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Research article

Simulation tools for FACTS devices optimization problems in electrical power systems

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Abstract: Technological advancements and ongoing scientific research have significantly contributed to addressing challenges within electrical networks. The emergence of FACTS (Flexible AC Transmission Systems) devices has introduced new opportunities for enhancing the safety and efficiency of these networks. A key focus for researchers in this domain has been optimizing FACTS devices, particularly in terms of identifying the most suitable locations, sizes, and types of controllers within electrical systems. The advent of simulation software has played a crucial role in the evolution of electrical and electronics engineering. Both offline and real-time simulation tools have gained traction in recent years, proving essential for the effective management of power systems and FACTS controllers. In this paper, we present a comprehensive overview of modeling, classification, and simulation-based approaches to various optimization challenges associated with FACTS controllers. We examined a range of simulation platforms, including MATLAB/Simulink, PSAT, EMTDC/PSC etc., assessing their effectiveness in evaluating the performance of optimized FACTS controllers and their dynamic interactions within power networks.

Keywords: FACTS controllers; FACTS optimization problem; simulation tools; MATLAB/Simulink; EMTDC/PSCAD; PSAT

Abbreviations: FACTS: flexible AC transmission system; PSAT: Power System Analysis Toolbox; TCSC: Thyristors Controlled Series Capacitor; NETOMAC: Network Torsion Machine Control; TCPS: Thyristor-controlled phase shifter; ETAP: Electrical Transients & Analysis program; SVC: Static var compensator; PSIM: Power Simulator; TSC: Thyristor Switched Capacitor; PSPICE: Personal Computer Simulation Program with Integrated Circuit Emphasis; TCR: Thyristor controlled reactor; PSCAD: Power System Computer Aided Design; TCSR: Thyristor Controlled Series Reactor; EMTP-RV: Electromagnetic Transients Program Restructed Version; TCPST: Thyristor Controlled Phase Shifting Transformer; IPC: Interphase Power Controller; TCPAR: Thyristor Controlled Phase Angle Regulator; STATCOM: Static Synchronous Compensator; SSSC: Static Synchronous Series Compensator; UPFC: Unified Power Flow Controller; IPFC: Interline power flow controller; PSB: Power System Blockset; UPQC: Unified Power Quality Conditioner; RTDS: Real Time Digital Simulator; TTC: Total Transfer Capability; PTC: Power Transfer Capability

1. Introduction

In recent years, FACTS devices have emerged as power electronics-based controllers that enhance the efficiency and security of electric networks. These devices are becoming increasingly important in the transportation sector, as they can help to ensure a stable and secure supply of power to electric vehicles and other forms of transportation. One of the key benefits of FACTS devices is that they can enhance the stability of the power grid by regulating the flow of electricity within the system. This can help prevent blackouts and other power outages, which can have significant economic and societal impacts [1–4]. Another benefit of FACTS devices is that they can help optimize the use of existing infrastructure and equipment. This can be particularly important in the transportation sector, where the cost of building new infrastructure can be high [5–8]. Therefore, the use of FACTS controllers in the transportation sector is likely to become increasingly important in the coming years, as operators seek to enhance their infrastructure and optimize equipment usage, and ensure a secure and stable supply of power to their customers. While FACTS devices are primarily utilized in the transmission system to enhance the PTC (Power Transfer Capability), voltage control, and stability, they can also be employed in the distribution system, where they are commonly known as D-FACTS (Distribution FACTS) devices. D-FACTS devices are designed to address specific challenges and improve the performance of distribution systems. These devices offer similar functionalities as their transmission system counterparts but are tailored to the requirements and characteristics of the distribution network. Common types of FACTS devices include static var compensators (SVCs), static synchronous compensators (STATCOMs), and unified power flow controllers (UPFCs). Each device type possesses distinct capabilities and can be deployed to address specific power system issues. Determining the best placement, size, and type of FACTS controllers in electric networks involves solving a FACTS allocation problem. This complex optimization problem aims to give the most combination of FACTS controllers that maximize system performance while minimizing costs. Specialized tools and techniques are employed to analyze and solve this optimization problem effectively [9]. The integration of FACTS devices in both transmission and distribution systems offers several advantages. These include enhanced stability, improved power system efficiency, increased security, and the ability to mitigate voltage fluctuations and power quality issues. By carefully analyzing and optimizing the placement, type, and size of FACTS devices, engineers and operators can leverage their benefits to achieve a more reliable and efficient power system. Therefore, FACTS devices find widespread use in the transmission system, but their application as D-FACTS devices is also valuable. The optimal selection and placement of these devices, determined through careful analysis and optimization, contribute to the stability, efficiency, and security of the power system.

The incorporation of power electronics in electric power systems has paved the way for the development of FACTS devices, which offer numerous advantages, such as:

- Enhanced Transmission Capacity: One of the significant advantages of FACTS devices is their ability to boost the PTC of transmission lines. By actively controlling the flow of active and reactive power, these devices help alleviate congestion in the network and enhance the overall capacity of the electric network. This enables more efficient utilization of existing infrastructure and reduces the need for costly transmission line expansions.
- Voltage Stabilization: FACTS devices play a crucial role in stabilizing voltage levels within the power grid. This is particularly important in modern electric networks with a high integration of RES, which often exhibit intermittent generation characteristics. By dynamically regulating voltage levels, FACTS devices guarantee a dependable and efficient power supply, mitigating voltage fluctuations and maintaining optimal operating conditions.
- Oscillation Suppression: Oscillations in the power grid can arise from various factors such as changes in load and disturbances in the system. FACTS devices are capable of detecting and suppressing these oscillations, thereby enhancing the stability of the power grid. By dampening undesirable oscillatory behavior, FACTS devices contribute to grid reliability, prevent cascading failures, and reduce the risk of blackouts or voltage collapses.
- Improved Power Quality: FACTS devices can ameliorate the quality of power supplied to consumers. They can effectively reduce harmonics, voltage sags, and other power distortions that can degrade the performance of sensitive equipment. By actively mitigating these power quality issues, FACTS devices help ensure a clean and reliable power supply, minimizing disruptions and maximizing the efficiency of electrical systems.

Therefore, FACTS devices offer a range of advantages that positively impact the operation and performance of electrical networks. Their ability to increase transmission capacity, stabilize voltage levels, suppress oscillations, and improve power quality contributes to a more reliable, efficient, and resilient power grid. As a result, FACTS devices have become essential tools in modern power systems, empowering utilities to meet the demands of an evolving energy landscape. The suitable location of the FACTS controller using soft computing approaches offers a promising solution to address critical operational challenges in power systems. Determining the suitable locations for FACTS controllers in power grids represents a crucial step toward establishing a secure, efficient, and reliable power system. However, identifying the optimal placement of FACTS controllers poses a significant challenge due to the complex nature of the problem. It involves addressing multiple constraints, considering various system states, and dealing with a highly constrained and multimodal optimization problem. To overcome these challenges, simulation tools tailored for FACTS device optimization have been developed and are summarized in this paper.

