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Optimal Placement of Reactive Power Supports for Loss Minimization: The Case of A Georgian Regional Power Grid

Thesis for the Degree of Master of Science

Otar Gavasheli

Division of Electric Power Engineering
Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, November 2007

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Sweden

Cover page courtesy of ABB Power Capacitors

„მარალ და ყველგან
საქართველოვ მე ვარ შენთანა"

Abstract

Power system operators/planners are always faced with the problem of how to minimize the transmission loss. There are a number of ways to achieve this goal. In this thesis, new methods for optimal capacitor placement for transmission loss minimization are proposed. Proposed methods are based on the optimal power flow formulations, which enable the cost-benefit analysis and multi-objective optimization assessment of reactive power support investment. For better illustration of proposed methods, they are applied to a real and test transmission networks.

In the cost-benefit analysis, reactive power supports are applied to the power system for transmission loss minimization. The candidate places for reactive power support allocation are defined in advance according to where the highest reactive power flow is observed. The benefits after application of reactive power supports are calculated. Benefits considered are the benefits from recovered transmission losses due to the reactive power addition. The benefits are then compared with investments, which would be required for the addition of reactive power supports and in this way the economical justification in reactive power support addition can be made. This method is applied to the real transmission network of a Georgian regional grid. After analyzing the obtained results, we can observe that in some cases even though the losses are minimized up to the minimal level, economically it is not optimal since in such cases, high investment costs are involved. The optimal cases are those where the losses are a bit higher than possible minimum and the investments are minimal also compared to what is required for achieving of minimal transmission losses. Only these optimal cases can justify the investments, made for loss minimization. In the multi-objective optimization several objective functions are proposed in one overall objective function. The optimized functions are minimization of total investment in reactive power support, average voltage deviation, minimization of total system loss and total system cost. At the beginning, optimum values for each objective function is found one by one separately and these optimal values are included while solving for overall objective function. During optimization of all these objectives within one overall objective, we have opportunity to optimize each objective according to what is our interest in it compared to other optimized objectives. This is done using the priority order multipliers, which has each of the objective functions. CIGRE 32 bus test system is used for illustration of this method. Three cases with different values of priority order multipliers are solved and discussed. In the obtained results we can observe how the values of optimized objective functions are changed to reflect their priority orders assigned in the overall objective function.

***Key words*: Loss minimization, reactive power support, optimal power flow, cost-benefit analysis, multi-objective optimization.**

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1

Introduction

In this chapter the general overview of thesis and its topic-power losses are discussed. The ways for reduction of power losses will be reviewed here. Solution methods, which will be used for solving of the problems, will be discussed and the content of the thesis will be presented, as well as the publication from this thesis.

1.1. Technical losses

Technical losses are inescapable physical phenomenon occurring during the transfer of energy from generating plants to load centers. During this transfer process some of the input energy is dissipated in conductors and transformers along the delivery route. Losses occur in all conductors, and may be any of three types: copper, dielectric and induction radiation losses. The main portion of total transmission losses consists of copper losses. Copper losses are the I^2R losses that are inherent in all conductors because of the finite resistance of the conductors. These losses are due to the current flowing in the electrical network. In AC systems the copper losses are higher due to skin effect.

Technical losses can be calculated based on the natural properties of components in the power system: resistance, reactance, capacitance, voltage, current, and power, which are routinely calculated by utility companies as a way to specify what components will be added to the systems, in order to reduce losses and improve the voltage levels.

Transmission losses in the network constitute economic loss providing no benefits. Transmission losses are construed as a loss of revenue by the utility. The magnitude of each of these losses needs to the accurately estimated and practical steps taken to minimize them. From the utility perspective, transmission losses need to be reduced to their optimal level.

In a typical system, network losses are in range of 5 to 10% of the total power system, which would cost millions of dollars every year [1]. Therefore, loss minimization is one of the important objectives in operating the transmission networks. It is even more so in the context of deregulated power system, since fair allocation of the network losses has very important impact on all users. This is because unfair allocation causes cross subsidies and it gives wrong indicative signals to the network operator and users. A user who causes more network losses must be charged more while a user who helps to reduce the losses, due to counter flow, must be rewarded.

One commonly used way for transmission loss reduction and improving voltage levels in power systems is addition of reactive power supports to where it is necessary. Reactive power addition can be beneficial only in case if it is correctly applied. Correct application means choosing the correct position and size of reactive power support. Different types of reactive power supports can be applied, but for our case we will use widespread reactive power support type-shunt capacitors.

1.2. Proposed methods

In this thesis, two methods to evaluate the optimal placement of reactive power supports are proposed.

One method is based on the cost-benefit analysis. The costs are economic costs, which include direct and indirect costs. The direct cost of reactive power sources are investment and operating costs. The indirect cost would include the opportunity cost of generators which reduce real power production for reactive power production. The benefits from reactive power supports are defined as the reduced generation costs due to reduced losses as well as other quantifiable benefits of reduced total system cost. The dispatch costs could be reduced due to the fact that power generation schedules can be changed by increased transmission capability in the network which will allow for more generation from cheap sources to be delivered to the load centers. The benefits can also stem from the fact that more energy can be sold to the customers which will increase the sales (and profits) due to higher transmission capacity.

Another proposed method optimizes several objective functions at the same time within one general objective. The optimized objectives are minimization of total investment in reactive power support, average voltage deviation, minimization of total system loss and total system cost. These objective functions are one of the most important objectives for every transmission and distribution systems.

1.3. Scope of the thesis work

The scope of work of this thesis work includes developing of methods for correct reactive power allocation in power systems with the objective function of loss minimization. The multi-objective optimization is also included. The modeling of Georgian regional grid and further simulations using newly developed method for loss minimization will be done in CYME [10] power engineering software. Also another model of CIGRE 32 bus system [23] will be made in GAMS software [22], where we will implement our method with multi-objective optimization. The obtained results will be discussed and analyzed.

1.4. Thesis overview

This thesis consists of six chapters. In chapter 2 the literature review about technical losses is given. Also the discussion about this work is included. In chapter 3 the chosen methodologies for solving the problem are discussed. In chapter 4 applications of our discussed theories to the real network and test system will be shown. In the same chapter the review of the simulated Georgian regional grid and CIGRE 32 bus test system together with simulation results are given. In chapter 5 the conclusions are made and in chapter 6 the future work is discussed.

In appendix A the publication from our thesis can be found. Publication includes the method with cost-benefit analysis that was applied to the Georgian regional grid. Methodology description and results of application of the method to the real power system as well as analysis of the obtained results are included also in this publication.

2

Literature Review

In this thesis we are studying the technical losses reduction method-optimal allocation of reactive power in electrical power systems as well as the way of optimization of several objective functions at the same time. Both these methods we are implemented based on Optimal Power Flow framework. Accordingly the logical first step is to understand what Optimal Power Flow is and complete picture of power systems technical losses. What is reactive power and why the reactive power allocation could help in reducing of losses. In this chapter the basic idea of Optimal Power Flow will be presented. Technical losses as well as reactive power compensation as loss reduction method will be presented. The general types of shunt capacitors and ways for optimal capacitor placement will be reviewed. Also some interesting papers about loss minimization and optimal reactive support allocation will be discussed.

2.1. Optimal Power Flow

Optimal Power Flow (OPF) was first introduced in early 1960s as an extension of the conventional Economic Load Dispatch problem to determine optimal settings for control variables while satisfying different constraints.

In practice power flow in power system follows the *Kirchoff's Laws*, which are commonly known as a load flow equations. When these load flow equations are introduced in economic load dispatch as demand-supply balance constraints, the optimum solution is obtained, where the set of decision variables are satisfying the physical laws of electricity while the pre-defined objective function is optimized. Objective function can be loss minimization, cost minimization etc. This kind of problem formulation is called *Optimal Power Flow (OPF)*, which is a static, constrained, nonlinear optimization problem.

The main equations used in OPF are the active and reactive power demand-supply balance equations, which are obtained from basic *Kirchoff's Laws*:

$$P_i - PD_i = \sum_{j}^{\cdot} |V_i|\,|V_j| Y_{i,j} cos(\theta_{i,j} + \delta_j - \delta_i) \tag{2.1}$$

$$Q_i - QD_i = -\sum_{j}^{\cdot} |V_i|\,|V_j| Y_{i,j} sin(\theta_{i,j} + \delta_j - \delta_i) \tag{2.2}$$

Where V is bus voltage, δ is the angle associated with V, $Y_{i,j}$ is the element of bus admittance matrix, θ is the angle associated with $Y_{i,j}$, P and Q are the active and reactive power generations respectively, PD and QD are the active and reactive power consumptions respectively.

Beside of these basic equations, we also have active and reactive power generation limits as follows:

$$P_i^{Min} \leq P_i \leq P_i^{Max} \tag{2.3}$$

$$Q_i^{Min} \leq Q_i \leq Q_i^{Max} \tag{2.4}$$

Here P^{Min} and P^{Max} Stand for lower and upper limits for active power generation and Q^{Min} and Q^{Max} are for lower and upper limits of reactive power generation.

For voltages we have limitations also:

$$V_i^{Min} \leq V_i \leq V_i^{Max} \tag{2.5}$$

Where V^{Min} and V^{Max} are minimal acceptable voltage levels at each bus.

2.2. CYME and GAMS Softwares used for OPF modeling and simulations

In this thesis for modeling of power systems and simulations we use CYME and GAMS simulation softwares. Brief description of these softwares is given here.

Modeling of Georgian regional grid was done in PSAF part of CYME software systems. PSAF is the same as Power System Analysis Framework. Optimal Power Flow analysis module of PSAF, which we used for our simulations, gives us possibility to make advanced system planning studies to optimize system performance, examine cost-efficient operational planning alternatives, define system control strategies and optimize equipment utilization. As a result we get better overall system management possibility.

OPF module of FSAF software relies on robust barrier-method based on nonlinear optimization techniques that permit fully coupled optimization, with the entire set of system control variables, including generation schedules, transformer taps, phase shifter settings, etc.

PSAF OPF module gives us possibility to include various constrains in model. Constrains can be bus voltage magnitude limits, branch flow limits (MW, MVAR, MVA, Amps), generator reactive power limits, generator active power limits, Transformer tap changer limits etc.

PSAF OPF module also gives us opportunity to optimize different objective functions at the same time, while strictly respecting system constraints. System controls are automatically adjusted to provide least cost design or an operational mix.

The optimal solution insures that system losses, generation costs, Reactive Power support requirements and different objectives are simultaneously optimized.

For implementation of method with multi objective function we use GAMS software. The General Algebraic Modeling System (GAMS) is high-level modeling software for mathematical programming and optimization. Modeling futures of GAMS software includes possibility of modeling of linear, nonlinear and mixed integer optimization problems. The software is designed for complex, large scale modeling applications, and allows the user to build large maintainable models. The system contains a group of integrated solvers, such are LP (Linear Programming), NLP (Non Linear Programming), MINLP (Mixed Integer Non Linear Programming) and other solvers.

In our case CIGRE 32 bus test system was modeled in GAMS. We are using NLP solver for solving of our multi objective function.

2.3. Technical losses in power systems

Technical losses are naturally occurring losses (caused by actions internal to the power system) and consist mainly of power dissipation in electrical system components such as transmission lines, power transformers, measurement systems, etc. due to their internal electrical resistance. If we express the transmission losses in term of bus voltages and associated angles, then the losses can be expressed with equation (2.1) [l3]:

$$Loss = \frac{1}{2}\sum_{i}\sum_{j} G_{i,j}\left(V_i^2 + V_j^2 - 2 \times V_i \times V_j \times \cos\left(\delta_j - \delta_i\right)\right) \tag{2.6}$$

Where $G_{i,j}$ is the conductance of the line i-j, V_i and V_j are line voltages and δ_i and δ_j the line angles at the line i and j ends respectively.

It is not possible to achieve zero losses in a power system, but it is possible to keep them at minimum. From figure 2.1, taken from [9] which belongs to our investigated Georgian regional grid, we can observe, that losses are becoming higher when the system is heavily loaded and transmission lines are transmitting high amount of power. The transmitted power for this case consists of active and reactive power. Necessity of reactive power supply together with active power is one of the disadvantages of the power generation, transmission and distribution with alternating current (AC). Reactive power can be leading or lagging. It is either generated or consumed in almost every component of the power system. In AC system each component's impedance consists of two components, resistance and reactance. Reactance can be either inductive or capacitive, which contribute to reactive power in the circuit. In general most of the loads are inductive and they should be supplied with lagging reactive power.

2.4. Reactive power compensation

We need to release the power flow in transmission lines for partially solving of problem of losses as well as other problems. We can't do anything with active power flow, but we could supply the reactive power locally where it is highly consumed in a system. In this way the loading of lines would decrease. It would decrease the losses also and with this action the problem of voltage drops could be solved also. By means of reactive power compensation transmission system losses can be reduced as shown in many papers in the literature, see e.g., [2]-[4]. It has also been widely known that the maximum power transfer of the transmission system can be increased by shunt reactive power compensation, typically by capacitors banks placed at the end of the transmission lines or a the load terminals [5]. Therefore, planning of reactive power supports would give benefits to the users of the transmission systems, in terms of loss reduction, among other technical benefits, such as improving steady-state and dynamic stability, improve system voltage profiles, etc. which are documented in [6]. The reactive power planning problem involves optimal allocation and sizing of reactive power sources at load centers to improve the system voltage profile and reduce losses. However, cost considerations generally limit the extent to which this can be applied.

"The book Edited by T. J. E. Miller contains perfect summary of why we must use reactive compensation: "…the transmission of active power requires a difference in *angular phase* between voltages at the sending and receiving points (which is feasible within wide limits), whereas the transmission of reactive power requires a difference in *magnitude* of these same voltages (which is feasible only within very narrow limits). But why should we want to transmit reactive power anyway? Is it not just a troublesome concept, invented by the theoreticians, that is best disregarded? The answer is that reactive power is consumed not only by most of the network elements, but also by most of the consumer loads, so it must be supplied somewhere. If we can't transmit it very easily, then it ought to be generated where is needed." (Reference Edited by T. J. E. Miller) [14]

"Reactive power is needed to form magnetic fields in motors and other equipment, but it cannot perform any actual work itself. The more reactive power that is distributed in the electrical system, the less space is left for productive or active power. By generating reactive power as close as possible to the machine which is to use it, there is less need to waste valuable resources in transporting it in the power network. This is known as reactive power compensation improvement in the power factor - the efficiency rating - of the plant. The best part is, everyone is a winner." [15]

Shunt capacitors are employed at substation level for the following reasons:

1. Voltage regulation: The main reason that shunt capacitors are installed at substations is to control the voltage within required levels. Load varies over the day, with very low load from midnight to early morning and peak values occurring in the evening between 4 PM and 7 PM. Shape of the load curve also varies from weekday to weekend, with weekend load typically low. As the load varies, voltage at the substation bus and at the load bus varies.

Since the load power factor is always lagging, a shunt connected capacitor bank at the substation can raise voltage when the load is high. The shunt capacitor banks can be permanently connected to the bus (fixed capacitor bank) or can be switched as needed. Switching can be based on time, if load variation is predictable, or can be based on voltage, power factor, or line current.

2. Reducing power losses: Compensating the load lagging power factor with the bus connected shunt capacitor bank improves the power factor and reduces current flow through the transmission lines, transformers, generators, etc. This will reduce power losses (I^2R losses) in this equipment.

3. Increased utilization of equipment: Shunt compensation with capacitor banks reduces kVA loading of lines, transformers, and generators, which means with compensation they can be used for delivering more power without overloading the equipment. Reactive power compensation in a power system is of two types—shunt and series. Shunt compensation can be installed near the load, in a distribution substation, along the distribution feeder, or in a transmission substation. Each application has different purposes. Shunt reactive compensation can be inductive or capacitive. At load level, at the distribution substation, and along the distribution feeder, compensation is usually capacitive. In a transmission substation, both inductive and capacitive reactive compensation are installed. [16]

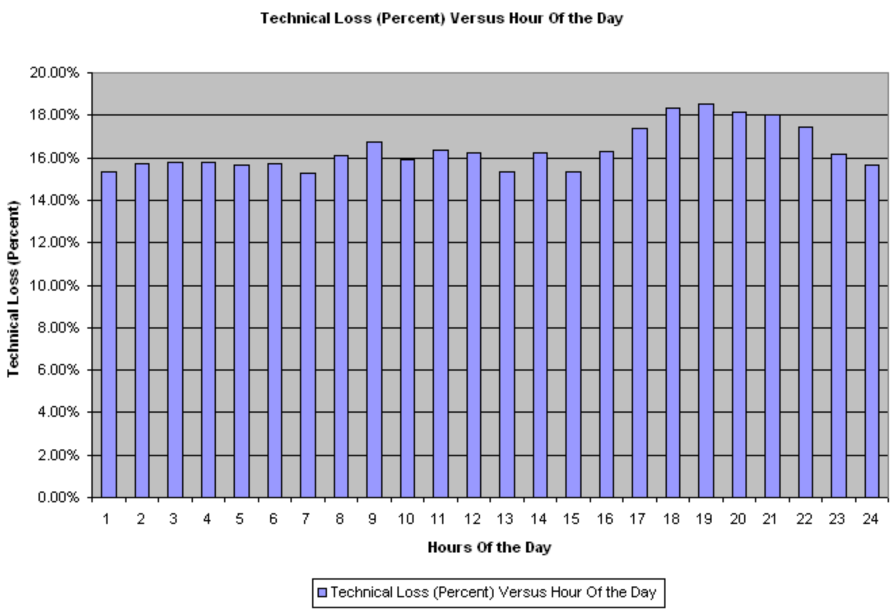


Fig.2.1. Technical losses versus hours of the day. Samtskhe-Javakheti region, Georgia.

Very interesting definition of benefit with capacitor application can be found in [17]:

"One of the main benefits of applying capacitors is that they can reduce distribution line losses. Losses come from current through the resistance of conductors. Some of that current transmits real power, but some flows to supply reactive power. Reactive power provides magnetizing for motors and other inductive loads. Reactive power does not spin kWh meters and performs no useful work, but it must be supplied. Using capacitors to supply reactive power reduces the amount of current in the line. Since line losses are a function of the current squared, I^2R, reducing reactive power flow on lines significantly reduces losses.”

2.3. Shunt capacitors and their types

So we know that reactive power support is very beneficial if correctly applied to the power systems, but what is the principle of operation of the reactive power sources and what are their main types? These questions are answered below:

One of the simplest sources for providing the reactive power locally is shunt capacitors. In our study the shunt capacitors are used, so this type of capacitors will be discussed here. Shunt capacitors are simple devices, where the insulating dielectric is placed between two metal plates. When charged to certain voltage, charges are accumulated on both sides of the dielectric and with this way the charges are stored. In our case, when the capacitors are used in AC systems the capacitors store the energy just only for one half cycle. During the first half cycle capacitor charges and in next half cycle discharges back to the system. In this way capacitors are providing the reactive power when it’s needed and the capacitors and reactive power loads are exchanging the reactive power back and forth.

Capacitor banks can be the series or parallel combinations. They can be installed in distribution systems or in substations on different voltage levels. Distribution capacitors can be pole mounted or pad mounted. Other configuration of distribution system capacitors can also exist. Example of pole mounted capacitor by ABB is taken from [18] and is shown on fig. 2.2. below:

Fig.2.2. Pole mounted capacitor from ABB. Image courtesy of ABB Power Capacitors

The pole mounted capacitors are the least expensive way for providing the reactive power from the point of view of installation. These types of capacitors normally provide 300 to 3600 kVAR of reactive power. Mainly such capacitors are controlled by local control system or from the central control systems using different communication systems.

