Optimal Allocation of Series Capacitor

Thesis submitted in partial fulfillment of the requirements for the award of degree of

Master of Engineering
in
Power Systems & Electric Drives

Thapar University, Patiala

By:
Sanju Bala
(80641020)

Under the supervision of:
Mr. Parag Nijhawan
Sr. Lecturer, EIED

JUNE 2008

ELECTRICAL & INSTRUMENTATION ENGINEERING DEPARTMENT
THAPAR UNIVERSITY
PATIALA – 147004

Certificate

I hereby certify that the work which is being presented in the thesis entitled, **"Optimal Allocation of Series Capacitor"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in *Power Systems & Electric Drives* submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Mr. Parag Nijhawan, Sr. Lecturer, EIED.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

Sanju Bala
(SANJU BALA)

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Parag
28/06/08
(PARAG NIJHAWAN)
Sr. Lecturer
Electrical & Instrumentation Engg. Department
Thapar University
Patiala

Countersigned by

S. Ghosh
12/8/08
(S. GHOSH)
Professor & Head
Electrical & Instrumentation Engg. Department
Thapar University
Patiala

RK Sharma
(R.K.SHARMA)
Dean(Academic Affairs)
Thapar University,
Patiala.

Acknowledgement

Words are often less to reveal one's deep regards. An understanding of work like this is never the outcome of the efforts of a single person. I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this thesis.

First of all I would like to thank the Almighty, who has always guided me to work on the right path of the life. My greatest thanks are to my parents who bestowed ability and strength in me to complete this work.

This work would not have been possible without the encouragement and able guidance of my supervisor **Mr. Parag Nijhawan.** His enthusiasm and optimism made this experience both rewarding and enjoyable. Most of the novel ideas and solutions found in this thesis are the result of our numerous stimulating discussions.

I take this opportunity to express my gratitude and sincere thanks to **Dr. Samarjit Ghosh, Prof. & Head, Electrical & Instrumentation Engineering Department** for their valuable suggestion and for providing me the opportunity to complete my thesis work simultaneously.

I am most indebted to the P.G. coordinator **Dr. Sanjay Kumar Jain** for his help, assistance and suggestions during my work.

I am also very thankful to the entire faculty and staff members of Electrical and Instrumentation Engineering Department for their direct–indirect help, cooperation, love and affection, which made my stay at Thapar University memorable.

I wish to thank all my classmates for their time to time suggestions and cooperation without which I would not have been able to complete my work.

(SANJU BALA)
(80641020)

Abstract

In recent years, energy, environment, right-of-way and cost problems have delayed the construction of both generation facilities and new transmission lines. These problems have necessitated a change in the traditional concepts and practices of power systems. Better utilization of existing power system capacities by installing compensating devices has become imperative.

Series capacitors can be utilized to change the reactive power flow through the line. Thus the power transfer capabilities will be increased and the transmission investment cost will be reduced. This compensation scheme is one facet of FACTS that has been widely accepted as a solution for the limitations created by overstretched generation and transmission systems.

The objective of this study is to find the optimal location of compensation devices. This will lead to the better utilization of the existing infrastructure like transmission lines. Parameters like sensitivity analysis, line flow index etc. are calculated and analyzed to find the best location for the compensation device.

Some computational tools are needed in assisting the analysis of the effects on the system performance due to the control settings and the new devices. The existing system analysis tool is Optimal Power Flow (OPF). Thus, it is necessary to extend the existing traditional OPF to include the representation of variable series capacitors. Since the main concern in this study is to compensate reactive power flows and then optimize the system using Linear Programming. In this thesis work IEEE 30 bus test system is considered.

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Chapter 1
Introduction

1.1 Overview

The transmission of electricity differs from transportation of any typical commodity by some inherent aspects such as: the production needs to match the consumption at the same time; system control is not an easy task; the electricity flows do not usually follow the economic law. The last aspect is normally observed when transmission systems are included in an economic dispatch problem. One way to minimize the operational costs caused by an overloaded transmission system is through the installation of Flexible AC Transmission System (FACTS) devices in the system or some reactive power compensating device like Series Capacitor. They are able to change power flows by modifying the network parameters. The optimal allocation and utilization of compensating devices are important issues primarily due to their cost. Recently network blackouts related to voltage collapse tend to occur from lack of reactive power support in heavily stressed conditions, which are usually triggered by system faults. Power electronics based equipment, or Flexible AC Transmission Systems (FACTS), provide proven technical solutions to active and reactive power control and voltage stability problems.

The FACTS is a concept based on power electronic controllers, which enhance the value of transmission networks by increasing the use of their capacity. As these controllers operate very fast, they enlarge the safe operating limits of a transmission system without risking stability. Series Capacitor, Shunt Inductor etc. are the backbone of FACTS devices. The best or optimal location of the Series Capacitor is tried to be obtained. The same idea can be extended to find out the optimal location of FACTS device.

These devices make the application of a large amount of Var compensation more efficient, flexible and attractive. Consequently, a series of questions have been raised frequently by utility planners and manufacturers: Where is the right location and what is the right size for the installation of reactive power compensators considering technical and economic needs? Can the models, methods, and tools used for static Var planning be applied in dynamic Var planning? The answers to these questions are needed for utilities to make better use of these new power electronic controlled Var sources. In order to answer the above questions, it should be stated that optimal allocation of static and dynamic Var sources belongs to the Reactive Power Planning (RPP) or Var planning category. RPP deals with the decision on new Var source location and size to cover normal, as well as, contingency conditions. The planning process aims at providing the system with efficient Var compensation to enable the system to be operated under a correct balance between security and economic concerns. This report focuses on the ability of compensating devices mainly Series Capacitor to change the overall losses of the system and its allocation in the power system, then system is optimized using Linear Programming.

1.2 Literature Review

Several research papers and reports addressed the subject of optimal capacitor placement in distribution systems. The followings present a brief review of the work undertaken so far.

Kaplan presented a computerized trial and error heuristic method for optimizing the present worth of revenue savings [17]. The savings are associated with released system capacity and the energy loss reductions. Both fixed and switched capacitor banks and their installation cost were also considered. The availability of the capacitor banks in accordance with the standards and released capacity cost were included as well.

The optimization process consists of three major steps. First is the choice of the location and type for the smallest standard size bank. The program scans all feeder branches moving along the branch toward the substation. Second is the improvement of the solution considering the standard bank size. The aim of this step is to increase the objective function. Third is the selection of the type of control for switched banks. The method, however, does not consider system voltage limitations or the economic effect of voltage rise resulting from capacitor applications.

S. Rama Iyer et al. defined the objective function of the optimal capacitor placement problem as a maximization of revenue savings resulting from power loss reduction [25]. The objective function is solved by a mixed-integer programming technique subjected to the following constraints:

1. Upper and lower limits of generator voltage magnitudes.

2. Upper and lower values for the transformer tap settings.
3. Upper limit on the number of units in each capacitor bank due to technical reasons such as switching voltage surges.

The proposed method finds the optimal location of a capacitor by the coordinated variation of generator voltages, transformer tap settings and the number of units in each capacitor bank. The method has some features which result in considerable savings in computer time and memory. First is the elimination of dependent variables in the problem formulation. Second is the decomposition of the problem into two smaller sub problems. Third is the avoidance of the load flow calculation.