These simulation tools leverage soft computing approaches, which encompass a range of computational techniques such as evolutionary algorithms, neural networks, fuzzy logic, and swarm intelligence. By integrating these approaches into the optimization process, the simulation tools can effectively search for optimal FACTS controller locations within the power grid. Ultimately, the goal of the study is to provide guidance on the suitable location of FACTS controllers in electrical power systems, including which devices to use, how many to use, where to place them, and what parameters to use. This information can be valuable for power system operators, engineers, and researchers who are working to improve the performance and reliability of the power grid using a Simulation Tools for FACTS device optimization problems. Simulation tools are computer programs that are designed to model and simulate the behavior of complex systems, such as electrical power grids. These simulation tools can be used to simulate the behavior of FACTS devices in different scenarios and to optimize the placement, type, and size of these devices to achieve specific performance goals. Here, we aim to provide a comprehensive overview of various simulation tools that have been employed to address the optimization problem associated with FACTS devices. By exploring the capabilities and characteristics of these simulation tools, a comprehensive understanding of the advancements in FACTS device optimization can be gained.

The optimization problem related to FACTS devices encompasses finding the optimal configuration, placement, and control strategies for these devices in a power system. Solving this problem is crucial to enhance the system's performance, reliability, and efficiency. Simulation tools have emerged as valuable resources in tackling this complex optimization challenge.

We discuss different simulation tools that have been extensively utilized in FACTS device optimization. These tools encompass a wide range of methodologies and algorithms, including mathematical programming, evolutionary algorithms, heuristic techniques, and metaheuristic approaches. Each simulation tool has its strengths and limitations, and its suitability depends on various factors such as problem complexity, solution space, computational resources, and user preferences. By providing an overview of these simulation tools, we aim to highlight their unique features, advantages, and applications. It will explore the methodologies employed by each tool, along with the underlying algorithms and optimization techniques. Furthermore, the paper will discuss the performance evaluation criteria used to assess the effectiveness and efficiency of these simulation tools in solving the FACTS devices optimization problem. The insights provided in this paper are valuable to researchers, engineers, and practitioners working on power system optimization and FACTS device deployment. By understanding the capabilities and limitations of different simulation tools, stakeholders can make informed decisions regarding the selection and utilization of appropriate tools for their specific optimization needs. Hence, simulation tools can be a valuable tool for optimizing FACTS devices in power systems, as they allow engineers to test and evaluate different strategies before implementing them in the real world.

The major motivations and contributions of this survey study are outlined below:

- Exploration of Key Performance Factors: We delve into the crucial elements and constraints that must be considered to attain best performance in addressing the FACTS devices optimization problem. The highest success rates are sought while exploring strategies that support these performance factors.
- Comprehensive Overview: We provide comprehensive tables that outline the strategies employed, FACTS devices investigated, and the specific objectives addressed in each reviewed document. This overview offers a clear understanding of the methodologies and research scopes applied in the field.
- Discussion of Optimization Techniques: The survey provides the advantages and disadvantages of different optimization methods employed in solving the FACTS devices optimization problem. By analyzing the existing literature, we highlight the effectiveness and limitations of different approaches, contributing to a deeper understanding of the field.
- Addressing Key Questions: We aim to answer important questions related to FACTS device optimization. It provides insights into which FACTS devices should be utilized, the optimal quantity of devices, the most suitable locations for deployment, the parameters to be considered, and the associated installation costs. By synthesizing information from various studies reported in the literature, this survey offers valuable insights into these crucial aspects.

- Benefits of FACTS Devices: We recognize the benefits of FACTS devices, which utilize power electronics to facilitate accurate and continuous control over power flows. These advantages encompass the ability to keep voltage levels within permissible limits at load buses, manage the flow of active and reactive power in thermally limited transmission lines, improve safety protocols, and enable electrical systems to operate near their maximum capacity. The creation of efficient tools, including the application of FACTS controllers, is essential for the effective management and optimization of electrical networks.
- Simulation-Based Approaches: We highlight the use of simulation-based approaches in solving the FACTS devices optimization problem. Various techniques based on simulations have been applied to address this issue, recognizing the importance of developing tools that facilitate the efficient operation of electrical networks.

Thus, this survey study offers a comprehensive analysis of the FACTS controllers optimization problem. It explores key performance factors, presents an overview of strategies and test systems employed, discusses the advantages and limitations of optimization methods addresses important questions regarding the application of FACTS controllers, and recognizes the advantages of FACTS controllers in power system operation. By focusing on simulation-based approaches, this study contributes to the advancement of effective solutions for optimizing FACTS controllers in electric networks.

This paper is organized into seven sections, each addressing key aspects of the FACTS allocation issue. The outline of the sections is as follows:

Section 1 is reserved for the Introduction: In this section, we provide a concise introduction to the topic, setting the stage for the subsequent sections. Section 2 is restricted to the Fundamentals of Electrical Power Systems Operations: In this section, the fundamental principles and rules governing the operation of electrical power systems are discussed. This provides the necessary background knowledge for understanding the challenges and opportunities associated with FACTS device allocation. In Section 3, we explore the different categories of FACTS controllers, which include series, shunt, and combined types. We delve into the modeling techniques, control strategies, and optimal placement of these devices within electrical power systems. By providing an in-depth analysis of these aspects, we aim to enhance the understanding of the deployment and functionality of FACTS devices in improving system performance. In Section 4, we present the mathematical formulation for the issue of FACTS device allocation. This formulation encompasses all the relevant constraints and considerations specific to the power system under study. By formulating the problem mathematically, it becomes possible to apply optimization techniques to find optimal solutions. Section 5 contains the Simulation-Based Methods for Solving the issue of FACTS device allocation: In this section, we focus on reviewing different simulation-based methods that have been employed to address the FACTS allocation issue. These techniques leverage computer simulations and computational algorithms to enhance the allocation of FACTS devices within power systems. Various methods, such as evolutionary algorithms, neural networks, and heuristic techniques, are discussed in this section. In Section 6, we provide a comprehensive discussion of the findings and insights derived from the previous sections. Here, we highlight the strengths and limitations of the simulation-based methods and offers critical analysis of the current state of FACTS allocation research. In the final section, we conclude by summarizing the major findings and contributions. Additionally, we provide recommendations for future studies and areas of further exploration to advance the field of FACTS allocation.

2. Operations in electric networks

To ensure the proper operation of an electrical network, several fundamental rules must be followed. These rules aim to maintain a balance between generation and demand while maintaining a constant frequency and adhere to the permissible limits of various network parameters. One such important rule, as stated in [10], is to ensure equality between production and consumption at all times.