Pad mounted capacitors by ABB are shown on fig. 2.3. below. Like previous figure this figure is taken from [18] also:

Fig. 2.3. Pad mounted capacitor from ABB. Image courtesy of ABB Power Capacitors

Pad mounted capacitors are used where the power distribution circuit is placed underground. The disadvantage of this kind of capacitors can be the big size and aesthetics.

For higher voltage levels with the purpose of substation installation different kind of capacitors are used. Substation capacitors are normally open-air rack type. Usually such capacitors are elevated to reduce hazards. Capacitor banks are stacked in rows. An example of substation capacitor is taken from [18] and is shown on fig. 2.4.:

Fig.2.4. Substation capacitors from ABB. Image courtesy of ABB Power Capacitors

2.4. Methods for optimal capacitor placement

Reactive power can be beneficial for power system if correctly applied and controlled. Correct application means to apply the reactive power optimally, exactly wherever it's needed and just the size that would be optimal at that location. We can have different objective functions when applying capacitors. Objective functions can be to improve the voltage level, correct the power factor, and minimize losses or all these objectives at the same time.

In [17], the description of one of the methods of reactive power allocation with the objective function of loss reduction in distribution systems is presented. This method is called 2/3 rule:

”Using capacitors to supply reactive power reduces the amount of current in the line. Since line losses are a function of the current squared, I^2R, reducing reactive power flow on lines significantly reduces losses. Engineers widely use the “2/3 rule” for sizing and placing capacitors to optimally reduce losses. Neagle and Samson (1956) developed a capacitor placement approach for uniformly distributed lines and showed that the optimal capacitor location is the point on the circuit where the reactive power flow equals half of the capacitor VAR rating. From this, they developed the 2/3 rule for selecting and placing capacitors. For a uniformly distributed load, the optimal size capacitor is 2/3 of the VAR requirements of the circuit. The optimal placement of this capacitor is 2/3 of the distance from the substation to the end of the line. For this optimal placement for a uniformly distributed load, the substation source provides VARs for the first 1/3 of the circuit, and the capacitor provides VARs for the last 2/3 of the circuit (see figure 2.5).

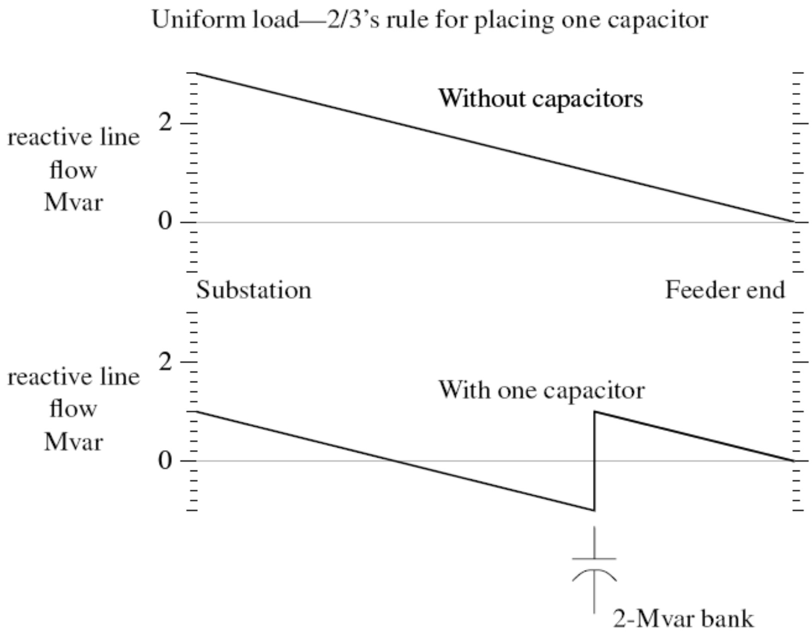


Fig.2.5.: Optimal capacitor loss reduction using the two-thirds rule. (Copyright © 2002. Electric Power Research Institute. 1001691. *Improved Reliability of Switched Capacitor Banks and Capacitor Technology*. Reprinted from [17])

A generalization of the 2/3 rule for applying n capacitors to a circuit is to size each one to $2/(2n+1)$ of the circuit VAR requirements. Apply them equally spaced, starting at a distance of $2/(2n+1)$ of the total line length from the substation and adding the rest of the units at intervals of $2/(2n+1)$ of the total line length. The total VARs supplied by the capacitors is $2n/(2n+1)$ of the circuit’s VAR requirements. So to apply three capacitors, size each to 2/7 of the total VARs needed, and locate them at per unit distances of 2/7, 4/7, and 6/7 of the line length from the substation."

Grainger and Lee provided another simple and optimal method for capacitor placement. This method is useful for circuits with any load profile, not just for uniformly distributed load profile. Here also the main principle is to place the capacitor at the point of circuit where the reactive power equals one half of capacitor rating. With this 1/2-kVAR rule, the capacitor supplies half of its VARs downstream and half are sent upstream.

The 2/3 rule as well as the method suggested by Grainger and Lee are very simple and usable methods, but these theories can be applied to the radial distribution systems.

When we are working with looped networks of power systems, the comparably simple method like 2/3 rule or method by Grainger and Lee for capacitor placements becomes not applicable and another solution should be found. The looped power systems are usually the higher voltage level systems compared to radial distribution networks. The solution methodologies for optimal reactive power placement for optimizing different objective functions in looped power systems will be discussed below in this chapter.

Very interesting method for optimal reactive power allocation for loss minimization and voltage improvement can be found in [24]. In this method the artificial immune system is used for reactive power planning.

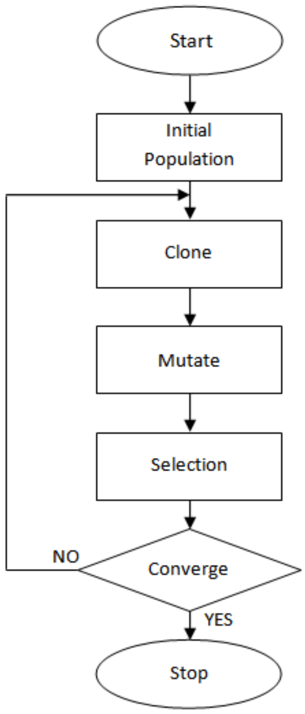


Fig. 2.6.: The flow chart for artificial immune system technique

Artificial immune system uses an idea which is taken from immunology in order to develop systems capable of performing different tasks in various areas of research. The authors are reviewing the clone selection concept together with the affinity maturation process and demonstrate that these biological principles can be very useful for development of useful computational tools. The artificial immune system optimization technique is implemented in following steps: first the initial values for the reactive power supports are generated randomly. After implementing the load flow, the total system losses are calculated. This technique is repeated until ten values of total losses subject to voltage range are obtained at each bus. As a second step the size of the reactive power support and losses are cloned. Then the value of clone was mutated and the load flow is run again and the new value of total system loss is obtained. The process is repeated until the minimal total system loss is obtained. The flow chart of the method using artificial immune system is taken from [24] and shown at figure 2.6.

Another interesting method can be found in [25], where the B-Loss coefficients are used. The B-Loss Coefficients express transmission losses as a function of the outputs of all generation plants. The B matrix loss formula was originally introduced in early 1950 as a practical method for loss calculations. In this paper the power flow is used for calculation of system losses. In their method the authors of this paper express system losses with George's formula [26], which is given below in equation (2.2):

$$P_L = \sum_{m=1}^{k} \sum_{n=1}^{k} P_m B_{mn} P_n \tag{2.7}$$

Where P_L is active power losses, P_m and P_n are the power generations from all sources, B_{mn} is referred as the loss coefficients. The B coefficients are not constant and vary with unit loadings. The more general formula (Kron's loss formula) for losses is given by (2.3):

$$P_L = K_{LO} + \sum_{m=1}^{k} B_{m0} P_m + \sum_{m=1}^{k} \sum_{n=1}^{k} P_m B_{mn} P_n \tag{2.8}$$

In equation (2.3) constant K_{L0} and $\sum_{m=1}^{k} B_{m0} P_m$ has been added to the original equation from (2.2) . This shows, that losses are depended on active power generation only.

The loss coefficient B_{mn} is defined by equation (2.4) below:

$$B_{mn} = \frac{\cos(\sigma_m - \sigma_n)}{|V_m||V_n|(Pf_m)(Pf_n)} \sum_k N_{km} N_{kn} R_k \tag{2.9}$$

Where σ_m and σ_n are the phase angles of currents I_m and I_n. V_m and V_n are the voltages at bus m and n, N_{km} and N_{kn} are the current distribution factors. Pf_m and Pf_n are power factors and R_k is the line/branch resistance.

Finally we find out, that the real power losses are the function of the generation and B-losses coefficient. Varying the generations to fulfill the power demand would change the losses accordingly. If we will be able to minimize the B-losses, we will reduce the losses also. B-losses coefficients are the functions of resistances, voltages and power factors at each generation, while the resistances are the physical properties of the equipment and they are constant, improving the voltage would minimize the B-loss coefficient. For the purpose of the voltage control the authors of the paper use the transformer's tap changers and/or capacitors/reactors and the location they define by optimal power flow calculations.

In [21] the method of On-line optimal reactive power flow by energy loss minimization is proposed. The three objectives are included in this method: the first objective is to maintain the voltage profile of the network into acceptable range; second objective is to minimize the total system loss while satisfying the first objective and the third objective is to avoid the excessive adjustments of the system configurations. The variables for this case are VAR/voltages of the generators, transformer tap settings and amount of reactive power generation of reactive power sources. During the steady-state conditions total power loss can be minimized by finding the optimal reactive power dispatch for the system.

In the method that is proposed in [21] the total system loss is minimized on the basis of on-line load conditions and the load forecast during the next hour. For minimizing the total loss, the method uses all the continuous and discrete variables. The voltage constraint violations are removed by running the optimal reactive power flow every 15 minutes. In these simulations only continuous control variables are allowed to vary. The method will improve the voltage levels and minimize the total system loss, if accurate load forecast is provided for the next hour.

The way of loss minimization for real time power system operations is proposed in [27]. This method is designed to operate in an energy control center environment. The authors develop the optimal power flow based on loss minimization objective function for real time power system corrective actions by energy control center dispatchers. The corrective actions include the adjustments of generators outputs (Voltage and VAR), reactive power compensation devices and transformer tap changers. The optimal coordination of these devices leads to the improvement of economic and security aspects of the power system operations. During the solution process for loss minimization the following constraints are satisfied: Power flow equations, Interchange transaction constraints, branch flow limits, bus voltage limits and control variable limits. The general design of the operation process of the suggested methodology is taken from [27] and shown at figure 2.7. below:

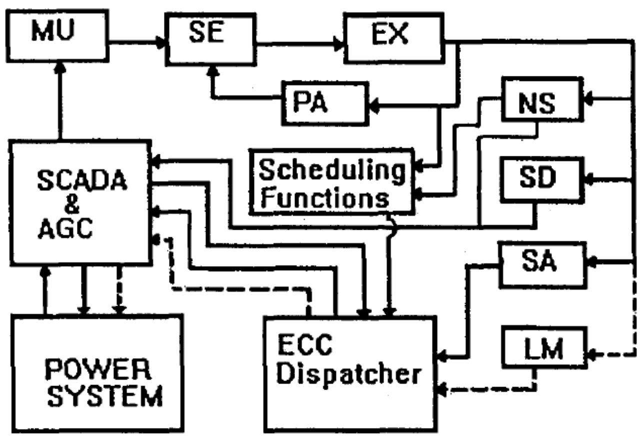


Fig. 2.7.: The general design of the operation process for real time power system operations with the objective function of loss minimization [27]

In figure 2.7. the remote terminal units gather network data from generation plants and transmission and distribution substations. Then the Supervisory Control and Data Acquisition (SCADA) system processes and populates the received raw data for other functions. The

Real Time Sequence is the online data processing functions of Energy Management Software and it is composed by Model Update (MU), State Estimator (SE), External Estimator (EX), Network Sensitivity (NS), Parameter Estimator (PA), Security Analysis (SA) and Security Dispatch (SD). In addition the loss minimization is proposed. The dashed line in figure 2.7. describes the "Open Loop Control" system, which is used for loss minimization function implementation. Loss minimization is periodically executed as a part of the real time sequence. Loss minimization calculates the optimal operation decisions based on the real time network state solved by State Estimator and External Estimator. Loss minimization provides control decisions to Energy Control Center dispatchers for real time power system implementation.

In our case, for solving the capacitor placement problem with the objective function of active power loss reduction we used the following method: first we solve the basic optimal power flow and define the key places for capacitor placement depending to where the highest power flow is observed in the system and then iteratively apply the shunt capacitors one by one or several capacitors at the same time to different key places. After finding the optimal solutions we compare the investments with the maximum amount of funds available for investments. If investment for modification is less than the maximum available amount for investment, then the solution is successful, otherwise the solution is not successful. This method is applied to the real power network of Georgian regional grid and the solution examples are given below.

The method which we just discussed is very useful and easy for implementation, but if we want to reach more accurate and optimal solutions, then the linear and nonlinear programming with multi objective functions can be used. Multi objective function allows us to optimize different objective functions at the same time, for instance we can minimize losses and improve the average voltage deviation at the same time. Interesting solution methods with multi objective functions including optimal capacitor placements can be found in [19] and [20]. Brief reviews of these methods are given here below:

In [19] the Ant Colony Optimization algorithm is applied to the reactive power compensation problem in a multi objective context. The two objective functions, F_1 and F_2 are chosen.

F_1 represents the investments in reactive power compensation devices and its formulated as follows:

$$F_1 = \sum_{i=1}^{n} |B_i| \qquad s.t. \quad \begin{cases} 0 \leq F_1 \leq F_{1m} \\ 0 \leq B_1 \leq B_{1m} \end{cases} \tag{2.10}$$

Where F_1 is the total required investment, B_i is the compensation at busbar i in MVAr, F_{1m} is maximum amount available for investment and B_m is the maximum amount of compensation allowed at bus i. n represents the number of busses in investigated grid.

F_2 is the average voltage deviation. The voltage deviation is defined as follows:

$$F_2 = \frac{\sum_{i=1}^{n} |V_i^* - V_i|}{n} \tag{2.11}$$

Here F_2 is the average voltage deviation, V_i is the actual voltage at bus i in per unit and V_i^* is the desired voltage at bus i.

The solution, which includes the abovementioned objective functions, gives us possibility to allocate the reactive power support devices so that to satisfy the economical and operational constrains at the same time. For solving of problem the authors of the paper use Electric Omicron (EO) method. We will not go through this solution method here, as in this case for us the objective functions, chosen by authors are the sphere of interest.

Paper [20] is also very interesting. Here, as in our case, the authors apply the theory to the real power network of Paraguay. Multi objective reactive power compensation technique is applied to the system. The objective functions are chosen so that to satisfy the following aspects of system planning :

- Amount of compensation devices;
- Active power losses;
- Quality of service, related to adequate voltage profile;
- Voltage security in order to avoid instable operating points and to ensure proper voltage stability margins.

Total six objective functions are chosen:

Objective function F_1 is to minimize the amount of reactive power compensation devices:

$$F_1 = \sum_{i=1}^{n} B_i \qquad s.t. \quad \begin{cases} F_1 \le F_{1max} \\ B_1 \le B_{1max} \end{cases} \tag{2.12}$$

Where F_1 is the total required compensation, B_i is the compensation at busbar i in MVAr, F_{1m} is maximum amount reactive power that can be distributed in a system and B_m is the maximum amount of compensation allowed at bus i;

Second objective function F_2 is active power loss minimization and it's formulated below:

$$F_2 = P_g - P_l \tag{2.13}$$

Here F_2 is the total transmission active power losses in MW and it's calculated by the difference between total generated active power P_g and total consumed active power by loads P_l;

Third objective F_3 is the average voltage deviation. The expression for this objective function is similar to (2.3)

Objective function F_4 is the maximal voltage deviation from the desired voltage value:

$$F_4 =_i^{max} (V_i - V_i^*) \tag{2.14}$$

Where F_4 is the maximum voltage deviation from the desired value.

F_5 is fifth objective function and it is voltage security, denoted by λ_* and represents the additional loading factor, which can be applied to the base load flow case until the system reaches critical point.

$$F_5 = \lambda_* \qquad (2.15)$$

The last objective function for this case is F_6 and represents total static VAr generation:

$$F_6 = \sum_{i=1}^{nsvc} Q_i \leq Q_{svc} \qquad (2.16)$$

Where F_6 is the total VAr generation and injection to the system by the existing static VAr compensators. Q_i represents the generation of SVC and nsvc the number of SVC's in a system.

The optimization problem that should be solved is as follows:

$$\text{Optimize } F=[F_1 \;\; F_2 \;\; F_3 \;\; F_4 \;\; F_5 \;\; F_6] \qquad (2.17)$$

Here F represents so called objective vector, subject to the set of nonlinear power flow equations and above mentioned constraints.

The problem is solved based on modified strength Pareto Evolutionary Algorithm and optimal solutions has been obtained, which can be found in [20]

Interesting method with optimal reactive power scheduling method for loss minimization and voltage stability margin maximization with successive multi-objective fuzzy linear programming technique can be found in [28].

For our case we will also use the multi objective function as in this case we can optimize the objective functions that are more important for us. These objective functions include minimizing the total active power losses, improving the voltage levels at each bus and at the same time minimize the investments, spent on reactive power sources that are applied and minimization of system total cost. Each of these objectives will have its own weighting factor that will give us possibility to set the order of importance for each optimized objective. The method will be demonstrated in further chapters of this thesis.

3

Methodology

Reactive power support is one of the best ways for reduction of power losses together with other benefits, such are improving of voltage profiles, unloading of overloaded system components and with this stopping the fast ageing processes of the equipment. We discussed the ways how to allocate the reactive power sources in power system so that to consider different objective functions together or one by one. The criteria for planning of reactive power compensation used in the literature has been to minimize the losses, the cost of new reactive power sources (capacitors, condensers) or a combination of the two. A number of papers deal with the reactive power planning and scheduling problems, e.g., [7]-[8]. However, only the costs of reactive power are treated, and the economic benefits are often left out, but if we want to apply these changes to the real system, one of the most important questions from the network owner will be how expensive will be such modification and what will be the financial benefit from it? Will the benefit from such modification recover the investments made? Another innovative idea is the priority order multiplier. In our method, that will be applied to the CIGRE 32 bus system, the multi objective function is used, where each objective function has its own priority order multiplier which gives us opportunity to adjust our interest in each optimized objective function within the general objective. This chapter contains description of methodologies used by us, for solving the problem with cost-benefit analysis and problem with multi objective functions, applied to Georgian regional grid and to the CIGRE 32 bus system respectively.

3.1. Method applied to Georgian regional grid

In this method, the candidate positions of reactive power sources will be first identified using an optimal power flow (OPF) framework with the minimum total cost objective including costs of new reactive power sources. After solving the basic OPF we choose the candidate locations for optimal allocations of reactive power to the system. Then the reactive power sources are applied to different candidate places one by one and at several candidate places at the same time iteratively. The cost-benefit analysis will then be worked out against the candidate locations, with different standard sizes of reactive power sources, so as to arrive at the optimal plan for reactive power support in an iterative manner.

