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THE USE OF FACTS TECHNOLOGIES FOR MINIMIZING POWER LOSSES AND IMPROVEMENT OF POWER STABILITY IN ELECTRICAL GRIDS

Doctoral Thesis

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Declaration

I hereby declare that this dissertation is my own original work and has not been submitted before to any institution for assessment purposes.

Further, I have acknowledged all sources used and have cited these in the reference section.

Prague, 28. 11. 2018 . . . .

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Abstract

In the modern electric power industry, Flexible AC Transmission Systems (FACTS) have a special place. In connection with the increased interest in the development of “smart energy”, the use of such devices is becoming especially urgent. Their main function is the ability to manage modes in real time: maintain the necessary level of voltage in the grids, control the power flow, increase the capacity of power lines and increase the static and dynamic stability of the power grid. The problem of system reliability and stability is related to the task of definitions, optimizations, and planning indicators, design and exploitation. The main aim of this thesis is the definition of the best placement of the STATCOM compensator, with the purpose of providing stability and reliability to the grid, while minimizing power losses, using mathematical algorithms, such as Partical Swarm Optimization, Genetic Algorithm and etc. All calculations were performed in MATLAB

The presented research includes simulation results for Power System with 14 and 30 node. This research was provided with STATCOM operation using a developed algorithm in both normal and emergency modes of electric power systems. This simulation confirmed the effectiveness of using STATCOM during the adjusting and balancing of a node’s voltage, as well as showed the high speed of STATCOM. These are sufficient for stable operation of STATCOM in emergency modes of the network.

The main practical importance of the work is to increase the effectiveness of the used algorithms for energy management and the development of energy systems. This leads to improved technical and economic indicators of the power sector, reducing the technological consumption of electricity associated with its transfer, improvement of the functioning quality of the power system, as well as the promptness and reasonableness of future decisions.

Keywords:

STATCOM, FACTS, Power compensation, Particle Swarm Optimization algorithm, Power losses, Stability, Reliability, Optimal Power Flow.

Abstrakt

V moderním elektroenergetickém světě, zaujímají systémy FACTS (Flexible AC Transmission Systems) nebo flexibilní přenosové systémy střídavého proudu, velice důležitý význam. V souvislosti s rostoucím zájmem o rozvoj “intelektuální energie”, nabývá používání těchto technologií značné důležitosti. Jejich hlavní funkcí je schopnost “flexibilně” ovládat režimy v reálném čase: udržovat požadovanou hladinu napětí v sítích, řídit toky výkonu, zvyšovat kapacitu elektrických vedení a zvyšovat statickou i dynamickou stabilitu přenosové soustavy. Problematika spolehlivosti a stability energetického systému přímo souvisí s definováním optimalizačních úloh, řízením toku výkonu a kompenzací jalového výkonu. Hlavním cílem této výzkumné práce je definování nejlepšího umístění kompenzátoru STATCOM s ohledem na zajištění stability a spolehlivosti sítě a s požadavkem na minimalizaci ztrát elektrické energie za použití matematických algoritmů. Všechny výpočty byly prováděny v programu MATLAB.

Současný výzkum se zabývá simulacemi pro 14 uzlovou síť a 30 uzlovou síť. K výzkumu byly vytvořeny případové studie s provozem kompenzátoru STATCOM v normálním a nouzovém režimu v elektrických sítích. Které potvrdily účinnost kompenzátoru STATCOM při nastavování a vyrovnávání napětí v připojovacích bodech, projevila se vysoká rychlost působení kompenzátoru STATCOM, dále stabilní provoz sítí s použitím STATCOM v nouzovém režimu.

Hlavním významem práce v praxi je zvýšení efektivity užívání algoritmů v oblasti řízení energetiky, dále rozvoj energetických systémů, které kladně ovlivňují technické a ekonomické ukazatele v energetickém sektoru, snižují ztráty elektrické energie v přenosových soustavách, zvyšují kvalitu energetické soustavy.

Klíčová slova:

STATCOM, FACTS, tok výkonu, minimalizace ztrát, optimalizace hejnem částic, stabilita sítě, spolehlivost sítě, optimální tok výkonu.

Content

Author’s Publications

Publications in Impact factor magazine (WOS):

1. TUZIKOVA V., TLUSTY J., MULLER Z. Novel power losses reduction method based on Particle Swarm Optimization Algorithm using STATCOM. Energies 2018. *Energies 2018,* Volume 11, Issue 10, 2851. (33%; 33%; 33%)

2. NIZHEGORODOV A. I., BRYANSKIKH T. B., GAVRILIN A. N., MOYZES B. B., GRADOBOEV A. V., VAVILOVA G. V., TLUSTY J., TUZIKOVA V. Testing a new alternative electric furnace for vermiculite concentrates heat treatment. Bulletin of the Tomsk Polytechnic University-geo assets engineering. Monthly. ISSN: 2500-1019, Tomsk Polytechnic University,Publishing House, 30, Lenin Ave, Tomsk, Russia, 63405. Link: http://izvestiya.tpu.ru/assets/files/2018/n-4_329_2018_maket_a4.pdf (12,5%; 12,5%; 12,5%; 12,5%; 12,5%; 12,5%; 12,5%; 12,5%)

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1. FEDOROV E., CHICHERINA N., TUZIKOVA V., TLUSTY J. Diffraction control methods of extended products’ diameter. ISSN: 0255-5476. Trans Tech Publications Ltd. Will publish in journal: Materials science forum in October 2018. (25%; 25%; 25%; 25%)

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1. MULLER Z., MULLER M., TUZIKOVA V., TLUSTY J., CERNAN M., BECK Y., GOLAN G. Novel method of optimization of losses in power grid. 2016 IEEE International Conference on the Science of Electrical Engineering (ICSEE), 10.1109/ICSEE.2016.7806044, Electronic ISBN: 978-1-5090-2152-9; Print on Demand(PoD) ISBN: 978-1-5090-2153-6, Eilat, Israel, Link: https://ieeexplore.ieee.org/document/7806044/ (14%; 14%; 14%; 14%; 14%; 14%; 14%)

2. SIMUTKIN M., TUZIKOVA V., TLUSTY J., TULSKY V., MULLER Z. Method of Calculating the Correction Factors for Cable Dimensioning in Smart Grids. In: IOP Conference Series: Materials Science and Engineering. 5th

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1. AKCHURINA S., TUZIKOVA V.: Ekonomická proveditelnost výstavby a optimální parametry zatížení centra zásobovaciho systému ve velkých městech. ISBN 0375-8842. Index 46507. (50%; 50%)

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Another publications:

1. TUZIKOVA V., TLUSTY J.: Razrabotka prijemov modelirovanija fazovogo upravlenija na baze promishlennoj programmi / Разработка приемов моделирования фазового управления на базе промышленной программы. ISBN 978-5-383-00839-3 (Tom 4).

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Introduction

Scientific and technological progress in the field of electric power transmission systems is evolving to increase the manageability, stability and reliability of said systems, while maintaining a high quality of power supply. The most optimal and comprehensive results of these objectives can be achieved through the use of flexible alternating controlled transmission systems (FACTS) containing modern multifunction devices, and in particular, reactive power control devices – STATCOM. STATCOM is a controlled static device configured by an inverter voltage, set in parallel within the electric network.

Implementation of STATCOM can be similar to other FACTS devices: controlled by the longitudinal compensation (TCSC), static synchronous series compensator (SSSC), static VAR compensator (SVC).

Control algorithms of such converters must be able to ensure high quality of the converter in steady-state mode conditions (low losses, satisfying the requirements of the voltage harmonic distortion standards) and also to ensure the efficiency and high performance of STATCOM in emergency and post-emergency conditions of network. The actual problem is the development of algorithms for balancing the voltage in an electrical network with the STATCOM devices.

The main aim of this research is to design and develop the algorithms with STATCOM device operation to maintain and manage the voltage at substations of electric power systems in normal and emergency conditions, researching the use of optimization algorithms for finding the optimal location for the installation of STATCOM, as well as providing analysis of power flow, reactive power compensation and subsequently minimize losses by using optimization methods. This work is devoted to the use of FACTS devices in order to minimize operating losses in the power system. However, since these devices are relatively expensive, they will not be used exclusively for this purpose, but instead used on a larger scale. The aim of the presented research is not only to reduce operating losses in the network but also to enhance voltage stability and increase the capacity of the line.

The problem of reactive power compensation has always taken an important place among the many complex issues involved with improving the efficiency of the transmission, distribution and consumption of electrical energy. The correct solution of such problems influence the economy of financial and material resources, as well as improving the quality of electricity supply. The main issues for reactive power compensation should be considered when taking into account modern views and the vision of new technical solutions in this area.

Reactive power can be regarded as a characteristic rate of energy exchange between the generator and the magnetic field of the power appliance. The active power that is used for useful work serves to generate magnetic fields in inductive appliances (e.g., in motors, transformers etc.), circulating all the time between the current source and appliances. [3] On the contrary, the reactive power does not perform useful work. The acuteness of the problem of reactive power compensation at the present stage is caused by several factors:

- the concentration and centralization of power generators
- the implementation throughout politics, resource management, and energy saving
- optimization of reactive power, including the use of local compensation devices that allow for significantly reduced power losses in the network
- high requirements for the power quality. Reactive power significantly affects the change of the voltage in electrical grids and the insufficient installed capacity of compensating units in the distribution networks.

The problem of reactive power compensation includes a number of technical and economic problems, namely:

- carrying out of activities to reduce reactive power for power consumers themselves
- the selection of types of installation sites and compensating devices
- multi-criteria optimization of operation modes, compensating devices throught their development, and operation of power systems.

Optimization problems in power systems are currently one of the main areas of research in the electric power industry. The main reason for the increased attention to optimization problems in power systems is the ability to achieve cost savings in the solution of the problem without any additional capital investment for equipment or other activities with the help of optimization and analysis of a problem. [9,10]

The present stage of development in Power System is characterized by the increasing requirements for their operation in conditions with significant limitations on the selected resources increasing power consumption while maintaining low rates of input, modernization of power, and insufficient expansion of existing electricity in transmission networks].

Currently, proposed solutions to technical problems include the use of artificial intelligence methods: fuzzy logic, artificial neural networks, evolutionary algorithms (EA).

Though this work the method for determining the optimal place of FACTS devices while combining the methods of optimization the network and the influence of disturbances in the nodes and power flows in the lines has been improved.

Also one of the main problems nowadays for the electric power industry is associated with overloads of electrical equipment by currents of higher harmonics due to the increasing number of non-linear power devices from consumers within the electrical network [82]. Existing standards with respect to the amount of emissions of current higher harmonics cannot provide an interference limit for a safe level in a power grid. Thus, at the design stage of the electric network and its operation, a correction factor to the maximum long-term current of equipment must be used. This would allow engeneeres to consider the additional heating of equipment from higher harmonics of the currents flowing through it.

This research also proposes an engineering method for determining a correction factor for the permissible long-term current of the cable, which takes into account the impact of overloading. Using mathematical models in the software ELCUT [85], in which was described thermal processes in the cable during the non-sinusoidal current flow. According to the results of measurements in the distribution of the network, we obtained the spectrum of the higher harmonics of some nonlinear aplliances. This data was used to calculate the specific values of the correction factors for the permissible long-term currents. Developed theoretical principles, methods, and mathematical models allow us to calculate the correction factor to account for the effect of higher harmonics in the current spectra for network equipment in any type of non-linear load. Obtained values of the correction coefficients may be used as recommendations for the design of new and also existing distribution networks that supply residential areas. This method can also determine the economic impact of higher harmonics allowing assessment of the appropriateness of measures used to compensate for current harmonics for the distribution networks.

The purpose and objectives of present research:

The aim of this thesis is to study and develop the algorithms and codes used for the optimization of electric power systems, allowing the minimization of total power losses using FACTS devices. To achieve this goal the following tasks were formulated:

1. The development of algorithms for power system optimization and for power losses minimization.
2. Optimization of the selection parameters and installation of FACTS devices in the Power system.
3. Comparative study of evolutionary algorithms and methods of nonlinear programming in optimization problems of electric power systems.

Research methods

To achieve the above mentioned tasks, the presented used: the theory of optimal management, methods of mathematical modeling of electric power modes systems, FACTS systems and the use of evolutionary algorithms: Genetic algorithm (GA), Particle Swarm Optimization (PSO), *fmincon* function, and all simulations were performed in mathematical package MatLab.

Scientific results for the defense

1. Complex optimization algorithm for Power Systems modes and the minimization of power losses.
2. A method of optimization for selection parameters and installation of FACTS devices (reactive power sources, linear regulators) in the Power system.

3. Methods for the practical application of evolutionary algorithms for optimization of Power systems modes include: the systematization of recommended parameters of evolutionary algorithms for the optimization of Power system.

The accuracy of scientific statements and the results stated in the present thesis, are supported by the correct use of theory parts of the optimization of nonlinear programming techniques and evolutionary algorithms (genetic, bee, ant).

Practical value of the presented research

1. Evolutionary algorithms show themselves effective in problems which require taking into account the discreteness of variables for complex differentiable functions (increase technical and economic parameters, reduction of computing time) that operate with large amounts of data, and a variety of options that are under consideration.
2. The developed optimization schemes, based on evolutionary algorithms, can be used in dispatching, management and planning modes within design organizations, as well as experienced as learning models for students for higher education purposes. The scientific result of this research is the development of models and algorithms for power system modes, utilizing the principles of using evolutionary techniques with the application of FACTS devices.

1. CURRENT STATE OF THE ART

1.1 Power systems as an object of Optimization

In early 1920th, classical mathematical methods were starting to be used for the control of power modes, but essentially the wide application of modern methods begins with the 1950ies. Mathematically, energy management tasks are very complicated, and applying them effectively is not possible with already known methods without amandments. [4].

At the present time for the various optimization tasks significant materials for the development and analysis of models and methods are collected for their solution. Therefore, for any further research in this area it is extremely relevant and appropriate to consider the basic principles underlying the formation of the nowadays classic algorithms.

An inseparable part of any scientific research is a detailed description of the object that should be approved. At the same time its purpose should directly correspond to the issues from the perspective of which it will be analyzed. Thus, it is necessary to strictly outline the range of tasks that should be solved, to disassemble the main properties of the object and, as a consequence, to formulate the features of this class of problems, taking into account the specifics of the subject of research.

Though solving problems of the power industry, it inevitably grows a necessity to determine the optimal mode, in other words, the best way of operation for the system. Thus under the operation mode means a state of the system at any given time or at a certain time interval [7, 8]. It is necessary to distinguish the main types of modes in electric power systems [9]:

- **normal steady state**, related to which power system is designed and determined by technical and economic indicators;
- **postemergency steady state**, coming after the emergency shutdown of any element or set of elements of the system;
- **transition state**, when the system changes from one state to another.

In addition it should be noted that hereafter analyzing the normal steady-state modes of electric power systems, because each mode characteristic is defined by a set of certain specific issues. In particular, the normal modes of electric power systems are inherent to the following optimization management tasks and planning of the development on different time perspective [25]:

- optimal load distribution between the power plant units and between powerplants as a whole,
- optimal distribution of reactive loads,
- selection of the optimal composition of power units,
- selection of the optimal design of the electrical network,
- optimal frequency and voltage regulation,
- current modes planning of power systems,
- planning of technical and economic indicators.

As shown in [4, 6, 23], power systems, as large artificial system have the following characteristic properties:

- development of space and time within defined limits, mainly defined by external relations system,
- multiple nonlinear dependencies, describing the relationship of the system parameters,
- the probabilistic nature parameter changes and impacts,
- interconnection of a large number of elements and as a result, the presence of multiple internal and external elements, including feedback,
- hierarchical management structure,
- the reliability of operation with redundant links and items.

This combination of properties allows us to formulate the main features of the power industry’s optimization problem:

- The presence of several criteria for optimal solution. The most commonly used criterias in real optimization problems are economy, reliability and quality of electricity. Any special multicriterial methods of accounting are not widely used [7]. These are usually given by the main optimization criteria based on the features of the problem, and considers them as the objective function, and the rest – in the form of imposed restrictions;
- High dimensional problems. Optimization problems are differentiated by a large number of variables, mainly due to a complex complex hierarchical structure of the system and an extensive schme of electrical networks with a large number of nodes. In such cases finding the solution for all levels at the same time of the system is not possible. That is why decompensation methods for the solution of such a problém for a specific level or subsystem are often applied [7]. The decomposition is based on the principles of hierarchical control of power systems;
- The presence of random factors and indeterminacy of the original information. Parameters of the mode of power system mainly are the values, which changes has the random property. Consideration of such property is made by applying a probabilistic mathematical model or using statistical methods [8, 9].

1.2 Traditional methods for solving optimization problems

Design and operation of the power systems – are the complex technical and economical tasks that are inherently always dynamic, non-linear and multivariate, and should be solved using non-linear programming methods. The choice of the appropriate method of calculation is mainly determined by the type of mathematical model with the required degree of accuracy of the obtained results, which has disposable computing resources. The mathematical formulation of the mode's management tasks of power system determines the application of the methods of nonlinear programming for their solution. Among the most common of them are the method of Lagrange Multipliers, various modifications of the gradient method, the Newton second order, etc. The review of the application of this group of methods is quite effective in most cases, but they still have a number of disadvantages that limit their field of application, and reduces efficiency. For example, the Lagrangian method works well for smooth unimodal functions. In cases where all calculation of variables of derivatives are not a serious problem, this approach is also the most efficient [2, 6, 14, 18, 20, 26].

At the same time, the Lagrange method has several significant disadvantages that limit its field of application. First of all, it should be noted that there is a general lack of nonlinear programming methods – a requirement for differentiable functions. This is directly reflected in the computational cost of solving the problem, if possible to determine the partial derivatives of functions. Further, it is a necessity to note that the Lagrangian method does not allow optimization problem with constraints in the form of inequalities to be solved, which is not typical for real problems in Power Systems.

Among the main features of the gradient method it is necessary to allocate that it is fast enough for solving optimization problems, although its convergence depends on the choice of the initial approximation [14, 15, 18, 20, 7, 28]. The disadvantage of this technique is that it does not guarantee the optimality of the found solution. This method is ideal for application in so-called unimodal problems where the objective function has only a local extremum. Another disadvantage is the presence of additional changes in accounting inequality constraints. For this purpose, it is expected together application of the basic method with the penalty function method. Separately should be noted the complex procedure for the computation, because of differentiation of the objective function and as a consequence, the complexity of its implementation.

Another representation of the iterative algorithms, the Newton method of a second order is sufficiently accurate, universal, and characterized by high speed [21, 27-29]. At the same time, the method does not work with a very unsuccessful initial approximation, as well as volume calculations in Newton's method at each step is much more, for example,then in the methods of the first order.

Summarizing the above-mentioned we can select some differences that are typical for most traditional methods:

- sensitivity to the initial approximation for solving the problem,
- the presence of additional requirements for the mathematical model of the problem in the form of continuity, differentiability, and unimodal optimization criterion.

- implementation of a complex calculation procedure due to the differentiation of the objective function,
- the inability to determine a global extremum of the function.
- depending of the type of constraints of the problem that to be taken into account.
- poorly adaptance for problems with the discrete nature of the variables, etc.

The presence of these and other disadvantages causes the necessity to use and research new non-traditional methods for solving optimization tasks. Therefore, in this research, solutions of technical problems with the help of FACTS devices and evolutionary algorithms were considered.

1.3 Justification of the application of genetic algorithms in the Power systems

In the electrical power industry typical practical task's are usually multimodal and multidimensional. There is no universal method for it that would allow finding a quick solution that will be close to the optimal.Therefore, the aim of research is to find an approach that would be better answered to all requirements imposed on them. Genetic algorithm is precisely presents this combined method. The mechanisms of crossover and mutation in some ways are implementing exhaustive part of search method, which allows to use it in tasks that having a combinatorial nature and selection of the best decisions – gradient descent, which determines the sufficiently high speed of the algorithm. Such combination enables to provide a stable and good efficiency of the genetic search for all types of tasks.

The genetic algorithms (GA) in various versions currently find a huge number of different applications in many scientific and technical problems [30-33].

Modern computer technology and new programming techniques allow the implementation of quite complex, but at the same time powerful algorithms, to which also includes GA. Through this it is possible to calculate the existing in most human activity areas tasks, which solution by using the classical methods was difficult.

In the power sector, have been made attempts using genetic algorithms to solve the problem, associated with management, optimization and planning modes of electric power systems. It is shown that any complex optimization problem can be effectively solved by the methods of genetic search.

The essential feature of the considered approach is that it is applicable not only as a fundamental method. Therefore, one of the trends of the application of genetic algorithms is their combination with classical methods. Below is a brief overview of some electricity problems whose solution showed a clear advantage of using evolutionary algorithms.

Optimization development of energy systems

The problem of optimal development of the electrical system has a dynamic nature because the requirements for the transmission of electric energy is changing over time. In this case, the problem is often simplified to planners to solve it in statics. Thus, the goal of development optimization is to minimize the costs for the construction of new transmission lines with operating restrictions and compliance grids.

In [34-38], this problem is considered as a multidimensional nonlinear discrete optimization problem, which requires the use of heuristics and combinatorial algorithms, such as evolutionary algorithms, because they can provide the best solution in comparison with classical optimization methods.