2.1. Regulation of power flow in a transmission line

The primary function of a transmission line in an electrical network is to transport active power. While reactive power is also conveyed, its magnitude should be minimal compared to active power. To ensure the proper performance of a transmission line, it must satisfy the subsequent conditions, as mentioned in [11]:

- Voltage Stability: The voltage along the length of the transmission line should remain relatively constant, regardless of the load. Fluctuations in voltage can negatively impact the operation of connected equipment and devices. Therefore, measures should be taken to maintain voltage stability within acceptable limits.
- Low Losses: The transmission line should have low power losses to ensure efficient power transfer. Losses in the form of heat, known as Joule losses, occur due to the resistance of the conductors. Minimizing these losses is essential to optimize the line's performance and prevent excessive heating of the conductors.
- Thermal Limits: Excessive Joule losses can lead to overheating of the transmission line conductors, which can compromise their integrity and increase the risk of failure. It is crucial to ensure that the line's thermal limits, such as the maximum allowable temperature, are not exceeded. Adequate cooling mechanisms and conductor sizing should be implemented to prevent overheating issues.

If a transmission line does not satisfy these criteria, a supplementary device must be installed to meet the necessary requirements. For instance, voltage control devices, such as tap changers or voltage regulators, can be employed to maintain voltage stability. Loss reduction techniques, including improved conductor materials or optimization of the line's geometry, can help minimize power losses. Moreover, measures like proper insulation and cooling systems can be implemented to mitigate thermal issues and prevent conductor overheating.

By satisfying these conditions, the transmission line can effectively transport active power while minimizing reactive power, maintaining voltage stability, reducing losses, and preventing overheating. Additional equipment and measures may be necessary to ensure that all these requirements are met, enabling the line to operate optimally within the electrical network.

Figure 1 shows the equivalent circuit of a lossless transmission line (km) with a voltage source G and a load $\overline{Z}$ [12].

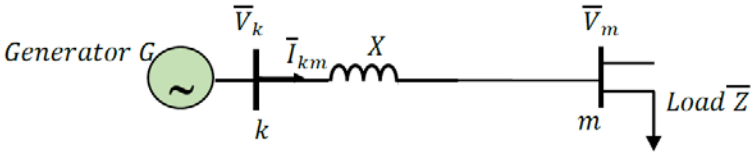


Figure 1. Line connecting generator and load.

The real and reactive powers transmitted in the transmission line from bus k to a bus m can be represented by the following expressions [10].

$$P_{km} = \frac{V_k V_m}{X} sin(\delta_k - \delta_m) \tag{1}$$

$$Q_{km} = \frac{{V_k}^2}{X} - \frac{V_k V_m}{X} cos(\delta_k - \delta_m) \tag{2}$$

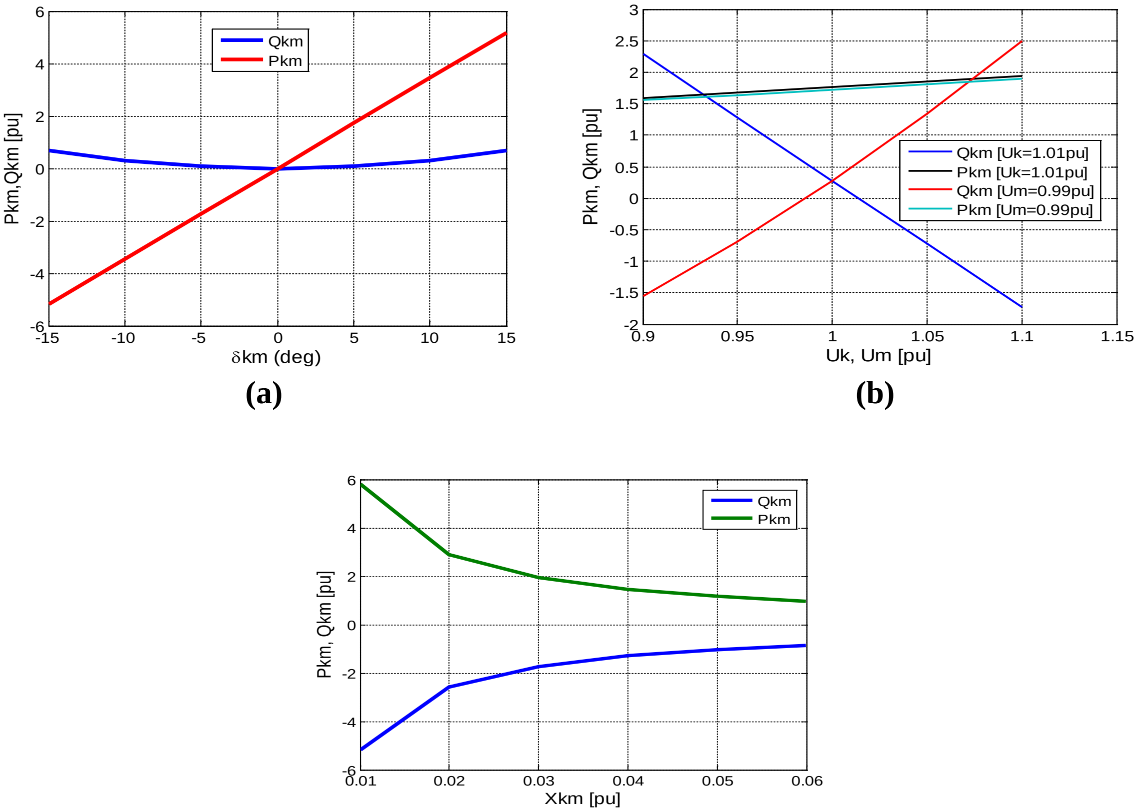
where (V_k, V_m) and (δ_k, δ_m) are modules and phases of the voltages at the nodes k and m, respectively.

According to Eq 1, the power transits can be controlled by adjusting:

- The transport angle, $(\delta_k - \delta_m)$ by a phase shifter system.
- The reactance of the line by compensation.
- The voltages V_k and V_m at the ends, low margin due to the need to maintain the voltages in order to limit line losses.

Figure 2 illustrates the impact of changes in each of the three parameters on the transmitted real and reactive powers. It highlights that:

- The modification of the phase shift mainly acts on the active power transmitted.
- The voltage control at the nodes mainly modifies the reactive power flows.
- The variation of the line reactance acts simultaneously on the active and reactive powers.



(a) **(b)**

(c)

Figure 2. Influence of different parameters on the power transmitted in a line. (a) Power angle δ_{km}; (b) Voltage at buses U_k,,U_m; (c) Variation of the line reactance X_{km}.

By acting on one or more of these parameters, FACTS devices allow precise control of reactive power transmissions and optimization of active power transmissions in an existing network.

