ck})^2}{2k_p (k_p \sum_{i \in S_k}^k r_i + k_{cm} \sum_{i \in S_k}^k x_i) - \frac{k_{cm} \sum_{i \in S_k}^k x_i [2k_p \sum_{i \in S_k}^k r_i I_i + 2k_{cm} \sum_{i \in S_k}^k x_i I_i - k_{ck} V_{ck}]^2}{4(k_p \sum_{i \in S_k}^k r_i + k_{cm} \sum_{i \in S_k}^k x_i)^2}} \tag{28}$$

VII. Load Flow Analysis Using Newton-Raphson Method

This method requires more time per iteration where it does not requires only a few iterations even for large networks. However, it requires storage as well as significant computing power. Let us assume:

$$S_i = I_i^* V_i \tag{29}$$

$$I_i^* = \sum_{m=1}^n Y_{im}^* V_m^* \tag{30}$$

$$Y_{im} = \rho_{im} + j\beta_{im} \tag{31}$$

Because of the quadratic convergence of the Newton-Raphson method, a solution of accuracy can be achieved in just a few iterations. These characteristics make the success of the Fast Decoupled Load Flow and the Newton-Raphson.

7.1 Fast Decoupled Load Flow (FDL)

The variation of the active power is less sensitive to the variation of the voltage V, on the other hand, it is more sensitive to that of phase δ . On the other hand, the variation of the reactive power is more sensitive to the variation of the voltage V, and is less sensitive to that of phase δ . The elements of JACOBIEN J_{PV} are calculated:

$$\frac{\partial P_i}{\partial |V_j|} = |V_i| \cdot |Y_{ij}| \cdot \cos(\theta_{ij} - \delta_i + \delta_j) \tag{32}$$

Where, $\theta_{ij} \approx 90^\circ$ and $\delta_i \approx \delta_j$ then $\frac{\partial P_i}{\partial |V_j|} \approx |V_i| \cdot |Y_{ij}| \cdot \cos(90^\circ) = 0.0$

Now, we calculate the elements of JACOBIEN $J_{Q\delta}$:

$$\frac{\partial Q_i}{\partial \delta_j} = -|V_i| \cdot |V_j| \cdot |Y_{ij}| \cdot \cos(\theta_{ij} - \delta_i + \delta_j) \tag{33}$$

Where, $\theta_{ij} \approx 90^\circ$ and $\delta_i \approx \delta_j$ then $\frac{\partial Q_i}{\partial \delta_j} \approx -|V_i| \cdot |V_j| \cdot |Y_{ij}| \cdot \cos(90^\circ) = 0.0$

Consequently, the sub-matrices of the JACOBIEN $J_{Q\delta}$ and J_{PV} are null.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{PV} & 0 \\ 0 & J_{QV} \end{bmatrix} \cdot \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \Rightarrow \begin{aligned} \Delta P &= J_{P\delta} \cdot \Delta \delta = \frac{\partial P}{\partial \delta} \cdot \Delta \delta \\ \Delta Q &= J_{QV} \cdot \Delta |V| = \frac{\partial Q}{\partial |V|} \cdot \Delta |V| \end{aligned} \quad (34)$$

The elements of JACOBIEN $J_{P\delta}$ are calculated:

$$\begin{aligned} \frac{\partial P_i}{\partial \delta_i} &=? \quad (35) \\ \frac{\partial P_i}{\partial \delta_i} &= \sum_{j=1}^N |V_i| \cdot |V_j| \cdot |Y_{ij}| \cdot \sin(\theta_{ij} - \delta_i + \delta_j) \\ &= -|V_i|^2 \cdot |Y_{ii}| \cdot \sin(\theta_{ii}) + \sum_{j \neq i}^N |V_i| \cdot |V_j| \cdot |Y_{ij}| \cdot \sin(\theta_{ij} - \delta_i + \delta_j) \quad (36) \end{aligned}$$

Where,

$$\frac{\partial P_i}{\partial \delta_i} = -|V_i|^2 \cdot |Y_{ii}| \cdot \sin(\theta_{ii}) - Q_i \quad (37)$$

And

$$\begin{aligned} Q_i &= \sum_{j=1}^N |V_i| \cdot |V_j| \cdot |Y_{ij}| \cdot \sin(\theta_{ij} - \delta_i + \delta_j) \quad (38) \\ |Y_{ii}| \cdot \sin(\theta_{ii}) &= B_{ii}, B_{ii} \gg Q_i \Rightarrow \frac{\partial P_i}{\partial \delta_i} = -|V_i|^2 \cdot B_{ii} \text{ and } |V_i|^2 = |V_i| \text{ so } \frac{\partial P_i}{\partial \delta_i} = -|V_i| \cdot B_{ii} \end{aligned}$$