A. A. El-Kib et al. presented a new model for radial distribution systems in [1]. The model considers asymmetrical and multi-grounded feeders. They also supply unbalanced loads. Based on the model, the optimal size, locations and switching intervals of fixed and switched capacitors are determined. The paper, however, did not discuss optimal number of fixed and/or switched capacitors to achieve the maximum savings. Capacitor sizes are treated as continuous variables which is not the case in real-life where capacitor sizes are discrete. A numerical example is presented for a real multi-grounded, three-phase feeder with lateral branches and five wire sizes.

S. Ertem and J. Tudor presented an objective function representing monetary savings that result from capacitor allocation in terms of system voltages and angles and the reactive power to be allocated [26]. The constraints are the maximum and minimum system voltages. The method takes the load uncertainty into account. This is done to prevent both over-compensation and the under-compensation. To reduce system variables and to avoid the numerical instability, sensitivity analysis and pattern recognition techniques are used. The proposed solution is based on non-linear programming technique where two models are presented. The first one solves the problem subject to approximate constraints. The output of this model is used as a starting solution to the second model. The second model has the exact formulation of the constraints using the method of approximate programming.

R. Rinker and D. Rembert presented a method to optimally allocate capacitors along a distribution line using the data gathered by reactive current recorders installed at major feeder taps [23]. The data is used later to achieve maximum savings by placing the proper sizes of capacitors at the appropriate places. The method assumes that the current readings recorded at a node are applicable to the entire section which follows the node. It places the capacitors in different types and sizes in a systematic trial and error procedure. It can also be improved if the program is extended to handle split feeders or nodes placed on significant branches. M. Baran and F. Wu presented a nonlinear mixed integer programming formulation to solve the capacitor placement problem [19]. The objective function to be maximized is the revenue savings resulting from energy loss reduction minus the capacitors installation costs. Voltage constraints and load variations are considered as the problem constraints. The solution methodology decomposes the problem into a master and a slave subproblem. In the master sub-problem an integer programming is used to find the optimal location and the number of capacitor banks to be placed. The slave sub-problem is used by the master sub-problem to find the capacitor type and settings. The proposed solution model was tested by considering two different test systems. Although voltage regulators were not considered in this paper, the method can be extended to account for their presence.

Y. Baghzoz presented an exhaustive search method to solve for the optimal solution of the capacitor placement problem and nonlinear load models are incorporated in the problem formulation [30]. The paper assumes that the system is balanced and that all loads vary in a conforming way. The active and reactive powers represent the fundamental frequency quantities. The loads are partitioned into linear and non-linear loads. The nonlinear loads are assumed to have the same displacement factor. To show the effect of the load model on the final solution, the problem considers three different load models. These are the base case model, the most accurate model and the constant impedance model. The problem constraints are the maximum number of capacitors assigned at a particular location. They also include the maximum number of capacitors on the entire feeder. The maximum and minimum r.m.s. voltage at a certain bus, the maximum peak value and the total harmonic distortion are also considered. Numerical results show that consideration of load non-linearity substantially changes the optimal solution of the problem; the test system used by the author in this paper is a small one with 9 buses only. Exhaustive search, however, shows that it is not possible to be used for large systems.

S. Tripathy and M. Haridas discussed an analytical method for the problem of installing shunt capacitors on distribution feeders [27]. The paper gives a detailed derivation for the loss reduction in a distribution feeder. Based on this, the optimal size and locations of shunt capacitors are calculated. The paper also discusses the use of the normalization technique in case of different conductor sizes and non-uniformly distributed reactive loads.

C. Chen et al. presented a computer simulation program to solve the optimal capacitor placement problem by means of non-linear programming while considering the mutual coupling among phase conductors [5]. Mutual coupling is determined by the types of conductors, horizontal and vertical distance among conductors. The objective function to be minimized consists of peak power losses, energy losses and capacitor installation cost. It is assumed that the installation cost/kVar is constant. Also, the capacitor values are treated as discrete variables. The minimum and maximum bus voltages are taken as the system constraints. A 34-bus unbalanced and 10-bus balanced test system was considered. Simulation results revealed that the inclusion of mutual coupling is very important. If ignored, serious overcompensation and extra power losses may result. In addition, the effect of mutual coupling is more important for unbalanced systems.

Bala et al. presented a sensitivity-based optimization method to optimally allocate shunt capacitors among a radial distribution feeder [11]. The solution should find optimal size, type and location of the capacitors. Several researchers attempted to solve the capacitor placement problem by using different heuristic and iterative methods. These methods provide reasonable solutions with minimum complexity. Chiang et al. solved the general capacitor placement problem in a distribution system by means of the simulated annealing method [7,8]. The objective of this work is to maximize the energy loss reductions in the system while considering the capacitors installation costs. The capacitor cost function is step-like and non-differentiable. The constraints are the upper and lower voltage limits and the load variations.

Chiang et al. presented a more comprehensive methodology based on simulated annealing mixed with greedy search to solve the general capacitor placement problem [9,10]. The purpose of this mix is to get a good-quality solution in a shorter time. The proposed method can be applied to large scale unbalanced, radial or loop distribution network. Accurate mathematical modeling of distribution lines, shunt capacitors, transformers, loads and co-generators were employed. The aim is to find the optimal location to install (or replace or remove) capacitors, types and sizes during each load level and the control schemes for each capacitor. The objective function takes into consideration the installation (or replacement or removal) cost of capacitors and the system energy losses. The constraints of the problem are load flow, line flow capacity and voltage magnitude constraints. The cost function of capacitors is a step-like and hence a non-differentiable function. Capacitor sizes and control settings are treated as discrete variables.

Sundhararajan and Pahwa solved the general capacitor placement problem in a distribution system using a genetic algorithm [28]. Genetic Algorithm, as an optimization technique can reach a near optimal solution in a lesser time than that of the simulated annealing. The objective function presented is not constrained. However, if a constraint is to be incorporated, then a penalty function should be included. Sensitivity analysis is used in this paper as an aid for the Genetic Algorithm to help select the candidate locations of capacitors. Top two or three buses in each lateral branch are chosen as candidate locations. A 9-bus and a 30-bus test systems were used to check the robustness of the method. Yann-Chang Huang et al. introduced a Tabu Search-based method to solve the capacitor placement problem [32]. To start with, heuristic and engineering judgments are used to select the potential locations where capacitors can be installed. Then, a sensitivity analysis is used to determine the candidate locations. In comparison with simulated annealing, the authors concluded that Tabu Search method gives the same results with shorter computing time.

Z. Wu proposed to solve the capacitor placement problem by means of Maximum Sensitivity Selection (MSS) method [33]. The MSS decomposes the problem into sub- problems to make the solution simpler. The objective function considers the peak power loss, energy losses and the installation cost of capacitors. The problem constraints are system minimum and maximum voltages and total harmonic distortion. The paper assumes that all loads change in a conforming way, load variations can be approximated by discrete levels, loads are linear and balanced, skin effect of higher harmonics is neglected and the substation is the only harmonic source. Karen Nan Miii et al. proposed to solve the general capacitor placement problem by a Genetic Algorithm followed by a sensitivity-based heuristic method [16]. Genetic algorithm is employed to find a high quality solution that is used as an initial guess for the sensitivity-based heuristic. The objective function includes the cost of placement or replacement of capacitor banks and the cost of real power loss. The problem constraints are the power flow constraints, operational constraints on bus voltages and the line flow ratings. Simulation results revealed that the proposed hybrid algorithm outperformed the Genetic Algorithm alone and the sensitivity heuristic alone in tents of both speed and quality.