2.2. Voltage drop regulation

Referring to Figure 1 we can draw the following voltage vector diagram [10–13]:

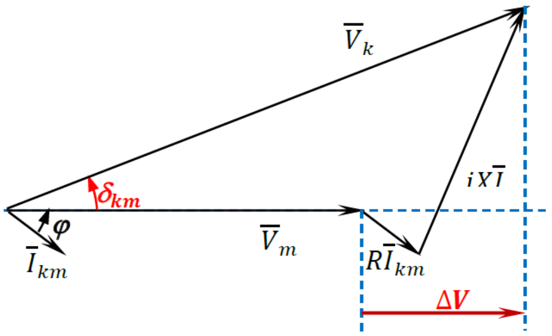


Figure 3. Voltage vector diagram.

The complex power absorbed by the load at node *m* is

$$\overline{S}_m = P_m + jQ_m \tag{3}$$

From the Figure 3, if φ designates the phase shift of the current in relation to the voltage at the terminals of the load, voltage drop ΔV and angular difference between the voltages or the angle of transport δ_{km} will be given by the following equations, respectively, when Vk = 1 pu.

$$\Delta V = RI_{km}cos\varphi + XI_{km}sin\varphi = \frac{RP_m+XQ_m}{V_m} \tag{4}$$

$$sin\,\delta_{km} = XI_{km}cos\varphi - RI_{km}sin\varphi = \frac{XP_m-RQ_m}{V_m} \tag{5}$$

In the case of a high-voltage transmission line (practically $R \ll X$) and if the network is lightly loaded (δ_{km} is small), Eqs (4) and (5) can lead to the following simplified expressions,

$$\Delta V \cong \frac{XQ_m}{V_m} \tag{6}$$

$$\delta_{km} \cong \frac{XP_m}{V_m} \tag{7}$$

Under these conditions, relations (6) and (7) prove that the voltage decrease is due to the transmission of reactive power on the line, while the angle of transport is mainly due to the transmission of active power. To maintain the voltage within an acceptable range and minimize the voltage decrease, it is therefore sufficient to avoid transporting the reactive power, and it is therefore necessary to produce it at the place of its consumption. This action is carried out by the use of compensation devices (capacitor bank, rotary or static compensators, FACTS).

2.3. Classification of FACTS devices

FACTS devices can be categorized into three major classes, as mentioned in references [10] and [13]. These classes are differentiated by their control systems and structures:

- Conventional Control Systems: The first class of FACTS systems utilizes conventional control systems that employ thyristors for control purposes.
- Static Converters with GTO-Based Control: The second class of FACTS systems employs static converters based on power semiconductors, specifically gate turn-off thyristors (GTOs). These systems are characterized by their structures and control mechanisms. Two types of static converters are included in this class:
- Alternating Current Dimmer or Reactance Control: This subtype comprises devices such as SVC and TCSC. They are controlled by a thyristor valve and can adjust the reactance or impedance of the system in response to changing conditions.
- Voltage Source Converter: This subtype includes devices that utilize a voltage source converter to generate an adjustable amplitude, frequency, and phase alternating voltage. Examples of devices in this category are the SSSC, STATCOM, UPFC, and IPFC.

A classification diagram illustrating the different FACTS devices can be found in Figure 4, where FACTS systems can be classified into three categories: conventional control systems, static converters with GTO-based control (including the alternating current dimmer/reactance control subtype and the voltage source converter subtype). These systems employ various devices and control mechanisms to improve the flexibility and regulation of alternating current transmission systems.

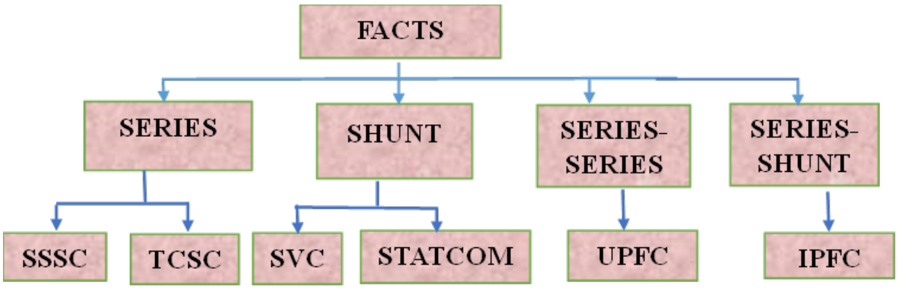


Figure 4. Classification of FACTS devices.

2.3.1. FACTS shunt devices

-Shunt Compensation

Shunt compensation plays a crucial role in the electric network by either absorbing or generating reactive power at the connection point. Its primary objectives include maintaining voltage levels at nodes during steady-state operation and enhancing system performance during dynamic conditions. These benefits are achieved through the following mechanisms, as referenced in [14]:

- Voltage Regulation: In steady-state conditions, shunt compensators help regulate and control the voltage levels at various nodes in the electric network. By consuming or producing reactive power as needed, they ensure that voltages remain within acceptable limits, preventing overvoltage or undervoltage situations.

- Transient Stability Improvement: During dynamic conditions, such as disturbances or faults, shunt compensators contribute to improving transient stability. They help dampen power oscillations and mitigate the effects of system disturbances, improving the power system's stability and reliability.

When transmitting power over extended lines, it becomes necessary to improve the PTC by dividing the line into multiple sections. Shunt compensators are then installed at the midpoints of these sections to adjust the voltage levels. This approach enables efficient power flow and maintains voltage stability along the transmission line.

The optimal location of parallel compensation devices is typically at the midpoint of the transmission line, as indicated in [10]. This strategic positioning allows for effective voltage control and minimizes the impacts of reactive power flow on both ends of the line. By installing shunt compensators at suitable locations, voltage deviations can be minimized, ensuring reliable power transmission and system operation.

Also, shunt compensators fulfill important functions in power systems, including voltage regulation during steady-state conditions, improvement of transient stability, and adjustment of voltage levels in long transmission lines. Their optimal placement in the middle of transmission lines contributes to efficient power flow and voltage control, enhancing the overall performance and reliability of the electrical network.

Figure 5 presents the case of a transmission line connecting two generators in which, a perfect compensator connected in the middle. The latter makes it possible to maintain the voltage at the midpoint O at the same order of magnitude as those of the ends k and m $(V_k = V_m = V_o = V)$. It cuts the line into two equal portions of reactance $X/2$ [15].