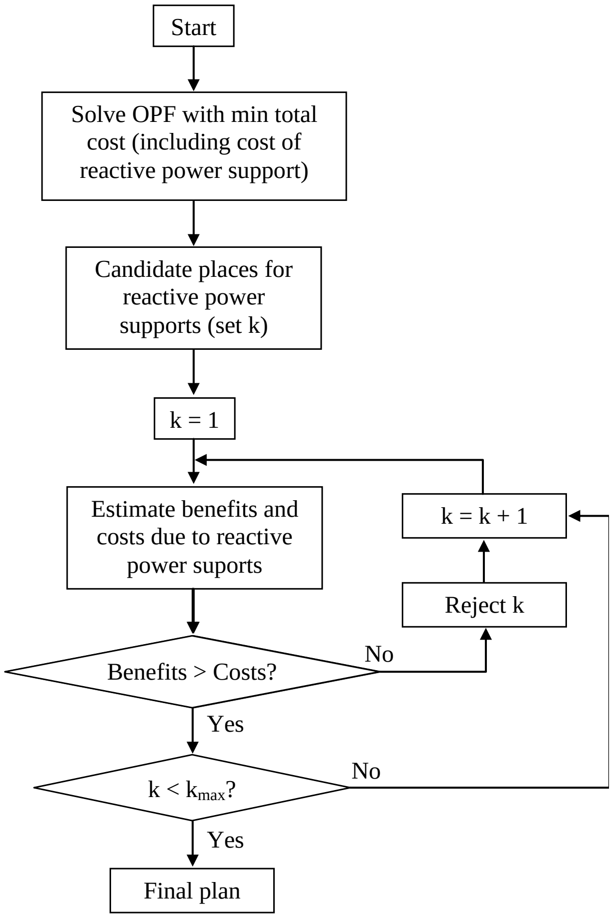


Fig.3.1. Procedure of optimal selection of location of reactive power support using cost-benefit analysis

Fig. 3.1. presents the solution procedure of the proposed method. The selected positions and sizes of reactive power are those which generate the system benefits larger than the costs involved which make the investment economically justifiable. The method will be presented in details in the thesis below and will be applied to the real power system of Georgian regional grid to find the optimal placement of reactive power sources. Description of the system and its problems is given in the following section.

The method that is presented above in this chapter is quite simple and realistic to be applied to the real power systems. The simulations and results of this method will be given in further chapters below.

3.2. Method with multi objective function applied to CIGRE 32 bus system

The method with cost-benefit analysis, which we applied to the Georgian regional grid and discussed in 3.1 of this thesis, is effective method and gives us possibility to find the economically justified method for loss reduction. The results from this method are reasonable. However more accurate methods could be obtained. Also the method is optimizing single objective and we are not able to consider two or more objectives, which represents our interest, while finding optimal solution.

In this thesis another method for optimizing several objective functions will be presented also. The method includes the multi objective function and it optimizes four objective functions at the same time.

The objective functions have been chosen considering the most prioritized problems of the discussed Georgian power system and at the same time the general problems of almost all power systems. The optimized objective functions, which we are optimizing, are F_1, F_2, F_3 and F_4. These objective functions are total investment, average voltage deviation, total active power losses and total system cost respectively.

The objective functions are defined as follows:

The objective function for total investment, F_1, is defined with the same way as in equation (2.2) in [19]:

$$F_1 = \sum_{i=1}^{n} |B_i| \qquad s.t. \qquad \begin{cases} 0 \le F_1 \le F_{1m} \\ 0 \le B_1 \le B_{1m} \end{cases} \tag{3.1}$$

Where as in [19] F_1 is the total required investment, B_i is the compensation at busbar i in MVAr, F_{1m} is maximum amount available for investment and B_m is the maximum amount of compensation allowed at bus i. n represents the number of busses in investigated grid.

The second objective function F_2 represents the average voltage deviation. This objective function is defined as follows:

$$F_2 = \sum_{i=1}^{n} |V_i^* - V_i| \tag{3.2}$$

Where V_i is the actual voltage at bus i in per unit and V_i^* is the desired voltage at bus i. Minimizing this objective function would lead us to improving of voltage levels at each bus.

Third objective function F_3, that we will optimize, is minimizing of total losses and it's defined with the similar equation as equation (2.1), which is taken from [13]:

$$F_3 = \frac{1}{2} \sum_{i} \sum_{j} G_{i,j} \left(V_i^2 + V_j^2 - 2 \times V_i \times V_j \times \cos\left(\delta_j - \delta_i\right) \right) \tag{3.3}$$

Where $G_{i,j}$ is the conductance of the line i-j, V_i and V_j are line voltages and δ_i and δ_j the line angles at the line i and j ends respectively.

The forth objective function F_4 is the total system cost. Equation for the total system cost is taken from [13] and it's defined as follows:

$$\mathrm{F}_4 = \sum_{\mathrm{i}=1}^{\mathrm{NG}} \mathrm{C_i}\,(\,\mathrm{P_i})\tag{3.4}$$

Here NG is the set of all generating units, C_i is the price of energy at bus i and P_i is the power, generated at bus i.

For optimizing all these four objective functions at the same time, we use the following equation:

$$J = \sqrt{\alpha\left(\frac{F_1}{F_1^*}\right)^2 + \delta\left(\frac{F_2}{F_2^*}\right)^2 + \gamma\left(\frac{F_3}{F_3^*}\right)^2 + \varepsilon\left(\frac{F_4}{F_4^*}\right)^2} \tag{3.5}$$

Here J is the overall objective function that optimizes the above mentioned objective functions F_1, F_2, F_3 and F_4. The multipliers α, δ, γ and ε are the priority order multipliers by which we can set the priority orders of the objective functions, that are optimized. The sum of priority order multipliers is 100%:

$$\alpha + \delta + \gamma + \varepsilon = 100\% \tag{3.6}$$

F_1, F_2, F_3 and F_4 are the objective functions as described in this chapter above. F_1^*, F_2^*, F_3^* and F_4^* are the optimal values of objective functions F_1, F_2, F_3 and F_4 respectively.

Beside the equations for objective functions we are using the general load flow equations for active and reactive powers, which has been described in chapter two of this thesis:

$$P_i - PD_i = \sum_j |V_i|\,|V_j| Y_{i,j} cos(\theta_{i,j} + \delta_j - \delta_i) \tag{3.7}$$

$$Q_i - QD_i = -\sum_j |V_i|\,|V_j| Y_{i,j} sin(\theta_{i,j} + \delta_j - \delta_i) \tag{3.8}$$

Where V is bus voltage, δ is the angle associated with V, $Y_{i,j}$ is the element of bus admittance matrix, θ is the angle associated with $Y_{i,j}$, P and Q are the active and reactive power generations respectively, PD and QD are the active and reactive power consumptions respectively.

Formulation of the multi objective function as it is given in equation (3.5) gives us opportunity to optimize several objective functions at the same time. During optimization we have possibility to set the priority order of the objective functions and to put them according to the importance for us.

The optimal power flow with above defined multi objective function is solved using the non linear programming solver of [22] below. For the purpose of testing of our developed method it will be applied to CIGRE 32 bus system [23]. The application procedures and results are given in further chapters.

4

Simulations with Real Networks

To be able to test the theory the best way is to apply it to practice. To illustrate our developed methods, we applied them to the real power systems.

In this chapter modeling, solving strategy and solution results description, review and result analysis are given for Georgian regional grid and for CIGRE 32 bus system.

4.1. Simulations with Georgian regional grid

The real network of Georgian regional power grid was chosen as a test power network. The single line diagram of the network is given at figure 4.1. below. This regional network can be assumed as the typical for the whole country's network in terms of its existing problems and design.

4.1.1. Description of investigated Georgian regional grid

The technical losses are one of the serious problems for the investigated Samtskhe-Javakheti regional network and for Georgian power system in general. The power system is old and mostly uncompensated in terms of reactive power. Due to the not adequate planning most of the equipments like transmission lines and transformers are overloaded during the peak-hours. Also many transmission lines are not the sizes that they are designed to be. As a result there are very high losses and serious voltage drops at the ends of the lines in a system beside of other problems that cause many technical problems in the system in general.

The problem of line overloading, voltage drops and technical losses becomes more problematic during the heavy load seasons. For Georgian power system such season is winter. As we can see on fig.4.2, which is taken from [11]

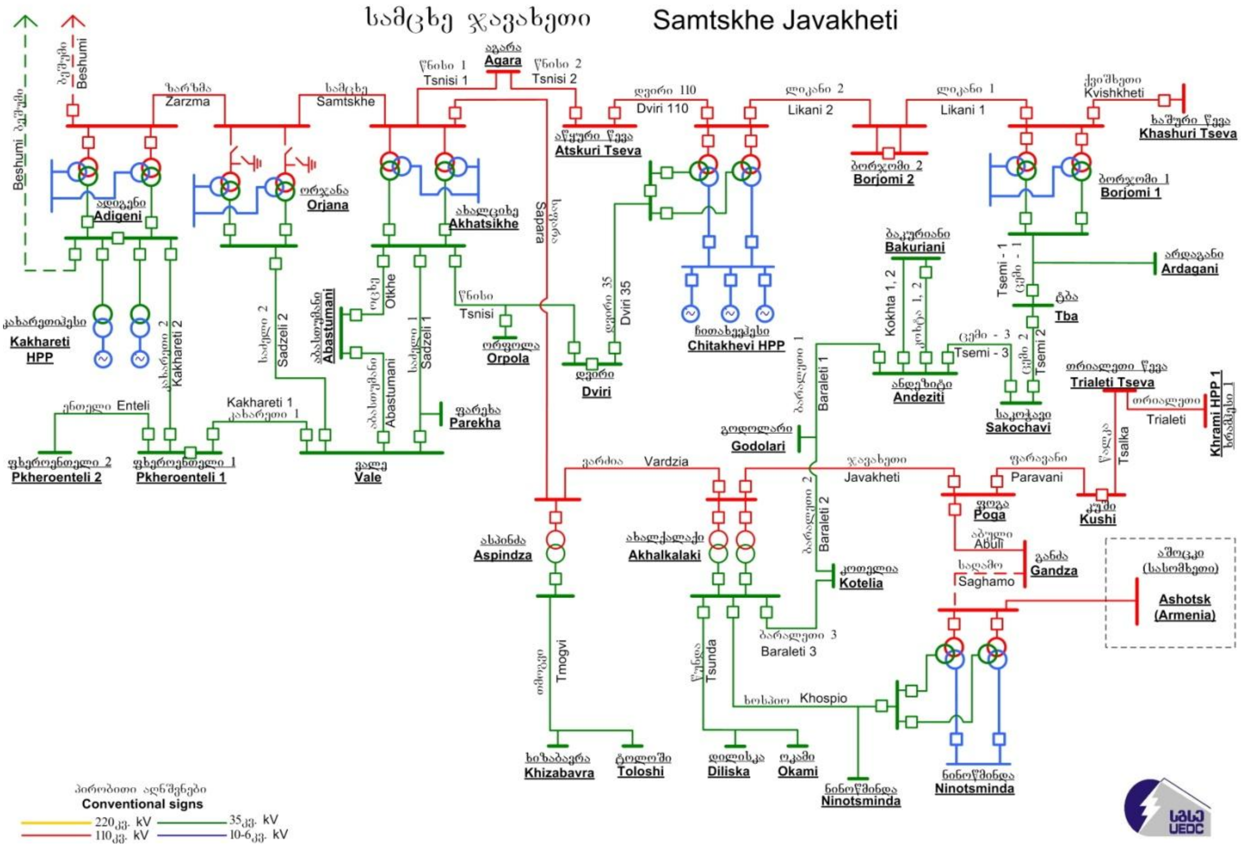
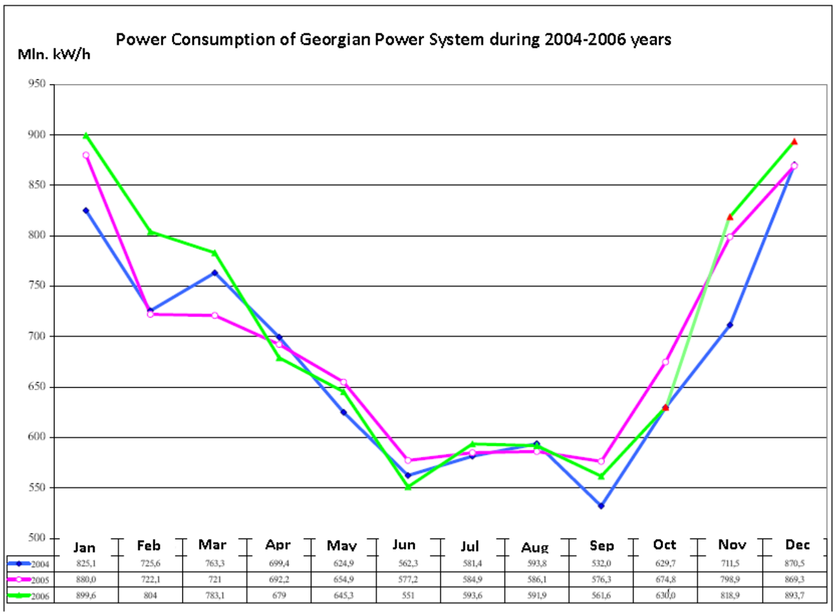


Fig.4.1. Single line diagram of Samtskhe-Javakheti region, Georgia.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	825,1	725,6	763,3	699,4	624,9	562,3	581,4	593,8	532,0	629,7	711,5	870,5
2005	880,0	722,1	721	692,2	654,9	577,2	584,9	586,1	576,3	674,8	798,9	869,3
2006	899,6	804	783,1	679	645,3	551	593,6	591,9	561,6	630,0	818,9	893,7

Fig.4.2. Power consumption of Georgian power system

During the power deficit, mainly in winter, in heavy load seasons, sometimes Georgia is importing the electrical energy from Armenia through the region, which is chosen by us for investigation. Here the losses are extremely high. The reason is that the imported power is transmitted through the grid in not optimal way. The imported power is passing from 110 kV substation “Ninotsminda” to another 110 kV substation “Akhalkalaki” through the 35 kV line, what makes the 35 kV line overloaded. Normally the grid is fed from 110 kV “Khashuri-Tseva” substation and from hydro power plants (See Fig.4.1.). Owner utility makes investigations about amount of losses and levels of voltage drops of its system and about ways of their reduction. According to the utility’s data, losses are 2.9%; 4.2% and 8.2% for 110 kV, 35 kV and 10/6 kV voltage levels, respectively. The highest losses are observed during the peak hour operations, when the loading of the system is highest. The typical loading shape for the discussed system is taken from utility’s data [9] and is shown at fig.4.3 below. The loading shape on fig.4.3 can be approximated as typical shape for whole Georgian distribution system.

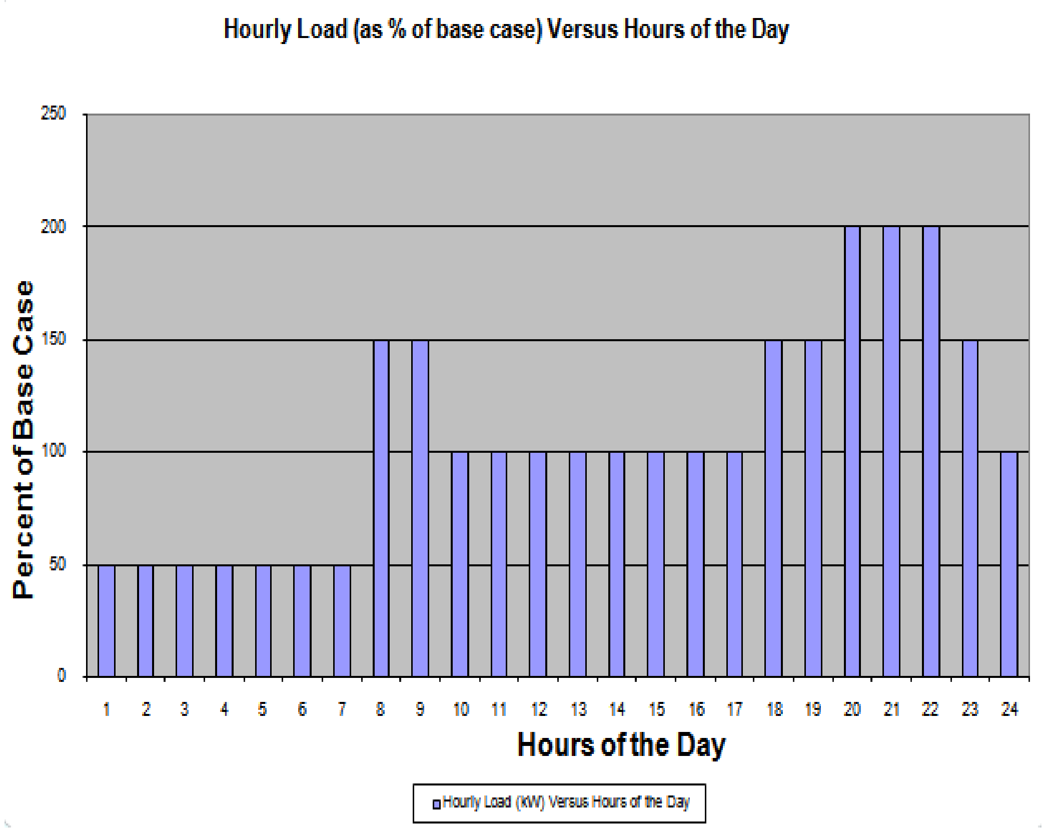


Fig.4.3. Hourly load versus hours of the day

The technical losses versus load are shown in fig. 4.4. The curve on fig.4.4 can also be assumed as typical for all Georgian power networks. It can be observed from fig. 4.4 that the losses do not increase linearly with the increase in total system load, but there is certain minimum of losses, which is occurring somewhere between very light and heavy loads.

As we mentioned above the transmission lines are not always able to transmit the required active power due to the transfer capability limits. This happens during the peak hour operations. Very often, the system experiences very low voltages at the load sides of the lines and there is a problem of not optimal power factor value [9].

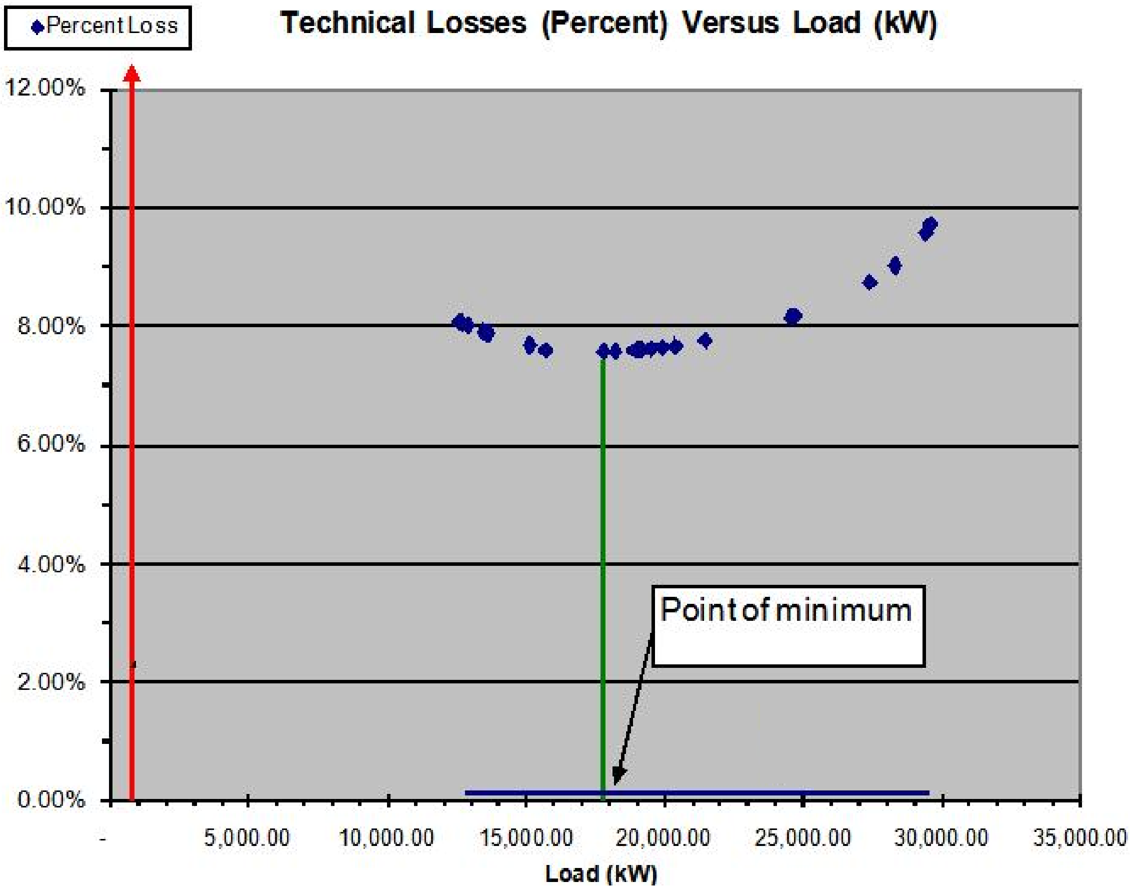


Fig.4.4. Technical losses versus load

One obvious solution to the above mentioned problems could be to build additional transmission lines, but the construction would require large investments, which the network owner cannot afford. As an example if 110 kV “Saghamo” line (see fig. 4.1.) was re-built, the power transfer would be released from the 35 kV line “Khospio”.