Calculation of steady-state regimes in Power systems

Examples of the application of genetic algorithms for the calculation of steady-state modes of electrical systems are extremely small. From the know papers may be noted studies that conducted by scientists group Artificial Intelligence and Power Systems. In [39, 40], this problem is presented as an optimization problem: minimize the total imbalance of active, reactive power and voltage.

The proposed algorithm has several advantages, namely: insensitivity to initial approximation, the ability to find the set of solutions of the steady-state, as well as the possibility of finding a solution to weight mode. At the same time the use of a simple genetic algorithm does not lead to a zero total unbalance. The authors suggest several effective, as shown the results, methods of avoiding this disadvantage and, moreover, improve the performance of the algorithm.

Economic dispatch in power systems

Due to attention been focused on environmental pollution in recent years, the problem of economic dispatching of thermal power plants received a special importance. It consists in minimizing the cost of producing electrical energy while limiting the marginal harmful emissions. At the same time it is necessary to take into account mode's limitations of energy systems. The given problem has nonlinear feature. Methods with application of the Lagrange multiplier as the gradient methods do not allow to find the global optimal solution. The [41] application of evolutionary computation for economic dispatching, which allows operating with flow characteristic of power units of various forms and any kind of impact on the environment.

Mode's optimization of Power System according to reactive power

Optimum planning of mode's in Power System for reactive power is to determine the location and capacity of compensating device which installation provides minimal costs under given constraints. The purpose of the task is to find a solution that provides maximum economic benefits in compliance with all technical conditions of normal operation of power grids and power receivers. In some cases, separately is considering the problem of optimal placement of capacitor banks [42, 43].

Global optimization methods such as genetic algorithms are used in different variations of the problem [44-47]. Genetic algorithm can operate both on discrete (binary and integer) variables determining the place of installation of new sources of reactive power, and with the continuous variables related to the power of CB.

Settings of the equipment parameters

With the wide application of voltage regulators and controllers of different types it stands the necessity for optimal setting of their parameters. This process should follow the changes in modes of power system because previously used settings can not correspond to new conditions of operation of power energy system. The settings in this case can be regarded as the optimization process, which makes it possible to hold it through the genetic algorithms. However, they are most often used as an auxiliary method in conjunction with other methods of artificial intelligence: FACTS systems and neural networks. [47]

Optimal placement of power flow control devices. Regulation of power flows along the lines of the electrical network provides a significant reduction in the cost of electric energy transmission on them. Thus the problem is to determine the optimal location of the available number of devices and getting economic efficiency from that event.

Using traditional methods of optimization is quite difficult task, because the variables, that are corresponding to installation site of regulating devices, are discrete. As a result, in recent years the application of genetic algorithms for solving this problem [32-37] as a method, based on representations of variants of the decision which lies the binary system (0 – no setup, 1 – there is a setting device in the line) has been considered.

Short-term planning of Hydro and Thermal power plants modes.

Evolutionary algorithms are used to determine the hourly plan for electric power generation in hydroelectric and thermal power plant [39-47]. The objective function of the optimization problem is to minimize the total operating costs of electricity generation on the power plant, while respecting various restrictions on the operation, as hydroelectric power stations, and the entire power system as a whole. Solution of the problem involves some difficulties, in particular related with the nonlinear relationships between the parameters of the problem, features of hydro-power plant operation, temporary factors, some of which are usually accounted as quality assumptions. Application of evolutionary algorithms, in contrast to other methods, can solve the problem without the usual simplifications.

The best results were obtained in collaboration of evolutionary methods with simulation of annealing and tabou searching as auxiliary methods that optimize the operation of the main – genetic algorithm [42].

These examples demonstrate that the technology of genetic algorithms applied in many areas. There is no doubt that the application of a genetic approach in other areas of human activity – it just a question of time.

2. METHODS OF RESEARCH

At different time’s of day distribution systems have different loading values. These changes of load can cause distribution feeders to be overloaded at sometimes and not loaded enough at others. The operating state of the distribution system is also shifting because of this load change. If the compensation is not quite enough, voltage at different noades goes out of nominal range and real losses on the feeders also are increasing, resulting in high operating cost of the power system.

Nowadays almost all distribution grids are using a low number of monitoring procedures. In particular with local and manual control of primary parameters like voltage regulators and without appropriate support for the system's operators.

At the same time there is an increasing interest to automate distribution systems and to improve their reliability, effectiveness, and service quality. The perfect state for power losses in an electric system should be around 4 to 7 %. For the developing countries it should be no bigger than 10 %. But the real situation is far from the perfect state. In developing countries the amount of active power losses is around 20 %, that is the reason why utilities in the electric part are very interested in reducing losses in order to be more competitive, since the electricity prices in deregulated markets are related to the system losses.

For the program of a controll the losses reduction in a distribution system it is important to use effective and strong computational steps that allow quantifying the losses in different grid elements to reduce power losses. [1]

The main aim of the transmission network is the delivery of electric energy and to combine power plants and load centers for minimizing the total power generation capacity and fuel cost.

For the procedure of delivering electricity to the loads with the minimum cost with a necessary percent of reliability it is possible to use transmission interconnections that allow a presence of sources, variety of loads, and adequate price for the fuel.

In case’s when the energy supply system is a compound of radial lines from local generators without being part of a big grid system, many generation resources would be needed to supply the load with the same reliability and the cost for electricity will be much higher.

With that perspective, transmission is often an alternative to a new generation resource. Less transmission capability means that more generation resources would be required regardless of whether the system is made up of large or small power plants. In fact small distributed generation becomes more economically viable if there is a backbone of a transmission grid. One cannot be really sure about what the optimum balance is between generation and transmission unless the system planners use advanced methods of analysis which integrate transmission planning into an integrated value-based transmission/generation planning scenario.

The power systems of today, by and large, are mechanically controlled. There is a widespread use of microelectronics, computers and high-speed communications for control and protection of present transmission systems; however, when operating signals are sent to the power circuits, where the final power control action is taken, the switching devices are mechanical and there is little high-speed control. Another problem with mechanical devices is that control cannot be initiated frequently, because these mechanical devices tend to wear out very quickly compared to static devices.

In effect, from the point of view of both dynamic and steady-state operation, the system is really uncontrolled. Power system planners, operators, and engineers have learned to live with this limitation by using a variety of ingenious techniques to make the system work effectively, but at a price of providing greater operating margins and redundancies. These represent an asset that can be effectively utilized with prudent use of FACTS devices on a selective, as needed, basis.

In recent years, greater demands have been placed on the transmission network, and these demands will continue to increase because of the increasing number of non-utility generators and heightened competition among utilities themselves. Added to this is the problem that it is very difficult to acquire new rights of way. Increased demands on transmission, the absence of long-term planning, and the need to provide open access to generating companies and customers, all together have created tendencies toward less security and reduced quality of supply. The FACTS devices is essential to alleviate some, but not all, of these difficulties by enabling utilities to get the most service from their transmission facilities and enhance grid reliability. It must be stressed, however, that for many of the capacity expansion needs, building of new lines or upgrading current and voltage capability of existing lines and corridors will be necessary.

An optimal power flow (OPF) approach is proposed to minimize the energy loss of the electricity network with reactive power and FACTS control, while satisfying the network operating voltage and thermal limits.

2.1 Optimization of Power Flow

Optimization of the steady-state power system can significantly contribute to streamlining in its operation. Within are solved partial tasks such as calculation of power flow in energy system, optimum distribution of active and reactive performances at the specified number of sources, delivering optimal selection of an aggregates required performance, determination of the optimal rotating reserves, optimizing quality indicators of electricity - the voltage and frequency, the choice of optimal structure (network configuration) of power system, or optimizing the development of the power system [12].

The efficiency of the power system operation is provided at two levels. In the first level, it is necessary to ensure maximum operating efficiency of the individual parts of the power system with the required operating mode, called the technological economy. The second level is necessary to ensure the optimal cooperation of individual parts of the system, which is called mode economy. This is therefore the determination of the operation of the power system in which the maximum technological efficiency of individual cells gives maximum economic efficiency. This mode ensures optimal performance of distributing the power system load to the various sources of production and optimizing the transmission and distribution of the energy system [12].

2.1.1 Optimization task formulation

The optimum decision of the optimization task should be known [13]:

a) the mathematical model of the object of provided operation,

b) the objective function,

c) marginal conditions (limiting conditions).

Minimization task can be written in the following way:

$$f(x) \rightarrow min, x \in X \tag{2.1}$$

In this case f is called the objective function, X is the set of admissible solutions and each of its element x is called a feasible solution.

Mathematical model of the operation object – the mathematical model uses mathematical description to describe the behavior of the system. Compilation task and its mathematical formulation form a challenging part of the optimization process.

Objective function – also called target function it formulates a mathematical goal of optimization. The variable x, is the parameter that affects the function of the target. If variable x_j(for j=1, 2, .., n) may change continuously on the entire axis of real numbers ($D_j = \{x_j, -\infty \leq x_j \leq \infty\}$)then the problem is called a continuous task. If all the D_j are discreet group, it is going to tell about discrete task.

In most cases, through the optimization process goes about finding the minimum target of function. In case,if instead of minimizing task is envisaged the maximization task $f(x) \rightarrow max$, it is equivalent to the task $-f(x) \rightarrow min$.

Marginal conditions (limiting conditions) – limiting conditions of inequality type generally entrap the physical capacity limitations in the possibilities and limitations of the standard. The condition is formulated in that way that a physical quantity should be placed at intervals defined limits. [14]

2.1.2 OPF-Active Power Loss Minimization

Minimization of active power losses is usually used if the main aim is the minimization of costs controlled by varying the value of active power generators. If the minimization of fuel costs were used for all controllable variables the next minimization would not have brought further improvement.

If the cost minimization is provided only with the active power generation like a control variable, the followed minimization of losses uses a several numbers of variables that can be controlled and can be used to achieve better voltage level and a lower current flow through the lines.

Minimization of losses is graphically represented in Figure 1, where it is demonstrated that the process is trying to minimize the square of the distance between two vectors that are connected via a line. In Figure 1 we can see that in loss minimization both magnitudes and phase angle of voltage vectors across each line, are minimized. There are two approaches to the minimization process, one of them is the approach of the slack bus and the expression of active power as the sum of losses on all lines. The approach of the slack bus is the less complicated, where generation is minimized in the slack bus.

In this case, the objective function is linear and can be resolved using any method of linear or non-linear programming. The disadvantage of this approach is that it is possible to minimize only the total active power losses in the ES (it can not be used to reduce losses in a specific area of ES). The second approach does not have this disadvantage, but it is, more difficult for calculation. The objective function is more complicated, nonlinear, and its optimization is usually used for nonlinear programming [2].

The optimization process of active power losses in the ES is usually controllable by the following variables:

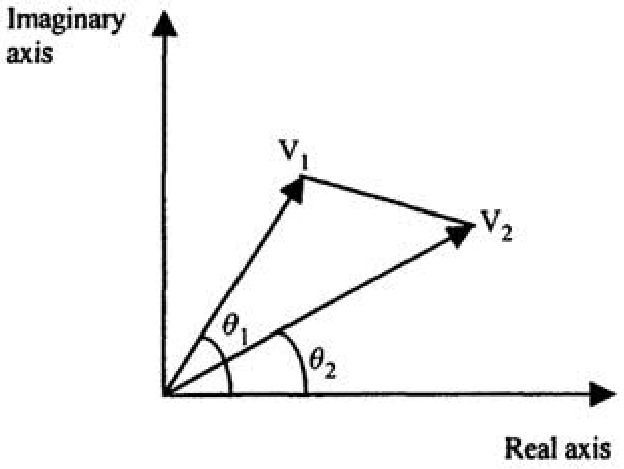
- the voltage values on the generator,

- the values of taps on transformers,

-the connection of parallel capacitors and reactors,

- angular regulation of phase.

Figure 1 – Graphical representation of loss minimization [2]



2.2 Mathematical description of the objective functions for loss minimization

The mathematical description of the objective function for minimizing losses of active power in ES is based on the expression of active power losses as a sum of active losses in all lines, transformers, and in particular parts of lines (or the whole system) where the active power losses are minimized. Therefore thus approach of the slack bus to minimize active power losses further is not considered. Power losses represent the difference between performances and generator power loads.

$$\Delta\dot{S} = \sum_{i=1}^{n} \dot{S}_i = \sum_{i=1}^{n} \sqrt{3}\,\dot{U}_i \dot{I}_i^{\,*} = \sum_{i=1}^{n} \dot{U}_i \sum_{j=1}^{n} \dot{y}_{ij}^{*}\, \dot{U}_j^{\,*} \tag{2.2}$$

$$\Delta\dot{S} = \sum_{i=1}^{n}\sum_{j=1}^{n} U_i\,(cos\delta_i + j.sin\,\delta_i).\left(g_{ij} + j.b_{ij}\right).U_j\left(cos\delta_j - j.sin\delta_j\right) \tag{2.3}$$

$$\Delta\dot{S} = \sum_{i=1}^{n}\sum_{j=1}^{n} U_i\,U_j\left(g_{ij} + j.b_{ij}\right)\begin{bmatrix}\left(cos\delta_i\,cos\delta_j + sin\delta_i\,sin\delta_j\right) - \\ -j.\left(cos\delta_i\,sin\delta_j - sin\delta_i\,cos\delta_j\right)\end{bmatrix} \tag{2.4}$$

$$\Delta\dot{S} = \sum_{i=1}^{n}\sum_{j=1}^{n} U_i\, U_j\left(g_{ij} + j.\, b_{ij}\right)\left[\cos\left(\delta_i - \delta_j\right) + j.\sin\left(\delta_i - \delta_j\right)\right] \tag{2.5}$$

Equation (2.2) represents total power losses in the Power System with n nodes as a delivered sum and taken of total power in the various nodes ES. The function of active power losses in the ES is the real part function of the total power losses in ES:

$$\Delta P = \mathrm{Re}\left(\Delta\dot{S}\right) = \sum_{i=1}^{n}\sum_{j=1}^{n} U_i\, U_j\left[g_{ij}\cos\left(\delta_i - \delta_j\right) - b_{ij}\sin\left(\delta_i - \delta_j\right)\right] \tag{2.6}$$

Where:

$\dot{S}_i[VA] -$ complex power flow at node *i*,

$\dot{U}_i[V] -$ voltage in *ith* node,

$\dot{U}_i^*[V] -$ complex conjugated value of voltage in the *jth* node,

$\delta_i, \delta_j[°]$ –voltage angles $\dot{U}_i$ and $\dot{U}_j$,

$\dot{y}_{ij}^*[S] -$ complex conjugated value of the element of nodal admittance matrix,

$\dot{y}_{ij}[S] -$ element of nodal admittance matrix,

$\dot{g}_{ij}, \dot{b}_{ij}[S] -$ real and imaginary part of the element $\dot{y}_{ij}$,

$\dot{g}_{ij}[S] -$ real part of the element $\dot{y}_{ij}$,

Restrictive conditions in the present equation represents the balance of active and reactive power in the network:

$$\sum_{k=1}^{N_g} P_{gi} - P - \Delta P = 0 \tag{2.7}$$

$$\sum_{k=1}^{N_g} Q_{gi} + \sum_{j=1}^{N} Q_{cj} - Q - \Delta Q = 0 \tag{2.8}$$

Where:

$P_{gi}[W] -$ active power supplied by *ith* generator,

$P, Q[W, VAr] -$ the sum of all active supplier's, respectively reactive power in the network,

$\Delta P[W] -$ active losses,

$\Delta Q_{gi}[VAr] -$ reactive power supplied by *ith* generator,

$\Delta Q_{ci}[VAr] -$ reactive power supplied by jth capacitor,

$\Delta Q[VAr] -$ reactive losses in network.

Restrictive conditions in the form of inequality represent the physical limits of equipment in ES, as well as restrictions to ensure the security of the ES. These restrictive conditions are:

Voltage values in nodes – represent max. and min. permitted levels of voltage in the individual nodes of ES within the tolerance limits.

$$U_{i-min} \leq U_i \leq U_{i-max} \qquad i = 1, \ldots n \tag{2.9}$$

Where, *Ui-min*, *Ui-max*[V]-min a max permited voltage value in i-th node.

Active power generation in generators in ES - active power supplied by each generator in ES is limited to its maximum and the minimum value [1]:

$$P_{gi-min} \leq P_{gi} \leq P_{gi-max} \qquad i = 1, \ldots N_g \tag{2.10}$$

Where:

Pgi – unit MW generated by *ith* generator,

Pgi-max – specified maximum MW generation by *ith* generator,

Pgi-min – specified minimum MW generation by *ith* generator,

Ng – number of all generators.

Reactive Power Generation in generators in ES – reactive power supplied by each generator in ES is limited to its maximum and minimum value:

$$Q_{gi-min} \leq Q_{gi} \leq Q_{gi-max} \qquad i = 1, \ldots N_g \tag{2.11}$$

Where:

Qgi-max, *Qgi-min* – specified maximum MW generation by *ith* generator, *Generation of reactive power by capasitors to ES* – restriction represents the maximum and minimum value of reactive power supplied via the capacitors in the EC.

$$Q_{cj-min} \leq Q_{cj} \leq Q_{cj-max} \tag{2.12}$$

Where,

Qcj-max, *Qcj-min* – specified maximum MW generation by *ith* capacitor,

The values of taps on transformers – restriction represents the minimum and maximum possible setting turns in transformers,

$$\tau_{i-min} \leq \tau_i \leq \tau_{i-max} \tag{2.13}$$

Thermal constraints of all transmission lines – max. power flow through the conduit shall not exceed the maximum value,

$$|S_i| \leq S_{imax} \qquad i = 1, \dots, N_L \tag{2.14}$$

Where,

S_i [VA]: the complex power flow at line *i*,

$S_i max$ [VA]: the maximum complex power flow at line *i*,

N_L [-]: number of transmission lines in a system.

2.3 Optimisation methods

At the present time there are many optimization algorithms, each of which is suitable to solve a different kind of the problem. Therefore, it is important to determine the characteristics of the present problem to be satisfied with the chosen method to solve it. For each group of problems, there are various minimization methods, differing by the calculation requirements, the convergence properties, etc. Optimization problems are characterized by objective function, limits and control variables. Probably the most important thing is to know the nature of the objective function. [1]

Table 1 – Classification of the objective function

Characteristics	**Features**	**Insertion**
Number of control variables	One	No-dimensional
	More then one	Multivariate
Type of control variables	Modulating real numbers	Modulating
	Whole numbers	Discrete
Function	Modulating real and total numbers	The combined numbers
	Linear fiction of control variables	Linear
	Quadratic function of controlled variables	Quadratic
	Other nonlinear functions	Nonlinear
Formulation of problem	Bounded	Bounded
	Not bounded	Not bounded

There are many types of optimization methods (according to various parameters), then we see only one of them:

a) Optimization methods based on classical methods

b) Optimization methods based on evolutionary techniques

Classical optimization methods have certain disadvantages compared to the evolutionary algorithms (eg. the length of computing time complexity of the algorithm). This makes evolutionary algorithms more popular and they do not require detailed information about the problem solution.

Choice of the appropriate method depends on the type of solved problem. Some optimization techniques are more difficult to calculate than others, and therefore the time it takes for the calculation is the important criterion. The time needed for the calculation changes according to the knowledge of the problem. All optimization techniques have their own internal parameters that must be tuned to achieve the best performance.

2.3.1 Classical optimization methods

Classical optimization methods are based on computational techniques and random techniques. These methods function well to solving applicable problems, but there are certain limitations to these methods. Some are unable to ensure that solutions have become trapped in a local optimum. Another disadvantage is that they require all information about the target function according to each variable, and it is necessary to know the nature of the function. Also they assume that the function is continuous. Because of these characteristics, classical methods are not appropriate for a number of problems in real life, where there is sufficient information on the mathematical model of the system relative on parameters and other information. [1]

Optimization methods that are included in the Optimal Power Flow (OPF) can be classified based on boptimization techniques that use:

1. linear programming,

2. nonlinear programming,

3. integer programming,

4. separable programming,

5. combined integer programming.

Linear programming is especially recognized as a reliable technique for solving a wide spectrum of specialized optimization problems characterized by linear objectives and constraints. The number of programs available for solving optimization problems in the ES for planning or operations comprises linear programming.

2.3.2 Evolutionary techniques

The development of computer technology and the increasing complexity of optimization problems in ES has led to the necessity of a specialized application of programming techniques for large-scale problems. These include dynamic programming, lagrange multipliers, heuristics techniques and evolutionary techniques such as genetic algorithms. These techniques are often in conjunction with other intelligent systems incorporating artificial neural networks, expert systems, tabu search algorithms and fuzzy logic.

Several heuristic tools have been developed to facilitate solutions for optimization problems that were previously very difficult to solve, or even unsolvable. They include evolutionary computing techniques, simulated annealing, a tabu scan, swarms of particles (Particle Swarm Optimization) and so on. These new heuristic tools are combined with each other and with traditional approaches such as static analysis, in order to solve extremely difficult problems. Development of solutions to these instruments offers two main benefits. [1]

1) The calculation time is shorter than with conventional approaches.