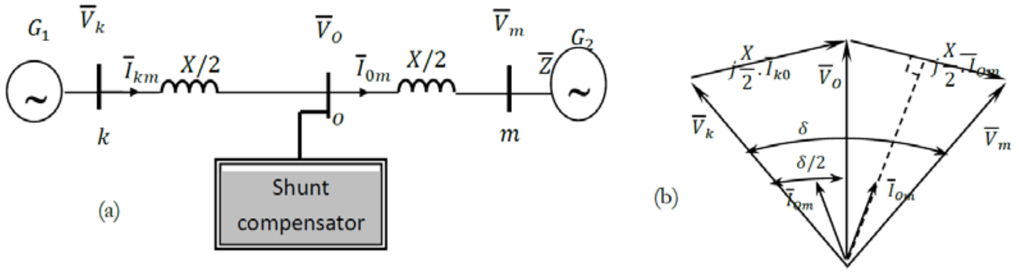


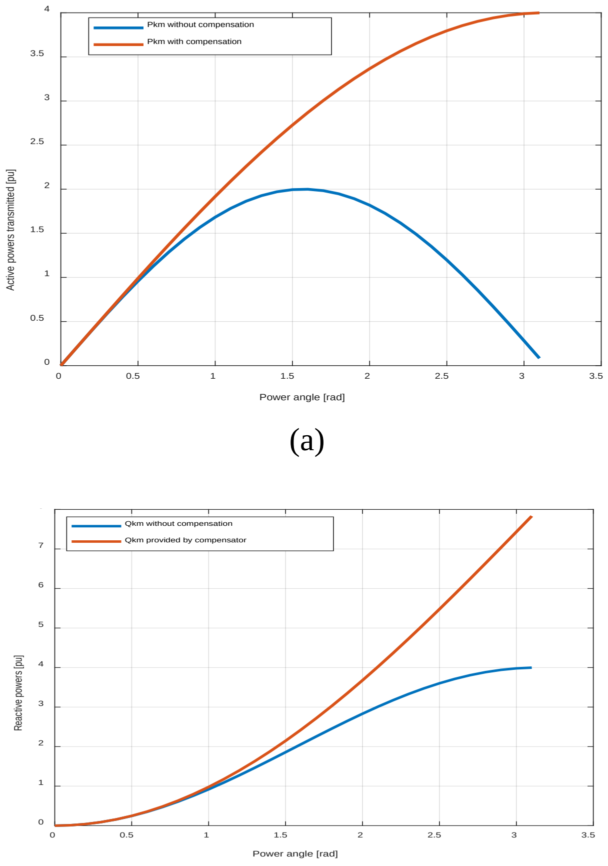
Figure 5. (a) Parallel compensator to the middle of the line (b) Voltage vector diagram.

Referring to Eqs (1) and (2) applied to each section, the active power transmitted from k to m and the reactive power supplied by the compensator will be given respectively by the following equations.

$$P_{km} = 2\frac{V^2}{X}sin\frac{\delta}{2} \tag{8}$$

$$Q_C = 4\frac{V^2}{X}\left(1 - cos\frac{\delta}{2}\right) \tag{9}$$

Figure 6 shows an increase in the real power transmitted by the transmission line after the installation of the shunt compensator. This increase is twice as large as the uncompensated one for a value of the angle δ of π. Also, an increase in reactive power when a compensator is present compared to the uncompensated case. Considerable reactive power at the connection point of the compensator.



(a)

(b)

Figure 6. Variation of real power (a) and reactive power (b) in relation with the power angle.

In the case of a long line supplying a load, the parallel compensator connects across the terminals of the load to keep the voltage constant. Figure 7 presents the case of a generator supplying a load through a transmission line. The parallel compensator acts directly on the voltage V_k at node k.

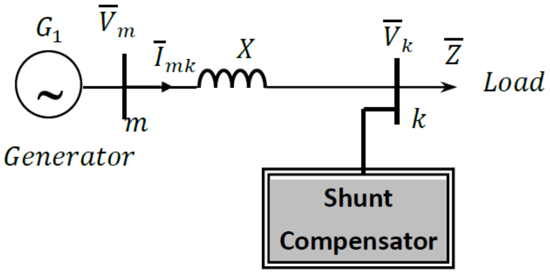


Figure 7. Parallel compensator across the load terminals.

2.3.2. FACTS series devices

Compensation devices, such as series compensators, are connected in series within the electrical network. Their main purpose is to modify the impedance of transmission lines by introducing an adjustable voltage source. These compensators can be implemented using variable impedances, either inductive or capacitive in nature, as referenced in [10] and [14].

The series compensators are strategically placed along the transmission lines to alter the line impedance and ameliorate the overall performance of the electric network. By incorporating a variable voltage source, these compensators enable control over the line's reactance and, consequently, its impedance.

Two types of variable impedances are commonly used in series compensation:

- Variable Inductive Impedance: This type of series compensator utilizes variable inductors to adjust the line impedance. By controlling the inductance, the compensator can modify the reactance of the line, effectively influencing the impedance seen by the power flow.
- Variable Capacitive Impedance: Another approach for series compensation involves using variable capacitors. By adjusting the capacitance, the compensator can modify the line's reactance and, consequently, the impedance. This enables control over the power flow and voltage levels within the system.

The ability to introduce an adjustable voltage source through variable impedances allows series compensators to influence the line impedance and optimize power transmission. By modifying the line parameters, these compensators help mitigate issues such as line losses, voltage drops, and voltage stability concerns.

Hence, series compensators play a crucial role in the electrical network by introducing adjustable voltage sources through variable impedances. These compensators effectively modify the line impedance, be it through variable inductive or capacitive elements, to enhance power transmission, voltage control, and system performance.

- Series compensation

Series capacitors have been used for many years to modify the effective inductive reactance X_{eff} of the line. Generally, they act by inserting a capacitive voltage to offset the voltage drop caused by inductive reactance on the line [10,13].

Equation (9) proves that the power transmitted in a line can be improved by reducing the link impedance between the two nodes (k) and (m). Figure 8 illustrates a series compensator installed in a transmission line connecting a generator G and a load $\bar{Z}$.

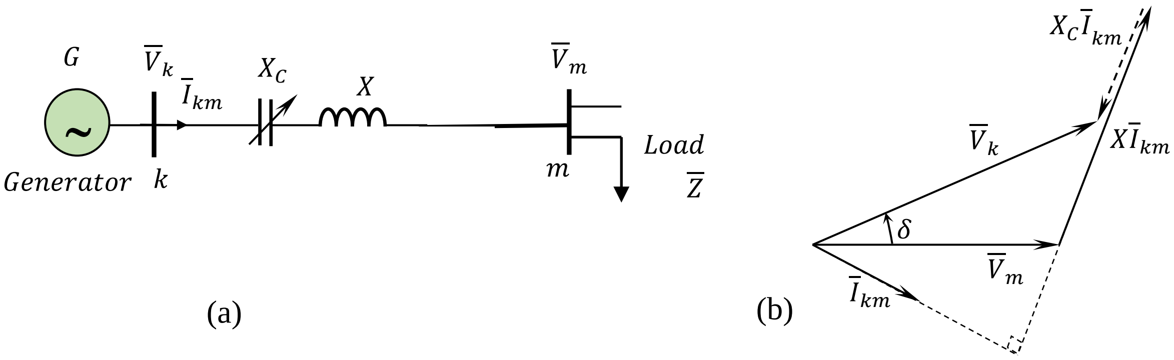


Figure 8. (a) Series compensator in the transmission line (b) Voltage vector diagram.