Another easier and cheaper solution is to add the reactive power support at the key places. For the moment there is no reactive power support used in the abovementioned grid. The reactive power support would help to minimize the total system losses, increase the active power transmission capabilities and at the same time solve the problem of voltages and power factor. Investments needed for this kind of modification are smaller as compared to those required for the construction of new lines and the resulting reduced total system losses can help recover the investments in a shorter time in case of appropriate planning.

4.1.2. Power system modeling and simulation for Georgian regional grid

In our study, we will model the Georgian regional grid with the three voltage levels of 6-10 kV, 35kV and 110kV. The data for the system is taken from [9] and the power flow simulation software CYME [10] will be used for execution of various optimal power flow solutions required in our proposed method to select the optimal position of reactive power supports.

As it was mentioned above, the regional grid is fed in two ways. Both ways of feeding are shown on Fig. 4.5 and Fig. 4.6. According to in which way the grid is fed, two models of our investigated grid are made.

In Case-1, which will be discussed below, the regional grid is fed through the 110 kV line, coming from the neighbor country as we can observe from the single line diagram (Fig. 4.5.).

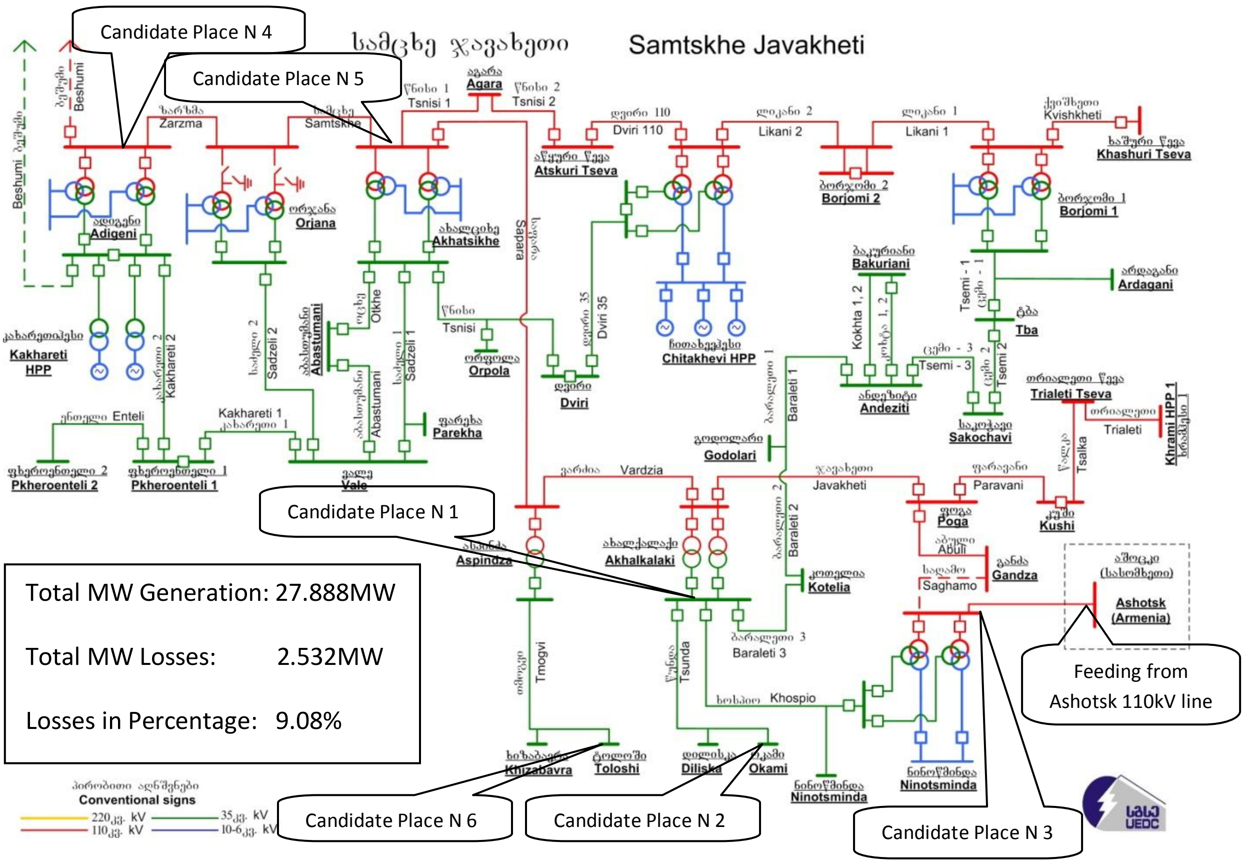


Fig.4.5. Losses and candidate places for reactive power supports for Case-1

The imported energy in this case is more expensive than locally produced, but in the case of power deficit, this way of feeding is the solution for the owner utility. On the single line diagram we can observe, that the 110 kV line, which is used for import of energy feeds 110/35/10.5 kV substation, which feeds the whole grid through the 35 kV line. This line by itself is not designed for transmission of such large amount of power. Therefore, it is becoming overloaded. As a result, we can observe that the total system loss for this case is 9.08%, which is a very high value.

In the normal operation case, which is referred to as Case-2 below, the regional grid is fed through another 110 kV line, which connects the regional grid to the rest of the power system of Georgia. At the same time, the hydro power plant with capacity of 21 MW is connected to the regional grid. The price of energy for this case is less than the imported energy. The losses are also lower compared to the previous case as in this case there are no overloaded lines in our investigated grid. The system for Case-2 is shown in Fig. 4.6.

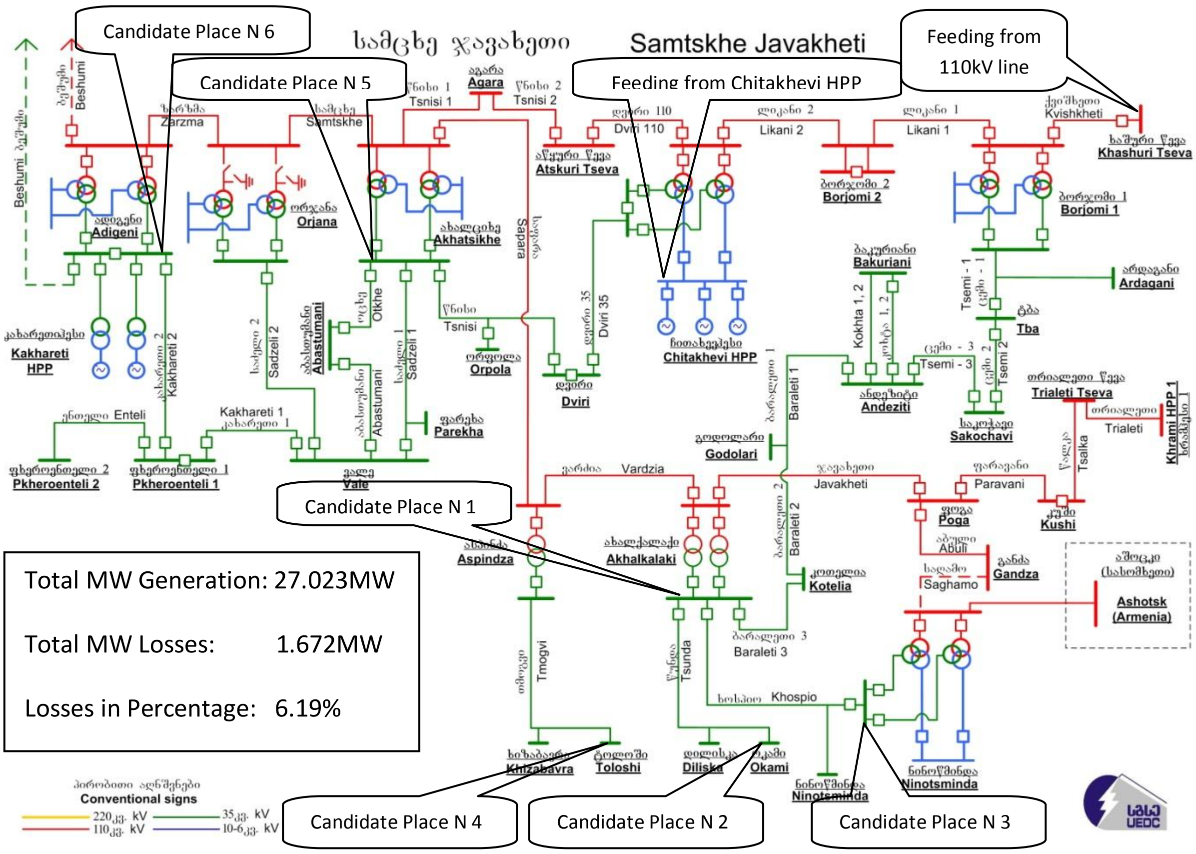


Fig.4.6. Losses and candidate places for reactive power supports for Case-2

According to our simulation results, in which way the grid is fed, the losses and other OPF results are different, therefore both cases will need to be investigated in details.

Two models/cases of the regional grid were modeled in CYME. The difference between the models is the source from where the grid is fed. As mentioned before, in Case-1, the energy is imported and in Case-2, the energy is supplied from within the local grid and from the hydro power plant. After modeling of power grids, the traditional min cost OPF was solved for both cases. As the result, the active power losses have been calculated. Also the candidate places for reactive power supports were defined. The identification of the candidate location of reactive power support is made according to where the highest reactive power flows. We defined at least six candidate places for each case. OPF results are given in Table 1. Candidate places for reactive power supports are shown on Fig. 4.5 and Fig. 4.6 for Case-1 and Case-2, respectively.

TABLE 4.1: OPF RESULTS FOR THE CASES 1 AND 2

	Case 1	Case 2
Total generation, MW	27.888	27.023
Total losses, MW	2.532	1.672
Losses, %	9.08	6.19

Now, once the candidate places for reactive power supports are defined, we need to connect the capacitors iteratively and after each connection of capacitors, the benefits and costs due to reactive power support should be estimated according to the algorithm shown in Fig. 3.1.

We need to calculate benefits due to the reduced or “saved” losses from capacitor installations and costs of the capacitors installed, and then we compare benefits and costs with those capacitors. For the calculation of benefits from saved losses, from [9] we know that price for 1kWh of energy at 110-35kV voltage level is 5.4 cents for Case-1 and 3.94 cents for Case-2. Prices are different for Case-1 and Case-2 since the sources of energy are different in these two cases as previously mentioned.

For the calculation of costs of capacitors, according to [11] we assume that investment cost of 1 kVAr of reactive power is 5.0 US$, we have at least three peak hours per day during 365 days (during one year) and our intention is to recover the investments at least in three years. We also assume the interest rate of 10.0 % per year. According to these assumptions, we calculate for the peak hour operations as the losses are reduced during the peak hours. So now with values given above for capacitors, we can calculate the cost of capacitors per hour of operation. Now, when we have defined the ways for calculation of benefit and investment cost of the reactive power support, we can start iterations and applying capacitors according to the flowchart on Fig. 3.1.

In our iterations we will choose the certain sizes of capacitors. These sizes will be obtained as a result of trial and error which leads us to choosing the final optimal sizes of capacitors.

4.1.3.Simulation results and their analysis for Georgian regional grid

Many iterations of OPF have been performed. However, only the significant iterations will be shown in the following sub-sections.

Iterative simulations for Case-I

Step-1: We install the capacitor of 7.9 MVAr at the candidate place N1 as indicated on the diagram in Fig. 4.5. Perform an OPF run, and calculate the total system loss. As a result of capacitor installation, the loss was decreased from 2.532 MW (9.08%) to 2.194 MW (7.96%). This means that benefit per hour with loss reduction per peak hour is therefore estimated as 338 kWh x 5.4 cents/kWh = $18.25. The cost of 7.9 MVAr of reactive power support is calculated to be $12.02 per peak-hour. As a result we have positive net benefit due to reactive power addition since the benefit is greater that the cost. This means that this case is successful and worthwhile for implementation.

Step-2: We install a capacitor of 7.4 MVAr at the candidate position N1 and a capacitor of 1.1 MVAr at the candidate position N2 as indicated in Fig. 4.5. Again we perform an OPF execution, the losses in this case will be decreased from 2.532 MW (9.08%) to 2.186 MW (7.92%). Similar to Step-1, in this case the benefit due to loss reduction per peak hour is calculated to be $18.68. The cost of 7.4 MVAr and 1.1 MVAr of reactive power support is calculated to be $12.94 per peak-hour. This case is also successful as the benefit is greater than the cost ($18.68 > $12.94).

Step-3: We install a capacitor of 6.8 MVAr at the candidate place N1, and a capacitor of 2.4 MVAr at the candidate place N2. We will be able to reduce the losses by with 353 kW per hour. The benefit per hour is again calculated to be $19.06. The cost of reactive power in this case is calculated to be $13.084. This case is successful as the benefit is greater than the cost ($19.06 > $13.084). This means that this case is also successful.

Step-4: It is still possible to reduce the loss a bit more than that of the previous step. We need to add at the candidate place N1 the capacitor of 6.1 MVAr, at the candidate place N3 5.1 MVAr, and candidate place N4 2.4 MVAr. With this modification, the loss could be reduced to 2.165MW (7.76%). The benefit per peak hour is $19.82. The cost is $20.67. However, this case is not successful since the benefit is less than the cost.

Step-5: There is possibility to reduce losses maximally. For this we need to add the reactive power as follows: at the candidate place N1 – 3.2 MVAr, at the candidate place N2 – 0.7 MVAr, at the candidate place N3 -7.7 MVAr, at the candidate place N4 – 4.0 MVAr. With this way, the losses are reduced to 2.163 MW (7.76%). The benefit per peak hour is $19.93. The cost of reactive power will be $23.74. This case is again not successful since the benefit is less than the cost ($19.82 < $23.74), even the losses could be maximally reduced.

As a result of iterations we could observe, that insertion of reactive power at candidate places N1 and N2 gave us successful results, while addition of capacitors at other candidate places were not successful even this action reduced losses more. For this case candidate places N1 and N2 will be chosen for successful addition of reactive power as only in this case the loss reduction becomes beneficial.

Iterative simulations for Case-II

In this case the grid is fed from the hydro power plant (3X7MW) and from the grid at the same time. As in previous case the basic optimal power flow was solved for this case also and active power losses have been calculated. Total generation is 27.027MW and total active power losses are 1.672MW (6.19%). The candidate places for reactive power supports were found. All these results are shown on single line diagram on Fig. 4.6.

Step-1: In case if we apply the reactive power of 10MVAr at candidate place N1 as shown on the diagram in Fig. 4.6, and perform an OPF run, then calculate the total system loss, the losses will be reduced from 1.672MW (6.19%) to 1.273MW (4.78%). With this modification we save $15.72 per peak hour. The cost of reactive power addition per peak hour is $15.22. For this case the benefit is more than the cost ($15.72 > $15.22), that means that this iteration is successful.

Step-2: In this iteration we apply the capacitor of 7.5MVAr at candidate place N1 and 5.4MVAr at candidate place N6 as indicated on the diagram in Fig. 4.6. In such a way we obtain the loss reduction from 1.672MW (6.19%) to 1.205MW (4.54%). It means that we save $18.4 per peak hour. Investment due to reactive power addition will be $19.63 per peak hour. Comparison of benefit with cost shows that cost needed for such modification is more than benefit. It means that this case is not successful and worthwhile.

Step-3: Now we install the capacitors of 5.6MVAr at candidate place N1, capacitor of 5.9MVAr at candidate place N5 and capacitor of 3.8MVAr at candidate place N6. With this modification we gain loss reduction from 1.672MW (6.19%) to 1.180MW (4.45%) and we save $19.39 per peak hour. The total cost of capacitors addition is $23.26 per peak hour. Comparison of benefit and cost shows that cost in this case is more than the benefit that means that this iteration is not successful.

Step-4: We apply the capacitors at the following places: Candidate place N1 – 4.2MVAr; candidate place N3 – 2.4MVAr; candidate place N5 – 5.9MVAr. With this change we have loss reduction from 1.672MW (6.19%) to 1.198MW (4.5%) and we save $18.68 per peak hour. The total cost of capacitors addition is $19 per peak hour. This iteration can't be successful as the cost is more than the benefit.

Step-5: In this case we gain the maximum loss reduction. We apply the capacitors at the following places: Candidate place N1 – 5.1MVAr; candidate place N2 – 0.3MVAr; candidate place N3 – 1.7MVAr; candidate place N4 – 1.1MVAr; candidate place N5 – 1.7MVAr; candidate place N6 – 3.7MVAr. With all these capacitors addition we get loss reduction from 1.672MW (6.19%) to 1.165MW (4.4%) and we save $19.98 per peak hour. The total cost of capacitors addition is $20.7 per peak hour. For this iteration the cost is more than the benefit that means that this iteration is not successful.

Iterative simulations for case-II showed us that insertion of reactive power was successful only in case if we insert the capacitors at candidate place N1. All the other cases were not successful and beneficial, even the loss reduction was more. As a result we conclude that for this case of iterations the successful place for reactive power placement is candidate place N1.

The summarizing tables for the results for case 1 and for case 2, obtained from simulations with Georgian regional grid can be found at table 4.2. and 4.3 respectively:

Capacitors at these cand. Places	**Total MVAr Installed**	**Cost of MVAr, $ per Peak/hour**	**Saved MW/h**	**Benefit from saved energy in $**	**Case Status**
N1-7.9MVAr	7.9	12.02	0.338	18.25	Successful
N1-7.4MVAr N2-1.1MVAr	8.5	12.94	0.346	18.68	Successful
N1-6.8MVAr N2-2.4MVAr	9.2	13.084	0.353	19.06	Successful
N1-6.1MVAr N3-5.1MVAr N4-2.4MVAr	13.6	20.67	0.367	19.82	Not Successful
N1-3.2MVAr N2-0.7MVAr N3-7.7MVAr N4-4MVAr	15.6	23.74	0.367	19.82	Not Successful

Table 4.2. Summarizing tables for the results of simulations with Georgian regional grid for case 1

Capacitors at these cand. Places	Total MVAr Installed	Cost of MVAr, $ per Peak/hour	Saved MW/h	Benefit from saved energy in $	Case Status
N1-10MVAr	10	15.22	0.399	15.72	Successful
N1-7.5MVAr N6-5.4MVAr	12.9	19.63	0.467	18.4	Not Successful
N1-5.6MVAr N5-5.9MVAr	11.5	23.26	0.492	19.39	Not Successful
N1-4.2MVAr N3-2.4MVAr N5-5.9MVAr	12.5	19	0.474	18.68	Not Successful
N1-5.1MVAr N2-0.3MVAr N3-1.7MVAr N4-1.1MVAr N5-1.7MVAr N6-3.7MVAr	13.6	20.67	0. 507	19.98	Not Successful

Table 4.3. Summarizing tables for the results of simulations with Georgian regional grid for case 2

After the performed simulations and analyzing of simulation results as a final plan for capacitor placement we can conclude that for case-I it is most beneficial to install 6.8MVAr of capacitor at candidate place N1 and 2.4MVAr at candidate place 2, what gives us $19.06 savings per peak hour, while for case-II the optimal solution is to insert the capacitor of 10MVAr at candidate place 1 and with this modification we will gain $15.72 saving per peak hour.