M. Baran and F. Wu solved the optimal sizing problem of capacitors placed on a radial distribution system as a special case of the general capacitor placement problem [18].The sizing problem is formulated as a nonlinear programming problem. The formulation incorporates the ac power flow model for the system and the voltage constraints.

Y. Baghzouz and S. Ertem solved the optimal sizing of distribution capacitors as a special case of the general capacitor placement problem using a simple heuristic method based on the method of local variations [31]. Potential harmonic iterations like resonance conditions, high harmonic distortion factor and additional harmonic power losses are considered in the problem formulation. The savings associated with power loss reduction may have to be sacrificed to control the total harmonic distortion to acceptable limits. The paper assumes that the line capacitance are negligible, system is balanced, all loads are linear and time invariant, harmonic generation is only from the substation voltage supply, only fixed capacitors are used and capacitors are represented as constant admittances.

J. Grainger et al. presented a generalized procedure based on non-linear programming for optimizing the net savings resulting from power loss reduction caused by capacitor installation [12]. The system unbalance is taken into account and mutual coupling between the phases is considered. The paper, however, assumes only fixed capacitors are to be installed. Moreover, capacitor sizes are treated as continuous variables. Also, capacitor installation cost is neglected. Jin-Chang et al. decouple the general capacitor placement problem into two sub- problems: the capacitor placement sub-problem and the real-time control sub-problem [13,14]. A quadratic integer programming based approach is proposed for the capacitor placement sub-problem to determine the number, locations and sizes of capacitors to be placed. The real-time control sub-problem is formulated as another quadratic integer programming problem to determine the control settings for the different loading conditions [2].

1.3 Scope of Work

From the literature review, it is observed that the work on the investigation on power with compensating devices is very much diversified. However it is observed that there is a scope to investigate the effectiveness of compensating devices in power flow solution without violating security constraints. And to find the location of these devices in Power System.

The objective of the proposed work is to study the optimal power flow solution with Series Capacitor and to devise the strategy for the allocation of Series Capacitor to improve the optimal power flow solution. The proposed work includes optimal allocation of Series Capacitor and then system is optimized using Linear Programming.

1.4 Organization of Thesis

Chapter 1 describes introduction to the problem. It presents the literature review on compensating devices and their allocation in power system to minimize losses.

Chapter 2 covers reactive power compensation. It presents a brief idea about series, shunt compensation etc. and its effects.

Chapter 3 describes Optimal Power Flow problem formulation and explains Linear Programming based optimization technique.

Chapter 4 presents the methodology to allocate Series Capacitor in power system to improve system performance. Various parameters like sensitivity coefficients, line flow index etc. are calculated to allocate the device.

Chapter 5 presents the conclusion of this thesis work and discusses the future scope of the work.

Chapter 2

Reactive Power Compensation

2.1 Introduction

Reactive power compensation is an important issue in electric power systems, involving operational, economical and quality of service aspects. Consumer loads (residential, commercial and industrial sectors) impose real and reactive power demand, depending on their characteristics. Real power is converted into “useful” energy, such as light or heat. Reactive power must be compensated to guarantee an efficient delivery of real power to loads [4].

The reactive power is essential for creating the needed coupling fields for energy devices. It constitutes voltage and current loading of circuits but does not result in average (active) power consumption and is an important component in all ac power networks. Reactive power control for a line is often called Reactive Power Compensation. External devices or subsystems that control reactive power on transmission lines are known as Compensators. The objectives of line compensation are

- To increase the power transmission capacity of the line, and/or
- To keep the voltage profile of the line along its length within acceptable bounds to ensure the quality of supply to the connected customers.

Because reactive power compensation influences the power transmission capacity of the connected line, controlled compensation can be used to improve the system stability by changing the maximum power- transmission capacity.

2.2 Shunt Compensation

When fixed inductors and/or capacitors are employed to absorb or generate reactive power, they constitute passive control. Shunt devices may be connected permanently or through a switch. Shunt reactors compensate for the line capacitance, and because they control over voltages at no loads and light loads, they are often connected permanently to the line, not to the bus. Shunt capacitors are used to increase the power transfer capacity and to compensate for the reactive voltage drop in the line. The applications of shunt capacitors require careful system design. The circuit breakers connecting shunt capacitors should withstand high-charging in-rush currents. The addition of shunt capacitors creates higher frequency resonant circuits and can therefore lead to harmonic over voltages on some system buses.

2.3 Series Compensation

Series capacitors are used to partially offset the effects of the series inductances of the lines. Series compensation results in the improvement of the maximum power-transmission capacity of the line. The reactive power absorption of a line depends on the transmission current, so when series capacitors are employed, automatically the resulting reactive power compensation is adjusted proportionately. Also, because the series compensation effectively reduces the overall line reactance, it is expected that the net line-voltage drop would become less susceptible to the loading conditions.

In an interconnected network of power lines that provides several parallel paths, for power flow between two locations, it is the series compensation of a selected line that makes it the principal power carrier. A practical upper limit of series compensation may be as high as 0.75 pu.

2.4 Synchronous Condensers

Synchronous condensers or synchronous compensators were the only fully controllable reactive power devices available for power systems until mid 1970s. A synchronous condenser is a synchronous machine, the reactive power output of which can be continuously controlled by varying its excitation current. When the synchronous machine is connected to the ac system and is under excited, it behaves like an inductor, absorbing reactive power from the ac system. However, when it is overexcited, it functions like a capacitor, injecting reactive power into the ac system. The machine is normally excited at the base current when its generated voltage equals the system voltage; it thus floats without exchanging reactive power with the system. A synchronous condenser is usually connected to the EHV ac system through a coupling transformer [24].

2.5 Effects of Reactive Power Compensation

2.5.1 Reduced Power System Losses

The reduction in power system losses, due to the installation of capacitor banks, can result in an annual gross return of as much as 15 percent on the capacitor investment. Although it is seldom sufficient to justify the installation of capacitor banks on the economical benefits of power loss reduction alone, it is certainly an added benefit [8]. In most industrial plant power distribution systems, the power losses vary from 2.5 to 7.5 percent of the load kWh. This depends upon hours of full load and no-load plant operation, wire size, and length of the main and branch feeder circuits. Capacitors are effective in reducing only that portion of the losses that is due to the kVars current. Losses are proportional to the current squared, and since current is reduced in direct proportion to power factor improvement, the losses are inversely proportional to the square of the power factor. Hence, as power factor is increased with the addition of capacitor banks to the system, the magnitude of the losses are reduced. The connected capacitor banks have losses, but they are relatively small. Losses account for approximately one third of one percent of the kVar rating.

2.5.2 Release of Power System Capacity

When capacitors are placed in a power system, they deliver kVars. This introduces furnishing magnetizing current for motors, transformers and other similar plant, thus reducing the current from the power supply. Less current means less KVA or load placed on the transformers and main branch feeder circuits. This means capacitors can be used to reduce overloading or permit additional load to be added to existing feeders. Release of system capacity by power factor improvement and especially with capacitors is becoming extremely important due to the associated economic and system benefits.

2.6 Drawbacks of Reactive Power Compensation

One of the main drawbacks that must be considered when introducing capacitor banks into a power system includes resonance. Resonance is a condition whereby the capacitive reactance of a system offsets its inductive reactance. This causes the resistive elements as the only means of impedance in the system. The frequency at which this offsetting effect takes place is called the resonant frequency of the system.

In the event of a harmonic generating source near or at the resonant frequency, dangerous amplification to voltages and currents will occur. In turn this can cause damage to capacitor banks and other electrical equipment connected to the system. Resonance can take the form of either series or parallel type. This depends on how the reactive elements are arranged throughout the system.