2) Systems are robust and are relatively resistant to interference or possible data loss.

Heuristic techniques are suitable candidates for dealing with crawled space solutions that are large and non-linear. Furthermore, two methods of evolutionary computing, genetic algorithms and the swarm of particles (Particle Swarm Optimization) will be described.

2.3.3 Genetic Algorithm

The genetic algorithm (GA) is a search algorithm based on natural selection. GA functions are different from other search techniques in several aspects. The algorithm is multi-path, looking for several peaks, in parallel, thus reducing the possibility of being trapped in a local minimum. In addition, the GA works with encoding parameters instead of their parameters. This helps genetic operators to evolve from the existing situation to the next with the minimum amount of calculations. GA needs to evaluate the objective function to direct its search.

At the beginning of the optimization process with the help of GA there are possible solutions set out which are encoded as members of the population. There are several ways to encode solution features e.g. binary, tree coding. Crossover and mutation operators based on reproduction are used to create a new population. Crossover combines solution elements in the first generation of elements to create the next generation. Mutation systematically changes solution elements from the original generation to create a new generation of members. Crossover and mutation research carried out by investigating the scope for creating diversity in the members of the next generation.

The use of GA was based on the fact that the algorithm will examine more areas in the studied area in order to find the global minimum. GA is suitable for the examination of complex, strongly nonlinear space because it can prevent them from being trapped in a local minimum. GA examines more solutions simultaneously. The GA approach is quite simple: [1]

1. randomly creates generation solutions,
2. evaluate the suitability of solutions,
3. if the iteration limits or time are not satisfied, then:
    - selection of parents (best solutions),
    - combining the parents, using parts of the original solution,
    - add possible random solutions,
    - suitability of the assessment solutions,
    - return to point 3.

Finding a multidirectional and GA requires a large number of iterations to converge slowly, particularly around the global optimum.

2.3.4 Particle Swarm Optimization (PSO) Algorithm

The method of particles swarms (particle swarm optimization (PSO)) is an interesting new methodology of evolutionary computational techniques. This method is a bit similar to the GA as the system is initialized with a random population of solutions. However, in contrast to other algorithms, each potential solution is assigned a random rate, which then passes through the problem area. It has been found that this method is very effective in dealing with a wide range of problems. Moreover, this method is very easy to apply, and the problem can resolve quickly. The PSO system, this group consists of all particles and all particles "overfly" multidimensional space. During the flight, each particle modifies its position based on its own experience and the experience of neighboring particles by exploiting the best position encountered by itself and its neighbors. Swarm direction of each particle is defined by a set of particles, their adjacent particles and their historical experience.

The main difference between the PSO and GA is that, that PSO has no genetic operators like mutation and crossover. The particles are updating themselves with a internal rate, also have the memory necessary for the algorithm. The PSO the best particle gives information to others. This uni-directional information sharing mechanism of evolution just looking for the best solution. All of the particles have a tendency to converge rapidly to the best solution. [1]

2.4 Possibilities of using new ways of voltage regulation

Flexible Alternating Current Transmission System (FACTS) are defined as AC transmission systems based on power electronics and other static controllers (not based on power electronics) or used to enhance controllability and increase power transmission ability.

The FACTS regulator is defined as a system based on power electronics and other static devices that provide control of one or more parameters of the AC transmission system. Among the adjustable parameters that can be known, are for example: voltage, current, impedance and phase angle.

2.5 The basic categories of FACTS

FACTS devices can be divided into four main categories[3]:

1. Parallel controllers
2. Series controllers
3. Combined series – series controllers
4. Combined series – parallel controllers

Parallel controllers - may regulate impedance (e.g. a capacitor or reactor) or regulate power supply based on power electronics with the appropriate frequency, or their combination. In principle, all parallel regulators inject current into the power system at the location of their connection.

Series controller – in the case of a parallel regulator, impedance regulated power supply or its combination may be adjustable. In principle, all series controllers are a voltage source connected in series with the line.

Combined series – series controllers – are availiable in two different versions.

The first version consists of a combination of coordinated, controlling, and separated series regulators connected to the line. The second case is a unified regulator in which the series regulator provides independent series reactive power compensation in each line and also the power flow of active power between lines in the one-way line connecting the regulators. Such vision is known as Interline Power Flow Controller and it allows control of active and reactive power flowing in the lines and thereby maximize this use of transmission capacity in the line [15].

Combined series – parallel controllers can also be in two versions.

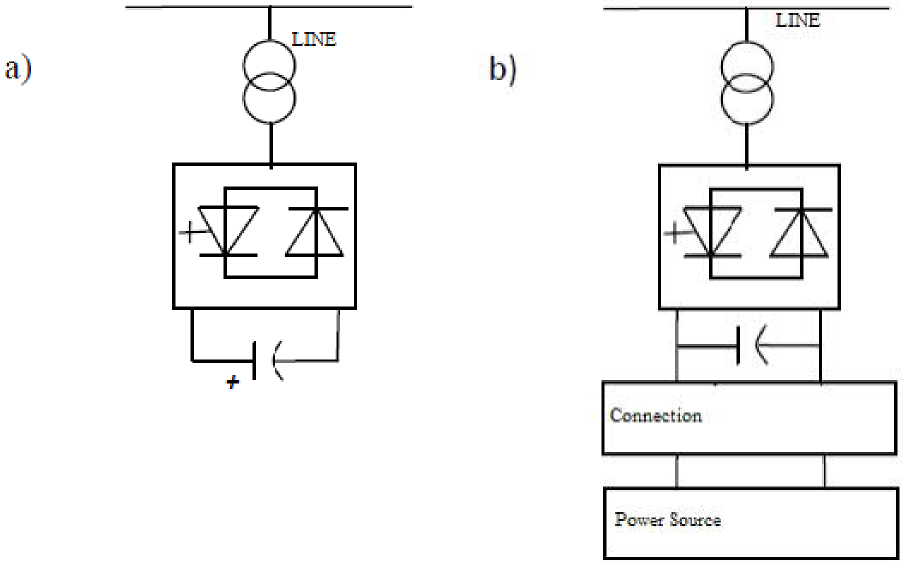
The first version is a combination of controlled separated series and parallel regulators. The second version known as the Unified Power Flow Controller (unified power flow controller), involves the combination of series and parallel controllers connected to the direct line. The advantage of the second version is that the series compensation and current injections into the system allow the active power exchange between the series and shunt regulators.

2.5.1 Parallel controllers

Static Synchronous Compensator (STATCOM) - Static synchronous generator operated as a parallel connected static var compensator, whose capacitive and inductive currents can be regulated independently from the alternating voltage in the system. It allows quick and accurately responds to the increase and decline of voltage in the system. Its function is similar to the rotary synchronous compensator; its benefits are better response speed, control accuracy, symmetric range ±Q, and it does not increase the short-circuit current in the ES [17].

Static Synchronous Generator (SSG)- The combination of the static synchronous compensator and energy source. This allows the regulation of the exchange of reactive and active power between the power system unit and the appropriate unit. The function of the power source in a static synchronous generator can perform for example, similar to battery, superconducting magnet or capacitor [17].

Figure 2 – Static synchronous compensator a) without power source, b) with power source [20]



Static Var Compensator(SVC) – Static Compensator of reactive power – Parallel connected static device or source of reactive power, whose function is the regulation of certain parameters in the system (usually it is voltage at the node in system). It is a universal name for thyristor control or switched inductor, capacitor or a combination thereof [17].

Static var compensators are constructed in many different designs, most of them consist of the following elements:

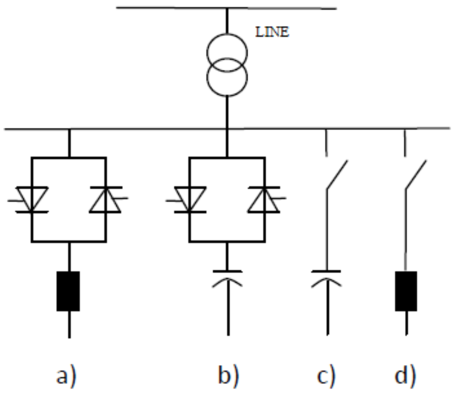
Thyristor Controlled Reactor (TCR) Reactive power can be changed continuously through the controlling of current through the inductor. Deformation of the current that flows through the device TCR is caused by switching thyristors and it leads to higher harmonics in this device. Multiples of the fundamental harmonic are dependented on the way thyristors are connected (triangle, star), their number (eg. 6-pulse, 12-pulse TCR) and from the mode of its operation. Filters of high harmonics operated in parallel with the TCR device are used for its elimination.

Thyristor Switched reactors (TSR) – In this case, the reactive power can be varied by switching reactors. TSR usually consists of several parallel-connected reactors, which according to their requirements are connected or disconnected from the system.

Thyristor Switched Capacitor (TSC) – Reactive power can be changed by switching capacitors. TSC usually consists of several capacitors connected in parallel, which according to the requirements are connected or disconnected to the system. In series the device connects the reactors to limit switching transients, damping surges and prevent resonances with inductive reactance of the network. By the appropriate use of TSC is possible to reduce the negative transients caused by switching [18].

Mechanical Switched Reactor a Mechanical Switched Capacitor (MSR a MSC)

Figure 3 – Static compensator of reactive power a) reactor cotrolled by thyristor and reactor switched by thyristor, b) condensator switched by thyristor, c) mechanical switched condensator, d) mechanical switched reactor [19]



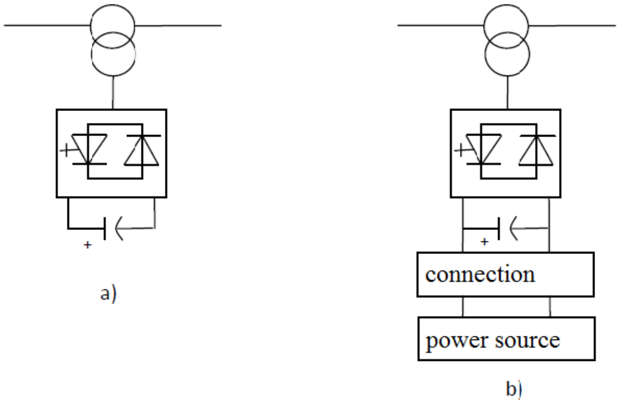
Thyristor Controlled Braking Resistor (TCBR)- Thyristor switched resistor (usually linear). It allows the stabilization of the energy system and reduces acceleration power a of generator during disorders. The best location of TCBR is near the generator, requiring an acceleration performance during transient unstable conditions.

2.5.2 Series controllers

Static Synchronous Series Compensator (SSSC) – In a static synchronous generator operated as a series compensator, the output voltage can be regulated independently of the current in the system. It allows to control of the power flow in both directions and absorbs oscillations. It is comparable to a controlled series capacitor, but is much more efficient and more accurate [3].

SSSC controller together with STATCOM controller is one of the most FACTS controllers.

Figure 4 – Static synchronous series compensator a) without power source, b) with additional power source [3]

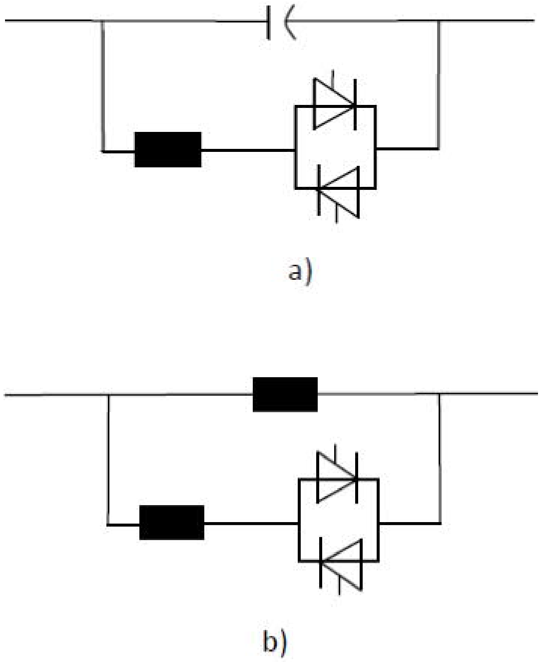


Interline Power Flow Controller (IPFC) - A combination of two or more static synchronous series compensators, which are interconnected by a one-way line for the purpose of two-way exchanges between the active power compensators. Compensators are controlled to regulate the flow of active power and maintain the required reactive power flow between the lines [3].

Thyristor Switched Series Capacitor (TSSC) – The compensator comprising thyristor controlled reactors (TCR), which is connected in parallel to the condensation. It provides discrete control of series impedance in line. Often TSSC configuration includes more capacitors, to which connected parallel thyristors in an antiparallel configuration. The degree of compensation is regulated in this case, in a discreet manner by increasing or reducing the number of capacitors that are connected to the system [3].

Thyristor Controlled Series Reactor (TCSR) - A Compensator consisting of reactors which are connected in parallel with thyristor controlled reactor (TCR). It provides full controll of series line impedance.

Figure 5 – a) Thyristor controlled series condensator and tyristor switched series condensator b) thyristor controlled series reactor and tyristor switched series reactor [3]


a)

b)

2.5.3 Combined series-parallel controllers

Unified Power Flow Controller (UPFC) – The combination of the static synchronous compensator (STATCOM) and a series synchronous static compensator (SSSC), which are interconnected by one-way line for bidirectional transfer between active power compensators. It provides voltage control, impedance and phase angle, in real time and in any combination. It enables independentl control of the flow of active power and reactive power in the line.

The basic functions of UPFC [3]:

a) voltage regulation,

b) series capacitive compensation

c) the regulation of the phase angle (in both directions) without changing the voltage.

d) flow control outputs or results from a combination of features a) b) c).

Figure 6 – a) Unified power flow controller, b) thyristor controlled transformator with angle regulation [3]

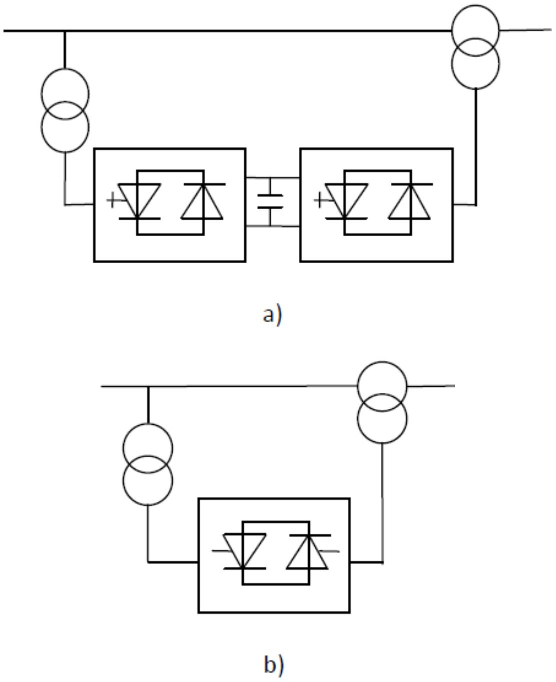


Table 2 – Application areas of FACTS devices [3]

Type of FACTS regulator	**Application area**
STATCOM without additional energy source	voltage control, reactive power compensation, damping oscillations, voltage stability
STATCOM with the additional energy source	voltage control, reactive power compensation, damping oscillations, static and dynamic stability, voltage stability
SVC, TCR, TSC, TSR	voltage control, reactive power compensation, damping oscillations, static and dynamic stability, voltage stability
SSSC without additional source of energy	current control, damping oscillations, static and dynamic stability, voltage stability, short circuit current limitation
SSSC with additional source of energy	current control, damping oscillations, static and dynamic stability, voltage stability
TCSC, TSSC	current control, damping oscillations, static and dynamic stability, voltage stability, short circuit current limitation
TCSR, TSSR	current control, damping oscillations, static and dynamic stability, voltage stability, short circuit current limitation
TCPST	active power regulation, damping oscillations, static and dynamic stability, voltage stability
UPFC	control of active and reactive power, voltage control, reactive power compensation, damping oscillations, static and dynamic stability, voltage stability, short circuit current limitation
TCVL	voltage limits during transient and dynamic storylines
TCVR	reactive power compensation, voltage regulation, damping oscillations, static and dynamic stability, voltage stability
IPFC	reactive power compensation, voltage regulation, damping oscillations, static and dynamic stability, voltage stability

Table 3 – Problem detection by FACTS devices [3]

Formulation	Problem	Corrective action	Convential solution	FACTS
Voltage levels	voltage drop at higher load	reactive power supply	underexcitation of generator, parallel capacitors, series capacitors	SVC, TCSC, STATCOM
	high voltage at low load	disconnection reactive power supply	turn off the line and / or parallel capacitor	SVC, TCSC, STATCOM
		absorbation of reactive power	turn off the parallel connection of capacitors or inductors	SVC, STATCOM
	high voltage as a result of failure	absorbation of reactive power	connection of reactor	SVC, STATCOM
		use of protection equipment	use od surge arrester	SVC
	low voltage as a result of failure	reactive power supply	connection of reactor	SVC, STATCOM
		overload prevention	series reactor, transformer with an angular regulation	TCPST, TCSC
	low voltage and overvoltage	reactive power supply	combination of two or more devices	TCSC, UPFC, STATCOM, SVC
Heating limits	overload of lines or transformers	overload reduction	connection of line or transformer	TCSC, UPFC, TCPST
			connection of series reactor	SVC, TCSC
	turn off the line	limitation of the line overload	connection of the series reactor	UPFC, TCSC

Circular flows	overload of parallel lines	correction of series reactance	connection of series reactor, change of power switch	UPFC, TCSC
		correction of phase angle	use of transformer with phase regulation	TCPST, UPFC
	change of power flow	phase angle correction	use of transformer with phase regulation	TCPST, UPFC
The level of short-circuit currents	exceeding the fault current circuit breaker	short-circuit limitation	series reactor connection	UPFC, TCSC
		change of power switch	change of power switch	-
		change of network connection	splitting of busbars	-
Sub synchronous resonance	potential damage of the turbines or generator	mitigation of oscillations	series compensation	TCSC

2.5.4 SVC

SVC is a FACTS device with the parallel connection consisting of a capacitor battery and a reactor that is controlled statically by thyristor switches. This device is used to regulate the voltage at the incorporation node [20]. The static reactive power compensator has been designed according to the principle of "internal control" mode of the electric network, which means the regulation of SVC passive elements that do not have their own EMF (capacitor batteries, reactors).

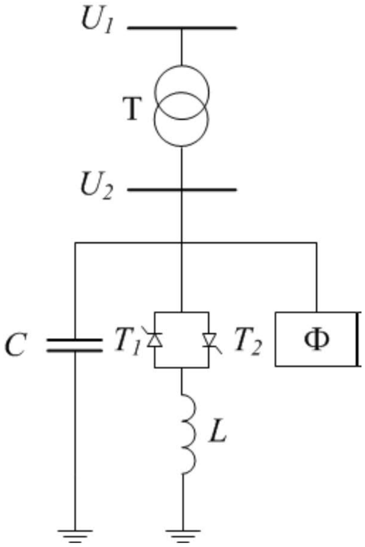
Depending on the managing cumulative electromagnetic field of energy elements, there are several schemes of the SVC [20]:

SVC – direct compensation. In this scheme, the equivalent resistance of the compensator changes discretely due to the stepped switching on the capacitor bank,

SVC – indirect compensation. This scheme is based on a smooth regulation of current through the controlled reactor (CR) and is shown in Figure 7,

Combined SVC, which is carried out for both principles.

Figure 7 – Sheme of SVC of indirect compensation [20]



Application of the SVC based on a controlled reactor allows a flexible approach to the problem of compensation of the reactive power to be found and reduces power losses in the electrical network. Speed operation of the SVC provides continuous generation or consumption of reactive power required to maintain a constant voltage on the network in different modes of its operation. The compensator is also able to damp power fluctuations.

At present, the scheme of indirect and combined compensation received the greatest application. Compared to the parallel connected capacitive battery, regulation of the equivalent resistance of the SVC, and, therefore, reactive power at its output, are carried out continuously. This is because the resistance of TRC, which is part of the static compensator, is continuously adjustable by changing the angle of the thyristor switch that is installed in series with the reactor.

Thus, it will gradually change the totall impedance of the SVC. In the proces, the reactor regulating its capacity will be reduced, and the resulting power of the compensator will have a capacitive character (if installed capacity of the reactor and the condenser batteries are equal) [17]. In order for the compensator to operate in reactive, power consumption mode, the installed capacity of the reactor must be greater than the installed capacity of the condensative battery.