The reactance of the line is then reduced from X to X_{eff}:

$$X_{eff} = X - X_c = (1 - K)X \tag{10}$$

$$K = \frac{X_C}{X} \tag{11}$$

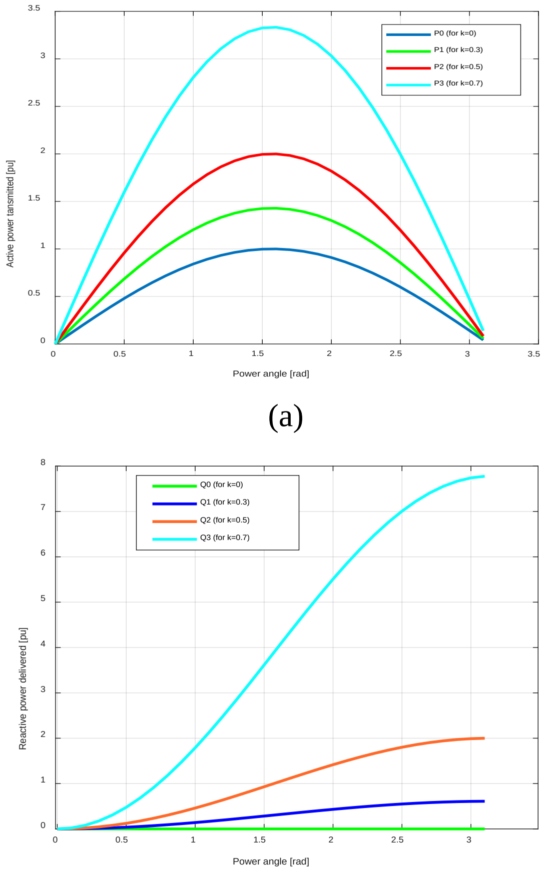
where K is the degree of series compensation expressed as follows.

The real power transferred between the two buses k and m, whose voltages are kept constant $(V_k = V_m = V)$, and the reactive power supplied by the series compensator are given by the following equations, respectively,

$$P_{km} = \frac{V^2}{\mathrm{X}(1-\mathrm{K})}\sin(\delta) \tag{12}$$

$$Q_C = \frac{2V^2}{X}\frac{k}{(1-k)^2}(1 - cos\delta) \tag{13}$$

Figure 9 shows the variation of the real power transmitted in a line and that of the reactive power supplied for different degrees of compensation. It highlights the possibility of increasing the transmissible power by series compensation. The compensator reactive power strongly increases with the degree of compensation. Theoretically, we can speak of a compensation of 100%, but practically this action is limited to around 40 to 75% in order to avoid the appearance of the phenomenon of resonance between the series compensator and the shaft of the generators of the groups of production. It is a phenomenon of hypo synchronous resonance SSR (Sub Synchronous resonance) [16].



(a)

(b)

Figure 9. Evolution of real power (a) and reactive power (b) in relation to the power angle for different values of the degree of compensation k = 0; 0.3; 0.5 and 0.7.

Different types of FACTS controllers are employed based on specific control objectives. The selection of a particular FACTS controller depends on the desired control actions and functionalities. Figure 10 illustrates the potential control strategies for regulating the transmitted active power in a transmission line.

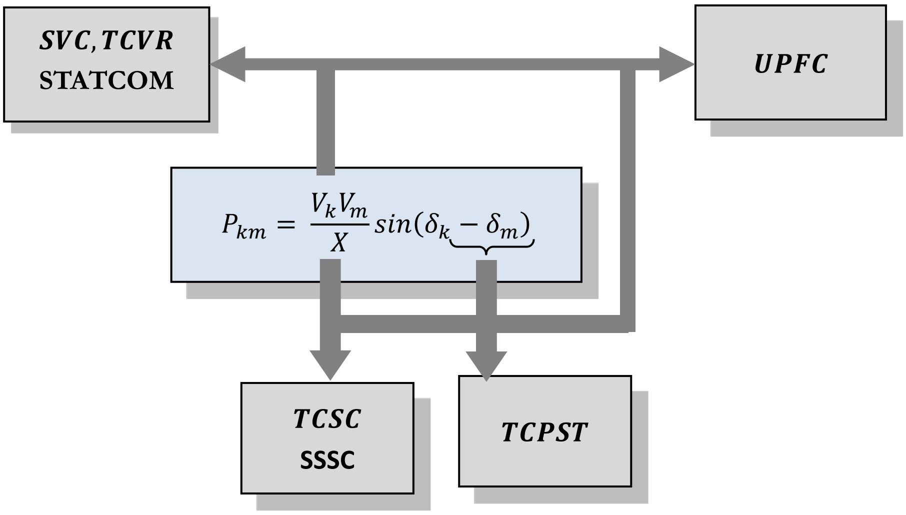


Figure 10. Enhancing power transmission: Control strategies for different FACTS controllers.

3. FACTS devices modeling

When incorporating the developed models of FACTS controllers into load flow programs, a common approach is to integrate them by modifying the admittance matrix. This integration method allows for the simulation and assessment of the impacts of FACTS controllers throughout the electric network.

Load flow programs are computer-based tools used to analyze and calculate the steady-state behavior of power systems. These programs take into account various system parameters, such as loads, generators, transmission lines, and transformers, to determine system voltages, currents, and power flows.

To incorporate the effects of FACTS controllers into load flow programs, the developed models of these controllers are integrated into the program's calculations. The admittance matrix, which represents the electrical properties and interconnections of the system components, is adjusted to reflect the presence and operation of FACTS controllers.

The modification of the admittance matrix involves updating the relevant entries to reflect the effect of FACTS controller actions on the electric network. This may include adjusting the admittance values associated with specific transmission lines or nodes affected by the presence of FACTS controllers.

By modifying the admittance matrix, load flow programs can simulate the behavior and interactions of FACTS controllers within the system. This enables the evaluation of various operational scenarios and control strategies, providing valuable insights into the effect of FACTS controllers on system voltages, power flows, and overall system performance.

Thus, integrating the developed models of FACTS controllers into load flow programs through admittance matrix modification allows for comprehensive simulation and analysis of their effects throughout the power system. This approach enhances the understanding of how FACTS controllers influence system behavior and aids in optimizing their deployment for improved system operation and performance.

3.1. Nodal admittance matrix (Y) modification

FACTS devices are regarded as components that directly alter the *Y* matrix of the power system, as referenced in [17]. These devices are inserted into the transmission lines, and their specific placement depends on the type of FACTS being modeled. Figure 11 illustrates the location of FACTS devices within the line.

The location of FACTS devices along the transmission line depends on their type and purpose. In some cases, the device is positioned at the center of the line, while in other cases, it may be placed at one end of the line.