As discussed previously, a high power factor makes better use of the available capacity of the power system. However, the occurrence of harmonics may create parallel and series resonance conditions, causing destructive consequences to the system. From the perspective of harmonic sources, shunt capacitor banks appear to be in parallel with the systems short circuit reactance. For ideal circuit elements, and neglecting saturation and other non-linear effects, inductive reactance increases directly as frequency increases while capacitive reactance decreases as frequency increases.

At the resonant frequency of the system, the parallel combination of the capacitor bank and the source reactance appears as large impedance. If this frequency happens to match with one generated by the harmonic source, then dangerous voltages and currents will increase disproportionately, causing damage to capacitors and other electrical equipment. Capacitors are also known to fail due to harmonic overload. Since the impedance of a capacitor is inversely proportional to frequency, harmonic currents may load capacitors beyond their limit causing them to fail [4].

Chapter 3

Optimal Power Flow

3.1 Introduction

Mathematical optimization (algorithmic) methods have been used over the years for many power systems planning, operation, and control problems. Mathematical formulations of real-world problems are derived under certain assumptions and even with these assumptions; the solution of large-scale power systems is not simple due to the uncertainties in power system problems. It is desirable that solution of power system problems should be optimum globally, but solution searched by mathematical optimization is normally optimum locally. These facts make it difficult to deal effectively with many power system problems through strict mathematical formulation alone.

Optimal power flow was first discussed by Carpentier in 1962 and took a long time to become a successful algorithm that could be applied in everyday use. The OPF constitutes a static nonlinear optimization problem which computes optimal settings for electrical variables in a power network, for given settings of loads and system parameters.

Economic dispatch, however, only considers real power generations and represents the electrical network by a single equality constraint, the power balance equation. The addition of losses to the network model, starting in 1943, resulted in the classical economic dispatch. The optimality conditions for these methods constitute the equal incremental cost criterion (EICC). These methods are simple and fast because they limit the network modeling to its simplest expression. Equal incremental cost methods constitute the most popular economic dispatch tool.

Optimal power flow methods satisfy the nonlinear constraints using an iterative scheme where iteration is based on some simpler linear subproblem. Nonlinear programming methods include successive approximation, gradient and successive linear programming. Linear programming method include simplex method, artificial variable method etc.. In this thesis IEEE 30 bus test system is optimized using Linear Programming [20].

3.2 OPF Problem Formulation

The objective function to be minimized is given below:

$$f = \sum_i F_i(Pg_i)$$

where

$$F(Pg_i) = a_i P_i^2 + b_i P_i + c_i$$

This is the sum of operating cost over all controllable power sources.

$F_i(Pg_i)$ = Generation cost function for Pgi generation at bus i.

The cost is optimized with the following constraints.

- The inequality constraint on real power generation at bus i

  $$Pg_i^{\min} \le Pg_i \le Pg_i^{\max}$$

  where

  $Pg_i^{\min} and.Pg_i^{\max}$ are respectively minimum and maximum values of real power generation allowed at generator bus i.

- The power flow equation of the power network

  $$g(V,\varphi) = 0$$

  where

  $$g(V,\varphi) = \begin{cases} P_i(V,\varphi) - P_i^{net} \\ Q_i(V,\varphi) - Q_i^{net} \\ P_m(V,\varphi) - P_m^{net} \end{cases}$$

  where

  Pi and Qi are respectively calculated real and reactive power for PQ bus i.

  Pi^{net} and Qi^{net} are respectively specified real and reactive power for PQ bus i.

  P_m and P_m^{net} are respectively calculated and specified real power for PV bus m.

  V and φ are voltage magnitude and phase angles at different buses.

- The inequality constraint on reactive power generation Qg_i at each PV bus

  $$Qg_i^{\min} \le Qg_i \le Qg_i^{\max}$$

  where $Qg_i^{\min}$ and $Qg_i^{\max}$ are respectively minimum and maximum value of reactive power at PV bus i.

- The inequality constraint on voltage magnitude V of each PQ bus

  $$V_i^{\min} \le V_i \le V_i^{\max}$$

where V_i^{min} and V_i^{max} are respectively minimum and maximum voltage at bus i.

- The inequality constraint on phase angle φ_i of voltage at all the buses i

  $$\varphi_i^{\min} \le \varphi_i \le \varphi_i^{\max}$$

  where φ_i^{min} and φ_i^{max} are respectively minimum and maximum voltage angles allowed at bus i.

- MVA flow limit on transmission line

  $$MVAf_{ij} \le MVAf_{ij}^{\max}$$

where $MVAf_{ij}^{max}$ is the maximum rating of transmission line connecting bus i and j

3.3 Linear Programming Based Optimal Power Flow

To obtain LPOPF firstly power flow equations are solved. The power flow equations can be for the DC representation, the decoupled set of AC equations, or the full AC power flow equations. The choice will affect the difficulty of obtaining the linearized sensitivity coefficients and the convergence test used. Firstly nonlinear input-output or cost functions (Figure 3.1) are expressed as a set of linear functions. Non-linear function can be approximated as a series of straight-line segments as shown in Figure 3.2. The three segments are represented as $P_{i1,}P_{i2,}P_{i3}$ and each segment has a slope designated: s_{i1}, $s_{i2,}$ s_{i3} for ith generator.

Then the cost function itself is

$$F_i(P_i) = F_i(P_i^{\min}) + s_{i1}P_{i1} + s_{i2}P_{i2} + s_{i3}P_{i3}$$

and $0 \le P_{ik} \le P_{ik}^{max}$ for kth segment

and $P_i = P_i^{min} + P_{i1} + P_{i2} + P_{i3}$

The cost function is now made up of a linear expression in the P_{ik} values.

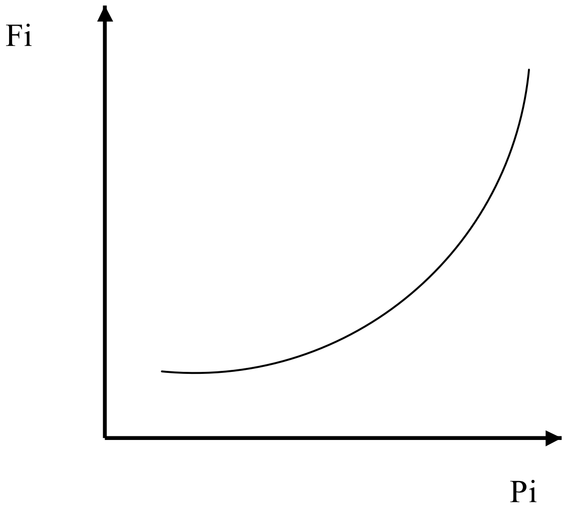

Figure 3.1: A Non-Linear Cost Function Characteristic.