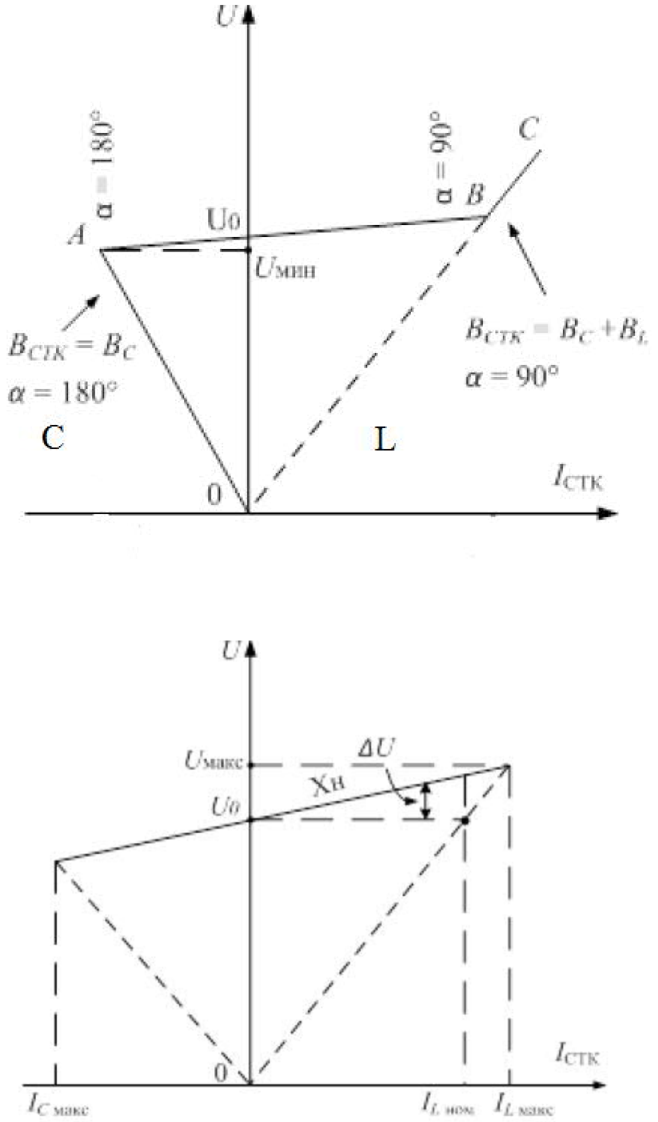
The volt-ampere characteristic of the SVC has an inclination, determined by the given conditions defined by precision voltage maintenance and the available capacity of the compensator. It helps to ensure the parallel operation of SVC.

The volt-ampere characteristic of the combined compensator or indirect compensation device is shown in Figure 8 [20].

There are three working areas that determine the functioning of SVC in the steady state:

1. range of regulation, which is supported by a predetermined value of the voltage at the node connecting to SVC. This area is determined by the operating point on the characteristic of AB as a result of generation or consumption of required reactive power;
2. the area of high voltage – BC, in which the compensator works as much as possible in the inductive mode similar to the non-regulated reactor;
3. area of low voltage – OA, where compensator works as much as possible in a capacitive mode, like the unregulated capacitive battery. It should be noted that in this mode for SVC the typical negative regulator voltage effect that is inherent to the capacitive battery.

Figure 8 – Volt-ampere characteristic of the SVC [20]



The boundaries of the regulation range are given by maximum values of current in capacitance and inductive modes. Reactance X_N corresponds to the slope of the volt-ampere characteristics of the compensator, and plays a major role in determining its produced characteristics. The bigger value of X_H leads to a significant change of the voltage at the node of the SVC connection. It is determined by an amplification factor of the voltage regulator in a steady state. Typically, the slope of U – I and static compensators are assumed to equal 1 ÷ 5 %.

The multifunctionality of SVC determines their reasonable application in networks, for solving a number of problems, such as:

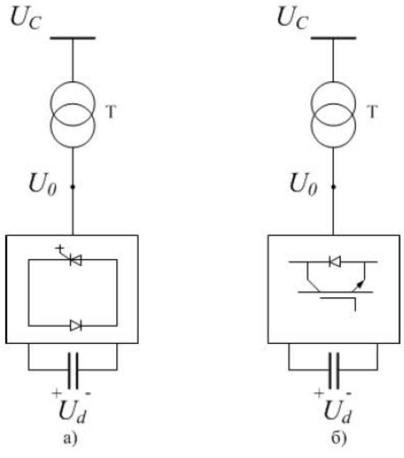
- reactive power compensation,
- increasing the transmission line capacity.

The problem reduces to provide voltage regulation and reactive power balance in an intermediate power transmission point [30, 32, 35]. If we install SVC in the middle of the line, it is possible to increase the capacity of transmission lines and reduced the value of the angle by half to ensure equal voltages at the beginning of the line and switching node of SVC. Such an increase of the line capacity will lead to a large increase in reactive power issued by SVC. Various compensators that are installed at intermediate points of the line divided into separate portions, which may lead to an increase of the power transmitted through the line by a multiplier of four [77]. However, its installation may not be appropriate on the basis of economic considerations.

2.5.5 STATCOM

STATCOM is a shunt unit which structure includes a voltage inverter with capacitive storage on the DC side, transformer, and control system. The sceme of a static compensator of the new generation is shown in Figure 9.

Figure 9 – STATCOM sheme a) with the tyristors GTO, b) with the transistors IGBT [20]



The compensator may be represented by a three-phase four-quadrant voltage converter, which is feeding from capacitor battery to the DC side, the system creates a three-phase voltage system in phase with the voltage in the network. This device can be associated with a synchronous compensator, which also creates a three-phase fundamental frequency voltage system controlled by the module.

Because of the similarity with synchronous compensators STATCOM is often called a static synchronous generator, which operates on the principle of external control mode parameters. In contrast to the synchronous machines, the new generation of static compensator has a high speed, which gives to them a "dynamic" operation.

The principle of STATCOM operation is based on the voltage change of gate windings. Depending on the voltage difference of the network and the power gate windings, static compensators can operate in inverting mode or in straightening and producing or consuming reactive power. It excludes the necessity of installation of high-power storage elements. If the voltage of network winding is bigger then the voltage of gate winding, then the static compensator consumes reactive power from the network, if it is less then it produces reactive power. Thus, the STATCOM is capable of providing both inductive and capacitive reactive power compensation. [20]

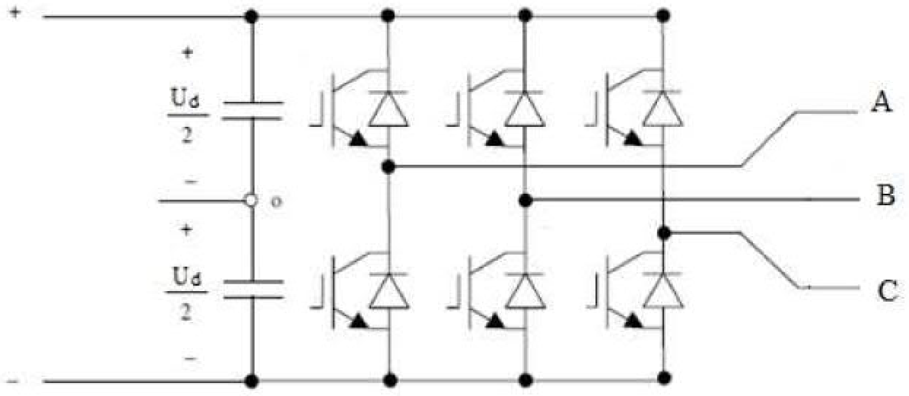
In principle, the static compensator provides the required reactive power, carrying out its exchange between the phases of the AC network. Generation or consumption of reactive power is the result of artificial switching completely controlled by gates. Installation of the capacitive storage of energy of the electromagnetic field is required under the terms of the electronic inverter key operation. However, the capacitor bank itself is not involved in the generation of reactive power, because of the frequency f = 0 Hz reactive power is zero. The role of the static compensator consists from of the combination of network phases, providing reactive power circulating between them. And the capacitor bank provides the circuit of reactive power flow and appears as a voltage source. If we consider that the purpose of the compensator is the generation or compensation of reactive power, the battery of capacitors that is installed on the DC side should not contribute to the generation of active power. However, STATCOM consumes a small amounts of active power for the losses compensation in the inverter elements and in the transformer.

Changing the voltage on the capacitor battery is accompanied by transferring converter to inverter or rectifier mode. To increase the voltage on the DC side, it is necessary to increase the charge on the capacitor, this means transfering the converter to the rectification mode (reactive power supply).

There are two available versions of voltage converters depending on their components. The first is based on the use of lockable thyristors GTO [81, 88]. The scheme of such a converter operates on the principle of the alternating switch, in which the valves of each phase are switched alternately with a certain interval. As a result, the converter creates a step voltage on the AC side.

In the second case, the voltage of the inverter circuit is based on the power transistors Figure 10. The principle of operation of the inverter is based on the pulse width modulation (PWM). It should be noted that the effectiveness of converter equipment depends on the modulation methods. PWM is a very popular technique of modulation due to the its flexibility, high performance and simplicity of digital performance. PWM creates pulse signals of one frequency and a variable duty cycle that allows the output voltage of any shape to be obtained. Using this modulation technique in a voltage converter provides a practically sinusoidal voltage on the AC side at the expense of modulation coefficient changes [20].

Figure 10 – Three-phase two-level converter scheme [20]



For high power systems and high voltage, voltage converters with three-phase multi-level circuit configuration there are installed. In other cases, voltage converters use a three-phase two-level circuit switching scheme [20]. STATCOM has vector control as a functional feature. It is the ability to simultaneously change the compensator module and the phase of the voltage, which underlines the superiority of the device over the SVC.

If we install energy storage on the DC side of the voltage converter, the STATCOM can be viewed as a source of active power. Thus storage can serve as a superconducting inductive energy storage (SPINE).

The volt-ampere characteristic of the STATCOM is shown in Figure 11 [20]. It confirms the ability of the compensator to operate with the overload in a capacitive or in an inductive mode. The maximum current generated by static compensator in a capacitive mode during large disturbances is determined by the maximum amount of current that can be commutate controlled valves of the converter. By reducing the voltage, STATCOM will generate the same reactive power due to overcurrent, increasing the limit of dynamic stability. While the power generated by the SVC will decrease in a square function of voltage. This indicates the STATCOM advantage over SVC, regarding operation in transient conditions caused by great indignation.

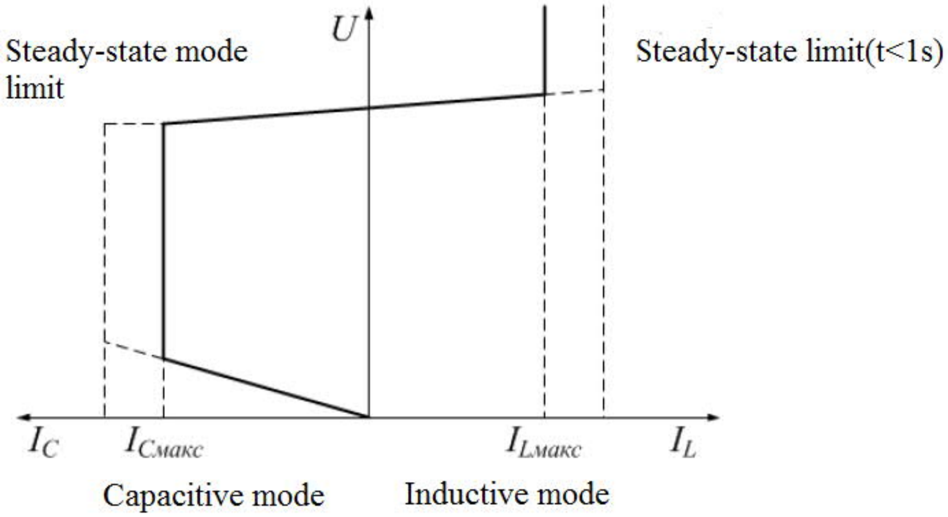
In steady-state modes operation of the EPS, both devices are equal. From a technical point of view, the difference between them is due to the influence of transients modes. For adequate comparison of SVC and static compensators of the new generation we need to take into account more criteria to assess their effectiveness.

STATCOM is able to solve all the tasks assigned to the SVC, but has a great advantage, based on technical specifications. Time of the response time of the STATCOM is much less than SVC. The speed of these devices can be characterized by the time constant switching of power switches. This, as shown in figure 11, is about 200 ÷ 350 ms for the second generation compensator and about 2,5 ÷ 5 ms for the compensator of the first generation. Installation of STATCOM is less than the installation of the SVC due to lack of storage elements. This allows the efficient use the territory of the substation, especially in urban environments. The use of the pulse width modulation (PWM) content of parasitic harmonics in phase current is very small, which eliminates the need for powerful filter compensative-devices in the STATCOM circuit.

Power losses in the ordinary thyristors are smaller than in the transistors or lockable thyristors that are used in the circuit of the voltage converter. However, the amount of total losses in both compensators is approximately 1,0 % during operation at rated power [55, 83].

One of the main evaluation criteria of the described compensators is their specific value, which is 45 ÷ 49 $ / kW for STATCOMs and 30 ÷ $ 34 / kW for SVC. Lower cost of a SVC of the first generation gives it a great advantage against STATCOMs.

Figure 11 – The volt-ampere characteristic of the STATCOM [20]



3. CURRENT HARMONIC SPECTRA OF INDIVIDUAL POWER CONSUMERS AND THEIR AGGREGATION

There are currents in neutral conductors for feeding non-linear consumers. The appearance of these currents, due to the lack of phase shift at higher harmonics are multiples of the three and fundamental frequency. In some cases, the RMS current in the neutral conductor may reach 1.5-2 times higher than in the phase conductor [84]. Overloading of neutral cable conductor caused by higher harmonic currents leads to a further increase of temperature above the limit of provided by the manufacturer, which accelerates the insulation aging of the cable and therefore reduces its lifetime [82, 83]. Current harmonics cause additional heating of the equipment; this should be taken into account for selection the conductor cross-section size and control allowable currents during operation [85].

To determine the possible effect of higher harmonics on cable lines it is necessary to assess the levels of interference caused by nonlinear electro receivers individually and collectively. For this purpose, there were performed experiments under certain types of power appliances with nonlinear voltage-current characteristics, which are most commonly used in residential and administrative buildings. The results show that these types of power appliances create high levels of distortion in the current waveform (third harmonic level reaches 80…90 [%], the fifth reaches 45 [%]), while all the above power-consuming equipment comply with the standard for emissions higher harmonic components of electro receivers with consumption current less than 16 [A] [86], and therefore can be freely used by consumers in the country. Thus, the requirements of the standard [86] can’t provide such levels of higher harmonics, which do not affect the electricity network. Measurements were performed on real objects (shopping center, specializing in the sale of computer equipment, office building and houses) to determine the possible values of current harmonic and spectra. The results are shown in Table 4. These spectra were used to calculate values for the correction factors for specific types of nonlinear consumers.

Table 4 – Range of harmonics current to different types of consumers to the maximum load

Number of harmonic	Shopping center I(n), [%]	Administrative building I(n), [%]	Residential building I(n), [%]
1	100,0	100,0	100,0
3	31,2	29,3	10,3
5	18,5	13,9	6,3
7	12,7	10,2	4,8
9	8,6	15,2	5,5
11	5,4	9,5	4,6
13	3,2	8,2	3,2
15	2,7	3,9	1,9
17	1,7	4,6	-
19	1,1	2,2	-
21	0,7	1,4	-

The flowing of non-sinusoidal current through the phase conductor of cable generates heat; power is determined by the loss of active power at the fundamental frequency and high harmonics [86]:

$$P_{\Sigma}^{ph} = I_1^2 \cdot R_1 + \sum_{n=2}^{40} I_n^2 \cdot R_n \tag{3.1}$$

where I_1 and I_n are currents of the fundamental frequency and high harmonics, R_1 and R_n – resistance at the fundamental frequency and high harmonics.

There are flowing harmonic currents of zero sequence in the neutral conductor under condition of balanced nonlinear load. This releases heat is power source, which is determined by the following formula:

$$P_{\Sigma}^{ph} = 3\sum_{n=3,9,15} I_n^2 \cdot R_n \tag{3.2}$$

Active resistance of the conductor on the n-th harmonic (R_n) in (1) and (2) for $n \geq 3$ is defined by the formula [9]:

$$R_n = R_1 \cdot (0.187 + 0.532 \cdot \sqrt{n}) \tag{3.3}$$

where R_1 is the resistance of the conductor at the fundamental frequency currents, n is number of the harmonic. The generated heat inside the cable, which is laid in the ground, is transmitted by the phenomenon of thermal conductivity into the surrounding space. The steady heat cable mode is described by Kirchhoff Law equation:

$$\alpha \cdot \nabla^2 T = 0 \tag{3.4}$$

where ∇ is the Laplace operator. To develop a mathematical model for the study of the cable and thermal processes in it under the influence of harmonic currents that determine the capacity of cable lines, the most common types of cables were chosen and for each of them was composed mathematical model in the software Elcut [10]. Using this program we calculate the temperature field of the cable according to the equation (4) for the stationary mode using the finite element method.

3.1 Method for Determination of Ampacity Reducing due to Harmonics

General active power losses in the cable are the sum of tripled active power losses in the phase conductor and losses in the neutral conductor. Using the algebraic manipulation and formulas (3.1) - (3.3), we get the formula of general active power losses in the cable into a form which differs from the loss at the fundamental frequency, only the additional loss factor (K_{add}).

$$P_{\Sigma} = 3 \cdot I_1^2 \cdot R_1 \cdot K_{add} \tag{3.5}$$

$$K_{add} = 1 + \sum_{n=2}^{40} (K_{I_n})^2 \cdot A_n + 3 \cdot \frac{R_1^n}{R_1} \sum_{\substack{n=6k-3 \\ n=3,9,15}}^{40} (K_{I_n})^2 \cdot A_n, \tag{3.6}$$

where K_{I_n} the current value of n-th harmonic component as a fraction of the current fundamental frequency, $A_n = 0{,}187 + 0{,}532 \cdot \sqrt{n}$

Then, we introduce the concept of an equivalent current (I_{eq}). Equivalent current is the current of the fundamental frequency which flows through the three conductors and it generates the same amount of heat as through a non-sinusoidal current flowing in the three conductors and the neutral conductor. By their energy essence, the notion of an equivalent current is the transition from four sources of heat (three cores and neutral) to the three sources (three conductors), and it is assumed that all heat from power distorted currents is replaced by an equal value of active power losses created by the current at fundamental frequency, as in terms of energy no matter which of the current heats the conductor: 50 Hz sinusoidal or non-sinusoidal. Given entered term formula can be written as:

$$P_{\Sigma} = 3 \cdot I_1^2 \cdot R_1 \cdot K_{add} = 3 \cdot I_{eq}^2 \cdot R_1 \tag{3.7}$$

where $I_{eq} = I_1 \cdot \sqrt{K_{add}}$

As a result, the desired correction factor to the permissible continuous current of the fundamental frequency (K_{hh} is factor of higher harmonics), which recognizes the influence of harmonic currents flowing through the cable is:

$$K_{hh} = 1/\sqrt{K_{add}} \tag{3.8}$$

This ratio is intended for selecting the power cable, as a correction value of permissible continuous currents to prevent overheating of the cable insulation. For the RMS value of the current it is better to use other coefficient K_{n-1}, which value is determined by the formula:

$$K_{n-1} = K_{hh} \cdot \sqrt{1 + \sum_{n=3} (K_{I_n})^2} \tag{3.9}$$

3.2 Example of correction coefficients calculation

Power cable ASB 4x150 feeds nonlinear load (shopping center). It is necessary to determine the value of the allowable long-term current at the fundamental frequency, RMS value currents in phase and neutral conductor and the coefficient of higher harmonics in which the cable insulation does not overheat. Phase current harmonic spectrum is shown in Table 4.

Resistance of cable conductor:

$$R_1 = R_1^n = 0{,}243\ \Omega/km$$

Manufacturer value of permissible continuous current is [11]:

$$I_{perm}^{old} = 281 \text{ A}$$

From the known spectrum of harmonics initially determined by the necessary formula (3.6), components: An,K_{In}^2, as well as their sum of the harmonics of zero sequence occurring at neutral, across the spectrum of the current phase in the conductors.