Now we calculate $\frac{\partial P_i}{\partial \delta_j} = ?$

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i| \cdot |V_j| \cdot |Y_{ij}| \cdot \sin(\theta_{ij} - \delta_i + \delta_j) \quad (39)$$

Since $\delta_j - \delta_i \approx 0$, therefore,

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i| \cdot |V_j| \cdot |Y_{ij}| \cdot \sin(\theta_{ij}) \quad (40)$$

Where, $|Y_{ij}| \cdot \sin(\theta_{ij}) = B_{ij}$, $|V_j| \approx 1$

$$\frac{\partial P_i}{\partial \delta_j} = -|V_j| \cdot B_{ij} \quad (41)$$

The elements of Jacobien J_{QV} are calculated:

$$\frac{\partial Q_i}{\partial V_j} = ? \quad (42)$$

$$\frac{\partial Q_i}{\partial |V_i|} = -2 \cdot |V_i| \cdot |Y_{ii}| \cdot \sin(\theta_{ii}) - \sum_{j=1}^N |V_j| \cdot |Y_{ij}| \cdot \sin(\theta_{ij} - \delta_i + \delta_j) \quad (43)$$

$$\frac{\partial Q_i}{\partial |V_i|} = -|V_i| \cdot |Y_{ii}| \cdot \sin(\theta_{ii}) - |V_i|^{-1} \sum_{j=1}^N |V_i| \cdot |V_j| \cdot |Y_{ij}| \cdot \sin(\theta_{ij} - \delta_i + \delta_j) \quad (44)$$

$$\frac{\partial Q_i}{\partial |V_i|} = -|V_i| \cdot |Y_{ii}| \cdot \sin(\theta_{ii}) - |V_i|^{-1} \cdot Q_i \quad (45)$$

Where $Q_i = -\sum_{j=1}^N |V_i| \cdot |V_j| \cdot |Y_{ij}| \cdot \sin(\theta_{ij} - \delta_i + \delta_j)$

$|Y_{ii}| \cdot \sin(\theta_{ii}) = B_{ii}$, $B_{ii} \gg Q_i \Rightarrow \frac{\partial Q_i}{\partial |V_i|} = -|V_i| \cdot B_{ii}$

And $\frac{\partial Q_i}{\partial |V_j|} = ?$

$$\frac{\partial Q_i}{\partial |V_j|} = -|V_i| \cdot |Y_{ij}| \cdot \sin(\theta_{ij} - \delta_i + \delta_j) \quad (46)$$

Since $\delta_j - \delta_i \approx 0$, therefore,

$$\frac{\partial Q_i}{\partial |V_j|} = -|V_i| \cdot |Y_{ij}| \cdot \sin(\theta_{ij}) \quad (47)$$

Where, $|Y_{ij}| \cdot \sin(\theta_{ij}) = B_{ij}$, $\frac{\partial Q_i}{\partial |V_j|} = -|V_i| \cdot B_{ij}$

The individual power change equations in $J_{P\delta}$ and J_{QV} are:

$$\Delta P_i = \sum_{j=1}^N -|V_i| \cdot B_{ij} \cdot \Delta \delta_j \Rightarrow \frac{\Delta P_i}{|V_i|} = \sum_{j=1}^N -B_{ij} \cdot \Delta \delta_j \quad (48)$$

$$\Delta Q_i = \sum_{j=1}^N -|V_i| \cdot B_{ij} \cdot \Delta |V_j| \Rightarrow \frac{\Delta Q_i}{|V_i|} = \sum_{j=1}^N -B_{ij} \cdot \Delta |V_j| \quad (49)$$

$$\frac{\Delta P}{|V_i|} = -B' \cdot \Delta \delta \Rightarrow \Delta \delta = -[B']^{-1} \cdot \frac{\Delta P}{|V_i|} \quad (50)$$

$$\frac{\Delta Q_i}{|V_i|} = -B'' \cdot \Delta |V| \Rightarrow \Delta |V| = -[B'']^{-1} \cdot \frac{\Delta Q_i}{|V_i|} \quad (51)$$

The fast decoupled method FDL performs the same execution times as that of Newton-Raphson for very small networks. However, it becomes faster for more and the usual tolerances.