4.2. Simulations with CIGRE 32 bus test system

For illustration of the method with multi objective functions the method was applied to the CIGRE 32 bus system.

4.2.1.Description of CIGRE 32 bus test system

The Swedish 32-node test system is used in this thesis to demonstrate the method with multi objective functions. The system of CIGRE 32 bus approximately represents the

Swedish transmission grid and the single line diagram of CIGRE 32 bus system is shown at Fig. 4.7. below. The system consists of four major areas, **[23]:**

- North- with basically hydro generation and some load
- Central- with a large amount of load and rather large thermal power generation
- Southwest- with a few thermal units and some load
- External- connected to the North. It has a mix of generation and load

Further details about CIGRE 32 bus system can be found in [23].

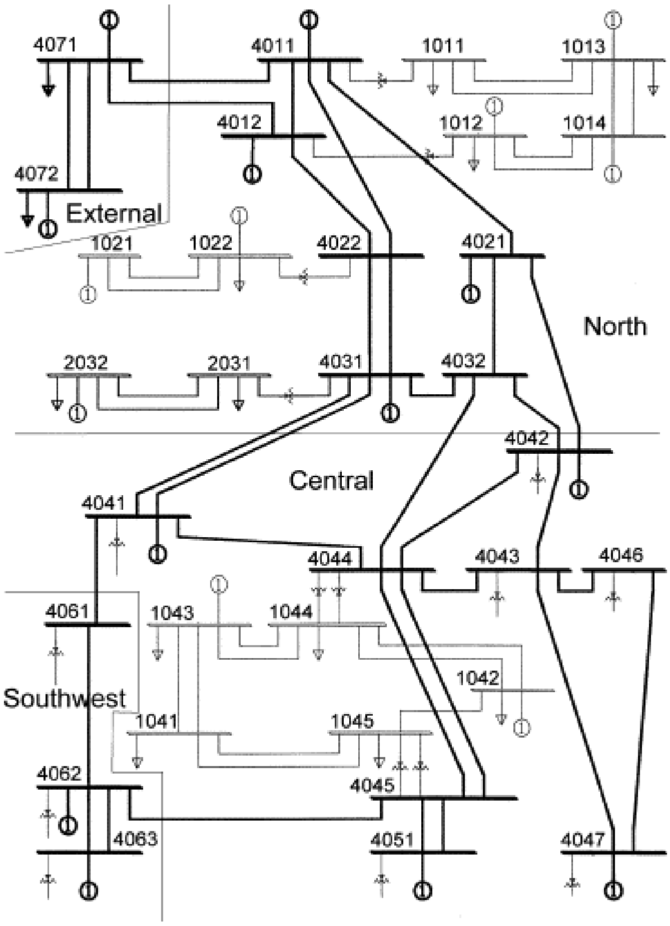


Fig.4.7. CIGRE 32 bus system

4.2.2.Power system modeling and simulations for CIGRE 32 bus system

For applying of our method with multi objective functions to the CIGRE 32 bus system, the system was modeled in GAMS software [22].

All the necessary data, such as Power generation and load, voltage limits for each bus etc are given.

As a basic network load flow equations we use the following equations:

$$P_i - PD_i = \sum_j |V_i| |V_j| Y_{i,j} cos(\theta_{i,j} + \delta_j - \delta_i) \quad (4.1)$$

$$Q_i - QD_i + QC_i = -\sum_j |V_i| |V_j| Y_{i,j} sin(\theta_{i,j} + \delta_j - \delta_i) \quad (4.2)$$

Here V is the bus voltage, δ is the angle associated with V, $Y_{i,j}$ is the element of bus admittance matrix, θ is the angle associated with $Y_{i,j}$, P and Q are the active and reactive power generations respectively, PD and QD are the active and reactive power consumptions respectively and QC is the additional reactive power support.

The network equations (4.1) and (4.2) are obtained from the basic Kirchoff's laws governing the loop flow and nodal power balance. These equations are taken from [13].

The other equations that we are using for modeling are the equation (3.1) for total investment, equation (3.2) for voltage deviation at each bus, equation (3.3) for total system losses, equation (3.4) for total system cost and equation (3.5) for the overall objective function.

The limits, that we consider are the active and reactive power generation upper maximal and lower minimal limits, equations (2.3) and (2.4) respectively, voltage limits at each bus as from 0.95 p.u. to 1.05 p.u., equation (2.5) and limit of reactive power support.

For better illustration of method the transformer tap changer is included in model also. Assumption is that two transformers have the tap changers. These transformers are installed between busses 1022 to 4022 and 1044 to 4044. Each transformer has total five tap positions and the tap changers are able to regulate the voltage in range of ±10%.

For the cost of reactive power we assume, that cost of 1 MVAr is 5000$.

For solving the problem the non linear programming (NLP) solver is used.

4.2.3.Simulation results and their analysis for CIGRE 32 bus system

In our program our intention is to optimize the overall objective function J, which is defined with equation (3.5):

$$J = \sqrt{\alpha\left(\frac{F_1}{F_1^*}\right)^2 + \delta\left(\frac{F_2}{F_2^*}\right)^2 + \gamma\left(\frac{F_3}{F_3^*}\right)^2 + \varepsilon\left(\frac{F_4}{F_4^*}\right)^2} \quad (3.5)$$

For solving this equation, as a first step we need to find the optimal values F_1^*, F_2^*, F_3^* and F_4^* that are the optimal values for total investment in reactive power, total system losses, voltage deviation at each bus and for total system cost respectively.

First we solve the OPF for the optimal value of total investment in reactive power, F_1^*. The obtained results are as follows:

The voltages at each bus after solving for optimal value of total investment in reactive power are given at figure 4.8.

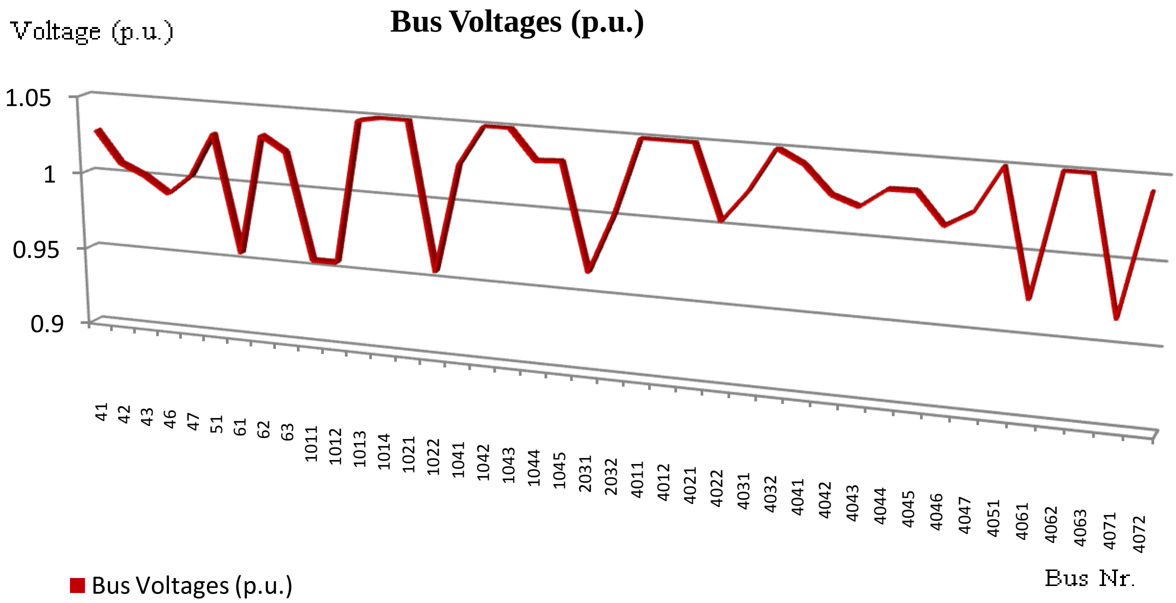


Fig.4.8. Voltages in p.u. at each bus after solving for optimal value of total investment in reactive power, F_1^*

The reactive power support is installed at only one location, at bus 1011 with the amount of 0.29256580 p.u.

The total system losses for this case are 9.10474333 p.u. and the optimal value of the investment is F_1^*=146282.9 $.

As we can observe at figure 4.8., the voltages are just in limits, from 0.95 to 1.05 p.u., but they have quite big deviation from the ideal voltage value, from 1 p.u. This is what we can expect from the minimization of investment costs, voltages are just in limits, losses are more or less acceptable and the minimum required number of reactive power support is allocated at only one bus, at bus 1011.

The next optimal value that we need to find is the optimal value for losses, F_2^*. After solving the OPF for optimal value for losses we obtain the results, which are given and discussed below:

The voltages at each bus are as shown at figure 4.9.

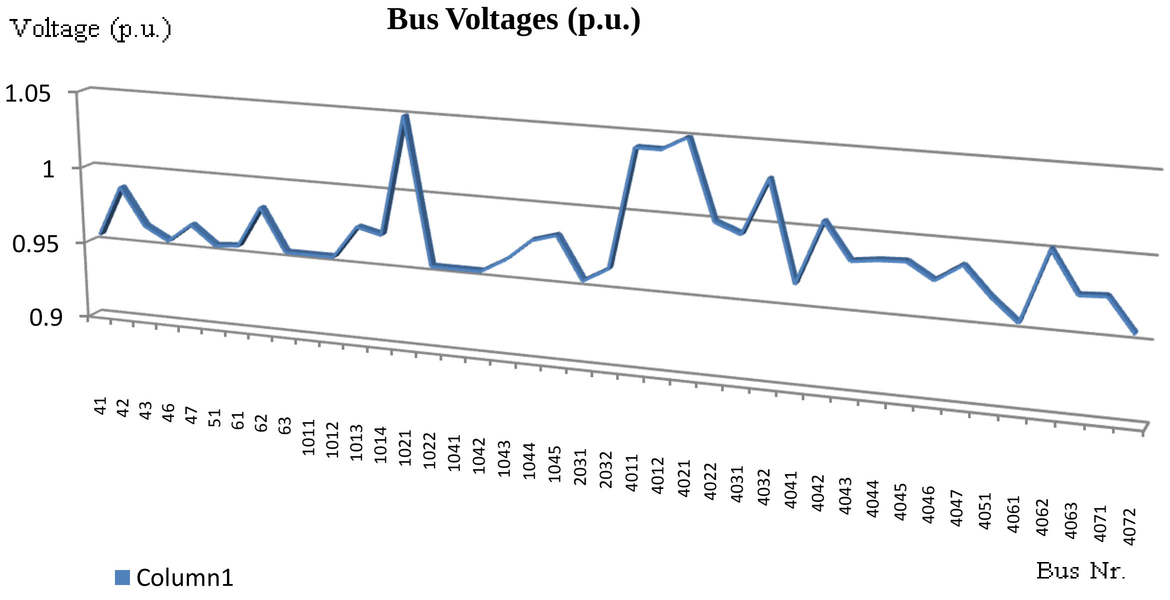


Fig.4.9. Voltages in p.u. at each bus after solving for optimal value for losses, F_2^*

The reactive power support has been applied at total nine different locations in the system, for gaining the minimal value of losses. The amounts and locations of reactive power supports are given in figure 4.10.

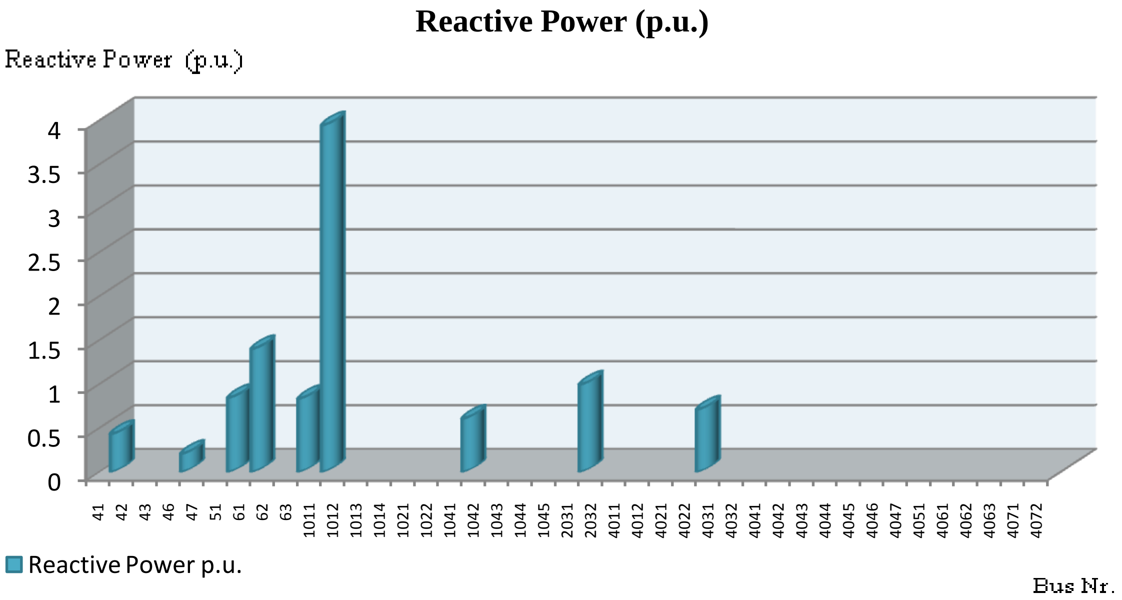


Fig.4.10. Reactive Power Support allocation and amounts after solving for optimal value of losses, F_2^*

The optimal value of total system losses are: F_2^*= 4.96669474 p.u.

The optimal value of total system losses are less than half as it was for the case when we solved OPF for optimal value of total investment in reactive power, F_1^*. This is obviously good result, but to reach this optimization, program was obliged to allocate the reactive power support in nine different locations. Even though the losses are minimized, still the voltage deviation is quite high from ideal value, 1 p.u. but looks better than it was in previous case, when we solved OPF for optimal value of total investment in reactive power, F_1^*.

The next step is to find the optimal value of voltage deviation, F_3^*. The voltage deviation is defined with the equation (3.2.). Our objective function is to minimize F_3^*, that would lead us to the maximal improvement of voltage levels at each bus.

After solving the OPF for optimal value of voltage deviation, F_3^*, we obtain the results, which are shown and analyzed below:

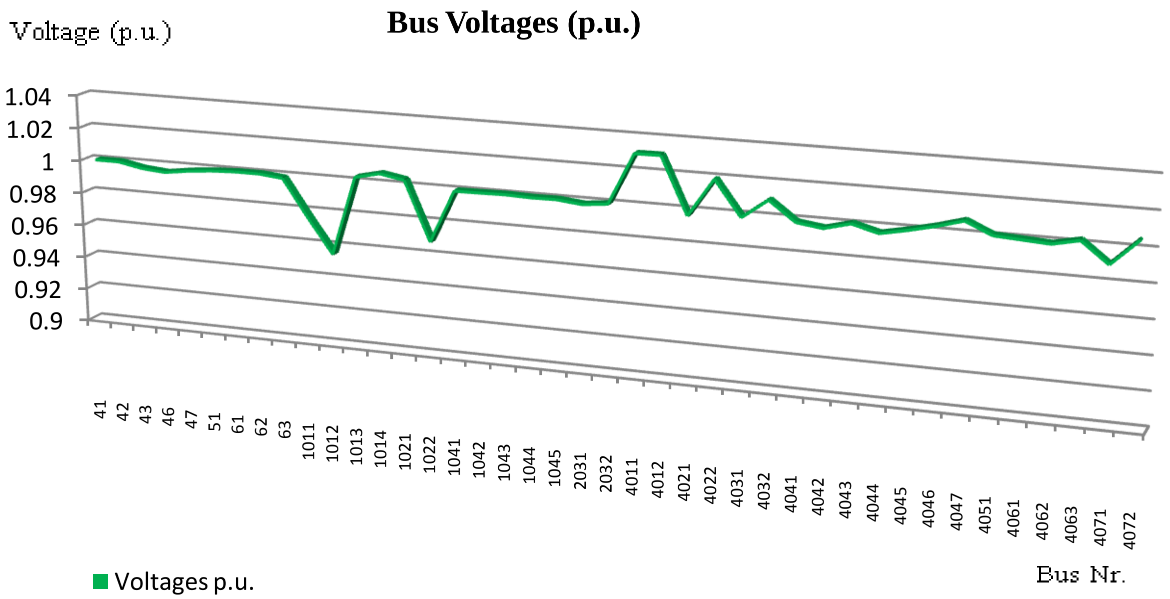


Fig.4.11. Voltages in p.u. at each bus after solving for optimal value of voltage deviation, F_3^*

As we can observe, the voltage levels here are very close to desired value, 1 p.u. Only at several buses it was impossible for the program to optimize the voltage level more.

From figure 4.12. we note, that for reaching the minimal deviation of voltages at each bus, the program needed to allocate quite high number and value of reactive power.

As a result the losses are 9.50988771 p.u. and the optimal value of voltage deviation, F_3^*=0.07906289 p.u. This is quite satisfying value for us.