These amounts equal to:

$$\sum_{n=2}^{40}(K_{I_n})^2 \cdot A_n = 0{,}2045; \sum_{\substack{n=6k-3\\ n=3,9,15\ldots}}^{40} (K_{I_n})^2 \cdot A_n = 0{,}1229$$

Further the calculated K_{add} coefficient, using formula (3.6), is:

$$K_{add} = 1 + 0{,}2045 + 3\frac{0.243}{0.243} \cdot 0{,}1229 = 1{,}573$$

With the known level of magnification of additional losses K_{add}, determination of the correction factor K_{hh} does not make a lot of effort:

$$K_{hh} = \frac{1}{\sqrt{K_{add}}} = \frac{1}{\sqrt{1{,}573}} = 0{,}797$$

Permissible continuous current is determined by the formula (3.9):

$$K_{n-1} = 0{,}797 \cdot \sqrt{1 + 0.10552} = 0{,}838$$

Allowable current value of long-term fundamental frequency corrected for harmonic currents power:

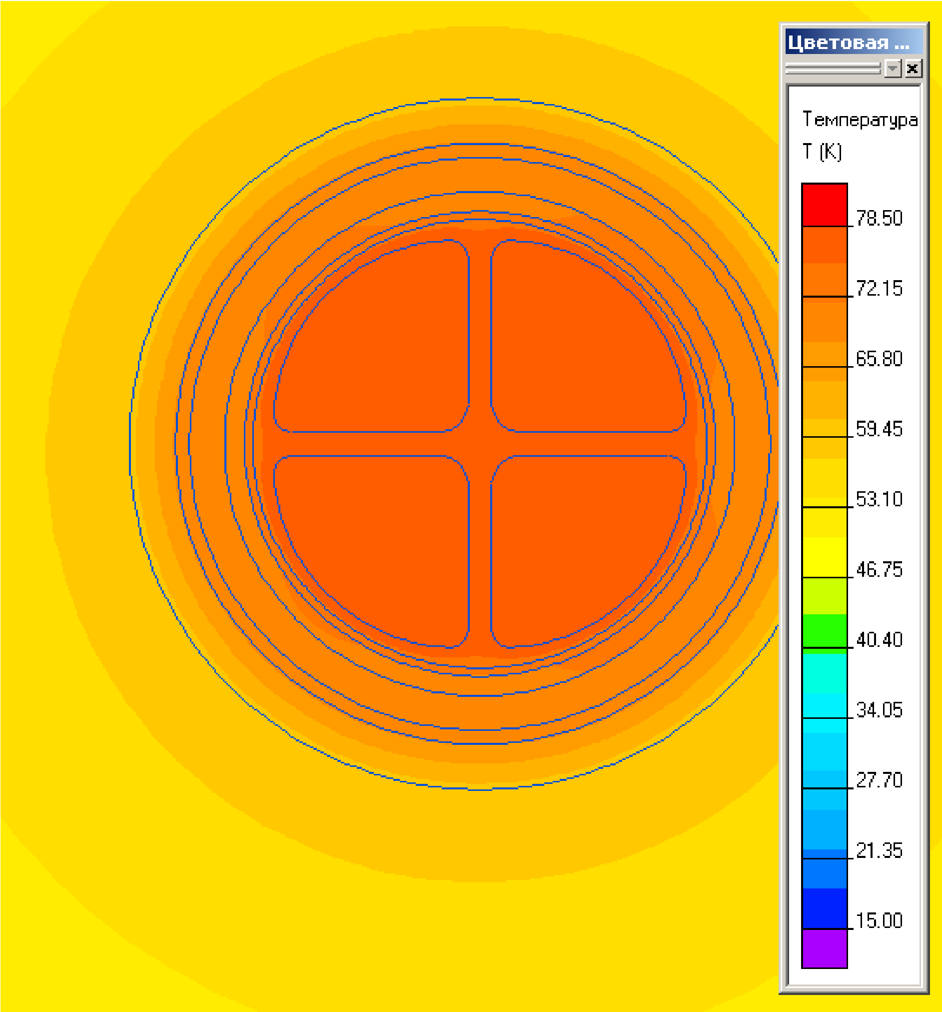
$$I_{perm}^{new} = I_{perm}^{old} \cdot K_{hh} = 281 \cdot 0{,}797 = 224{,}04 \text{ A.}$$

Table 5 – Results of calculation of coefficients for oferent cable design, supplying shopping center

Cable brand	ASB 3x120	ASB 3x120+1x70	ASB 4x120	APvbbShp 4x120
Kn-l	0,695	0,771	0,875	0,875

On the picture of the thermal field Figure 12 it is shown that the maximum temperature of the hottest point of the insulation is 78,5 °C. Thus, using the method described above can be relatively easy to obtain the correction values of the coefficients. However, this method introduces an error in determining the value of the correction coefficient. This is due to the fact that heat sources are separated by an insulation which is a thermal resistance. In fact, if the current RMS value in a neutral conductor is commensurate to the phase current and a neutral conductor cross-section is less than the cross-section of the phase conductor, the heat power in neutral conductor exceeds the value of the phase heat power. As a result, the most heated point of core insulation will be near the neutral conductor.

Figure 12 – Picture of the thermal field in the cable ASB 4x150



3.3 Use of the Described Method with Respect to the Measured Spectra of Harmonics

Relative to the previously measured spectra of harmonics for three types of consumers Table 4, were obtained the following correction factors to the current values of the long-term allowable currents of the fundamental frequency that is shown in Table 6.

Table 6 – Values of the correction factor for power cables 380 V, supply different types of non-linear load

Type of load	Value of factor Kn-l	
	For cables with phase conductor cross section greater than neutral	For cables with the same cross section neutral and phase wires
Shopping center	0,77	0,88
Administrative building	0,76	0,88
Residential building	0,96	0,97

After the calculations and the subsequent analysis of the results were made the following conclusions:

1. The value of the correction factor for the four-wire cable with smaller neutral cross-section size is less than for the cables with the same cross-section sizes of neutral and phases conductors. The wider range of harmonics generated by the nonlinear load, and the more the RMS value of current harmonics (especially harmonic multiples of three), the greater the difference of the above corrections for cable cross-sections for the same phase conductors.

2. Regardless of the phase conductor cross-section size, correction factor for all sections will have the same value.

3. An office building and shopping center have about the same impact on the cable in distribution network 380 V due to the proximity of non-linear power appliances that are located at the consumer.

Also it has been demonstrated using calculations if any changes for the value of the coefficients for the different types of cable designs claimed for one cross-section. Calculation with similar ratios for other cable types is considered at the example of the cable with 120 mm2 cross section size of the phase conductor. For comparison, previously selected three types of cables used for laying in trenches:

- ASB 4x120 cable with paper-oil insulation,

- ASB 3x120 +1x70 cable with paper-oil insulation,

- ASB 3x120 cable with paper-oil insulated neutral conductor, performed on the cable armature,

- APvBbShp 4x120 cable with XLPE insulation.

The results of calculation and simulation Table 6 showed that the value of the correction coefficient is not affected by the type of insulation, but defined by cross-section only by the neutral conductor.

The developed method may calculate only coefficients for the ampacity reduction due to harmonic currents, but as the heat problem is not solved it is impossible to know the temperature of the cable. Thermal resistance between the conductor and the sheath (S1) for three core cables with sector conductors and core wrapping insulation is determined by the formula:

$$S_1 = \frac{\rho_T}{2\pi} \cdot 3 \cdot \left(1 + \frac{3 \cdot t}{2\pi \cdot (d_x + t) - t}\right) \cdot \ln\left(\frac{d_a}{2 \cdot r_1}\right) \qquad (3.10)$$

Where:

ρT [K · m / W] – is the thermal resistance of insulation,

d_a [mm] – is core diameter,

r_1 [mm] – is the radius of the circle circumscribed around the cores,

d_X [mm] – is the diameter of a circular conductor with a cross sectional area and the degree of compaction, that the shaped conductor,

t [mm] – is thickness of insulation between core and metal wrapping.

Thermal resistance between the sheath and armor

$$S_2 = \frac{\rho_T}{2\pi} \cdot \ln\left(1 + \frac{2 \cdot t_2}{D_s}\right) \tag{3.11}$$

Where:

t_2 [mm] – is the thickness of the cushion under armor,

D_S [mm] – is outer diameter of surface.

Thermal resistance of the outer protective coating is:

$$S_3 = \frac{\rho_T}{2\pi} \cdot \ln\left(1 + \frac{2 \cdot t_3}{D_a}\right) \tag{3.12}$$

Where:

t_3 [mm] – is the thickness of the protective coating,

D_a [mm] – is outer diameter of armor (for unarmored take outer diameter element, usually located directly under the armor, i.e. shell, screen or pillows).

Thermal resistance of the environment for insulated cable laid in the ground is

$$S_4 = \frac{\rho_T}{2\pi} \cdot \ln\left(\frac{2 \cdot L}{D_e} + \sqrt{\left(\frac{2 \cdot L}{D_e}\right)^2 - 1}\right) \tag{3.13}$$

Where:

L [mm] – is distance from the surface of the ground to the cable,

D_e [mm] – is cable outer diameter.

Temperature of core insulation for four-wire cable will be equal:

$$\tau_c = P'_c \cdot S_1 + 3 \cdot P'_c(S_2 + S_3 + S_4) + \tau_a \qquad (3.14)$$

where τa [K] is ambient temperature.

For three-core cable with neutral conductor formed on the sheath:

$$\tau_c = P_c \cdot S_1 + 3 \cdot (P_c + P_n)(S_2 + S_3 + S_4) + \tau_a \qquad (3.15)$$

Formulas (3.15) and (3.16) show that the temperature of core insulation is directly dependent on the heat with the constant component that is equal to the ambient temperature. Using these expressions does not introduce a large error in the final result, which was confirmed by the results of calculation and subsequent comparison with the results of the mathematical simulation.The error was less than 2 %. This is primarily due to the fact that the greatest resistance is the thermal resistance of the earth; it is about 60 % of the total. Thus, the heat equivalent conversion from the conductors cannot make a significant error.

The proposed method of calculating the correction factors can be applied on the stage of cable selection which supplies residential areas, and during periodic monitoring of the current in distribution networks. The value of the correction factor depends on cross-section size of neutral and harmonic current spectrum. Regardless of the phase conductor cross-section size, correction factor for all cross-sections will have the same value. The approach can be used for three and four core cable lines for all types of insulation voltage up to 20 kV. Using of developed method in special software will protect distribution networks and gives an opportunity for management electricity consumption and operating network ampacity. Present method helps to reduce power loss in Power Grids and prolonge cable lifetime. Using this method with optimization techniques we can provide higher reliability and effectiveness of present Power systems.

4. PROBLEM FORMULATION

4.1 Algorithm for designing solutions for optimization problems

From the formulation of optimization tasks in Chapter 2 and from the known facts can be stated as follows:

The objective function is non-linear and in both linear and non-linear functions restrictions are occurring.

The objective function is a continuous function (voltage values) and integer, respectively discrete (positions of tap transformers) controlled variables.

Currently, there is no simple algorithm to solve this problem. In principle it is possible to solve the task by using appropriate classical numerical methods, or can be used to solve the appropriate alternative methods.

In this research, the use of the algorithm for finding a solution to minimize the active losses is formulated using the Optimization Tool of the MATLAB programming language, the specific function *fmincon*, which is used for solving tasks that are defined in the form of conventional numerical methods. The function was specified in a way which led to the determination of the minimum objective function by sequential quadratic programming. The sequential quadratic programming is currently one of the most popular numerical methods [20].

The algorithm was programmed in the programming language MATLAB and used to solve optimization problems in a model of a Power System.

4.1.1 Algorithm for the solution of optimization tasks using optimization tool by programming language MATLAB

MATLAB is a high-level programming language, matrix-oriented, designed for scientific and engineering calculations, modeling, the design of algorithms, simulation, analysis and presentation of data measurement and for processing of the results and proposals of control and communication systems. MATLAB authors provide different programmed functions that facilitate the work with the program itself and solve specific tasks. These functions are part of the programming language MATLAB. One of them is the optimization function *fmincon* which is described below.

4.1.2 Description of the optimization tool by programming language MATLAB and used optimizing tool

The optimization tool (Optimization Toolbox) is a Matlab function, which extends the application of this language to solve various optimization problems. It can be used to solve optimization problems without boundaries or with the borders, the linear and non-linear programming. To address the challenges formulated in the form it is determined by the function *fmincon*. Through its use it is possible to determine the minimum parametric nonlinear objective function over with the border type and gender inequalities. For the *fmincon* function to work it is necessary to specify the input parameters and to define the shape, which provides the syntax. By the number of input parameters and their contents it is possible to affect the course of calculation, including the choice of numerical methods using optimization tools for determining the minimum objective function. In the used algorithms the *fmincon* function was entered in a way,so a few input parameters can be used to solve the presented task.

The function has been entered using the following syntax [23]:

```
[x,s] = fmincon (fun,x0,A,b,Aeq,beq,lb,ub,nonlcon,options)
```

Where:

x is a vector containing the values of the parameters of the objective function, in which function gets at a minimum value (in our case it is a vector of controlled variables minimizing the objective function),

s is the resulting value of objective function,

fun represents the minimized objective function,

x0 is the vector of initial parameter values of the objective function (in our case, the initial values of controlled variables),

A is a matrix and b is vector, which determine the linear limits of given type of inequalities in form $\mathrm{A}\cdot\bar{x} \leq \bar{b}$,

Aeq is a matrix and beq is vector, which determine linear limits of given type of inequalities in form $A_{eq}\cdot\bar{x} \leq \overline{b_{eq}}$,

Lb and ub are vectors, containing the values of the lower and upper borders for the values of the vector x which minimizes the objective function,

Nonlcon represents the type of nonlinear boundary of type equalities and inequalities entered in the form $c(\bar{x}) \leq 0$ and $c_{eq}(\bar{x}) = 0$,

Options contain the optimization parameters specified in the specific type that designated by the function of MATLAB syntax *optimset* cooperating with the function *fmincon*. Optimization parameters can be determined by calculating the numerical methods, the number of iterations, and the used methods and etc.

Fmincon function was in the algorithm specified in the following form:

```
[X,s]=FMINCON('losses',X0,A,B,Aeq,Beq,LB,UB,'nelinohr',options)
```

The function in specified form require for its work to programming two functions:

1. A function called the *losses*, which inputs was the vector X containing parameters that minimize the objective function. In our case it was the vector of the

controlled. The output of this function was the value of active power losses for specific regulated, state and required variables.

2. *Nelinohr* function containing nonlinear boundaries. The input was a vector of the controlled variable X. The output from the function were vectors C and Ceq, which represent the type of nonlinear boundary equalities and inequalities that were used in optimization tools within the tool *fmincon*.

It was necessary to specify the optimization parameters that determined the structure options. These parameters were specified using MATLAB function *optimset* as follows:

```
options=optimset('Display','iter','TolX',1.e-6,'TolFun',
1.e-6,'MaxFunEvals',1000, 'LargeScale','off')
```

Where:

'Display','iter' was specified in order to display the results during execution after each iteration step of numerical methods.

'TolX', 1.e-6 defines accuracy for the vector of controlled variables.

'MaxFunEvals',1000 is the maximum number of calculations (valuation) of the objektive functions.

'LargeScale','off' allows the function *fmincon* to use the folowing: "Medium-Scale Optimization". This method of optimization does not require to specification of calculation for the gradient of the Hessian matrix of objective function, which was the reason for its use.

The progress of the iterative calculation in the case of the function *fmincon* was completed either in the case of an estimated accuracy, or in the case of a fixed maximum number of valuation objective fiction. The function returned a vector of controlled variables of functions, where the objective function got the minimum value and the value of the objective function for these variables.

Note: Description was prepared with using literature [23].

4.1.3 Description of sequential quadratic programming

Sequential Quadratic Programming (SQP) is an extension of Newton's method to solve nonlinear problems with a border in the form of equalities and inequalities. Consider the description of SQP regarding the task of minimizing of power losses is formulated as follows:

Minimize the function of n variables f (x), with restrictive conditions:

$$h_i\overline{(x)} = 0,\ i = 1, \dots, m \qquad m < n, \tag{4.1}$$

$$g_i\overline{(x)} \geq 0, i = 1, \dots, p \tag{4.2}$$

Using sequential quadratic programming the given task is formulated in the form of a quadratic programming task and then iteratively solved. Quadratic formulation role is based on a quadratic approximation of the Lagrangian and linearization constraints. Lagrange function has the following form:

$$L(\bar{x}, \bar{\lambda}, \bar{\mu}) = f\overline{(x)} + \bar{\lambda}{}^\wedge T\bar{h}\overline{(x)} + \bar{\mu}^T\overline{\bar{g}(x)} \tag{4.3}$$

Where $\bar{\lambda}$ *and* $\bar{\mu}$ are vectors of Lagrange multipliers.

By Sequential Quadratic programming the quadratic task is iteratively solved:

$$\nabla f(\bar{x}_k)\bar{d}_k + \frac{1}{2}\bar{d}_k^T\nabla_{xx}^{T}L(\bar{x}, \bar{\lambda}, \bar{\mu})\bar{d}_k = \nabla f(\bar{x}_k)\bar{d}_k + \frac{1}{2}\bar{d}_k^T[\nabla^2 f(\bar{x}_k) +$$

$$+ \bar{\lambda}_k^T\nabla^2\bar{h}(\overline{x_k}) + \bar{\mu}_k^T\nabla^2\overline{\bar{g}(x_k)}]\bar{d}_k \tag{4.4}$$

With the borders

$$\nabla\bar{h}(\bar{x}_k)\bar{d}_k + \bar{h}(\overline{x_k}) = 0 \tag{4.5}$$

$$\nabla\bar{g}(\bar{x}_k)\bar{d}_k + \bar{g}(\overline{x_k}) \leq 0 \tag{4.6}$$

The result of a quadratic tasks on the k-th iteration is a new vector:

$$\bar{x}_{k+1} = \bar{x}_k + \propto_k \cdot \bar{d}_k$$

SQP requires to count the Hessian matrix of Lagrangian fiction $H_k = \nabla_{xx}^T L(\bar{x}, \bar{\lambda}, \bar{\mu})$. It can be achieved with various techniques. The code used in

Matlab replaced the following matrix BFGS (Broyden, Fletcher, Goldfarb and Shanna) approximation to Qk, which is updated on each iteration. BFGS relation is as follows:

$$Q_{k+1} = Q_k + \frac{\bar{q}_k \bar{q}_k^T}{\bar{q}_k^T \overline{Q_k}} - \frac{\bar{Q}_k^T \bar{Q}_k}{\bar{d}_k^T Q_k \bar{d}_k} \tag{4.7}$$

Where:

$$\bar{d}_k = \overline{x_{k+1}} - \overline{x_k} \tag{4.8}$$

$$\bar{q}_k^T = \nabla x L\left(\bar{x}_{k+1,}\bar{\lambda}_{k+1}\right) - \nabla x(\bar{x}_{k,}\bar{\lambda}_k) \tag{4.9}$$

Sequential quadratic programming algorithm is as follows:

Determination of an acceptable initial vector $\bar{x}_{0,}$and initial positive definite matrix Q_0.

Solving the quadratic task (3.4) with constraints (3.5) and (3.6). To solve quadratic tasks in MATLAB is used the method of active convention (also known as a projection method), whose description is given in the literature [20]. If $\bar{d}_k = 0$ follows the end of solution, the minimum of objective function in the point $\bar{x}^* = \bar{x}_k$.

Determination of the vector $\bar{d}_k$ and then the following calculation $\bar{x}_{k+1} = \bar{x}_k + \propto_k \overline{d_k}$. In MATLAB there is a parameter $\propto_k$ is selected to ensure the decline of evaluation function formulated in the form:

$$\Psi(\bar{x}) + \sum_{i=1}^{m} r_i h_i\,(\bar{x}_k) + \sum_{j=1}^{p} r_j max\{0, g_i, (\bar{x})\} \tag{4.10}$$

The coefficients r_i, r_j are chosen in proportion to the use Lagrange multipliers in the following relation:

$$r_i = (r_{k+1})_i = max\left\{\lambda_i, \frac{1}{2}[(r_k)_i + \lambda_i],\right\} i = 1,2, \ldots m, \tag{4.11}$$

$$r_j = (r_{k+1})_j = max\left\{\mu_j, \frac{1}{2}[(r_k)_j + \mu_i],\right\} i = 1,2, \ldots p, \tag{4.12}$$

Updating of matrix Qk using BFGS relation and return to point 2.

Description was processed using literature [20, 23].

4.1.4 Procedure for solving tasks to minimize active power losses in ES using MATLAB optimization tool.

Procedure for solving tasks to minimize active power losses using MATLAB optimization tool consists of the following steps:

A. Loading input data from data files and determine the necessary parameters for the further calculation.
B. Calculation of steady mode without using regulation in the system. It was used for the calculation of the Newton iterative method.
C. Specifying nodes in which regulation should be performed. These nodes must be from the variety of the regulation (PU) nodes specified in the data file.
D. Optimization calculation while using the function *fmincon* and steady-state calculation. The steady-state equation was not part of the optimization calculation in the form of the border because of the type of equality in the case of already programmed function to calculate the steady state mode.
E. The following results were printed by the screen:

- active and reactive power, voltage and voltage angles in the nodes,
- current in the lines,
- optimal voltage in nodes capable of operating branches and establish the position and values of reactive powers for generators to achieve these tensions
- active power losses in the system elements specified by the user (where an optimization process is realized).

The results are active power losses and vector controlled variable containing an integer and continuous variables.

4.2 Problem Formulation

As seen in the previous chapter FACTS devices are able to influence network parameters (line impedance, the voltage in the nodes, etc.). These properties are used for different purposes (e.g. Management of power flow in the ES, increasing the voltage stability of the system, damping oscillation). One option is to use them to reduce the total active losses in the ES. It is important to mark that it is not used just for reducing losses, better to say it is an additional function. In practice it is not encounter cases where the FACTS devices are used only to reduce the active losses. Almost always this is achieved in conjunction with another factor (e.g. increasing the voltage stability, increased load ability of the ES).

FACTS devices are fully steerable and able to be connected to the ES in lines or nodes. In order to achieve their maximum contribution for solving the problem, further steerable variables for the optimization process need to be appropriately determined. Specifically, it is about the type of device(s) (or a combination of several), their number, the place where the device will be connected in ES e.g. lines and nodes respectively and it is also necessary to determine their parameters [94].