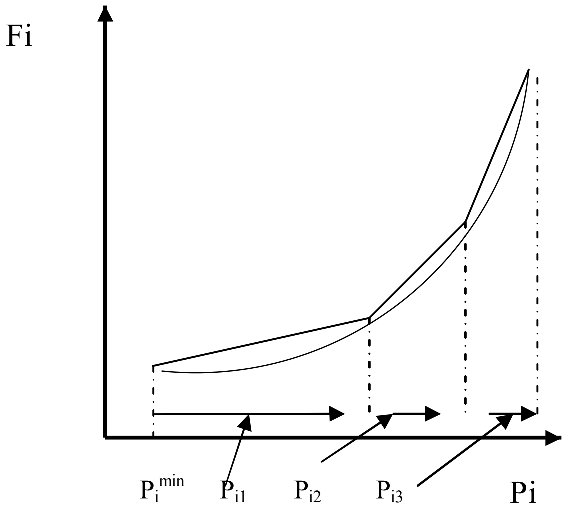

Figure 3.2: A Linearized Cost Function

In the formulation of the optimal power flow using linear programming, we have control variables (like generator output and generator bus voltage) in the problem. We do not consider to place the state variables into LP, nor all the power flow equations. Constraints are set up in the LP that reflects the influence of changes in the control variables only. The control variables are represented as the 'u' variable. The constraint that is considered in an LPOPF is the constraint that represents the power balance between real and reactive power generated and consumed in the load and losses.

The real power balance equation is:

$$P_{gen} - P_{load} - P_{losss}=0$$

The loss term represents the I^2R losses in the transmission lines and transformers. We can take derivatives with respect to the control variables, u, and this result in:

$$\sum_u \left(\frac{\partial P_{gen}}{\partial u} \right) \Delta u - \sum_u \left(\frac{\partial P_{load}}{\partial u} \right) \Delta u - \sum_u \left(\frac{\partial P_{loss}}{\partial u} \right) \Delta u = 0$$

If we make the following substitution:

$$\Delta u = u - u^0$$

then, the power balance equation becomes

$$\sum_u \left(\frac{\partial P_{gen}}{\partial u} \right) u - \sum_u \left(\frac{\partial P_{load}}{\partial u} \right) u - \sum_u \left(\frac{\partial P_{loss}}{\partial u} \right) u = K_p$$

where

$$K_p = \sum_u \frac{\partial P_{gen}}{\partial u} u^0 - \sum_u \frac{\partial P_{load}}{\partial u} u^0 - \sum_u \frac{\partial P_{loss}}{\partial u} u^0$$

A similar equation can be written for the reactive power balance:

$$\sum_u \left(\frac{\partial Q_{gen}}{\partial u} \right) \Delta u - \sum_u \left(\frac{\partial Q_{load}}{\partial u} \right) \Delta u - \sum_u \left(\frac{\partial Q_{loss}}{\partial u} \right) \Delta u = 0$$

where the loss term is understood to include I^2X as well as the charging from line capacitors and shunt reactors. A substitution using $\Delta u = u - u^0$ can also be done here.

The LP formulation restricts the control variables to move only within their respective limits, but it does not yet constrain the OPF to optimize cost within the limits of transmission flows and load bus voltages. For this a new constraint is added in the LP like MVA flow on line nm is constraint to fall within an upper limit:

$$\text{MVA flow}_{nm} \leq \text{MVA flow}_{nm}^{max}$$

This constraint is modeled by forming a Taylor's series expansion and only retaining the linear terms:

$$MVAflow_{nm} = MVAflow_{nm}^0 + \sum_u \left(\frac{\partial}{\partial u} MVAflow_{nm} \right) \Delta u \leq MVAflow_{nm}^{max}$$

we can substitute $\Delta u = u - u^0$ so we get:

$$\sum_{u}\left(\frac{\partial}{\partial u}MVAflow_{nm}\right)u \le MVAflow_{nm}^{\max} - K_f$$

where

$$K_f = MVAflow_{nm}^{0} + \sum_{u}\frac{\partial}{\partial u}MVAflow_{nm}u^{0}$$

Other constraints such as voltage magnitude limits, branch MW limits, etc., can be added in a similar manner. We can add as many constraints as necessary to constraint the power system to remain within its prescribed limits. The derivatives of P_{loss} and MVA $flow_{nm}$ are obtained from the linear sensitivity coefficient calculations [3,21].

3.3.1 Algorithm

Step 1- Input bus data, line data, cost functions, maximum and minimum values of control parameters etc.

Step 2- Solve power flow equations using any method like Gauss Seidel Method, Newton Raphson, Fast decoupled etc.

Step 3- Linearize the objective function.

Step 4- Obtain linearized constraint sensitivity coefficients.

Step 5- Get the solution using Linear Programming incorporating equality and inequality constraints of control variables.

Step 6- Test Convergence of solution.

Step 7- If it converges then there is no movement of control variables and we get the solution.

Step 8- If it does not converge, then adjust the control variables and go to step 2.

The results of the Linear Programming based Optimal Power Flow are given in Chapter 4.

Chapter 4

Selection for the Proper Location of Series Capacitor

4.1 Introduction

Many researches were made on optimal site selections for placement of compensating devices in power systems by considering different criteria. In this chapter, various parameters will be considered for their optimal allocations like sensitivity analysis, line flow index etc..

The best location, appropriate size and setting of compensating devices are important in the deregulated electricity markets. On one hand, there is considerable risk in the investment of these devices because of their high cost and the uncertain market transactions. There is a need to maximize the benefit from investment in compensating devices. On the other hand, the location and setting of these devices have direct and discriminatory impact on the market participants. Implementation of these devices can distort the prices at buses, directly affecting some generators and loads. Therefore, the location and setting of these devices require crucial consideration.

Capacitor banks are widely used in distribution systems for reactive power compensation, in order to achieve power and energy loss reduction, system capacity release and acceptable voltage profiles. The extent of these benefits depends on the location, size, type and number of capacitors (sources of reactive power) placed in the system. Hence an optimal solution for placement and sizing of capacitors in a distribution system is a very important aspect of power system analysis.

It is known that power flow through an AC transmission line is a function of line impedance, the magnitude and the phase angles between the sending and receiving end voltages. Variable series capacitors can be utilized to change the power flow by changing the parameters of the networks. Thus the power transfer capabilities will be increased and the transmission investment cost will be reduced [29].

Various parameters like sensitivity coefficients, line flow index etc. are calculated and analyzed to select the proper location of the device. These parameters are discussed below.

4.2 Various Parameters

4.2.1 Sensitivity Coefficients

Sensitivity coefficients give an indication of the change in one system quantity (e.g. MW flow, MVA flow, bus voltage etc.) as another quantity is varied (e.g. generator MW output, transformer tap position etc.). As the adjustable variable is changed, we assume that the power system reacts so as to keep all of the power flow equations solved. $\partial MVAflow_{ij} / \partial MWgen_k$ shows the sensitivity of the flow (MVA) on line (i to j) with respect to the power generated at bus k. In this work we calculate the change in active power (reactive power) flow with respect to the voltage at the bus and power angle. Eight parameters $\partial P_{ij} / \partial V_i$, $\partial P_{ij} / \partial V_j$, $\partial P_{ij} / \partial \delta_i$, $\partial P_{ij} / \partial \delta_j$, $\partial Q_{ij} / \partial V_i$, $\partial Q_{ij} / \partial V_j$, $\partial Q_{ij} / \partial \delta_i$, $\partial Q_{ij} / \partial \delta_j$ are calculated [6,22].