VIII. Optimal Location Using Particle Swarm Optimization (PSO)

In the proposed system, the location of TCSC in a particular bus system is decided by PSO algorithms. The objective function is minimized using the abovementioned technique. James Kennedy and Russell C. Eberhart

proposed a PSO approach in 1995. This approach is a heuristic method [40]. The evaluation of candidate solution of current search space is done on the basis of iteration process (as shown in Fig. 3). The minima and maxima of objective function is determined by the candidate's solution as it fits the task's requirements. Since PSO algorithm do not accept the objective function data as its inputs, therefore the solution is randomly away from minimum and maximum (locally/ globally) and also unknown to the user. The speed and position of candidate's solution is maintained and at each level, fitness value is also updated. The best value of fitness is recorded by PSO for an individual record. The other individuals reaching this value are taken as the individual best position and solution for given problem. The individuals reaching this value are known as global best candidate solution with global best position. The up gradation of global and individual best fitness value is carried out and if there is a requirement then global and local best fitness values are even replaced. For PSO's optimization capability, the updation of speed and position is necessary. Each particle's velocity is simplified with the help of subsequent formula:

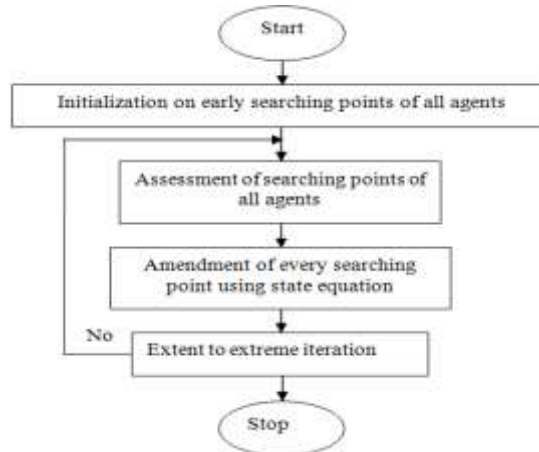
$$v_i(t + 1) = wv_i(t) + c_1r_1[\hat{x}_i(t) - x_i(t)] + c_2r_2[g(t) - x_i(t)] \quad (52)$$


Fig. 3. Flow chart of PSO algorithm [40]