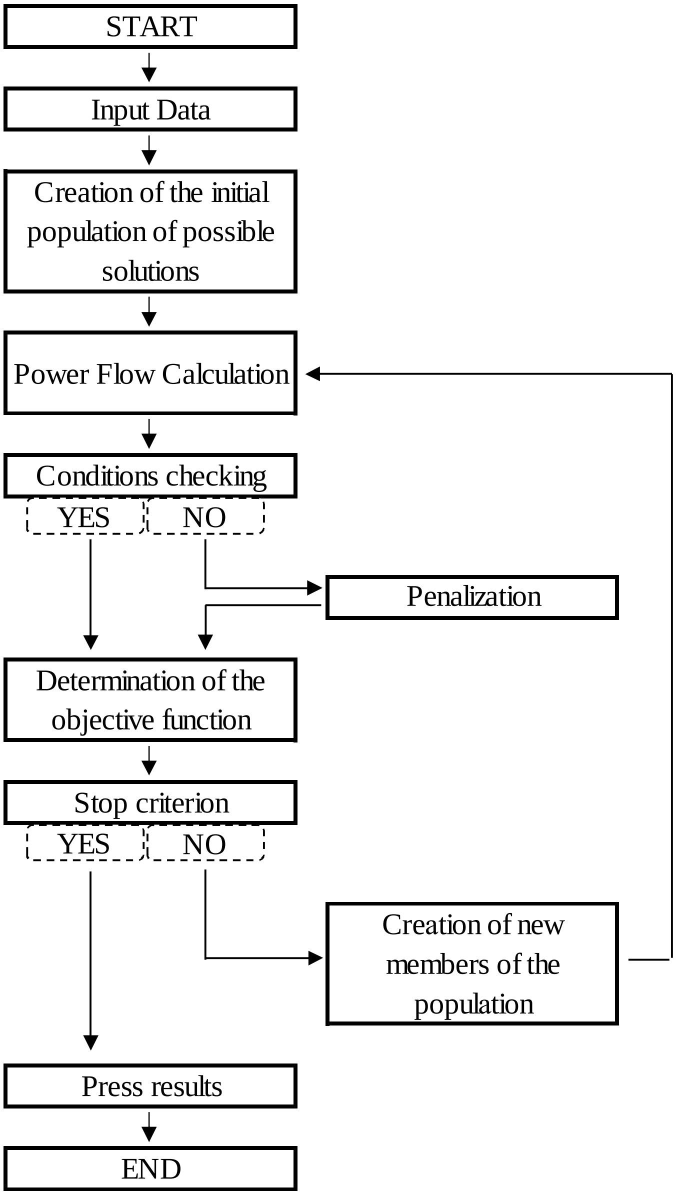
To solve the optimization problem, in the beginning it is necessary to indicate the conditions on which the procedure of further solutions will depends. Regarding the determination of what should be fixed and what is already predetermined and therefore unchangeable, and then variables that relate to FACTS devices can be discussed. At the beginning of the optimization process, the following tasks can be formulated:

1. It is the intended type of FACTS devices, their number and location in the ES. Searching for variables that specify those (optimal) parameters.
2. The intended type of FACTS devices and their number. Searching by variables for the point of connection to ES and the parameters of FACTS devices.
3. It is intended that only the type of FACTS devices, their number, the point of connection to ES, and the parameters should be identified.
4. There is nothing intended, it is necessary to determine the type, number, location and parameters of the FACTS devices.

5. It is intended that any combination of variables that define the type, number, location and parameters of the FACTS devices and unknowns should be determined.

In addition the above-mentioned combinations of options, as can be compiled. For optimization problems combination of several types of the FACTS devices are quite often used, because their properties are very complementary. In this case, it is possible to determine separately the numbers of the species of FACTS devices, the parameters and the places of the network connection.When searching for these variables more adjustable variablesare added.These variables define the size of the supplied reactive power of the generator, transformer tap settings and the usage of existing compensation devices. The flowchart of the proposal during the optimization process is in Figure 13.

Figure 13 – The flowchart of the proposal during the optimization process



At the beginning of the process input data is entering, which is represented by network parameters and other data that will not change the optimization process.

The use of the evolutionary computing techniques, at the beginning of optimization process will create an initial population of possible solutions, which will represent searched variables. Using this data (input data and data from the initial population solutions) we will be able to calculate the steady-state mode of the network. After its calculation, there are controlled operating restrictions such as magnitude of the voltage at nodes, the maximum permissible current flow in lines, taps of transformers settings etc. If all this data is within the permissible boundaries, the target (purpose) function will be determined. If not, before the determination of the target functions it will also add penalization, which represents the infringement of any of the restrictions, and therefore there is an increase of its value. The objective function selection is controlled by stop criterion, which can be represented as a variety of the maximum number of generation solutions, the maximum computation time, the completion of the optimization process by unimproved objective function for a certain period and under. Finally, the results will be printed, i.e., displays the searched variables. They will represent all searching data which would result from a given task. FACTS devices are able to influence the operating parameters in the Energy System (ES) and therefore reduce operating losses in the line. Active losses ΔP in Energy System (ES) with n nodes are determined by the following formula:

$$\Delta P = Re\left(\Delta \dot{S}\right) = \sum_{i=1}^{n} \sum_{j=1}^{n} U_i U_j \, [g_{ij} \cos\left(\delta_i - \delta_j\right) - b_{ij} \sin(\delta_i - \delta_j) \qquad (4.13)$$

The following Table 7 shows which FACTS devices can influence the parameters, i.e. size of voltage in the nodes, angles, and reactance in the lines.

Table 7 – FACTS devices and their adjustable parameters

Name of the device	**Adjustable parameters**
TCSC	Reactance of the line
SSSC	Reactance of the line
SVC	Voltage in nodes
STATCOM	Voltage in nodes
UPFC	Voltage in nodes
	Reactance of the line
	Angle of voltage

The main goal of this research is to define the best location for STATCOM compensators and minimize active power losses in the grid, using the Genetic algorithm, Particle Swarm Optimization and the *fmincon* function. Using different kinds of mathematical algorithms for different network topology power loss minimization can be reached. To approve this statement two case-studys were performed with different parameters: network topology, voltage level, generation/load data.

4.3 Case-study for a 14 node Power system

A 14 node power system with two voltage levels was considered: 400 kV and 220kV. The first five nodes are on 400 kV, and others are on 220 kV. Node 1 is a bus node (slack bus). Voltage levels are connected by three-phase power transformers 400/231 kV with regulating tap on the secondary side ± 11 x +1,13%.

In the presented research four main experiments were formulated:

1. The calculation of the network operating parameters without optimization.
2. The calculation of the network operating parameters after optimization was performed in order to reduce total active power losses in the system with and without using STATCOM.
3. Simulation of generating source outages gradually calculated cases with and without using STATCOM in which it was assumed sources outages, and in each case, it was assumed that the outage was in only one source. An outage in node 1, was not considered, because this node is a balanced node. In all cases, the optimization was performed in order to keep all operational restrictions under permitted deviations while reducing the total active losses in the network.
4. Simulation of disconnection lines between nodes 8 and 9. There were considered to disconnect the line between nodes 8 and 9 because this line is the second most overloaded line for the voltage level of 220 kV. The most overloaded line for level 220 kV is line between nodes 7-8, but disconnection of that line caused a similar state as was mentioned in case 3, i.e disconnect the source at node 7. The objective was to keep any operational restrictions under permitted deviations while reducing the total active losses in the network.

Control variables are reactive powers on generators and taps on regulating transformers for cases without STATCOM. Reactive power generating/load by STATCOM is a controlled variable in cases with STATCOM.

All simulations were performed in the program Matlab using the optimization method called Particle Swarm Optimization.

In all calculations the following operational restrictions we considered:

Max. permissible voltage deviations in the nodes - considering the max. permissible deviation of 5 % for both voltage levels

Max. /Min.possible reactive power supplied by generators – considering that the generators are capable / takes ± 50 MVAr compared to the values given in Table8.

Max. / Min. values set by tap transformers – transformers control range is from 202,3 to 241,4 kV. Since this method does not provide a continuous change of control, voltage always chooses the nearest possible value of the adjustable transformer.

Thermal constraints of all transmission lines – it is considered a line of 400 kV voltage level has max. permissible current of 2000 A, a line with a 220 kV voltage level has max. permissible current of 860 A

Max. / Min. possible supplied/consumed reactive power using STATCOM – considers that the max. / min. supplied / consumed output power using STATCOM is ± 100 MVAr.

Table 8 – Generating/load node for 14 nodes Power system

Nodes	**Active power [MW]**	**Reactive power [MVAr]**
1	Slack bus	Slack bus
2	200	50
3	200	50
4	-200	-100
5	-200	-100
6	200	50
7	200	50
8	0	0
9	-50	-25
10	-50	-25
11	-100	-50
12	-100	-50
13	-100	-50
14	-50	-25

Positive values in the Table 8 represent generation of active/reactive power; negative represents consumption active/reactive power.

4.3.1 Simulation results for 14 node Power system

In Figure 14 is shown simulated network, where the blue area is the generating/load area for a 400 kV voltage level, the green area is the generating/load industrial area and the red area is the generating/load housing estate for 220 kV voltage level.

Experiment 1 – In this case we did not consider using the optimization technique and STATCOM to achieve minimum active power losses. Total active power losses were 9,09 MW. Simulation results for this case are represented by black color in Figure 14, Figure 15, and Figure 16. As shown in Figure 15, voltages are out of permissible values.

Experiment 2 – in this case we applied the optimization technique to achieve minimum active power losses in the considered network. We performed two simulations with and without using STATCOM. Simulation results for these two states are shown in Figure 14, Figure 15, and Figure 16 and Table 9. The blue color represents the state after optimization without using STATCOM, where the red color represents state after optimization while using STATCOM. Total active power losses were 8,51 MW for the state without using STATCOM and 7,81 for state using STATCOM.

Figure 14 – 14 nodes Power system

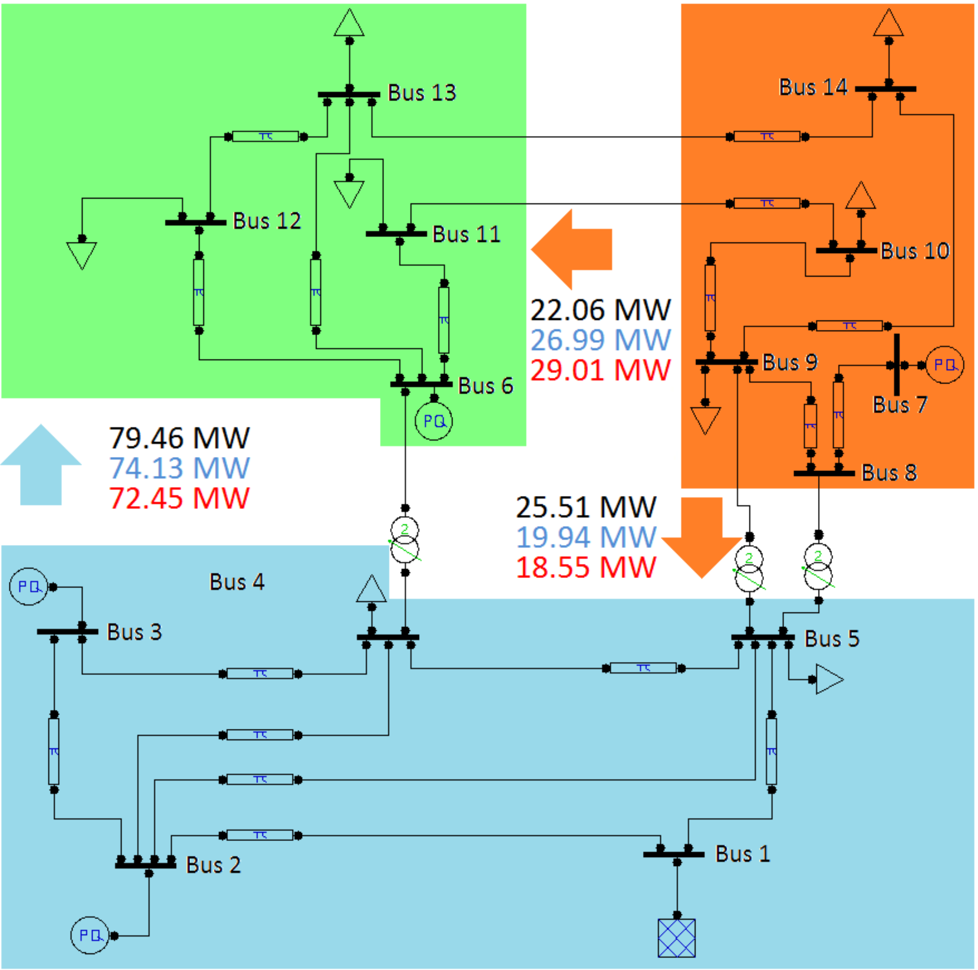


Figure 15 – Permissible values for voltage

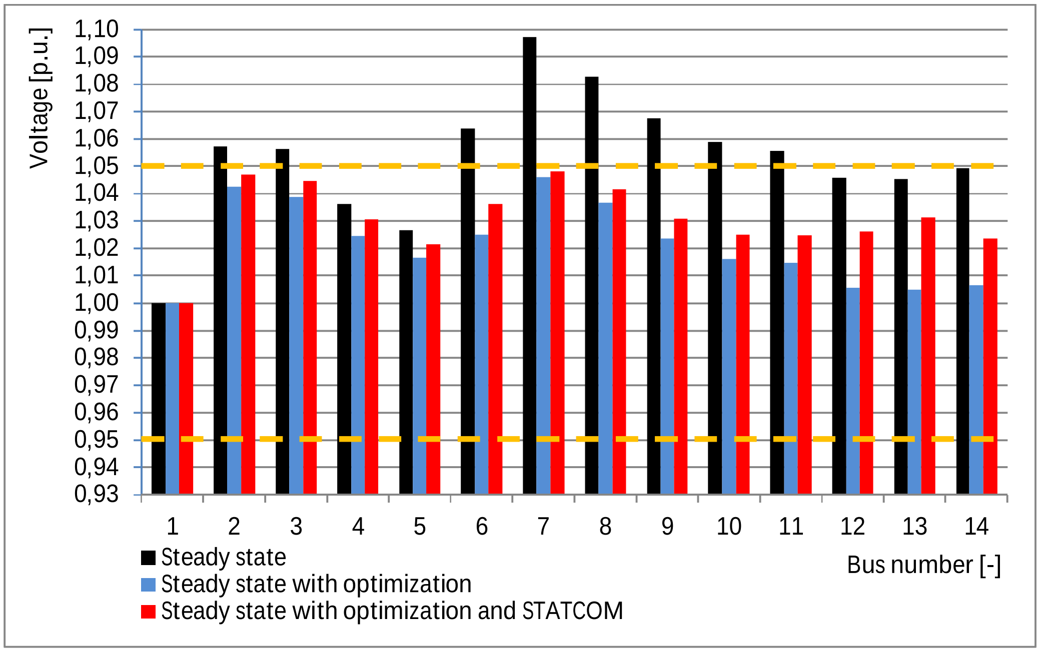
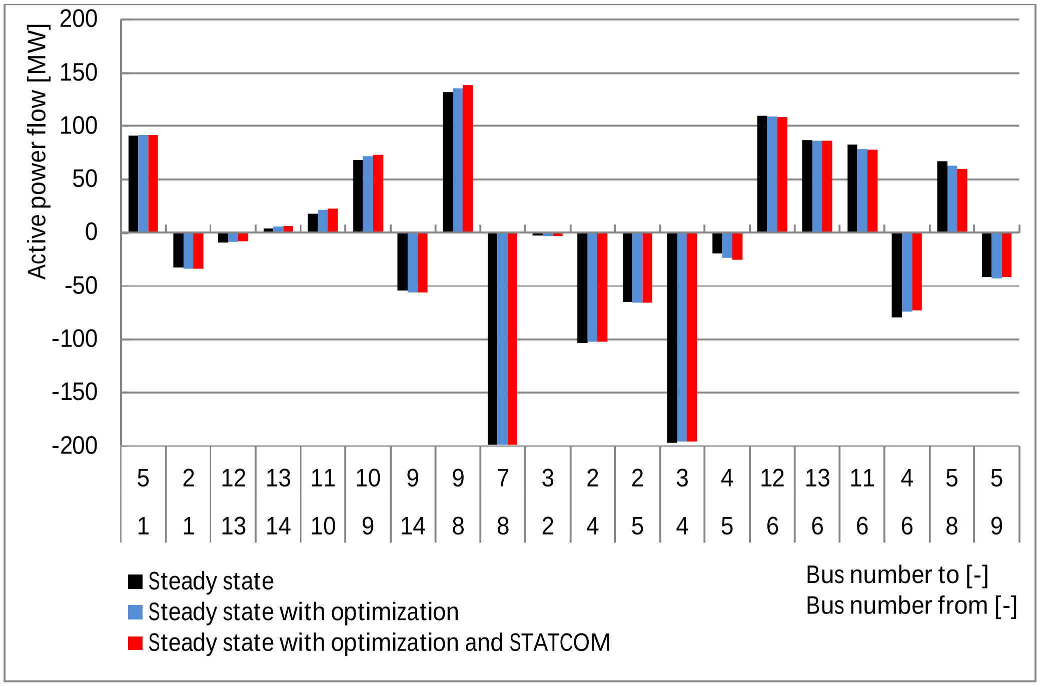


Figure 16 – Active power flow in all lines



Experiment 3 – In this case we considered generating sources outages (from case 2 to case 5).

Case 1: Optimization (total without switching) – this case represents simulation results captured in experiment 2.

The next four optimization processes were performed to achieve minimal active power losses with using STATCOM (orange color) and without (grey color) in cases when we consider generating source outage.

Case 2: Optimization (switch off generator 2)

Case 3: Optimization (switch off generator 3)

Case 4: Optimization (switch off generator 6)

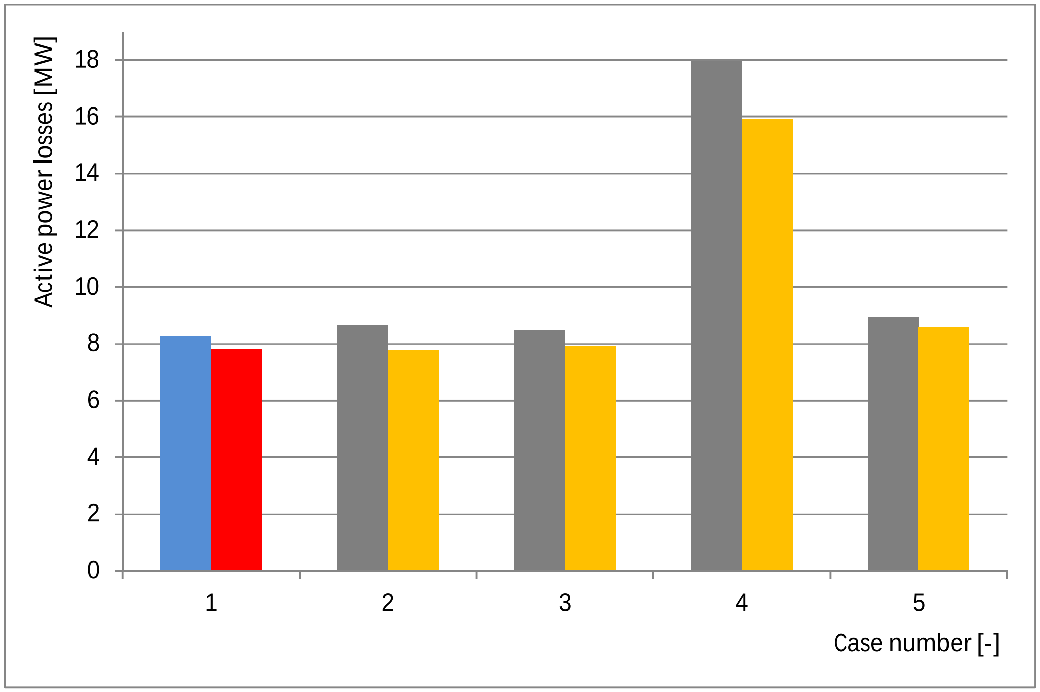
Case 5: Optimization (switch off generator 7)

Table 9 and Figure 17 show results of described above- mentioned research, for state with and without using STATCOM, bus number where was STATCOM connected and amount of reactive power that STATCOM supplied/absorbed from the network.

Table 9 – Simulation results for all five cases

Case	Active power losses [MW]		Bus number [-]	Reactive power [MVAr]
	without STATCOM	with STATCOM		
1	8,51	7,81	13	93,79
2	8,65	7,76	2	-99,99
3	8,48	7,94	2	-99,99
4	17,97	15,93	12	99,93
5	8,94	8,60	13	62,35

Figure 17 – Active power losses for all five cases with and without STATCOM



Experiment 4 – in this case we turn offline between nodes 8 and 9. The first case was simulation performed without using STATCOM (green color). In the second case we STATCOM (purple color) was used. As can be seen in Figure 18 with STATCOM lower active power losses in comparison with the case without STATCOM can be achieved. STATCOM was placed in node 13 and supplied 87,589 MVAr. Figure 19 shows the voltage profile for both states; Figure 20 shows changes in active power flow for all lines in both states.