As we know,

$$Line\ \text{Flow,S}_{ij} = V_i \times I_{ij}^* = P_{ik} + jQ_{ij}$$

S$_{ij}$ is the line flow between line i and j.

$$\begin{aligned}
then\ P_{ij} &= V_i^2 \cos^2 \delta_i \frac{Y_{ij}}{a^2} \cos\theta - \frac{Y_{ij}}{a} V_i V_j \cos\theta \cos\delta_i \cos\delta_j + V_i^2 \frac{Y_{ij}}{a^2} \cos\theta \sin^2 \delta_i \\
&+ V_i V_k \frac{Y_{ij}}{a} \sin\theta \cos\delta_i \sin\delta_j + V_i^2 \cos^2 \delta_n \frac{Bc}{a^2} + V_i^2 \sin^2 \delta_i \frac{Bc}{a^2} \\
&- \frac{Y_{ij}}{a} V_i V_j \sin\theta \sin\delta_i \cos\delta_j - \frac{Y_{ij}}{a} V_i V_j \cos\theta \sin\delta_i \sin\delta_j
\end{aligned}$$

$$\begin{aligned}
\text{and Q}_{ij} &= -V_i^2 \cos^2 \delta_i \frac{Y_{ij}}{a^2} \sin\theta + \frac{Y_{ij}}{a} V_i V_j \sin\theta \cos\delta_i \cos\delta_j - V_i^2 \frac{Y_{ij}}{a^2} \sin\theta \sin^2 \delta_i \\
&+ V_i V_k \frac{Y_{ij}}{a} \cos\theta \cos\delta_i \sin\delta_j - \frac{Y_{ij}}{a} V_i V_j \cos\theta \sin\delta_i \cos\delta_j + \frac{Y_{ij}}{a} V_i V_j \sin\theta \sin\delta_i \sin\delta_j
\end{aligned}$$

then various coefficients are calculated from above equations. These are given below-

$$\frac{\partial P_{ij}}{\partial V_i} = 2V_i \frac{Y_{ij}}{a^2}\cos\theta + V_j \frac{Y_{ij}}{a}\cos\left(\delta_j - \delta_i + \theta\right) + 2V_i \frac{Bc}{a^2}$$

$$\frac{\partial P_{ij}}{\partial V_j} = -V_i \frac{Y_{ij}}{a}\cos\left(\delta_i - \delta_j - \theta\right)$$

$$\frac{\partial P_{ij}}{\partial \delta_i} = \frac{Y_{ij}}{a} V_i V_j \sin\left(\delta_i - \delta_j - \theta\right)$$

$$\frac{\partial P_{ij}}{\partial \delta_j} = V_i V_j \frac{Y_{ij}}{a}\sin\left(\delta_j - \delta_i + \theta\right)$$

$$\frac{\partial Q_{ij}}{\partial V_i} = -2V_i \frac{Y_{ij}}{a^2}\sin\theta\cos 2\delta_i + V_j \frac{Y_{ij}}{a}\sin\left(\delta_j - \delta_i + \theta\right)$$

$$\frac{\partial Q_{ij}}{\partial V_j} = V_i \frac{Y_{ij}}{a}\sin\left(\delta_j - \delta_i + \theta\right)$$

$$\frac{\partial Q_{ij}}{\partial \delta_i} = -\frac{Y_{ij}}{a} V_i V_j \cos\left(\delta_j - \delta_i + \theta\right)$$

$$\frac{\partial Q_{ij}}{\partial \delta_j} = V_i V_j \frac{Y_{ij}}{a}\cos\left(\delta_i - \delta_j - \theta\right)$$

Where

S_{ij} is the Apparent Power Flow from ith bus to jth bus.

Pij is Active Power Flow from ith bus to jth bus.

Qij is Reactive Power Flow from ith bus to jth bus.

V_i is Voltage at bus i.

V_j is the Voltage at bus j.

Y_{ij} is the Admittance between bus i and j.

a is the Tap Changing Ratio.

θ is the Power factor angle.

δ_i is the Power Angle of bus i.

Bc is Line Charging Admittance value.

These sensitivity coefficients are calculated for IEEE 30 bus system. Its Bus data and Line data are given in Appendix I. There are 41 lines in the system. Sensitivity coefficients are calculated for these lines. Change in Active Power is more sensitive to power angle and change in Reactive Power is more sensitive to voltage of the bus. Sensitivity of the line is high if its coefficient values are high.

4.2.2 Line Flow Index

It is the ratio of the line flow between any two buses of the system to the total connected load of the system. Total connected load is constant for a particular system so it is like a base load value. This index is calculated for IEEE 30 bus test system. More is value of index more is the line flow between the buses.

4.2.3 Voltage Drop

Voltage drops are calculated by multiplying line flow between two buses to the impedance of the line. Resistive Drop and Reactive Drop are calculated.

$D = (P + jQ) \times (R + jX)$

Resistive Drop = $PR - QX$

Reactive Drop = $QR + XP$

These values are calculated for all lines of IEEE 30 bus test system.

Above parameters are calculated and analyzed to select the proper location of Series Capacitor.

4.3 Results and Discussions

Various parameters discussed previously are calculated for IEEE 30 bus test system. Its code is developed in MATLAB. Its Bus data and Line data is given in Appendix I. Values of these parameters are given in table below-

Line No.	i to j	$\partial P_{(i,j)}/\partial V_{(i)}$ (S_1)	$\partial P_{(i,j)}/\partial V_{(j)}$($S_2$)	$\partial P_{(i,j)}/\partial \delta_{(i)}$($S_3$)	$\partial P_{(i,j)}/\partial \delta_{(j)}$($S_4$)
1	1--2	14.943302	-4.036904	17.399608	-17.399608
2	1--3	3.245266	-0.64541	5.636709	-5.636709
3	2--4	4.951505	-1.438228	5.604189	-5.604189
4	3--4	24.693873	-7.840675	25.075666	-25.075666
5	2--5	3.413907	-0.702166	5.452078	-5.452078
6	2--6	4.760927	-1.2922	5.527199	-5.527199
7	4--6	19.147796	-6.019656	23.521307	-23.521307
8	5--7	9.022821	-3.076588	7.50257	-7.50257
9	6--7	10.663582	-3.377903	11.429276	-11.429276
10	6--8	19.060579	-6.204811	23.057083	-23.057083
11	6--9	0.192142	-0.188239	-5.035058	5.035058
12	6--10	0.133718	-0.131695	-1.97282	1.97282
13	9--11	-0.095501	0.091634	-5.442643	5.442643
14	9--10	0.284179	-0.285685	-9.81987	9.81987
15	4--12	0.312163	-0.30645	-4.11942	4.11942
16	12--13	-0.119292	0.114511	-8.432917	8.432917
17	12--14	5.023804	-1.605428	3.572892	-3.572892
18	12--15	10.152652	-3.236238	6.846911	-6.846911
19	12--16	6.443701	-2.065988	4.629608	-4.629608

20	14--15	2.278728	-0.756561	1.772042	1.772042
21	16--17	5.75749	-1.90115	4.680064	-4.680064
22	15--18	5.387097	-1.787385	3.823651	-3.823651
23	18--19	9.359667	-3.107307	6.43533	-6.43533
24	19--20	17.987637	-6.013466	12.166565	-12.166565
25	10--20	5.464152	-1.792051	4.241141	-4.241141
26	10--17	12.254373	-4.075507	11.034744	-11.034744
27	10--21	15.71812	-5.20381	11.696999	-11.696999
28	10--22	8.074631	-2.675546	5.755198	-5.755198
29	21--22	51.543916	-17.187503	35.783183	-35.783183
30	15--23	5.882231	-1.966045	4.102346	-4.102346
31	22-24	7.752496	-2.582372	4.106407	-4.106407
32	23--24	4.436986	-1.475727	3.072464	-3.072464
33	24--25	3.988458	-1.329842	2.352333	-2.352333
34	25--26	3.683307	-1.225818	1.862429	-1.862429
35	25--27	6.071174	-2.030731	3.943224	-3.943224
36	28--27	-0.179746	0.182603	-2.963223	2.963223
37	27--29	3.024075	-0.986824	1.989111	-1.989111
38	27--30	2.06096	-0.661046	1.363203	-1.363203
39	29--30	2.735048	-0.897373	1.76226	-1.76226
40	8--28	4.422012	-1.477033	4.721892	-4.721892
41	6--28	13.192289	-4.301784	16.093802	-16.093802