IX. Results Analysis

Load Flow Analysis Using Newton Raphson

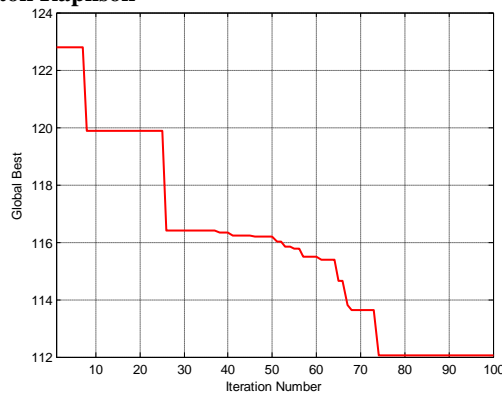


Fig. 4. PSO iteration graph

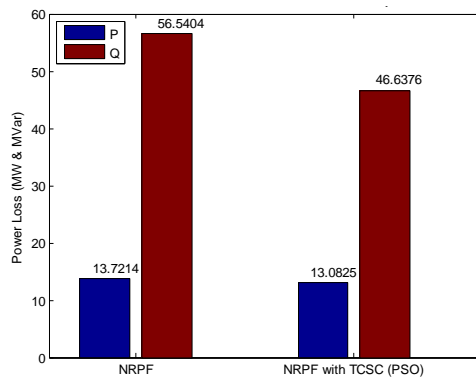


Fig. 5. Active & Reactive power losses in IEEE-14 bus system using PSO

Load Flow Analysis Using Newton Raphson with TCSC at optimal location

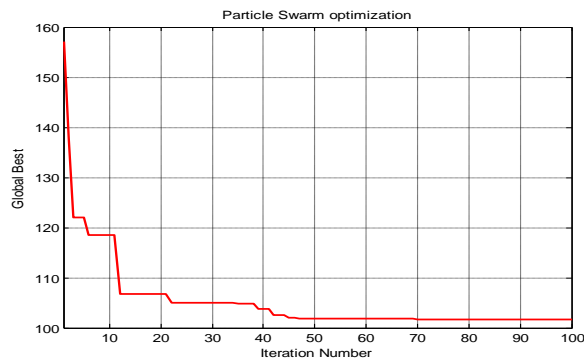


Fig. 6. PSO iteration graph

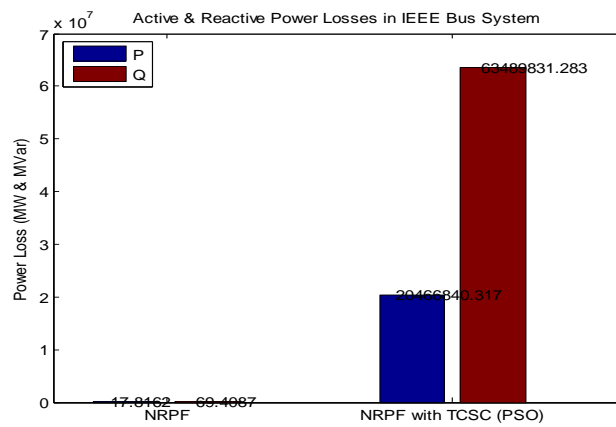


Fig. 7. Active & Reactive power losses in IEEE-14 bus system with PSO

Load Flow Analysis Using Newton Raphson

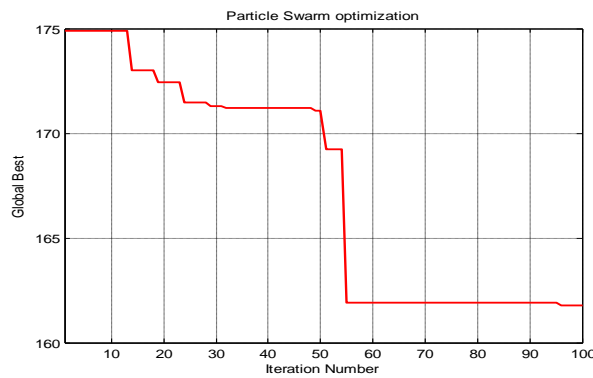


Fig. 8. PSO iteration graph

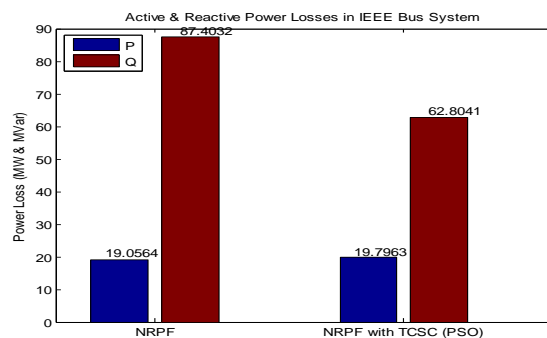


Fig. 9. Active & Reactive power losses in IEEE-30 bus system using PSO

Table 1.Comparative analysis for active power loss and reactive power loss

Method	Active Power Loss	Reactive Power Loss
14 bus system Using Newton Raphson	13.721	56.54
14 bus system using Newton Raphson with TCSC @ optimal locations	13.083	46.64
30 bus system Using Newton Raphson	19.056	87.40
30 bus system using Newton Raphson with TCSC @ optimal locations	19.796	62.80

X. Conclusion

In our work in this paper, we presented a solution for the problem of the circulation of strong reactive currents in balanced distribution networks. A PSO optimized technique based on a loss-of-power sensitivity factor has been proposed. In this method, the choice of the candidate nodes to receive the capacitor banks is arbitrated by the sensitivity of the power losses of the entire electrical system studied to the reactive load current of each node. The most sensitive node is therefore the one whose reactive current of charge produces the most loss reduction. The introduction of this sensitivity factor has made it possible to separate the search from the locations of the batteries to that of the optimum powers of the latter. The optimum sizes of the batteries are determined in such a way that they make the economic cost or return function maximum. In this objective function, and contrary to the authors who have treated the subject, the reduction of the reactive power losses has been introduced because the installation of the batteries reduces not only the active power losses but also the reactive losses. Because the batteries are installed one after the other, the optimum power determined by deriving the objective function is only an initial value from which is determined a standard size available on the market which satisfies the constraints of the problem namely a reduction of the positive power losses and reactive current of positive branch load. This last constraint comes to replace the stress on the tension which cannot lead to a solution if small limits are considered. The reduction of the reactive power losses, although significant, has very little effect on the reduction of the cost (objective function). This is due to the fact that we have no idea about the actual price of kVAR produced, which led us to take an average value of the price of kVar marketed which is relatively small.

During this work, the problem of the power flow in the distribution networks, which is a prerequisite for the conduct of the reactive energy compensation, is also taken care of, the calculation of the power flow is imperative. An iterative method has been developed for this purpose where a technique specific to us has been given to recognize the configuration of the network. Load flow analysis is also done using Newton-Raphson method. Particle Swarm Optimization is used to optimize the location of TCSC using the MATLAB model. The tests were performed taking TCSC as the FACTS device.

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