Figure 18 – Active power losses (line 8-9 switch off)

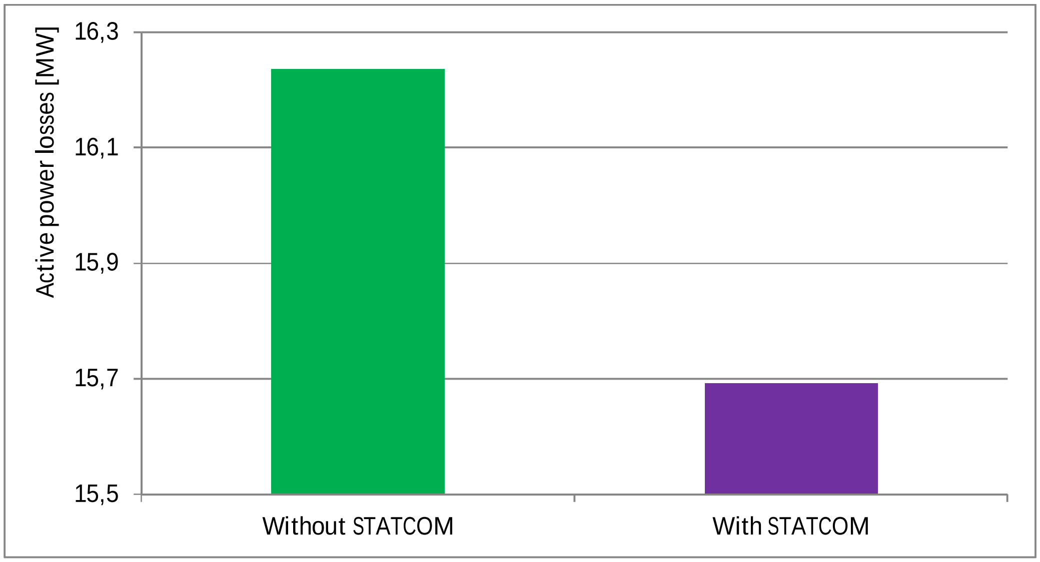


Figure 19 – Voltage profile (line 8 – 9 switch off)

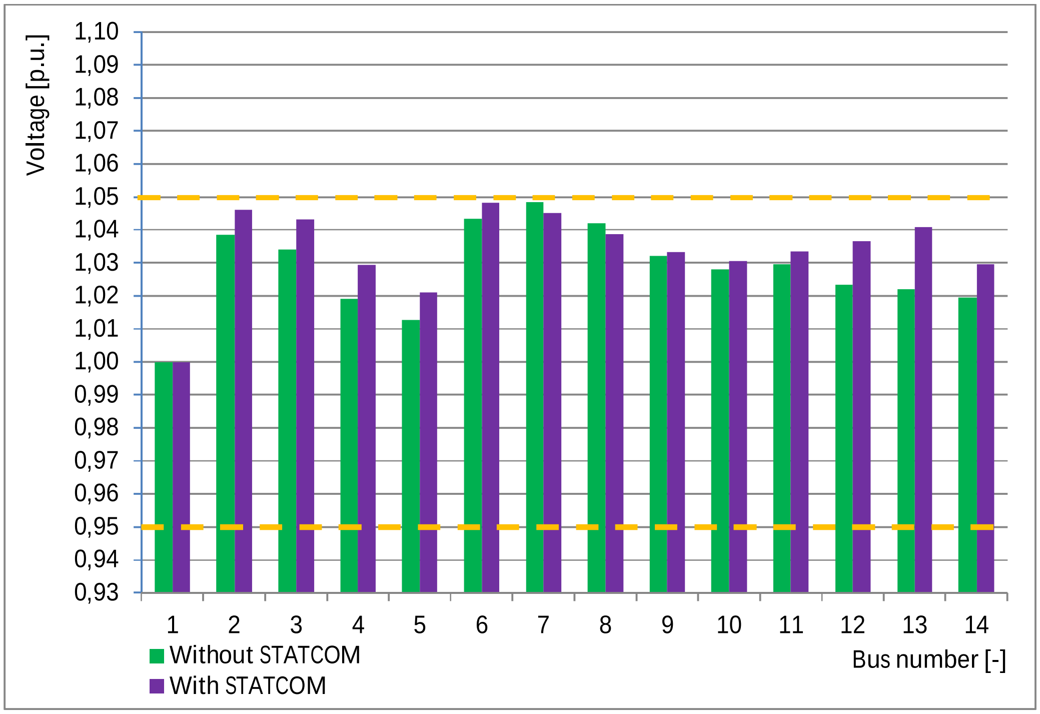
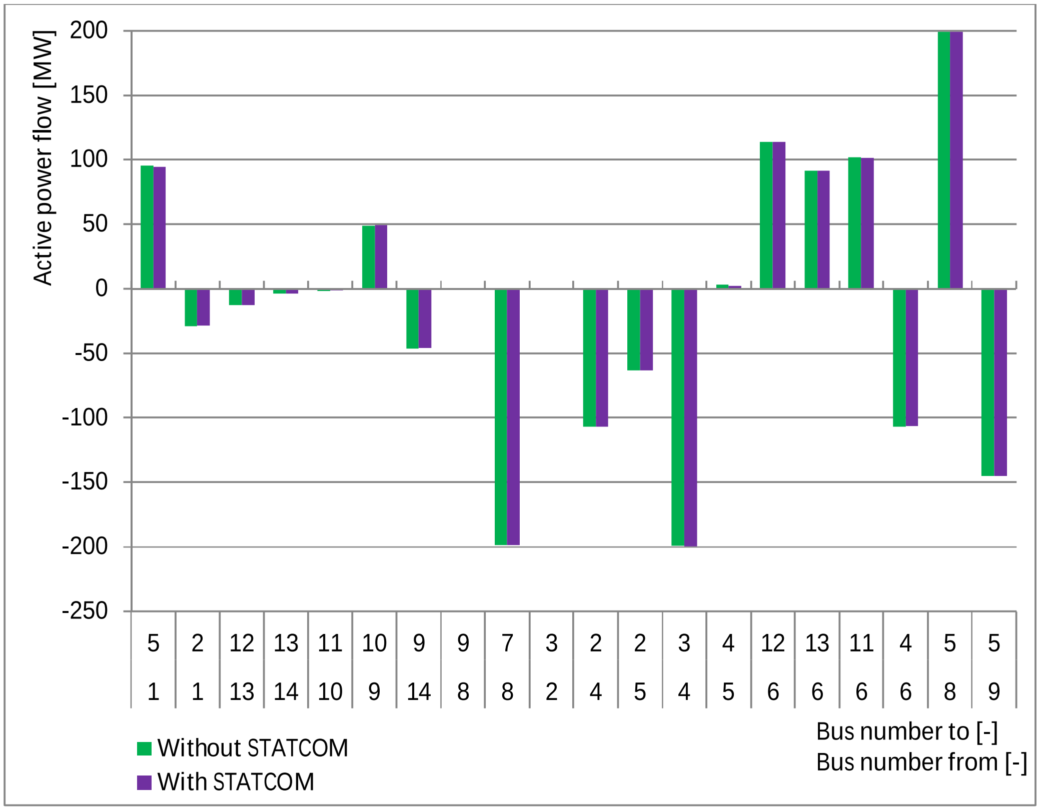


Figure 20 – Active power flow in all lines (line 8-9 switch off)



4.3.2 Result discussion

As shown in this research, using STATCOM, voltage at the node to which STATCOM is connected is able to be control and at the same time it is possible to reduce active power losses. Optimization of network parameters were also performed, due to which we get permissible values for voltage and power, this is shown in Figure 15. FACTS devices also lend themselfs to extending usable transmission limits in a step-by-step manner with incremental investment when required. Within the basic system security guidelines of these controllers enable the transmission owners to obtain one or more of the following benefits:

- Control of power flow as ordered. The use of power flow control, may be used to follow a contract, meet the utilities' own needs, ensure optimum power flow, ride through emergency conditions, or a combination thereof.

- Increase the loading capability of lines to their thermal capabilities, including short-term and seasonal conditions. This can be accomplished by overcoming other limitations and sharing of power among lines according to their capability. It is also important to note that the thermal capability of a line varies by a very large margin based on the environmental conditions and loading history.

- Increase the system security through raising the transient stability limit, limiting short-circuit currents and overloads, managing cascading blackouts and damping electromechanical oscillations of power systems and machines.

- Provide secure tie line connections to neighboring utilities and regions thereby decreasing the overall generation reserve requirements on both sides.

- Provide greater flexibility in siting of new generation.

- Lines upgrades.

- Reduce reactive power flows, thus allowing the lines to carry more active power.

- Reduce loop flows.

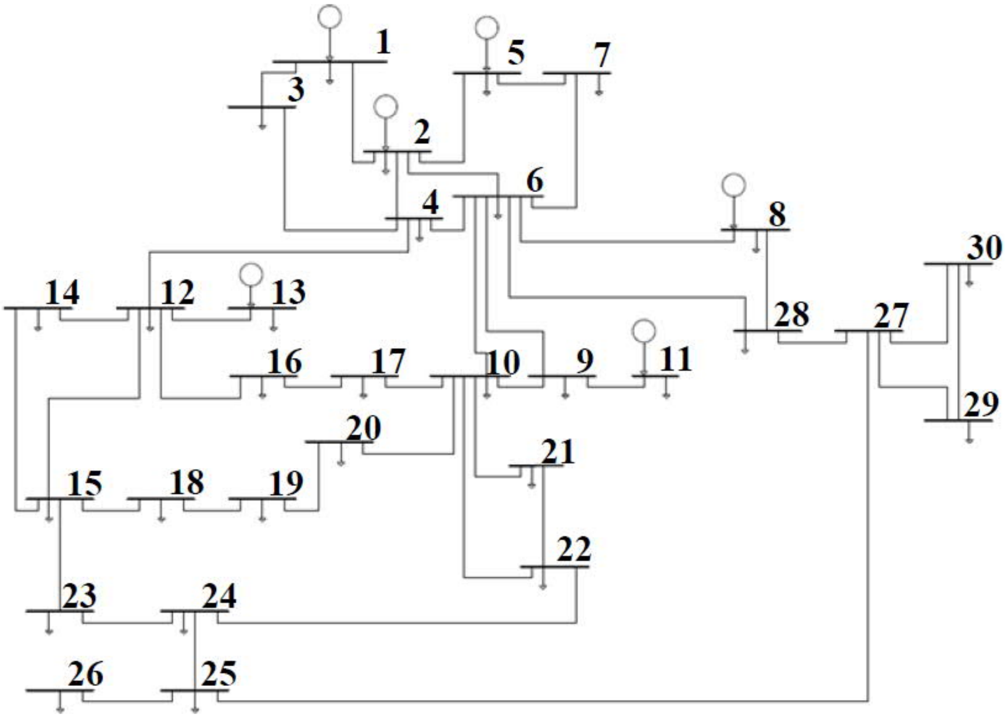
This study is describing theoretical and practical applications of FACTS such as STATCOM for voltage control and active power optimization. The idea and development with applying STATCOM for optimization are presented.

STATCOM provides an improvement in power quality and active power consumption stabilization. This effect could be used in application's where variable load voltage should be compensated. It would lead to power stability improvement and decrease the risk of critical events caused by those sources. Shown simulation provides information for devices design and placement in power grids.

4.4 Case-study for 30 node Power system

We consider the optimization of modes on an example of standard 30-node scheme IEEE (Institute of Electric and Electronic Engineers), shown in Figure 21. In the present system, there are 6 (generation node) thermal power plants (TPP) - node 1, 2,5,8,11,13 and 24 are load stations. Node 1 is a slack bus node.

Figure 21 – 30 node Power system



In the presented research four main experiments were formulated using the Genetic algorithm, Particle Swarm Optimization (PSO) and *fmincon* function:

1. Calculation of the network operating parameters without optimization. (Power Flow Calculation)

2. Calculation of the network operating parameters (Power Flow) calculation using optimization techniques (Genetic algorithm, PSO, *fmincon* function) – optimization was performed in order to reduce total active power losses in the system.
3. Calculation of the network operating parameters (Power Flow) calculation using optimization techniques (Genetic algorithm, PSO, *fmincon* function) – optimization was performed in order to reduce total active power losses in the system with using FACTS devices (STATCOM).
4. The calculation of an emergency situation, to check if the system still will be stable and if any overloads will occur in the system. The output of all generators.

Control variables are reactive powers on generators for cases without STATCOM. Reactive power generating/load by STATCOM is a controlled variable in cases with STATCOM.

All simulation's were performed in program MATLAB with using optimization methods called Genetic algorithm, Particle Swarm Optimization and *fmincon* function.

In all calculations we consider the following operational restrictions:

1. Max. Voltage permissible deviations in the nodes – considering the max. permissible deviation of 5% for the voltage level.
2. Max. / Min. possible reactive power supplied by generators – considering that the generators are capable / take ± 50 MVAr compared to the values given in Table 10.
3. Thermal constraints of all transmission lines – it is considered that a line of 400 kV voltage level has a max. permissible current of 2000 A.
4. Max. / Min. possible supplied/consumed reactive power using STATCOM – is considering that the max. / min. supplied / consumed output power using STATCOM is ± 100 MVAr.

Table 10 – Generating/load nodes for 30 nodes power system

Nodes	Active power [MW]	Reactive power [MVAr]
1	Slack bus	Slack bus
2	200	50
3	200	50
4	-200	-100
5	-200	-100
6	200	50
7	200	50
8	0	0
9	-100	-50
10	-100	-50
11	-100	-50
12	-100	-50
13	-100	-50
14	-100	-50
15	-100	-50
16	-100	-50
17	-100	-50
18	-100	-50
19	-100	-50
20	-100	-50
21	-100	-50
22	-100	-50
23	-100	-50
24	-100	-50
25	-200	-100
26	-100	-50
27	-100	-50
28	-100	-50
29	-100	-50
30	-100	-50

Positive values in Table 10. Represents a generation of active/reactive Power, negative represents consumption active/Reactive Power

4.4.1 Simulation results for 30 node of Power system

***Experiment 1* –** In this case using optimization techniques and STATCOM to achieve minimum active power losses was not considered. Total active power losses were 35,778 MW. Simulation results for this case are represented by blue color in Figure 22, Figure 23 and Figure 24. As shown in Figure 22, voltages are out of permissible values.

Experiment 2 – in this case we applied the optimization technique to achieve minimum active power losses in the considered network. We performed simulation without using STATCOM. Simulation results for these statements are shown in Figure 22, Figure 23 and Figure 24 and Table 11. The red color represents state after optimization. Total active power losses were 33,897 MW for the state without using STATCOM.

Experiment 3- in this case the optimization technique was applied to achieve minimum active power losses in the considered network and to find the optimal placement for STATCOM. We performed a simulation using STATCOM. Simulation results for these statements are shown in Figure 22, Figure 23, Figure 24, and Table 11. The green color represents the state after optimization with using STATCOM. Total active power losses were 33,491 MW for state while using STATCOM.

In Table 11 the results of different optimization techniques are shown. These results suggest that the best location for STATCOM installation is node number 10. The maximum compensated reactive power in this node is 191,38 MVAr. Power losses provided by different optimization techniques have approximately the same value. *Fmincon* function provides calculation results faster and with better result. That is why in further experiments only Fmincon optimization will be used. Using STATCOM device helps manage the voltage level in nodes (as seen in Figure 24), perform reactive power compensation, and also reduce power losses in the system.

Table 11 – Results of different optimization technique

Type of algorythm	Active power losses			Results		
	Power Flow [MW]	Optimization [MW]	Optimalisation with STATCOM [MW]	Bus number [-]	Reactive power [MVAr]	Time [s]
GA	36,4	35,8	34,4	10	190,10	>21
PSO	35,9	34,6	34,0	10	199,90	15
Fmincon	35,7	33,8	33,4	10	191,38	11

Table 12 – Data for each state of system

Bus number [-]	U [kV]		
	Power Flow	Optimization	Optimization with STATCOM
1	400,0000000	400,0000000	400,0000000
2	392,1732437	399,0791647	401,1763806
3	394,0923476	396,9570613	397,9469394
4	389,0648513	396,6693989	399,2985716
5	391,0880687	399,9827090	402,4612538
6	387,6902755	397,1133496	400,4091897
7	388,1361043	397,3354562	400,2346092
8	386,6544227	397,7065242	401,2272154
9	384,1668186	396,7981087	401,4194266
10	381,7730725	393,8560741	400,6746109
11	385,9513407	400,2409355	403,1356483
12	382,9617671	394,8733560	399,6737091
13	384,7504483	397,7626703	402,1442809
14	380,8786780	393,0105177	398,1398238
15	379,8394623	392,0997476	397,6645925
16	381,5355858	393,5608248	399,0594546
17	381,1416510	393,2238655	399,3963485
18	378,7462922	391,0506412	396,9716957
19	378,6895197	390,9802046	397,2306774
20	379,6853865	391,9033710	398,4541255
21	380,4876046	392,6853882	399,4148429
22	380,2614163	392,5144613	399,1231977
23	377,8020533	390,1514593	395,8137604
24	377,5108849	389,8495347	395,5420037
25	376,8287071	389,0959408	394,5307309
26	375,5803537	387,9001318	393,3572593
27	380,4931127	391,9050563	396,0660909
28	383,7675180	394,7562029	398,5249378
29	379,4566431	390,9226103	395,1027223
30	379,4566431	390,9226103	395,1027223