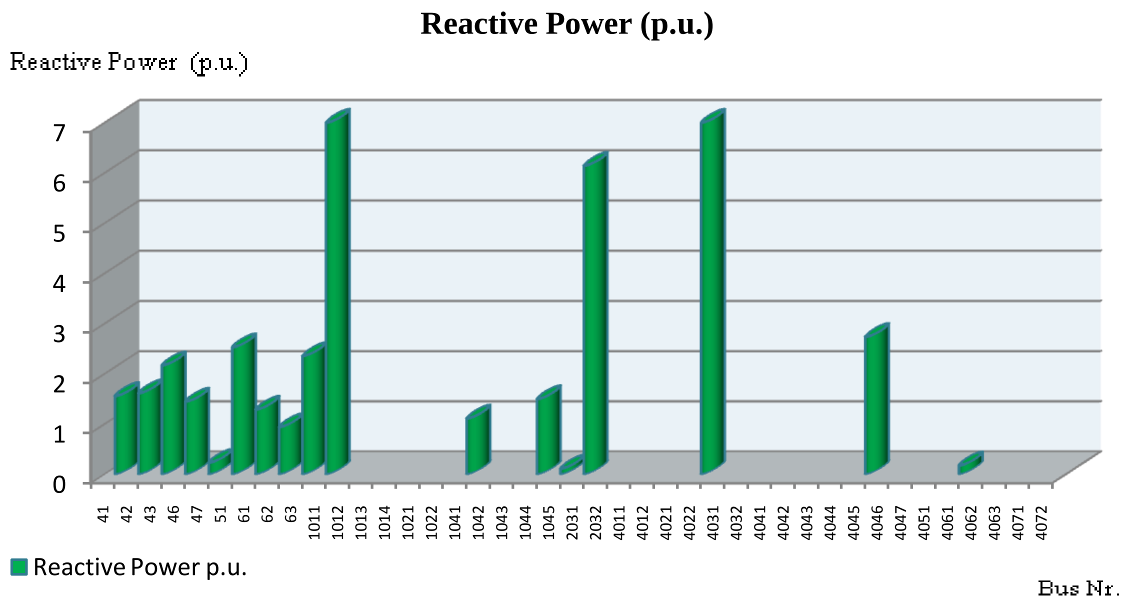


Fig.4.12. Reactive Power Support allocation and amounts after solving for optimal value of voltage deviation, F_3^*

The last optimal value, which we need to find, is the value of optimal total system cost F_4^*. We solve OPF for this case also and the optimal value with all the other needed values is received. The results are shown below:

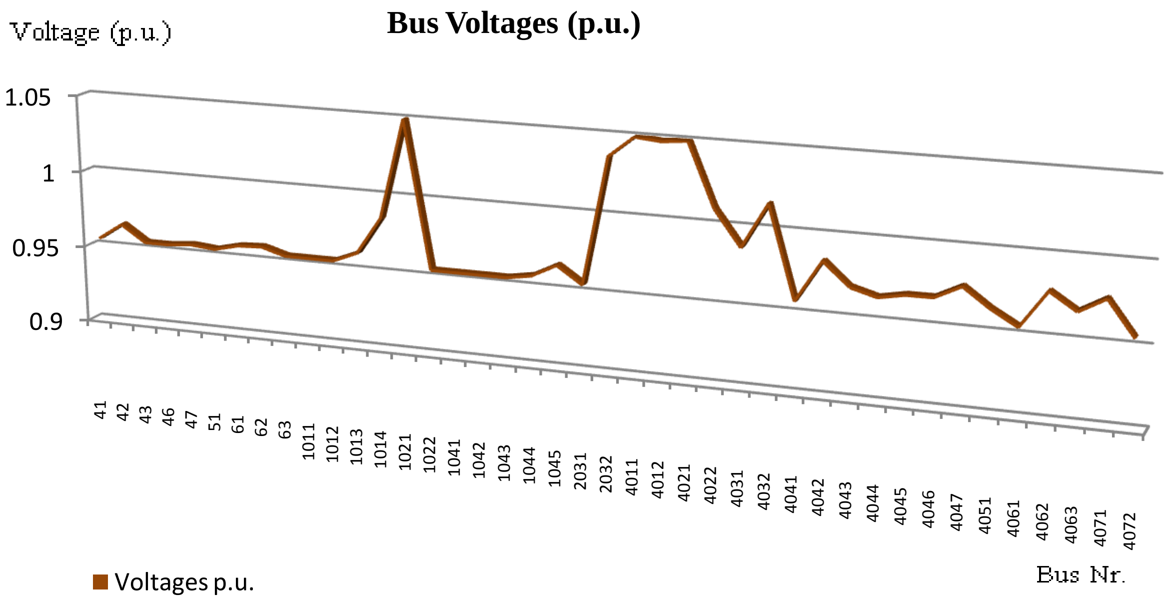


Fig.4.13. Voltages in p.u. at each bus after solving for optimal value of optimal total system cost F_4^*

As we can see from figure 4.13., the voltage deviation is very high, but still in acceptable range for this case. This is what we could expect, as our objective function is minimization of total system cost.

On figure 4.14. the reactive power support allocation and amounts are shown. This is the amount of reactive power, that is needed for keeping the voltages in acceptable limits and at the same time we obtain quite low value of total system losses, 5.85854309 p.u.

As a result our objective function, optimal total system cost F_4^* is minimized:

$$F_4^* = 1832.457 \text{ p.u.}$$

We have found the optimal values F_1^*, F_2^*, F_3^* and F_4^* that are the optimal values for total investment in reactive power, total system losses, voltage deviation at each bus and for total system cost. Now we are able to solve the overall objective function, which will include all these four objective functions at the same time.

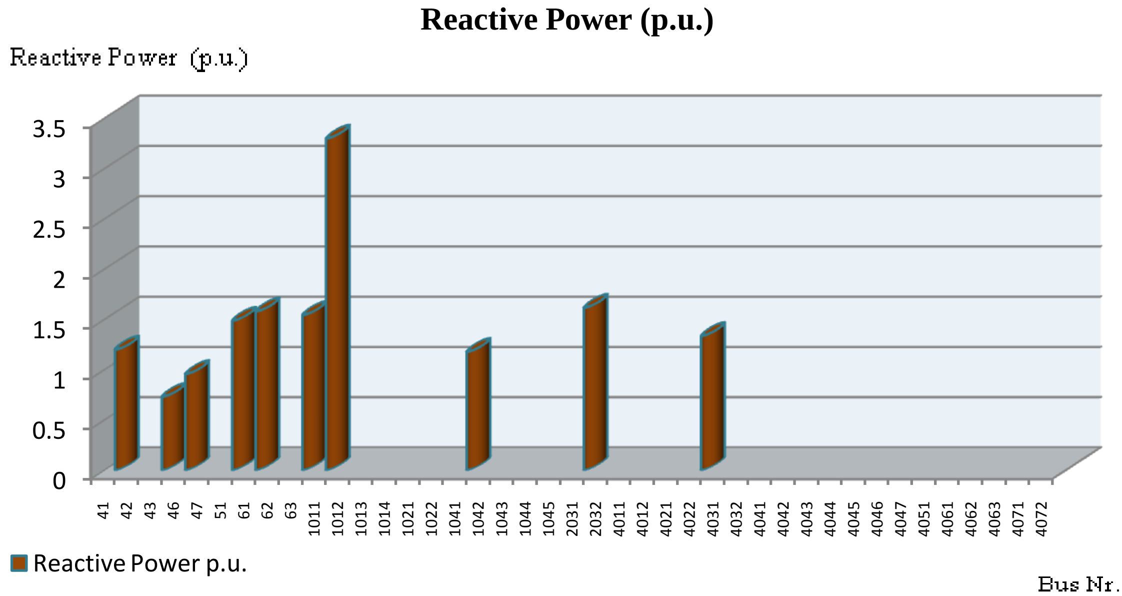


Fig.4.14. Reactive Power Support allocation and amounts
after solving for optimal total system cost F_4^*

In overall objective functions we have possibility to set the priority order multipliers for each optimized sub-objective. For better illustration of our method three different cases will be solved and shown here. Each case will have different value of priority order multipliers, which mean that in each of these three cases different sub-objective functions are prioritized. As we mentioned above, the sum of all priority order multipliers should be 100%.

During solving of OPF for overall objective function, the transformer tap-changers will be included also and we will be able to see the tap positions of the transformers, that are assumed to have the tap-changer.

After solving of all the three cases with different values of priority order multipliers, the results will be compared and discussed.

Case One

For the first case the priority order multipliers are divided as follows:

- Priority order multiplier for investment in reactive power support, α = 10%;
- Priority order multiplier for total system losses, δ = 30%;
- Priority order multiplier for average voltage deviation at each bus, γ = 30%;
- Priority order multiplier for total system cost, ε = 30%.

For more visibility of division of our interest between priority order multipliers for the case one the pie chart is given at figure 4.15. below:

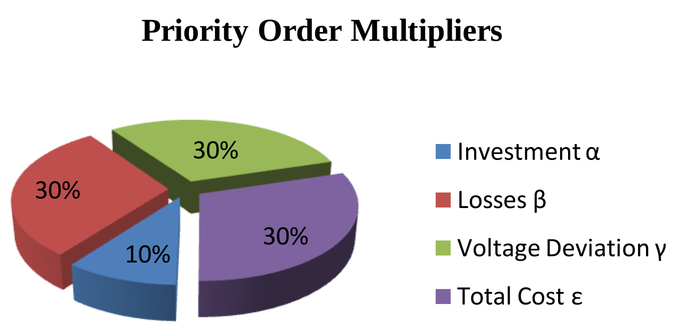


Fig.4.15. Division of our interest between priority order multipliers for the simulation case one

After solving NLP (Non Linear Programming) for minimization of overall objective function, we obtained the results that are given below:

The voltage levels at each bus are given in figure 4.16.

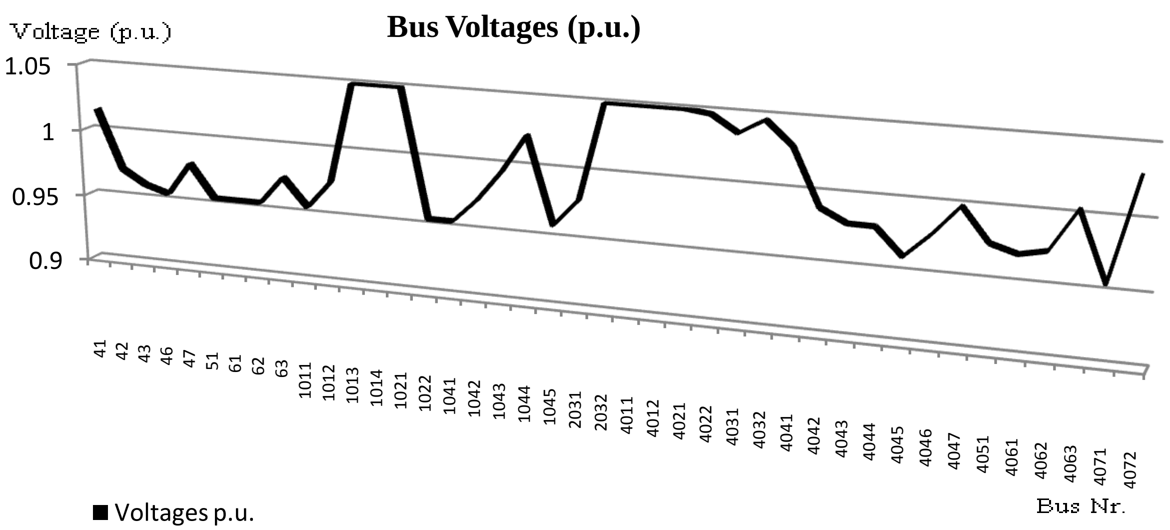


Fig.4.16. Voltages in p.u. at each bus for case one of optimizing overall objective function

The reactive power allocation and quantities are given in figure 4.17.:

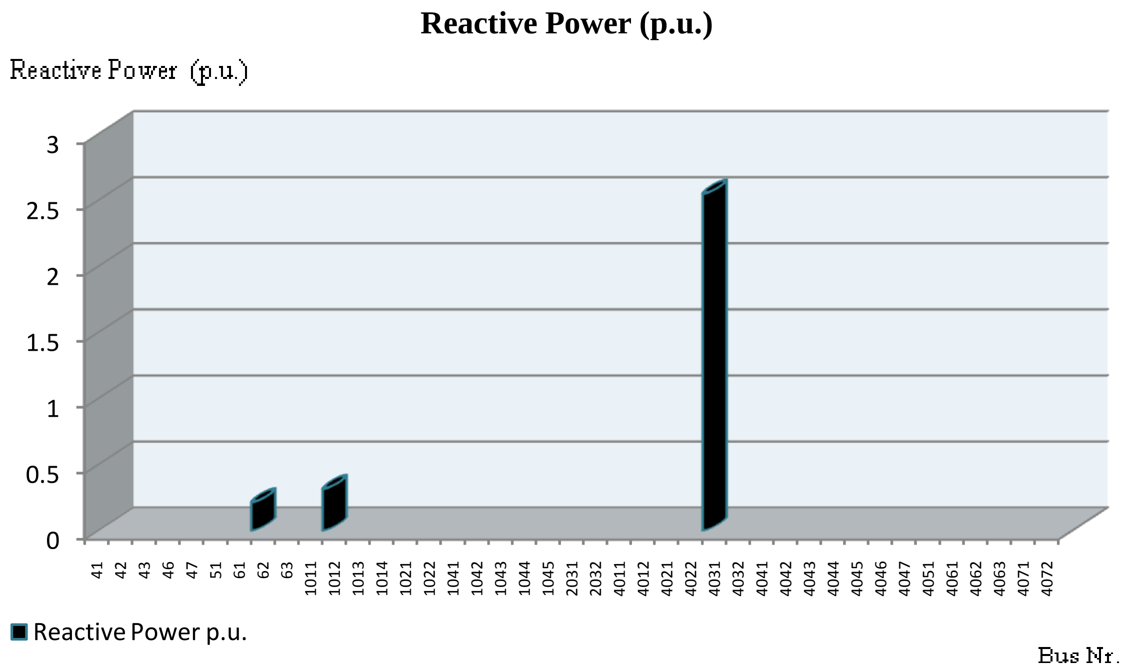


Fig.4.17. Reactive Power Support allocation and amounts after solving for case one of optimizing overall objective function

Tap Changer positions for the transformers:

- Transformer From bus 1022 To bus 4022: Tap Position IV. (105% of nominal voltage level)
- Transformer From bus 1044 To bus 4044: Tap Position II. (95% of nominal voltage level)

The total system loss for this case is 9.08059016 p.u., the total system cost is 742.5 $ and the overall objective function, J = 0.00013053 p.u.

As we can observe from the simulation results of case one, the voltage levels are improved. Only at some busses there are quite high deviations from the desired voltage level, but in general the voltage levels are in acceptable range. The total system losses are also in satisfactory level. While improving the voltage levels and reducing the losses, for keeping the total system cost and investments in reactive power supports on minimal values, the program allocated minimal reactive power supports in total three different busses.

These results are exactly what we could expect when we divided our interests by priority order multipliers for the case one.

Case Two

For case two the priority order for total system losses is more prioritized, then the other multipliers and the other three multipliers are equally divided:

- Priority order multiplier for investment in reactive power support, α = 20%;
- Priority order multiplier for total system losses, δ = 40%;
- Priority order multiplier for average voltage deviation at each bus, $\gamma = 20\%$;
- Priority order multiplier for total system cost, $\varepsilon = 20\%$.

The interest division between priority order multipliers for the case two can be seen better on the pie chart at figure 4.18. below:

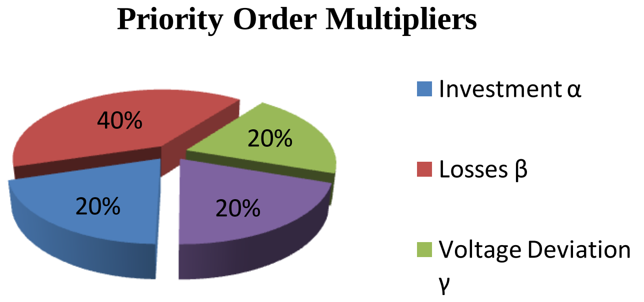


Fig.4.18. Division of our interest between
priority order multipliers for the simulation case two

As in previous case, here we solved the NLP for the overall objective function. The results of the solution can be found below:

Below the voltage levels at each bus are given:

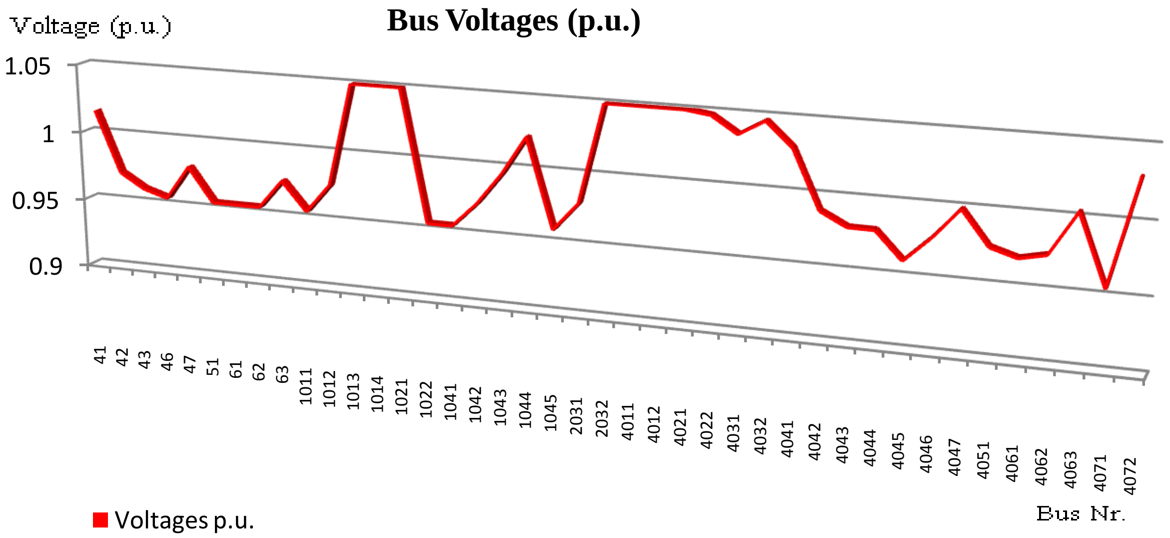


Fig.4.19. Voltages in p.u. at each bus for case two of optimizing overall objective function

For this case the voltage deviation wasn't as prioritized as total system losses. As a result the voltage levels are improved, but at some buses the voltage deviation still remains high. In general the voltage levels are in acceptable range.

The reactive power allocation and quantities of reactive power for case two can be found at figure 4.20. below:

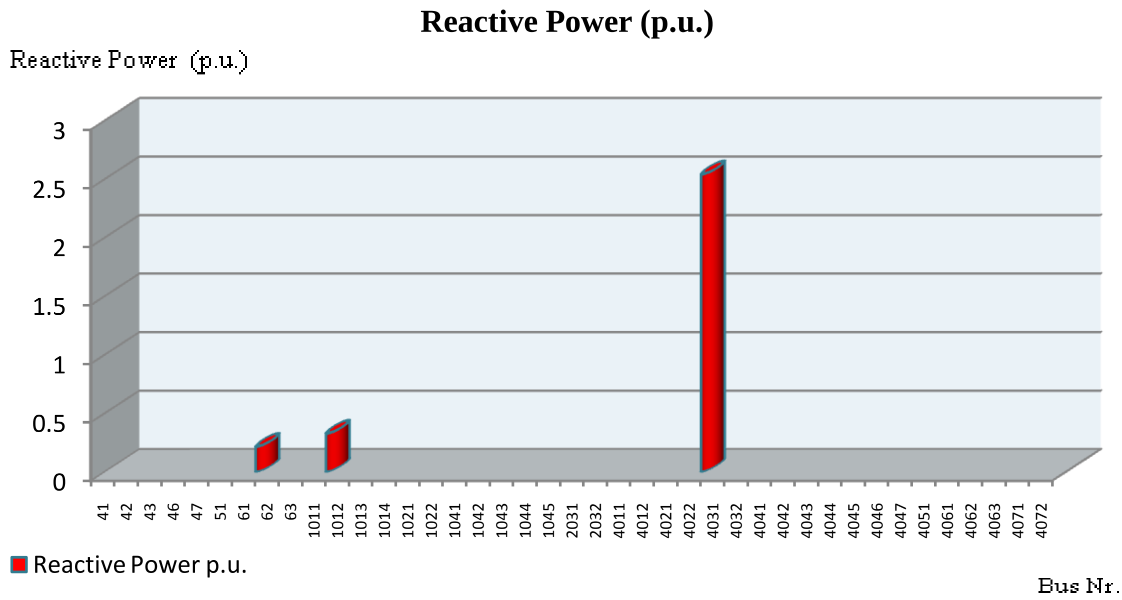


Fig.4.20. Reactive Power Support allocation and amounts after solving for case two of optimizing overall objective function

Tap Changer positions for the transformers are the same as fo the case one and they are as follows:

- Transformer From bus 1022 To bus 4022: Tap Position IV. (105% of nominal voltage level)
- Transformer From bus 1044 To bus 4044: Tap Position II. (95% of nominal voltage level)

The total system loss for this case is 9.07253424 p.u., the total system cost is 742.5 $ and the overall objective function, J = 0.00020602 p.u.

The reactive power support has been allocated at the same busses as in previous case, in case one, but for this case the amount of reactive power is slightly higher. The reason is, that program tries to minimize the total system losses with this action, and at the same time it's not affordable to increase the reactive power more, as in such case the investments will be higher. As a result the total system losses are decreased compared to case one, while all the other objective functions are optimized.