Line No.	**i to j**	$\partial Q_{(i,j)}/\partial V_{(i)}(S_5)$	$\partial Q_{(i,j)}/\partial V_{(j)}(S_6)$	$\partial Q_{(i,j)}/\partial \delta_{(i)}(S_7)$	$\partial Q_{(i,j)}/\partial \delta_{(j)}(S_8)$
1	1--2	16.287071	-16.843764	-4.170122	4.170122
2	1--3	5.333349	-5.469934	-0.665088	0.665088
3	2--4	5.150333	-5.464476	-1.475	1.475
4	3--4	22.727992	-24.450524	-8.041142	8.041142
5	2--5	5.147529	-5.420638	-0.706238	0.706238
6	2--6	5.060247	-5.412824	-1.319505	1.319505
7	4--6	20.871084	-23.034576	-6.146854	6.146854
8	5--7	6.215386	-7.4498	-3.098381	3.098381
9	6--7	10.020679	-11.348886	-3.40183	3.40183
10	6--8	19.770652	-22.538693	-6.347521	6.347521
11	6--9	-4.177604	4.830682	-0.196203	0.196203
12	6--10	-1.661629	1.902775	-0.136543	0.136543
13	9--11	-3.929515	5.010258	0.099542	-0.099542
14	9--10	-7.882884	9.471218	-0.296202	0.296202
15	4--12	-3.555164	3.943213	-0.320144	0.320144
16	12--13	-6.431119	7.748706	0.124622	-0.124622
17	12--14	3.023466	-3.466948	-1.654487	1.654487
18	12--15	5.826268	-6.675731	-3.319222	3.319222
19	12--16	3.90218	-4.477244	-2.136295	2.136295
20	14--15	1.343652	-1.72774	-0.775961	0.775961
21	16--17	3.541108	-4.541165	-1.959299	1.959299
22	15--18	2.799983	-3.75864	-1.8183	1.8183
23	18--19	4.726749	-6.336947	-3.155549	3.155549
24	19--20	8.81281	-11.927379	-6.134058	6.134058
25	10--20	3.238585	-4.157763	-1.827988	1.827988

26	10--17	8.331014	-10.707244	-4.200163	4.200163
27	10--21	8.912031	-11.424429	-5.327965	5.327965
28	10--22	4.381253	-5.618898	-2.740447	2.740447
29	21--22	26.534916	-34.935736	-17.604426	17.604426
30	15--23	3.031624	-4.039369	-1.996697	1.996697
31	22-24	3.120629	-4.062974	-2.609978	2.609978
32	23--24	2.306582	-3.039966	-1.491503	1.491503
33	24--25	1.720881	-2.308662	-1.354998	1.354998
34	25--26	1.423233	-1.860632	-1.227002	1.227002
35	25--27	2.857449	-3.818577	-2.097018	2.097018
36	28--27	-2.294175	2.915159	0.185613	-0.185613
37	27--29	1.507691	-1.963661	-0.999613	0.999613
38	27--30	1.042136	-1.361039	-0.662097	0.662097
39	29--30	1.274834	-1.759463	-0.8988	0.8988
40	8--28	4.074634	-4.645303	-1.501386	1.501386
41	6--28	13.990024	-15.83276	-4.372709	4.372709

Line No.	i to j	Line flow/conn.load	R drop	X drop	S
1	1—2	0.505	0.040776	0.088008	37.800
2	1—3	0.223	0.039466	0.12893	11.5647
3	2—4	0.111	0.033153	0.055493	12.2530
4	3—4	0.214	0.012237	0.023858	56.3254
5	2—5	0.22	0.034508	0.12849	11.3347
6	2—6	0.153	0.043265	0.07951	11.9926
7	4—6	0.193	0.0095736	0.024067	50.5088
8	5—7	0.038	-0.0077442	-0.011694	17.7984
9	6—7	0.111	0.0043044	0.029588	25.2732
10	6—8	0.075	0.0071279	0.0075221	49.4420
11	6—9	0.087	0.036026	0.040802	9.5729
12	6—10	0.046	-0.027811	0.075912	3.7733
13	9—11	0.073	0.040615	-0.020783	9.99128
14	9—10	0.097	-0.0061619	0.032578	18.5752
15	4—12	0.113	0.029387	0.081973	7.90719
16	12—13	0.116	0.045468	-0.0168	15.6105
17	12—14	0.024	0.0030874	0.021483	8.9433
18	12—15	0.061	0.0040386	0.027797	17.5458
19	12—16	0.024	0.0026238	0.016619	11.535
20	14—15	0.004	-0.00055164	0.0063548	4.2473
21	16—17	0.012	0.0026133	0.0075228	11.0185
22	15—18	0.019	0.0041562	0.014188	9.4887
23	18—19	0.009	0.0016884	0.0035886	16.2018
24	19—20	0.024	-0.000014379	-0.0057334	30.8374
25	10—20	0.032	-0.00048304	0.022949	10.1735
26	10—17	0.025	-0.0030421	0.0062513	25.0927
27	10—21	0.06	-0.0025662	0.015434	28.5393
28	10—22	0.029	-0.0020928	0.014948	14.2965
29	21—22	0.007	-0.000050541	-0.00055469	89.7635

30	15—23	0.018	-0.00070198	0.012436	10.2764
31	22-24	0.022	-0.0011534	0.014627	11.8475
32	23—24	0.006	-0.00080222	0.005669	7.73017
33	24—25	0.007	0.0019209	-0.0084798	6.38017
34	25—26	0.013	0.000024592	0.019489	5.52315
35	25—27	0.021	0.0024794	-0.01524	10.1795
36	28—27	0.064	0.027091	-0.068503	5.60868
37	27—29	0.02	0.0066884	0.029356	5.1146
38	27—30	0.023	0.01271	0.048033	3.49519
39	29—30	0.012	0.0061436	0.018236	4.56437
40	8—28	0.017	-0.0009573	0.0024572	10.44117
41	6—28	0.058	0.0015835	0.010964	34.571679

where

$$S = \sqrt{S_1^2 + S_2^2 + \ldots\ldots.. + S_7^2 + S_8^2}$$

Depending on these parameters the optimal location of the compensating device is selected.

Based on the values of S, Line Flow Index and Reactive Drop optimal location is found out. Location is selected where value of sensitivity is high and Line Flow is noticeable. Reactive Drop value is also considered. IEEE 30 Bus Test System is used. Its data is given in Appendix I. Based on the above parameters following lines are selected for compensating device-

- Line No. 4 between buses 3-4
- Line No. 7 between buses 4-6
- Line No. 10 between buses 6-8
- Line No. 13 between buses 9-11
- Line No. 16 between buses 12-13
- Line No. 29 between buses 21-22
- Line No. 34 between buses 25-26

A fixed capacitor having capacitive reactance of 0.02 ohm is placed in these lines. The reactive power compensated by the capacitor is given below:

Sr. No.	**Line No.**	**Compensated power (MVar)**
1	4	2.0778
2	7	2.7555
3	10	5.5201
4	13	3.2745

5	16	2.9544
6	29	0.15355
7	34	0.0033792

At Line no. 34 compensated power is very low inspite of high value of Sensitivity Index; this is due to the very low value of Line Flow Index.