The choice of placement is determined by various factors, including the desired control objectives and system requirements. For example, certain FACTS devices, such as series compensators, are typically installed at the midpoint of the line. This strategic placement allows for effective control over the line impedance and power flow.

On the other hand, other types of FACTS devices, such as shunt compensators or voltage source converters, may be located at one end of the line. This placement enables better control of reactive power and voltage levels at specific nodes or regions of the network.

The specific placement of FACTS devices is a crucial consideration in their modeling and implementation. It ensures that the devices can effectively modify the nodal admittance matrix and exert the desired influence on the power system.

Therefore, FACTS devices are inserted into transmission lines and directly alter the *Y* matrix in the electric network. The placement of these devices depends on their type, with some devices positioned at the midpoint of the line and others located at one end. The choice of placement is based on the intended control objectives and system requirements.

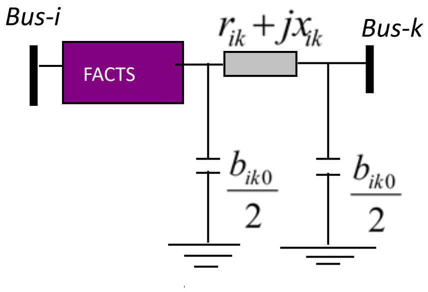


Figure 11. Incorporation of the FACTS device into a transmission line.

The Y matrix is modified as follows.

$$\underline{Y_{\text{mod}}}=\begin{pmatrix}\underline{Y_{ii}^{'}} & \underline{Y_{ik}^{'}}\\ \underline{Y_{ki}^{'}} & \underline{Y_{kk}^{'}}\end{pmatrix}=\underbrace{\begin{pmatrix}\underline{Y_{ii}} & \underline{Y_{ik}}\\ \underline{Y_{ki}} & \underline{Y_{kk}}\end{pmatrix}}_{line}+\underbrace{\begin{pmatrix}\underline{y_{ii}^{F}} & \underline{y_{ik}^{F}}\\ \underline{y_{ki}^{F}} & \underline{y_{kk}^{F}}\end{pmatrix}}_{FACTS} \tag{14}$$

Researchers [18] have focused on investigating the characteristics, control strategies, and performance of these FACTS devices. These devices offer various functionalities including reactive power compensation, voltage regulation, power flow management, and oscillation damping.

For each particular FACTS device and its location within the transmission line, certain coefficients of the nodal matrix Y will be modified to account for the device's presence and its impact on the power system. These modifications reflect the altered admittance values resulting from the insertion of FACTS devices at specific points along the transmission network presented in Figure 12.

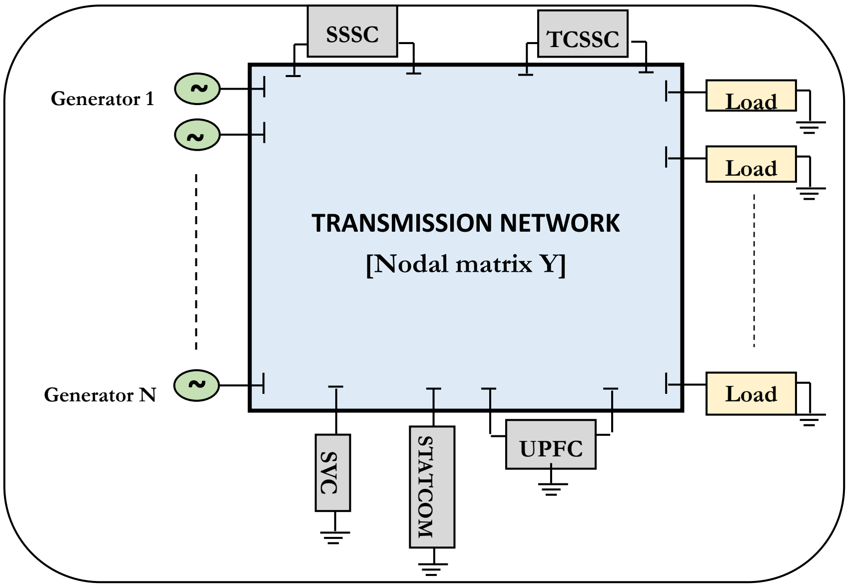


Figure 12. A graphical representation of electric network including FACTS controllers.

3.2. Electrical network including STATCOM

Figure 13 presents the model of a STATCOM connected to bus k of an electrical network of N buses. The STATCOM is modeled by a controllable voltage source E_p in series with an impedance Z_p. The imaginary part X_p represents the leakage reactance of the transformer, while the real part of the impedance R_p represents the ohmic losses of the power components and the main connection transformer [18].

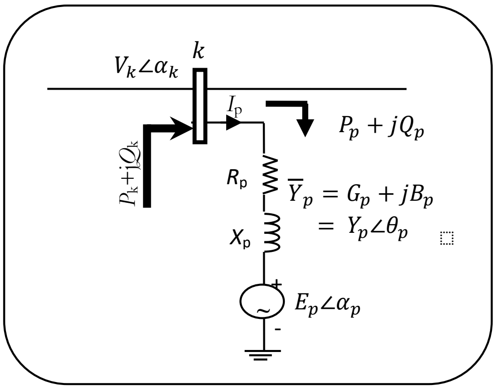


Figure 13. Steady state STATCOM model.

The STATCOM absorbs or provides reactive power from the electrical network to maintain the voltage V_k constant, this means that it therefore works as a voltage regulator. In Figure 13, the ohmic losses P_p due to the real part of the admittance Y_p, is incorporated into the power flow calculation. The term $(P_k + jQ_k)$ presents the net of the injected active and reactive powers into the bus k including the local load before the use of the STATCOM device. The power flow equations for all buses in the system with the STATCOM device, except bus k, are identical to those without the device. The real and reactive powers injected at bus k can be calculated as given by Eqs (15) and (16), respectively

$$P_k = P_p + \sum_{j=1}^{N} V_k \, . V_j . Y_{kj} . cos(\propto_k - \propto_j - \theta_{kj}) \tag{15}$$

$$Q_k = Q_p + \sum_{j=1}^{N} V_k \, . V_j . Y_{kj} . sin(\propto_k - \propto_j - \theta_{kj}) \tag{16}$$

The real and reactive powers injected at bus k for the system without FACTS are represented by the second terms in Eqs (15) and (16) (summation $\sum \square$), respectively. Moreover, P_p and Q_p represent the variations of the injected powers due to the use of STATCOM, and we can therefore write:

$$P_p = Real(\overline{V}_k . \overline{I}_p^*) \tag{17}$$

$$Q_p = Im(\overline{V}_k . \overline{I}_p^*) \tag{18}$$

We deduce:

$$P_p = G_p . V_k^2 - V_k . E_p . Y_p . cos(\propto_k - \propto_p - \theta_p) \tag{19}$$

$$Q_p = -B_p . V_k^2 - V_k . E_p . Y_p . sin(\propto_k - \propto_p - \theta_p) \tag{20}$$

where $V_k \angle \propto_k$ are modulus and argument of the voltage at bus k, respectively. Y_p and θ_p are modulus and argument of the admittance of the STATCOM device, respectively.