All the output results correspond to the division of interest between priority order multipliers that we gave to the program.

Case Three

One more case with different values of priority order multipliers will be shown below. For this case our priority is to minimize the losses and not to spend too much investment for reactive power support. Voltage levels are also important for us, but it will be enough if the voltages will remain just in their acceptable range. Some attention is paid to the total system cost also.

The priority order multipliers are divided as follows:

- Priority order multiplier for investment in reactive power support, α = 30%;
- Priority order multiplier for total system losses, δ = 40%;
- Priority order multiplier for average voltage deviation at each bus, $\gamma = 10\%$;
- Priority order multiplier for total system cost, ε = 20%.

Priority order multipliers for the case three are shown on pie chart at figure 4.21. below:

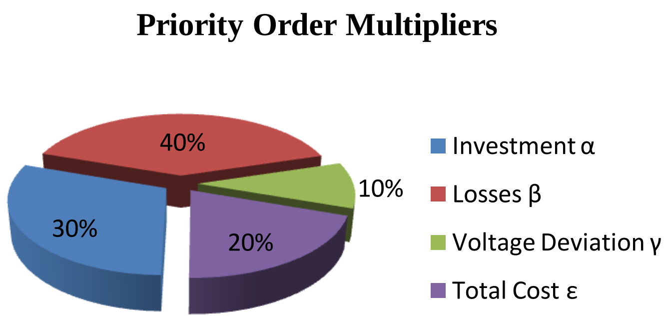


Fig.4.21. Division of our interest between
priority order multipliers for the simulation case three

We solve NLP and the obtained results are given and discussed below:

Tap Changer positions for the transformers:

- Transformer From bus 1022 To bus 4022: Tap Position III. (100% of nominal voltage level)
- Transformer From bus 1044 To bus 4044: Tap Position II. (95% of nominal voltage level)

The voltages at each bus are given in figure 4.22.

The total system loss here is 8.45444222 p.u., the total system cost is 743.4 $ and the overall objective function is minimized to: J = 0.00071248 p.u.

Our highest priority for this case was to minimize the total system losses and as we can see the losses are minimized compared to other three cases. Second priority was to make minimum investments in reactive power support and as we can observe at figure 4.23. the minimal amount of reactive support is added to only two locations. The total system cost is minimized, while the voltage levels are in acceptable ranges.

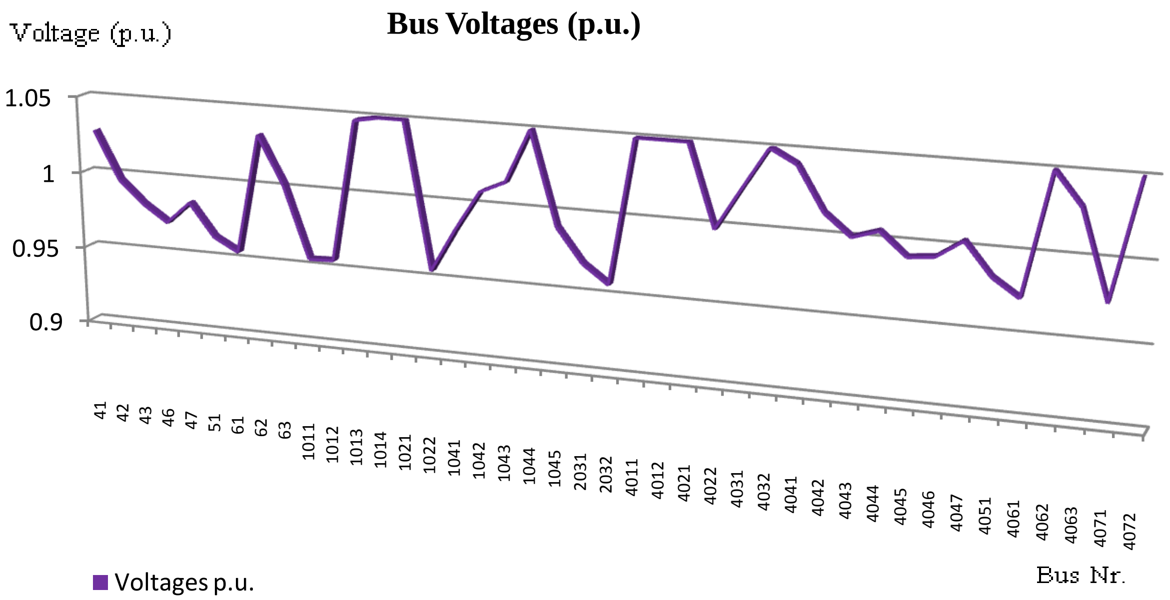


Fig.4.22. Voltages in p.u. at each bus for case three of optimizing overall objective function

The reactive power allocation and quantities are given in figure 4.23. below:

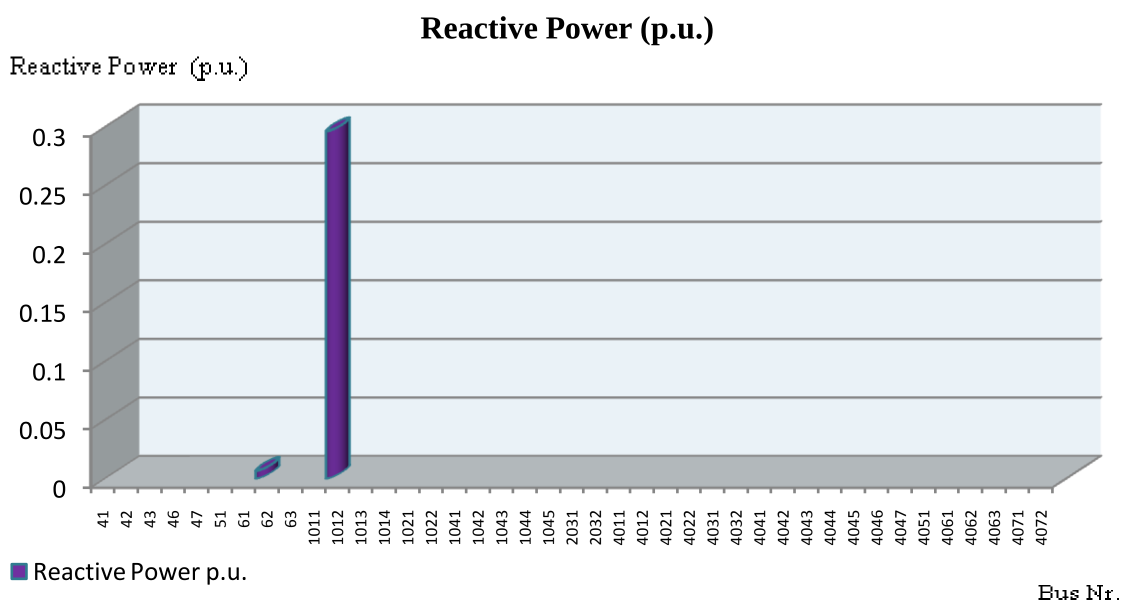


Fig.4.23. Reactive Power Support allocation and amounts after solving for case three of optimizing overall objective function

As we can see, these results are the outputs that correspond to the interests, that we added to the program, while simulating the case three.

Comparison between the results of simulation cases one, two and three

As we can see, all three simulation cases, where we gave different priorities to different objective functions, all cases were successful. We were able to see, that the objective functions, like investment in reactive power support, total system losses, voltage deviation and total system cost were optimized according to what was our interest in them. The simulation results are summarized in table 4.4. below:

	CASE 1	**CASE 2**	**CASE 3**
Total investment (p.u.)	1539718	1540275	151623.6
Average voltage deviation (p.u.)	0.23257235	0.23249908	0.21482606
Total active power losses (p.u.)	9.08059016	9.07253424	8.45444222
Total system cost ($)	742.5	742.5	743.4
Overall Objective function (p.u.)	0.00013053	0.00020602	0.00071248

Table 4.4. Summary for simulation results for method with multi objective functions

In case three the total system losses are lowest compared to other cases, because losses are prioritized more in case three. The reactive power support is also low for case three and it's allocated only at two buses. This is the result of importance of priority order in case three.

In case one and two program tried to minimize the voltage deviation and we can see the results at figures 4.16. and 4.19. To reach this voltage optimization value and minimization of total system losses, the reactive power support was allocated at three busses as we can see at figures 4.17. and 4.20. The reactive power support amount is more, than for case three, because here, in case one and two the minimization of investments in reactive power were not as prioritized as in case three.

5

Conclusions

In this thesis, the method for successful capacitor placement with the objective function of active power losses reduction together with cost-benefit analysis was proposed. The method was implemented on the example of real power grid of one of the Georgian regions.

As we could observe from our iterations, in case if we make investments for addition of reactive power in power system for loss reduction objective, reduced losses will easily recover investment costs caused due to the capacitors addition. However this was not true for all the cases in our iterations and some cases were not successful and effective. Our iterations, made on real power grid shows, that in some cases even though the losses are reduced, the investment cost could be so high, that economically it becomes not effective to implement such changes. Especially it is true when we maximally reduce losses and for this we need to apply many sources of reactive power in different locations of the grid. In such case it becomes even more difficult to operate the number of capacitors as with connection and disconnections of reactive power sources many factors of power system should be considered.

However in our iterations we made assumptions regarding the time for the investment recovery, average peak-hours per day and number of peak-hour days per year as well as the investment cost for reactive power support addition. If we change these assumptions, then the results of cost-benefit comparisons will change and unsuccessful iterations could become successful or vice versa.

Also our suggested method of reactive power addition for the loss reduction purpose becomes even more effective and economically worthwhile in power systems with higher loads and where peak-hour operations are longer.

For being able to significantly improve the performance of power systems and to reduce losses, reactive power should be applied properly and controlled. But if not properly applied or controlled, the reactive power from capacitor banks can create even more losses and high voltages. The greatest danger of overvoltage occurs under light load. Good planning helps to ensure that capacitors are placed and operated properly.

In this thesis another method with multi objective functions was introduced and applied to the CIGRE 32 bus test system. With this method we were able to optimize four objective functions at the same time. While solving for multi objective function, we were able to set the priority order of the objective functions that should be optimized. Beside of these advantages, the method has other advantages also, compared to the method, applied to the Georgian power grid. Advantages are more accurate results of iterations, as in the method with multi objective functions the full process of iteration is done by the program and program can give us the exact locations and sizing of reactive power support, which should be applied to the system for optimization of initially set multi objective functions.

In our case in method with multi objective functions we optimized only four objective functions, but optimization of more functions is also possible within the same method.

As a result the methods for proper allocation of reactive power support were developed in this thesis. Methods include different objectives and consider the financial factors. The methods, discussed here could be useful for power utilities like Georgian power system, where the technical losses and voltage drops are causing the problems.

6

Future work

In this thesis the way of active power loss reduction method with proper application of reactive power sources to the system is discussed and analyzed. However the method considers and the simulation has been done only for the peak hour operations, when the system is heavy loaded. The heavy load can normally last 3-4 hours each day, while during the rest of the time load is decreased and therefore the system is becoming able to transfer the needed power without overloading the system components. Accordingly the losses are becoming lower. In such a case, when the loads are lowered, the reactive power sources, which we applied to the system during the peak hour operations, become excessive and their injected reactive power can cause even more losses and destructive overvoltages. Therefore it's very important the reactive power sources to be properly operated and switched to the system only in case when they will be needed, i.e. during the heavy loads of the system.

Another phenomenon to be considered due to the reactive power compensation of the system is the transients, caused at the moment of connection and reactive power sources. As it is essential to apply the reactive power sources to the system only during peak-hours, the problem of transients becomes urgent for consideration while planning the locations and sizing of reactive power sources.

As a future work the ways to control the reactive power sources should be investigated. What could be the best way for the control system to sense which reactive power source is better to connect and when and when it's best moment to disconnect from the system.

The transients due to the reactive power compensation should be studied also. It should be investigated what is the maximum number and size of capacitors that could be added to the certain system without producing the transient problems. Also how serious consequence can have the case when two or more capacitors are switched on or off at the same time.

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Appendix A

2007 Large Engineering Systems Conference on Power Engineering

ENERGY FOR THE FUTURE

The Delta Centre-Ville Hotel
October 10 to 12, 2007, Montreal, Quebec, Canada

Optimal Placement of Reactive Power Supports for Transmission Loss Minimization: The Case of Georgian Regional Power Grid, Otar Gavasheli and Le Anh Tuan

Optimal Placement of Reactive Power Supports for Transmission Loss Minimization: The Case of Georgian Regional Power Grid

Otar Gavasheli and Le Anh Tuan

Abstract--**In this paper, a method to evaluate the optimal placement of reactive power support for minimization of transmission system losses based on a traditional cost-benefit analysis is proposed. The costs considered are economic costs associated with reactive power sources. The benefits from reactive power supports are defined as the reduced generation costs due to reduced losses as well as other quantifiable benefits, such as reduced total system cost. The dispatch costs could be reduced due to the fact that power generation schedules can be changed by increased transmission capability in the network which will allow for more generation from cheap sources to be delivered to the load centers. The benefits can also stem from the fact that more energy can be sold to the customers which would increase the sales (and thus profits) due to higher transmission capacity. The benefits will be worked out against the costs which will show the economic justification of the investments in reactive power sources. The method is based on an optimal power flow (OPF) framework which will be solved iteratively to arrive at the optimal solutions. The Georgian regional power grid is used in the simulation study to illustrate the method.**

Key words: **loss minimization, reactive power support, cost-benefit analysis, optimal power flow.**

I. Introduction

In a typical power system, network losses account for 5 to 10% of the total generation in the power system, which would cost millions of dollars every year [1]. Therefore, loss minimization is one of the important objectives in operating the transmission networks. It is even more so in the context of deregulated power system, since fair allocation of the network losses has very important impact on all users. This is because unfair allocation causes cross subsidies and it gives wrong indicative signals to the network operator and users. A user who causes more network losses must be charged more while a user who helps to reduce the losses, due to counter flow, must be rewarded.

Transmission system losses can be reduced by means of reactive power compensation as shown in many papers in the literature, see e.g., [2]-[4]. It has also been widely known that the maximum power transfer of the transmission system can be increased by shunt reactive power compensation, typically by capacitors banks placed at the end of the transmission lines or a the load terminals [5]. Therefore, planning of reactive power supports would give benefits to the users of the transmission systems, in terms of loss reduction, among other technical benefits, such as improving steady-state and dynamic stability, improve system voltage profiles, etc. which are documented in [6]. The reactive power planning problem involves optimal allocation and sizing of reactive power sources at load centers to improve the system voltage profile and reduce losses. However, cost considerations generally limit the extent to which this can be applied. The criteria for planning of reactive power compensation used in the literature has been to minimize the losses, the cost of new reactive power sources (capacitors, condensers) or a combination of the two. A number of papers deal with the reactive power planning and scheduling problems, e.g., [7]-[8]. However, only the costs of reactive power are treated, and the economic benefits are often left out.

In this paper, we propose a method to evaluate the optimal placement of reactive power support based on the cost-benefit analysis. The costs are economic costs, which include direct and indirect costs. The direct cost of reactive power sources are investment and operating costs. The indirect cost would include the opportunity cost of generators which reduce real power production for reactive power production. The benefits from reactive power supports are defined as the reduced generation costs due to reduced losses as well as other quantifiable benefits of reduced total system cost. The dispatch costs could be reduced due to the fact that power generation schedules can be changed by increased transmission capability in the network which will allow for more generation from cheap sources to be delivered to the load centers. The benefits can also stem from the fact that more energy can be sold to the customers which will increase the sales (and profits) due to higher transmission capacity.

The organization of the paper is as follows: The following section presents the procedure for optimal addition of reactive power support using cost-benefit analysis. In Section III, the Georgian regional grid is introducted and its existing high power loss problem is discussed. In section IV, the simulation study for loss minimization of the Georgian grid is performed

The authors are with the Division of Electric Power Engineering, Chalmers University of Technology S-41296 Gothenburg, Sweden. (emails: otar@student.chalmers.se; tuan.le@chalmers.se)

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for two possible feeding cases using our propsed methodology. Finally, conclusions are made in Section V.

II. The Proposed Selection Methodology

In this method, the candidate positions of reactive power sources will be first identified using an optimal power flow (OPF) framework with the minimum total cost objective including costs of new reactive power sources. The cost-benefit analysis will then be worked out against the candidate locations, with different standard sizes of reactive power sources, so as to arrive at the optimal plan for reactive power support in an iterative manner. Fig. 1 presents the solution procedure of the proposed method. The selected positions and sizes of reactive power are those which generate the system benefits larger than the costs involved which make the investment economically justifiable. The method will be presented in details in the paper and will be applied to the real power system of Georgian regional grid to find the optimal placement of reactive power sources. A brief description of the system and its problems is given in the following section.

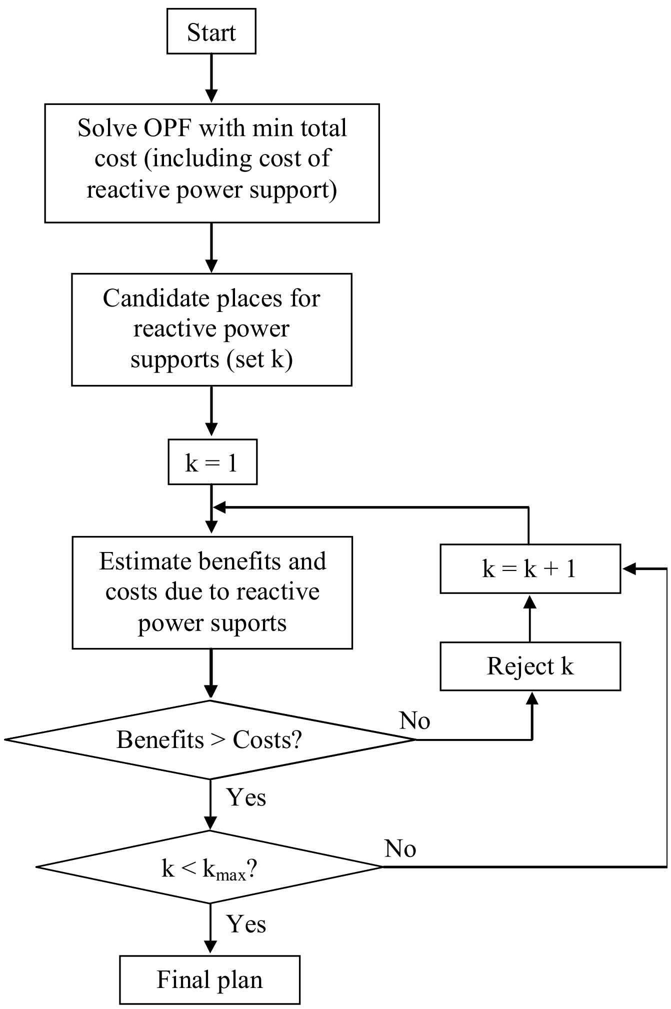

Fig. 1: Procedure of optimal selection of location of reactive power support using cost-benefit analysis

III. Georgian Regional Grid and Its Existing Problems

High power losses is one of the serious problems in the transmission and distribution systems in Georgia, where the power systems are aging and have not been optimized and often uncompensated in terms of reactive power. One typical example is the case of Samtskhe-Javakheti, a regional grid of Georgia. The single-line diagram of this regional grid is given in Fig. 2.