After placing the Series Capacitor system is optimized by using Linear Programming with only the power balance equation in the LP constraint set. Generation limits are incorporated. The unit cost functions are broken into three straight line segments. The break points taken for this problem are given below:

Unit	Break point 1 (Unit min.)	Break point 2	Break point 3	Break point 4 (Unit max.)
1	50	100	150	200
2	20	40	60	80
3	15	30	40	50
4	10	15	25	35
5	10	17	22	30
6	12	20	30	40

After running the AC power flow,

Line losses are 13.221 MW and 18.265 MVar.

Total cost for dispatch is **833.27$/hr**.

By applying LPOPF on these selected lines, the Line losses and operating cost obtained are:

Sr. No.	**Line No.**	**Losses (MW)**	**Losses (MVar)**	**Cost ($/hr.)**
1	4	11.407	12.516	808.37
2	7	11.401	12.528	808.35
3	10	11.409	12.631	808.39
4	13	11.410	12.633	808.39
5	16	11.408	12.667	808.38
6	29	11.406	12.522	808.38
7	34	11.406	12.521	808.38

Chapter 5

Conclusion and Future Work

5.1 Conclusion

This thesis deals with the problem of allocation of compensating device. The aim is to find the location of series capacitor in given power system such that we get maximum reactive power compensation. Various parameters like sensitivity coefficients, line flow index etc. has been calculated. By analyzing these parameters optimal location of series capacitor is found out. Firstly, LPOPF is implemented on parent system. Then, a known value of series capacitor is placed in the selected location or line. It changes the system parameters while running the load flow. LPOPF is obtained for the compensated system. The pre-compensated system results are then compared with post-compensated results. IEEE 30 bus test system is considered for the abovesaid problems. It has been noted that

- At optimal location reactive compensated power is maximum.
- System losses has been decreased.
- Operating cost is also minimum.

5.2 Future Work

The following points are recommended for future extension of work-

- Solve the problem by replacing other compensating devices like Flexible AC Transmission Systems (FACTS) devices instead of Series capacitor. FACTS device provide both series and shunt compensation.
- Optimal location can be found out by artificial techniques like Evolutionary Programming or other Heuristic techniques.

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Appendix I

IEEE 30 BUS TEST SYSTEM

Bus data =

Bus no.	Bus code	Vol. mag.	Angle (deg.)	Load MW	Load MVar	Gen. MW	Gen. MVar	Gen. Qmin	Gen. Qmax.	Inj. MVar
1	1	1.05	0	0.0	0.0	50	0	-20	150	0
2	2	1.033	0	21.70	12.7	20	0	-30	60	0
3	0	1.0	0	2.4	1.2	0	0	0	0	0
4	0	1.0	0	7.6	1.6	0	0	0	0	0
5	2	1.0058	0	94.2	19.0	15	0	-15	60	0
6	0	1.0	0	0.0	0.0	0	0	0	0	0
7	0	1.0	0	22.8	10.9	0	0	0	0	0
8	2	1.023	0	30.0	30.0	10	0	-15	50	0
9	0	1.0	0	0.0	0.0	0	0	0	0	0
10	0	1.0	0	5.8	2.0	0	0	0	0	19
11	2	1.0913	0	0.0	0.0	10	0	-10	-40	0
12	0	1.0	0	11.2	7.5	0	0	0	0	0
13	2	1.0883	0	0.0	0.0	12	0	-15	45	0
14	0	1.0	0	6.2	1.6	0	0	0	0	0
15	0	1.0	0	8.2	2.5	0	0	0	0	0
16	0	1.0	0	3.5	1.8	0	0	0	0	0
17	0	1.0	0	9.0	5.8	0	0	0	0	0
18	0	1.0	0	3.2	0.9	0	0	0	0	0
19	0	1.0	0	9.5	3.4	0	0	0	0	0
20	0	1.0	0	2.2	0.7	0	0	0	0	0
21	0	1.0	0	17.5	11.2	0	0	0	0	0
22	0	1.0	0	0.0	0.0	0	0	0	0	0
23	0	1.0	0	3.2	1.6	0	0	0	0	0
24	0	1.0	0	8.7	6.7	0	0	0	0	0
25	0	1.0	0	0.0	0.0	0	0	0	0	0
26	0	1.0	0	3.5	2.3	0	0	0	0	0
27	0	1.0	0	0.0	0.0	0	0	0	0	0
28	0	1.0	0	0.0	0.0	0	0	0	0	0
29	0	1.0	0	2.4	0.9	0	0	0	0	0
30	0	1.0	0	10.6	1.9	0	0	0	0	0

Line data =

Bus from	Bus to	R (pu)	X (pu)	0.5 B (pu)	Tap Ratio	MW flow limit
1	2	0.0192	0.0575	0.0264	1	1.3
1	3	0.0452	0.1852	0.02040	1	1.3
2	4	0.0570	0.1737	0.0184	1	.65
3	4	0.0132	0.0379	0.00420	1	1.3
2	5	0.0472	0.183	0.02090	1	1.3
2	6	0.0581	0.1763	0.01870	1	.65
4	6	0.0119	0.0414	0.00450	1	.9
5	7	0.0460	0.1160	0.01020	1	1.3
6	7	0.0267	0.0820	0.00850	1	1.3
6	8	0.0120	0.0420	0.00450	1	.32
6	9	0.0	0.2080	0.0	0.978	.65
6	10	0.0	0.5560	0.0	0.969	.32
9	11	0.0	0.2080	0.0	1	.65
9	10	0.0	0.1100	0.0	1	.65
4	12	0.0	0.2560	0.0	0.932	.65
12	13	0.0	0.1400	0.0	1	.65
12	14	0.1231	0.2559	0.0	1	.32
12	15	0.0662	0.1304	0.0	1	.32
12	16	0.0945	0.1987	0.0	1	.32
14	15	0.2210	0.1997	0.0	1	.16
16	17	0.0824	0.1923	0.0	1	.16
15	18	0.1073	0.2185	0.0	1	.16
18	19	0.0639	0.1292	0.0	1	.16
19	20	0.0340	0.0680	0.0	1	.32
10	20	0.0936	0.2090	0.0	1	.32
10	17	0.0324	0.0845	0.0	1	.32
10	21	0.0348	0.0749	0.0	1	.32
10	22	0.0727	0.1499	0.0	1	.32
21	22	0.0116	0.0236	0.0	1	.32
15	23	0.1000	0.2020	0.0	1	.16
22	24	0.1150	0.1790	0.0	1	.16
23	24	0.1320	0.27	0.0	1	.16
24	25	0.1885	0.3292	0.0	1	.16
25	26	0.2544	0.38	0.0	1	.16
25	27	0.1093	0.2087	0.0	1	.16
28	27	0.0	0.3960	0.0	0.968	.65
27	29	0.2198	0.4153	0.0	1	.16
27	30	0.3202	0.6027	0.0	1	.16
29	30	0.2399	0.4533	0.0	1	.16
8	28	0.0636	0.2	0.0214	1	.32
6	28	0.0169	0.0599	0.065	1	.32

Cost Coefficients=

c	b	a
0	2	0.00375
0	1.75	0.01750
0	1.00	0.06250
0	3.25	0.00834
0	3	0.02500
0	3	0.02500

Limits=

MW (min)	MW (max)	MVar (min)	MVar (max)
50	200	-20	150
20	80	-20	60
15	50	-15	60
10	35	-15	50
10	30	-10	40
12	40	-15	45