Figure 22 – Voltage diagramm for each state

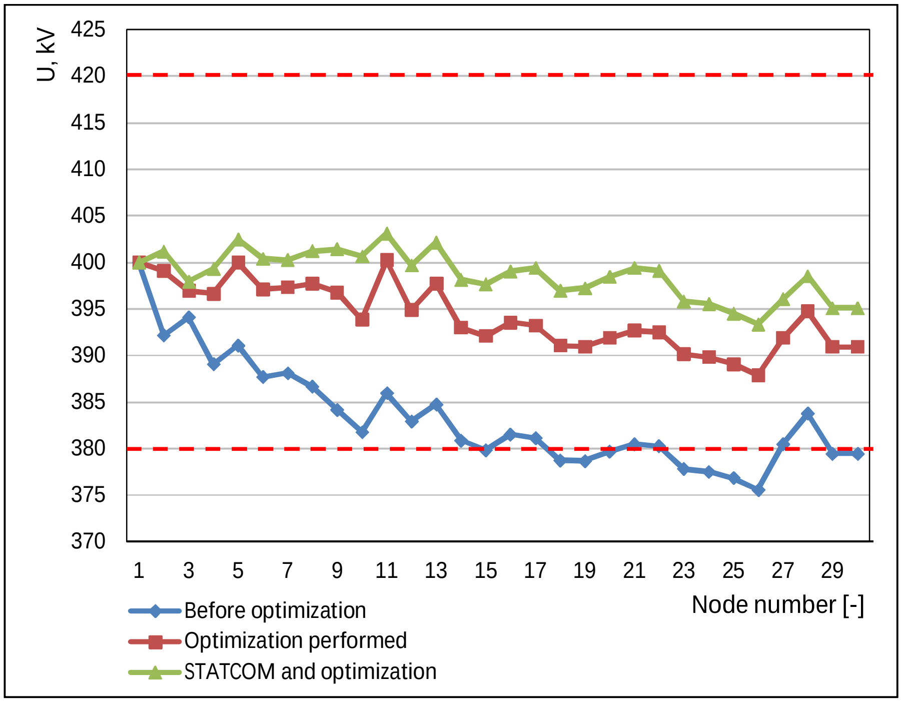


Figure 23 – Permissible values for voltage

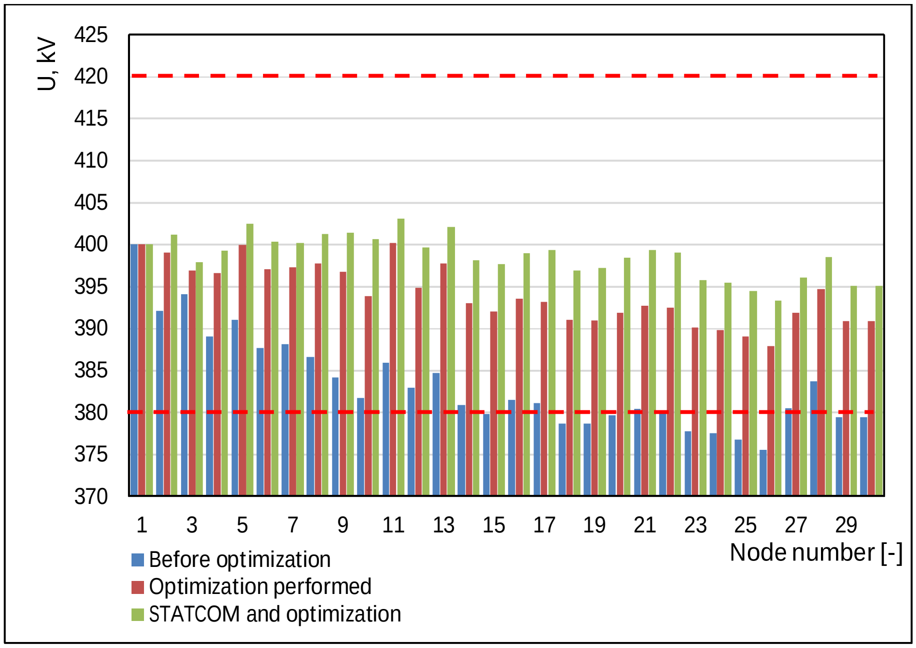
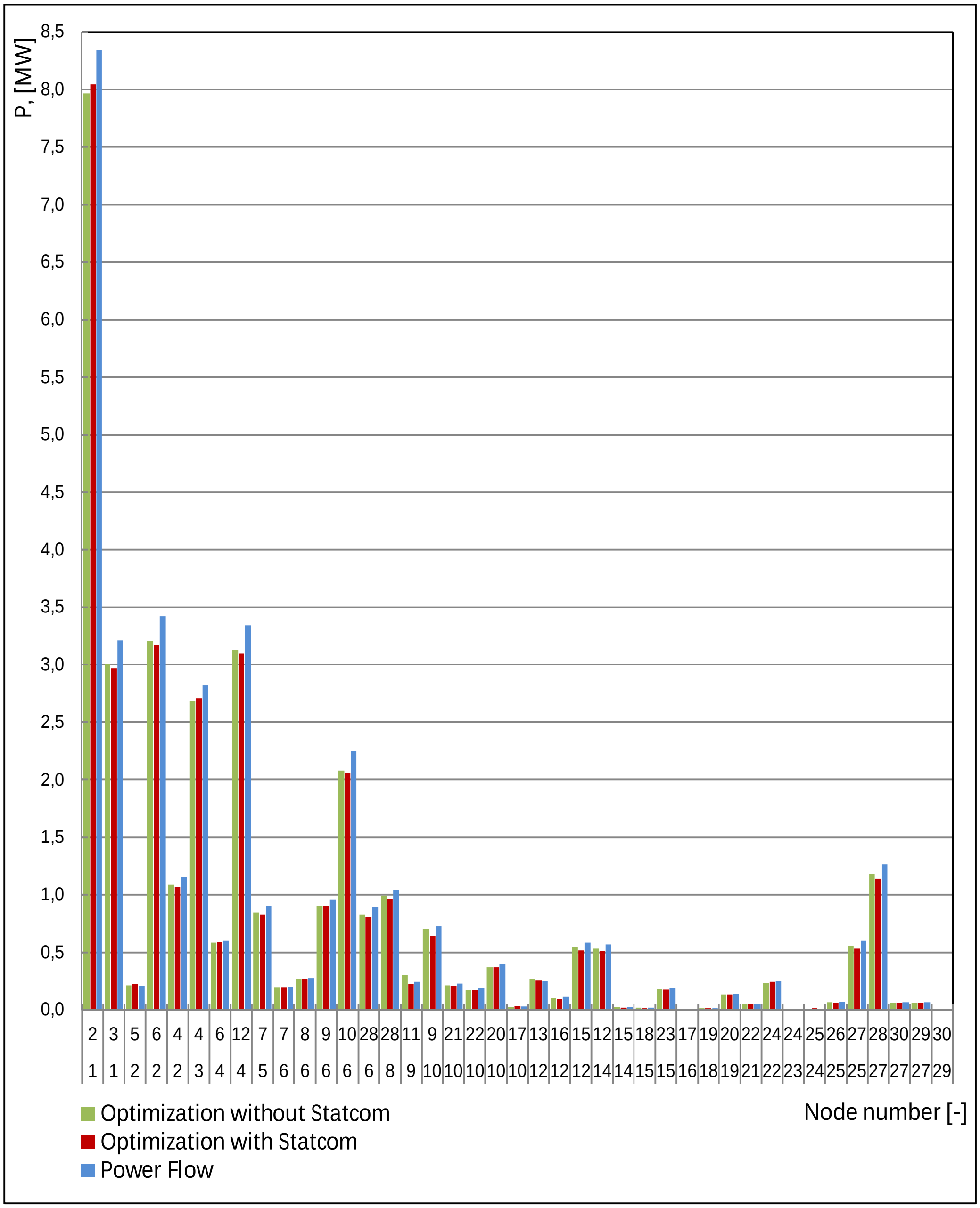


Table 13 – Power flow in the lines

Node number [-]		P [MW]		
		Optimization without Statcom	Optimization with Statcom	Power Flow
1	2	7,966333	8,041585	8,341126
1	3	3,006069	2,974901	3,216225
2	5	0,215194	0,224595	0,208355
2	6	3,211374	3,176403	3,423588
2	4	1,093218	1,067227	1,157858
3	4	2,689183	2,708542	2,826492
4	6	0,581335	0,592694	0,602463
4	12	3,128946	3,093591	3,343198
5	7	0,851291	0,826995	0,896957
6	7	0,198209	0,198346	0,205339
6	8	0,272149	0,271724	0,277408
6	9	0,902395	0,903100	0,959503
6	10	2,081601	2,059103	2,249173
6	28	0,826600	0,806567	0,894995
8	28	0,990414	0,961510	1,040868
9	11	0,303985	0,224537	0,244814
10	9	0,708114	0,641186	0,725729
10	21	0,215177	0,210532	0,230204
10	22	0,176655	0,173112	0,188689
10	20	0,371729	0,370314	0,397392
10	17	0,027980	0,037910	0,029244
12	13	0,275386	0,251553	0,246310
12	16	0,104142	0,091905	0,113025
12	15	0,543917	0,521403	0,583826
14	12	0,532248	0,514964	0,569209
14	15	0,026407	0,023977	0,028862
15	18	0,020854	0,014675	0,022552
15	23	0,183674	0,177680	0,196438
16	17	0,006070	0,006780	0,006895
18	19	0,016272	0,015988	0,017130
19	20	0,133427	0,134859	0,142316
21	22	0,050488	0,049300	0,053674

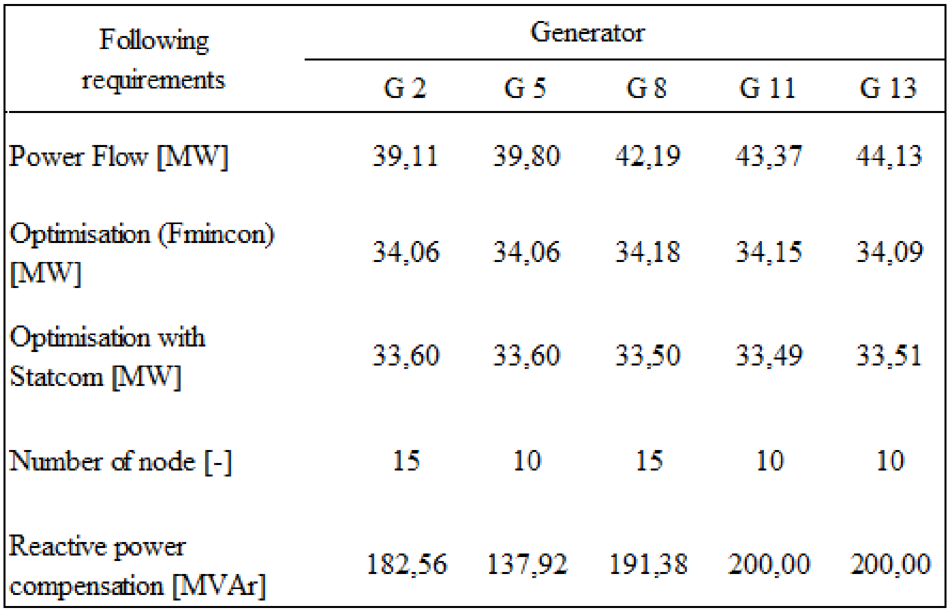
22	24	0,234666	0,242385	0,249392
23	24	0,007853	0,007581	0,008306
24	25	0,014300	0,018549	0,013951
25	26	0,065437	0,063526	0,070065
25	27	0,556957	0,532552	0,600751
27	28	1,180587	1,140458	1,266436
27	30	0,060850	0,059439	0,064970
27	29	0,060850	0,059439	0,064970
29	30	0,000000	0,000000	0,000000

Figure 24 – Active power flow in all lines



Also, calculation in an emergency situation was performed, results are shown in Table 14. The purpose was to check if the system will still be stable and if any overloads will occur the system. Therefore it was performed to switch off all generations in series. In the next table are shown the results for each state in case where generators were switched off.

Table 14 – Simulation results



Following requirements	Generator				
	G 2	G 5	G 8	G 11	G 13
Power Flow [MW]	39,11	39,80	42,19	43,37	44,13
Optimisation (Fmincon) [MW]	34,06	34,06	34,18	34,15	34,09
Optimisation with Statcom [MW]	33,60	33,60	33,50	33,49	33,51
Number of node [-]	15	10	15	10	10
Reactive power compensation [MVAr]	182,56	137,92	191,38	200,00	200,00

As shown in the presented research, using STATCOM with optimization techniques help to solve tasks with voltage regultion, power flow optimization and minimization of power losses. Compare different optimization tools as Genetic algorithm, Particle Swarm Optimization and *fmincon* function, we are able to provide calculations faster and provide better results for steady-state mode and energency mode.

Conclusion

A novel method based on the particle swarm optimization algorithm is proposed in this paper. From the both experiments we can see that the application of PSO shows the potentials to use this method in power grids to improve their operation and selected criteria. Using combination of mathematical algorithm with the static device as STATCOM we are able to provide the control of the voltage at the node to which is device connected and also it is possible to reduce active power losses. This method can be used as the solution for Optimal Power Flow tasks for distribution companies. In future research, we plan to research an algorithm that can provide us these calculations in a real time.

This paper describes theoretical and practical applications of FACTS devices such as STATCOM for voltage control and active power losses optimization. The idea and development with applying STATCOM for the optimization are presented. STATCOM provides an improvement in power quality and active power consumption stabilization. This effect could be used in applications where a variable load voltage should be compensated. It would result in a power stability improvement and decrease a risk of critical events caused by those sources.

The shown simulation provides an information for STATCOM design and placement in power grids. Applying Particle Swarm Optimization showed the potentials to use this method in power grids to improve their operation and selected criteria.

This paper describes theoretical and practical applications of FACTS devices such as STATCOM for voltage control and active power losses optimization. Using STATCOM, it is possible to control the voltage at the node to which this device is connected and at the same time it is possible to reduce active power losses.

The shown simulation provides information for STATCOM design and placement in power grids. Applying Particle Swarm Optimization showed the potentials to use this method in power grids to improve their operation and selected criteria.

Comparative results of the optimization calculations for the active power using simplified consumption characteristics and discontinuous characteristics are shown in Table 11 respectively. Power losses provided by different optimization techniques have approximately the same value. *Fmincon* provides calculation results faster than another algorithm. The paper provides an analysis of a mathematical algorithm and

methods suitable for solving optimization problems. After considering the use of each method for solving the problem of optimal voltage regulation it will use an algorithm based on sequential quadratic programming. The case study provides also results for emergency situation respecting n-1 criteria for connected generators.
It was provided the analysis of modern software and computing complexes for the control of Power systems, and also mathematical optimization methods, their features and disadvantages found that the most promising direction for solving problems of optimization is through the application of evolutionary algorithms and methods of swarm intelligence.

1. The proposed methodology for the practical application of evolutionary algorithms for the optimization of modes within electric power systems includes the systematization of recommended parameters for optimization of EPS modes.
2. The power flow distribution algorithms include:
    - optimization of EPS modes by active power,
    - optimization of EPS modes by reactive power,
    - complex optimization performed in the parallel optimization of, active power of generating plants, and reactive power compensation devices, with the restrictions as a dependent, and the independent variables respectevly.
    - finding the best location for the installation of reactive power compensation devices.
3. The use of evolutionary algorithms and reactive power compensation devices for the task of optimizing the complex electrical system modes allow the reducing of the task calculation time by almost half. By solving the problem and determining the optimal placement parameters of compensating devices we can reduce losses by 3%.
4. The developed software package (in MatLab) for the optimization of modes of electric power systems and user interfaces, are focused on the use of dispatchers in the management of power systems, as an advisor, in real time.

As presented in an article of A. A Abusorrah [11] about Linear Adapted Genetic Algorithm for Optimal Reactive power Dispatch, were also compared the classical optimization method and proposed LAGA approach. In this research the author also gets results that show that the system values corresponding to minimum loss conditions and the load bus-voltages are within the acceptable limits. In the presented research the same aim was shared, and successfully got the best values while using optimization techniques, the following were checked classical algorithms, the genetic algorithm, PSO and *fmincon* function. In the presented paper research regarding the complex for determining the best solution was conducted. The best solution found was to use the *fmincon* function together with a STATCOM device this helps determine the optimal suggested variables U and minimized the power losses in a system. The presented results suggest that the chosen complex of the solution is a reliable and promising tool for the presented task.

Regarding the main features that determine the effectiveness of the presented method, the following are of the special note: operating with a whole set of solutions that form the population, and at the same time, using traditional methods for determining each iteration have only the new solution.

- the use of different symbol models for representations of solutions regarding the original optimization problem that largely determines the efficiency and quality of applied EA

- easy programmability because EAs are simple but effective schemes of calculation

- the absence of any additional requirements for the mathematical model of the problem in the form of continuity, differentiability and unimodal optimization criterion

- stability determination of the global extremum target functions are independent of the number of programs started,

- uses the same strategy for finding the optimal solution, for the both the unimodal and for multi-extremal functions,

• taking into account the possibility of any kind of technical constraints imposed on the independent variables (a value range), and the dependent variables (as a penalty function),

• the possibility of using the presented approach, together with others,including both traditional and new methods of calculation.

The above allows concludions regarding the feasibility of using artificial intelligence methods, particularly GA, PSO and *fmincon*, which are powerful enough and can be successfully applied to a wide class of applications.

This paper considers a number of tasks related to the management of the development of electric power systems, namely:

- the choice of location of reactive power sources,
- placement of control power devices.

The considered problems of optimal allocation of the available set of reactive power compensation devices and power flow control show the basic information, and the appointment of power flow control system devices. It is shown that application of the latest methods allows for a more efficient use of existing power lines.

The use of the EA to solve the totality of these tasks is expected. Because these tasks are nonlinear and combinatorial, optimization problems are usually multi-dimensional and multimodal, for this the application of the evolutionary approach is the most effective. EA is the universal method of directed enumeration and therefore are best suited to the problems of having iterative and discrete natures of the variables.

The main focus of the thesis is related to the theoretical basis, the development and research of new scientific models and methods of optimization regarding electric power systems based on modeling of the evolution mechanism.

The most valuable and significant results should contain:

1. A study of the fundamental theoretical foundations. It shows the general characteristics of EA. Here were considered genetic operators, PSO and *fmincon* these showed their mathematical basis and principle of operation.

2. The theoretical review of the application of evolutionary algorithms (EA) of optimization problems in the electric power industry. Among these tasks it is possible to match the following: the calculation of steady-state modes of ES, the optimization of electrical systems for active and reactive power, the procude of the optimal design for the electrical network, the setting of the parameters for electrical equipment.
3. Proposed a new approach to determining the optimal distribution of power between the power generation and energy system based on EA. This methodology is characterized by a universal approach that allows you to quickly determine accurate solutions to complex problems. This allows using actual performance data to obtain more accurate values of the active power of each station.
4. There are questions of optimal power flow distribution across networks using power flow control. Utilizationof an EAis to proposed to search the best location for FACTS devices. There is displayed an undeniable effectiveness of this approach to the problem, having a combinatoric nature.
5. Studies show that the proposed algorithms are sufficiently powerful computational procedures.

It was found that the methods of EA research have doubtless advantages compared with traditional methods regarding problems of a discrete nature (optimization of network layout, optimizing the placement of compensative devices and linear regulators and optimization of transformation ratio), as well as in cases where the optimality criterion is inadequate differentiability and unimodal (optimization mode for active power).

Here is presented research regarding the operation of STATCOM devices in an electric power system in normal and emergency modes of the network (generator output).

The research displayed successful solutions to problems of voltage regulation and balancing network voltage supply using a STATCOM device.

Studies have confirmed the high performance of STATCOM utilizing a designed control system that allows it to work in emergency and post-emergency modes of the power system.

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Notation

Abbreviations

FACTS	Flexible Alternative Current Transmission Systems
STATCOM	Static Synchronous Compensator
TCSC	Technology Controlled By The Longitudinal Compensation
SSSC	Static Synchronous Series Compensator
SVC	Static Var Compensator
PSO	Particle Swarm Optimization
GA	Genetic Algorithm
EA	Evolutionary Algorithm
OPF	Optimal Power Flow
ES	Energy System
UPFC	Unified Power Flow Controller
SSG	Static Synchronous Generator
TCR	Thyristor Controlled Reactor
TSR	Thyristor Switched Reactor
TSC	Thyristor Switched Capacitor
MSR	Mechanical Switched Reactor
TCBR	Thyristor Controlled Braking Resistor
IPFC	Interline Power Flow Controller
TSSC	Thyristor Switched Series Capacitor
TCSR	Thyristor Controlled Series Reactor
EMF	Capacitor Batteries, Reactors

CR	Control Reactor
DC	Direct Current
GTO	Lockable Thyristor
AC	Alternative Current
PWM	Pulse With Modulation
SPINE	Superconducting Inductive Energy Storage
BFGS	Broyden, Fletcher Goldfarb And Shanna Approximation
TPP	Thermal Power Plant
EPS	Energy Power System
LAGA	Liner Adapted Genetic Algorithm
SQP	Sequential Quadratic Programming

Symbols

f	objective function
X	set of admissible solutions
x	feasible solution
D_j	discreet group
$\dot{S}_i$	the complex power flow at node *i*
$\dot{U}_i$	voltage in *i*-th node
$\dot{U}_i^*$	complex conjugated value of voltage in the *j*-th node
δ_i, δ_j	voltage angles $\dot{U}_i$ and $\dot{U}_i^*$

$\dot{y}_{ij}^{*}$	complex conjugated value of the element of the nodal admittance matrix
$\dot{y}_{ij}$	element of the nodal admittance matrix
$\dot{g}_{ij}, \dot{b}_{ij}$	real and imaginary part of the element $\dot{y}_{ij}$
$\dot{g}_{ij}$	real part of the element $\dot{y}_{ij}$
P_{gi}	active power supplied by *i*-th generator
P, Q	the sum of all active supplier, respectively reactive power in the network
ΔP	active losses
ΔQ_{gi}	reactive power supplied by *i*-th generator
ΔQ_{ci}	reactive power supplied by *j*-th capacitor
ΔQ	reactive losses in the network
Pgi	unit MW generated by *i*-th generator
Pgi-max	specified maximum MW generation by *i*-th generator
Pgi-min	specified minimum MW generation by *i*-th generator
Ng	number of all generators
Qgi-max, *Qgi-min*	specified maximum MW generation by *i*-th generator
Qcj-max, *Qcj-min*	specified maximum MW generation by *i*-th capacitor
S_i	the complex power flow at line *i*,

$S_i max$	the maximum complex power flow at line i,
N_L	number of transmission lines in a system
X_N	reactance
U	voltage
I	current
f	frequency
P_{Σ}^{ph}	power losses
I_1 I_n	currence of the fundamental frequency and high harmonics
R_1 R_n	resistance at the fundamental frequency and high harmonics
∇	Laplace operator
K_{add}	additional loss factor
K_{I_n}	current value of n-th harmonic component
I_{eq}	equivalent current
K_{hh}	factor of higher harmonics
I_{perm}^{old}	permissible continuous current
ρT	the thermal resistance of insulation,
d_a	core diameter,
r_1	the radius of the circle circumscribed around the cores,

d_X	the diameter of a circular conductor with a cross- sectional area and the degree of compaction, that the shaped conductor
t	is the thickness of insulation between core and metal wrapping
t_2	the thickness of the cushion under armor,
D_S	outer diameter of the surface
t_3	the thickness of the protective coating,
D_a	outer diameter of armor (for unarmored take outer diameter element, usually located directly under the armor, i.e. shell, screen or pillows)
L	distance from the surface of the ground to the cable,
D_e	is cable outer diameter
τ_a	ambient temperature
[x,s]	*x* is a vector containing the values of the parameters of the objective function, in which function get at a minimum value (in our case it is a vector of controlled variables minimizing the objective function); *s* is the resulting value of the objective function
fun	represents the minimized objective function,
x0	the vector of initial parameter values of the objective function (in our case, the initial values of controlled variables),
A, b	matrix, b is vector, which determine the linear limits of given type of inequalities in form $A \cdot \bar{x} \leq \bar{b}$,
Aeq	matrix and beq is a vector, which determines linear limits of given type of inequalities in form $A_{eq} \cdot \bar{x} \leq \overline{b_{eq}}$,
Lb and ub	vectors, containing the values of the lower and upper borders for the values of the vector x which minimizes the objective function

$\bar{\lambda}\ and\ \bar{\mu}$	vectors of Lagrange multipliers
$\bar{x}_0$	initial vector
Q_0	positive definite matrix
ΔP	active losses
MVAr	mega volt ampers (reactive)
A	amper
W	watts