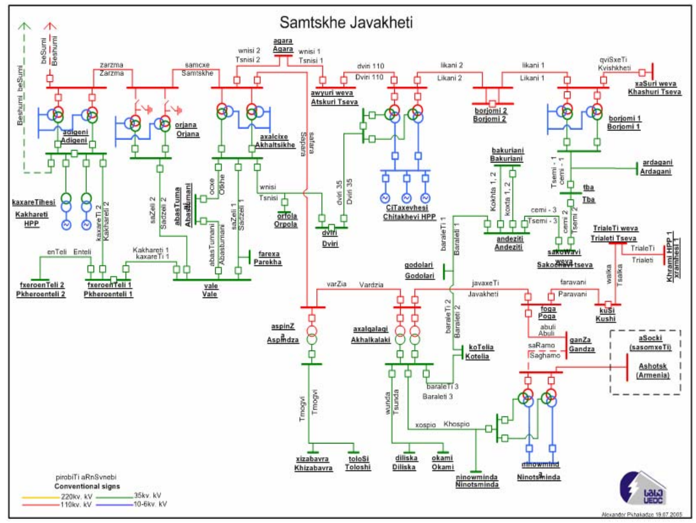

Fig. 2: Single-line diagram of Samtskhe-Javakheti regional grid

Through this region, Georgia is importing the electrical energy from Armenia during the time of power deficit. Here the losses are extremely high. The reason is that the imported power is transited through the grid in not optimal way. Owner utility makes investigations about amount of losses of its system and about ways of their reduction. According to the utility's data, losses are 2.9%; 4.2% and 8.2% for 110 kV, 35 kV and 10/6 kV voltage levels, respectively. The highest losses are observed during the peak hours, when the loading of the system is high. The typical loading shape for this discussed system is taken from utility's data [9] and is shown at Fig.3. The technical losses versus load are shown in Fig. 4. It can be observed from Fig. 4 that the loss does not increase linearly with the increase in total system load.

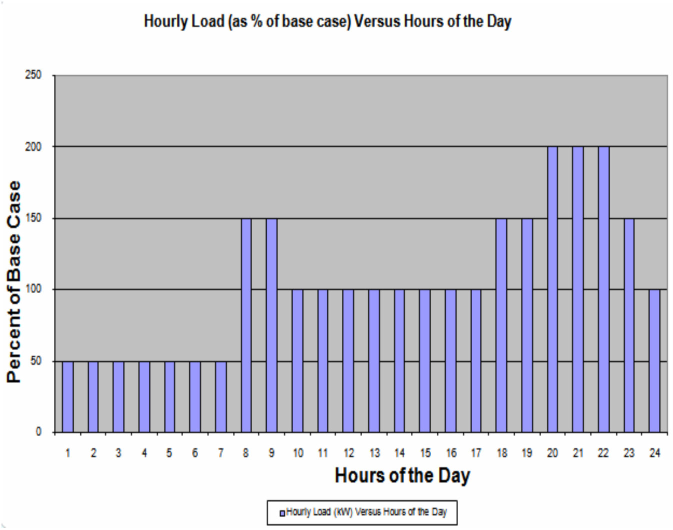

Fig.3: Hourly load versus hours of the day

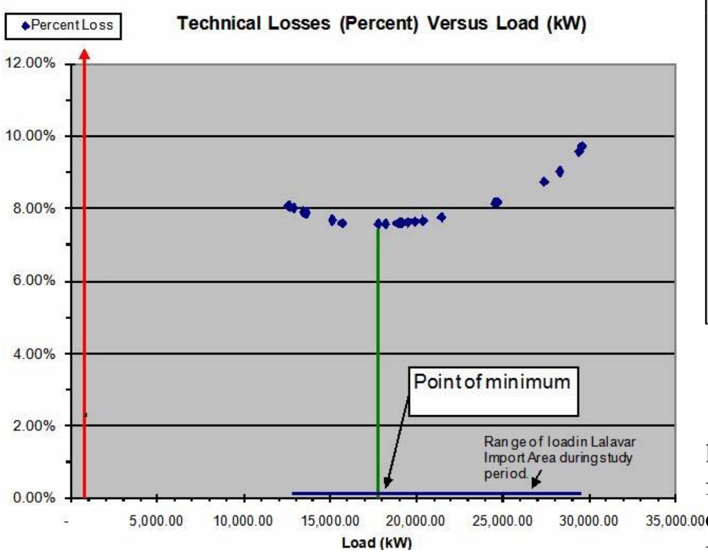

Fig.4: Technical losses versus total system load

Another problem of the system is that the transmission lines are not able to transmit the required active power due to the transfer capability limits. Very often, the system experiences very low voltages at the load sides of the lines and there is a problem of not optimal power factor value [9].

One obvious solution to the above mentioned problems could be to build additional transmission lines, but the construction would require large investments, which the network owner cannot afford. Another easier and cheaper solution is to add the reactive support at the key places. For the moment there is no reactive power support used in the above mention grid. The reactive power support would help to minimize the total system losses, increase the active power transmission capabilities and at the same time solve the problem of voltages and power factor. Investments needed for this kind of modification are smaller as compared to those required for the construction of new lines and the resulting reduced total system losses can help recover the investments in a shorter time in case of appropriate planning as will be shown in the following section.

IV. THE SIMULATION STUDY: GEORGIAN REGIONAL GRID

In our study, we will model the Georgian regional grid with the three voltage levels of 6-10 kV, 35kV and 110kV. The data for the system is taken from [9] and the power flow simulation software CYME [10] will be used for execution of various optimal power flow solutions required in our proposed method to select the optimal position of reactive power supports.

The regional grid is fed in two ways. Both ways of feeding are shown on Fig. 5 and Fig. 6. In Case-1, which will be discussed below (Fig. 5), the regional grid is fed through the 110 kV line, coming from the neighbor country.

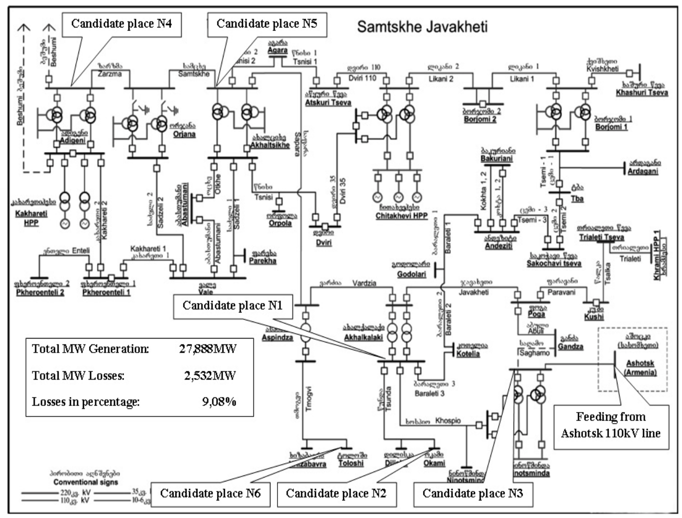

Fig. 5: Losses and candidate places for reactive power supports for Case-1

The imported energy in this case is more expensive than locally produced, but in the case of power deficit, this way of feeding is the solution for the owner utility. On the single line diagram we can observe, that the 110 kV line, which is used for import of energy feeds 110/35/10.5 kV substation, which feeds the whole grid through the 35 kV line. This line by itself is not designed for transmission of such large amount of power. Therefore, it is becoming overloaded. As a result, we can observe that the total system loss for this case is 9.08%, which is a very high value.

In the normal operation case, which is referred to as Case-2 below, the regional grid is fed through another 110 kV line, which connects the regional grid to the rest of the power system of Georgia. At the same time, the hydro power plant with capacity of 21 MW is connected to the regional grid. The price of energy for this case is less than the imported energy. The losses are also lower compared to the previous case as in this case there are no overloaded lines in our investigated grid. The system for Case-2 is shown in Fig. 6.

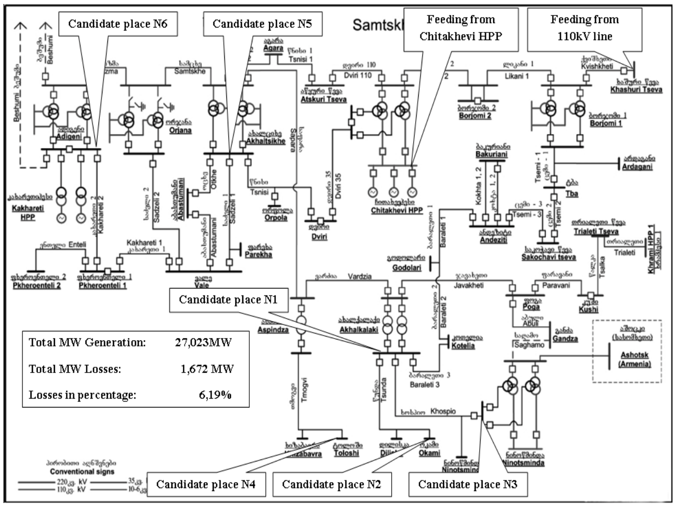

Fig. 6: Losses and candidate places for reactive power supports for Case-2

According to our simulation results, in which way the grid is fed, the losses and other OPF results are different, therefore both cases will need to be investigated in details.

Two models/cases of the regional grid were modeled in CYME. The difference between the models is the source from where the grid is fed. As mentioned before, in Case-1, the energy is imported and in Case-2, the energy is supplied from within the local grid and from the hydro power plant. After modeling of power grids, the traditional min cost OPF was solved for both cases. As the result, the active power losses have been calculated. Also the candidate places for reactive power supports were defined. The identification of the candidate location of reactive power support is made according to where the highest reactive power flows. We defined at least six candidate places for each case. OPF results are given in Table I. Candidate places for reactive power supports are shown on Fig. 5 and Fig. 6 for Case-1 and Case-2, respectively.

TABLE I: OPF RESULTS FOR THE CASES 1 AND 2

	Case-1	Case-2
Total generation, MW	27.888	27.023
Total losses, MW	2.532	1.672
Losses, %	9.08	6.19

Once the candidate places for reactive power supports are identified, we need to connect the capacitors iteratively and after each connection of capacitors, the benefits and costs due to reactive power support should be estimated according to the algorithm shown in Fig. 1.

We need to calculate benefits due to the reduced or "saved" losses from capacitor installations and costs of the capacitors installed, and then we compare benefits and costs with those capacitors. For the calculation of benefits from saved losses, from [9] we know that price for 1kWh of energy at 110-35kV voltage level is 5.4 cents for Case-1 and 3.94 cents for Case-2. Prices are different for Case-1 and Case-2 since the sources of energy are different in these two cases as previously mentioned.

For the calculation of costs of capacitors, according to [11] we assume that investment cost of 1 kVAr of reactive power is $5.0, we have at least three peak hours per day during during a year. We assume the economic life of the capacitors is three years. We also assume the interest rate of 10.0 % per year. According to these assumptions, we calculate for the peak hour operations as the losses are reduced during the peak hours. So now with values given above for capacitors, we can calculate the cost of capacitors per hour of operation. Now, when we have defined the ways for calculation of benefit and investment cost of the reactive power support, we can start iterations and applying capacitors according to the flowchart on Fig. 1.

Many iterations of OPF have been performed. However, only the significant iterations will be shown in the following sub-sections. In the iterative calculation, we will choose the certain sizes of capacitors. These sizes of the capacitors were obtained using "trials and errors", which leads us to choosing the final optimal sizes of capacitors.

A. Iterative simulations for Case-I

Step-1: We install the capacitor of 7.9 MVAr at the candidate place N1 as indicated on the diagram in Fig. 5. Perform an OPF run, and calculate the total system loss. As a result of capacitor installation, the loss was decreased from 2.532 MW (9.08%) to 2.194 MW (7.96%). This means that benefit per hour with loss reduction per peak hour is therefore estimated as 338 kWh x 5.4 cents/kWh = $18.25. The cost of 7.9 MVAr of reactive power support is calculated to be $12.02 per peak-hour. As a result we have positive net benefit due to reactive power addition since the benefit is greater that the cost. This means that this case is successful and worthwhile for implementation.

Step-2: We install a capacitor of 7.4 MVAr at the candidate position N1 and a capacitor of 1.1 MVAr at the candidate position N2 as indicated in Fig. 5. Again we perform an OPF execution, the losses in this case will be decreased from 2.532 MW (9.08%) to 2.186 MW (7.92%). Similar to Step-1, in this case the benefit due to loss reduction per peak hour is calculated to be $18.68. The cost of 7.4 MVAr and 1.1 MVAr of reactive power support is calculated to be $12.94 per peak-hour. This case is also successful as the benefit is greater than the cost ($18.68 > $12.94).

Step-3: We install a capacitor of 6.8 MVAr at the candidate place N1, and a capacitor of 2.4 MVAr at the candidate place N2. We will be able to reduce the losses by with 353 kW per hour. The benefit per hour is again calculated to be $19.06. The cost of reactive power in this case is calculated to be $13.084. This case is successful as the benefit is greater than the cost ($19.06 > $13.084). This means that this case is also successful.

Step-4: It is still possible to reduce the loss a bit more than that of the previous step. We need to add at the candidate place N1 the capacitor of 6.1 MVAr, at the candidate place N3 5.1 MVAr, and candidate place N4 2.4 MVAr. With this modification, the loss could be reduced to 2.165 MW (7.87%). The benefit per peak hour is $19.82. The cost is $20.67. However, this case is not successful since the benefit is less than the cost.

Step-5: There is possibility to reduce losses maximally. For this we need to add the reactive power as follows: at the candidate place N1 – 3.2 MVAr, at the candidate place N2 – 0.7 MVAr, at the candidate place N3 -7.7 MVAr, at the candidate place N4 – 4.0 MVAr. With this way, the losses are reduced to 2.163 MW (7.88%). The benefit per peak hour is $19.93. The cost of reactive power will be $23.74. This case is again not successful since the benefit is less than the cost ($19.82 < $23.74), even the losses could be maximally reduced.

As a result of the iterations presented above, we could observe, that insertion of reactive power at candidate places N1 and N2 was found to be beneficial, while addition of capacitors at other candidate places were not, eventhough they could reduced losses more than the former case. Therefore, the case candidate places N1 and N2 are chosen for the placement of reactive power support which could be cost-effective.

B. Iterative simulations for Case-II

In this case, the grid is fed from the hydro power plant (3 x 7 MW) and from within the grid. Similar to the previous case, the optimal power flow for the base case (i.e., without reactive power support) was solved and active power losses have been calculated. Total generation is 27.027 MW and total active power losses are 1.672 MW (6.19%). The candidate places for reactive power supports were identified and were shown in Fig. 6. The iterative process of finding optimal placement of capacitors in this case is given below.

Step-1: In case if we apply the reactive power of 10 MVAr at candidate place N1 as shown on the diagram in Fig. 6, and perform an OPF run, then calculate the total system loss, the losses will be reduced from 1.672 MW (6.19%) to 1.273 MW (4.78%). With this modification we save $15.72 per peak hour. The cost of reactive power addition per peak hour is $15.22. For this case the benefit is more than the cost ($15.72 > $15.22), that means that this iteration is successful.

Step-2: In this iteration, we apply the capacitor of 7.5 MVAr at candidate place N1 and 5.4 MVAr at candidate place N6 as indicated on the diagram in Fig. 6. In such a way, we obtain the loss reduction from 1.672 MW (6.19%) to 1.205 MW (4.54%). It means that we save $18.4 per peak hour. Investment due to reactive power addition will be $19.63 per peak hour. Comparison of benefit with cost shows that cost needed for such modification is more than benefit. It means that this case is not worthwhile.

Step-3: Now we install the capacitors of 5.6 MVAr at the candidate place N1, 5.9 MVAr at the candidate place N5 and 3.8MVAr at the candidate place N6. With this modification, we could gain a loss reduction from 1.672 MW (6.19%) to 1.180 MW (4.45%) and we save $19.39 per peak hour. The total cost of capacitor addition is $23.26 per peak hour. Comparison of benefit and cost shows that cost in this case is more than the benefit that means that this iteration is not successful.

Step-4: We apply the capacitors at the following places: candidate place N1 4.2 MVAr; candidate place N3 2.4 MVAr; candidate place N5 5.9 MVAr. With this change we have loss reduction from 1.672 MW (6.19%) to 1.198 MW (4.5%) and we save $18.68 per peak hour. The total cost of capacitor addition is $19 per peak hour. This iteration was not be successful as the cost is more than the benefit.

Step-5: In this case, we could gain the maximum loss reduction. We apply the capacitors at the following places: Candidate place N1 5.1 MVAr; candidate place N2 0.3 MVAr; candidate place N3 1.7 MVAr; candidate place N4 1.1MVAr; candidate place N5 1.7MVAr; candidate place N6 3.7MVAr. With all these capacitors addition we get loss reduction from 1.672MW (6.19%) to 1.165MW (4.4%) and we save $19.98 per peak hour. The total cost of capacitors addition is $20.7 per peak hour. For this iteration the cost is more than the benefit that means that this iteration is not successful.

Iterative simulations for Case-II showed us that insertion of reactive power was successful only in the case where we insert the capacitor at candidate place N1. All the other cases were not beneficial, eventhough the loss reduction was more. As a result we conclude that for this case of iterations the successful place for reactive power placement is candidate place N1.

C. Final selection of capacitor placement plan and the sensitivity issues

After performing all the simulations and analyzing the simulation results discussed in IV.A. and IV.B., we could arrive at the final plan for optimal capacitor placement for the Case-I when it is most beneficial to install the capacitors of 6.8 MVAr at N1 and and 2.4 MVAr at N2, which could return $19.06 of cost savings per peak hour. In the supply Case-II, the optimal solution is to insert the capacitors of 10 MVAr at N1 which would lead to a $15.72 cost saving per peak hour.

It could be observed from our iterations that if we make investments for addition of reactive power in power system for loss reduction objective, the reduced losses would recover investment costs of the capacitors addition. However, this was not true for all the cases in our iterations and some cases were found to be not effective. Our iterations, made on a real power grid, have shown that in some cases, even though the losses are reduced, the investment cost could be so high, that it becomes economically not effective to implement such changes. It is especially true when we maximally reduce losses and for this we need to provide many sources of reactive power at different locations of the grid. In such a case, it becomes even more difficult to operate the system with large number of capacitors, since they involve more frequent connection and disconnections of reactive power sources. For this problem, many factors of in the power system should be considered as well.

It should also be noted that in our simulation study, assumptions are made regarding average peak-hours per day, and number of peak-hour days per year, the investment cost for reactive power support addition, as well as the economic life of the capacitors. The results of cost-benefit analysis are based on these assumptions, hence are senstive to these. If these assumptions are to be altered, the results of cost-benefit comparisons will likely change and unsuccessful iterations could become successful and vice versa. Fortunately, in a real system study, one can obtain a more precise data than those we assumed here for the illustration purpose.

V. Conclusions

In this paper, we have proposed the method for optimal capacitor placement for the active power losses reduction using ordinary optimal power flow program in couple with the cost-benefit analysis. The method was implemented on the example of real power grid of one of the Georgian regions. The study has shown that the capacitors could help to reduce the system active power loss and the capacitor cost could be off-set by the total system costs reduction and the loss reduction. For being able to significantly improve the performance of power systems and to reduce losses, reactive power should be applied properly and controlled. But if not properly applied or controlled, the reactive power from capacitor banks can create even more losses and high voltages. The greatest danger of overvoltage occurs under light load. Good planning helps to ensure that capacitors are placed and operated properly.

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VIII. Biographies

Otar Gavasheli was born in Tbilisi, Georgia, on December 5, 1980. He received his BSEE degree from Georgian Technical University in 2002 and now he is working on his MSEE at Chalmers University of Technology, Sweden. His working experience and interests include installation and commissioning as well as design of power generation, transmission and distribution systems.

Le Anh Tuan received his Ph.D. in 2004 in Power Systems from Chalmers University of Technology, Sweden, and his MSc. degree in 1997 in Energy Economics from Asian Institute of Technology, Thailand. Currently he is an Assistant Professor at the Department of Energy and environment at Chalmers University of Technology. His research interests include issues related to the operation of power systems in deregulated market environment, power electronic solutions to optimize power system operation.