Two new variables $(E_p \; and \; \propto_p)$ are introduced by the insertion of STATCOM; however, V_k is now known. Therefore, to resolve the power flow issue, multiple equations are required. This new equation justifies the fact that the power P_{Ep} consumed by the source E_p must be zero in steady state. It is expressed by the following equation.

$$P_{Ep} = Real\left(\overline{E}_{Ep} . \overline{I}_p^*\right) = -G_p . E_p^2 + E_p . V_k . Y_p . cos(\propto_p - \propto_k - \theta_p) = 0 \tag{21}$$

3.3. Electrical network with SSSC

The purpose of using an SSSC is the regulation of the real power P_{km} transmitted to reach a preset value. The SSSC device is modeled by a voltage source E_s of amplitude and phase angle $\propto_s$ adjustable in series with an impedance $\overline{Z}_s$. The imaginary part of this impedance represents the leakage reactance of the transformer [19]. Whereas, the real part represents the ohmic losses of the semiconductors and the mains connection transformer. Figure 14 presents the model of an SSSC controller placed in a line (km) of an N buses electric power network. The admittance $\overline{Y}_s$ is the sum of the admittance of the SSSC device and that of the line where it is placed.

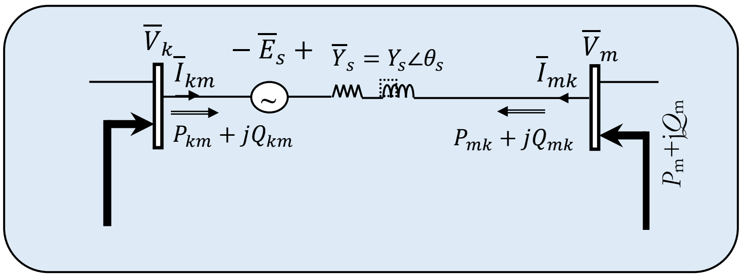


Figure 14. Steady state SSSC model.

Two new variables E_s and $\propto_s$ are introduced by the existence of the voltage source $\overline{E}_s$. Therefore, we need two new equations to solve the power flow problem. One is obtained by assuming that the power P_{Es} consumed by the voltage source is zero. The other corresponds to the equality between the transited power P_{km} and its set point value at a steady state. The power flow equations for all buses of the electrical network after the use of the SSSC device, with the exception of buses k and m, are identical to those of the system without FACTS. The powers injected at buses k and m are expressed as follows:

$$P_k = P_{km} + \sum_{j=1}^{N} V_k\,.V_j.Y_{kj}.cos\left(\propto_k - \propto_j - \theta_{kj}\right) \tag{22}$$

$$Q_k = Q_{km} + \sum_{j=1}^{N} V_k\,.V_j.Y_{kj}.sin\left(\propto_k - \propto_j - \theta_{kj}\right) \tag{23}$$

$$P_m = P_{mk} + \sum_{j=1}^{N} V_m\,.V_j.Y_{mj}.cos\left(\propto_m - \propto_j - \theta_{kj}\right) \tag{24}$$

$$Q_m = Q_{mk} + \sum_{j=1}^{N} V_m\,.V_j.Y_{mj}.sin\left(\propto_m - \propto_j - \theta_{mj}\right) \tag{25}$$

The summation terms in Eqs (22), (23), (24), and (25), represent the same equations of the system before the use of the SSSC controller and without considering the line (km). The transited powers P_{km}, Q_{km}, $P_{mk}\ and\ Q_{mk}$ are calculated as follows.

$$P_{km} = Re\left(\overline{V}_k.\overline{I}_{km}^{*}\right) = G_s.V_k^2 + V_k.E_s.Y_s.cos(\propto_k - \propto_s - \theta_s) - V_k.V_m.Y_s.cos(\propto_k - \propto_m - \theta_s) \tag{26}$$

$$\begin{aligned} Q_{km} = Im\left(\overline{V}_k.\overline{I}_{km}^{*}\right) &= -B_s.V_k^2 + V_k.E_s.Y_s.sin(\propto_k - \propto_s - \theta_s) \\ &- V_k.V_m.Y_s.sin(\propto_k - \propto_m - \theta_s) \end{aligned} \tag{27}$$

$$P_{mk} = Re\left(\overline{V}_m.\overline{I}_{mk}^{*}\right) = G_s.V_m^2 - V_m.E_s.Y_s.cos(\propto_m - \propto_s - \theta_s) \\ - V_m.V_k.Y_s.cos(\propto_m - \propto_k - \theta_s) \tag{28}$$

$$Q_{km} = Im\left(\overline{V}_m.\overline{I}_{mk}^{*}\right) = -B_s.V_m^2 - V_m.E_s.Y_s.sin(\propto_m - \propto_s - \theta_s) \\ - V_m.V_k.Y_s.sin(\propto_m - \propto_k - \theta_s) \tag{29}$$

The power consumed by the voltage source $\overline{E}_s$ is expressed by the following equation:

$$P_{Es} = Real\left(\overline{E}_s.\overline{I}_{km}^{*}\right) \\ = G_s.E_s^2 + E_s.V_k.Y_s.cos(\propto_s - \propto_k - \theta_s) - E_s.V_m.Y_s.cos(\propto_s - \propto_m - \theta_s) \tag{30}$$

3.4. Electrical network with UPFC

The UPFC offers control over the real and reactive power flows on the line where it is installed, as well as the voltage magnitude at the connection point. In the context of power flow analysis, this translates to controlling the transmitted powers P_{km} and Q_{km} and adjusting the voltage V_k at a specific bus or node [15,18].

Integrating the UPFC into the power flow problem introduces four additional variables: the voltage sources $\left(\overline{E}_p\right)$ and $\left(\overline{E}_s\right)$ from the two VSCs. To solve the power flow problem while keeping V_k fixed, three additional equations need to be added.

Figure 15 illustrates the UPFC model inserted on transmission line (km) of an electric network with N nodes. The figure showcases the specific arrangement and connections of the UPFC components within the power system.

By incorporating the UPFC model into the power flow analysis, engineers and researchers can study its impact on power transmission, control power flows, and regulate voltages within the network. The UPFC enables enhanced controllability and flexibility in managing power system operation and stability.

Therefore, the UPFC comprises two VSCs connected in series and parallel, allowing control over power flows and voltage regulation. By introducing additional variables and equations, the UPFC model is integrated into the power flow problem. This model, depicted in Figure 15, enables the analysis of power transmission, active/reactive power control, and voltage adjustment within an electrical network.

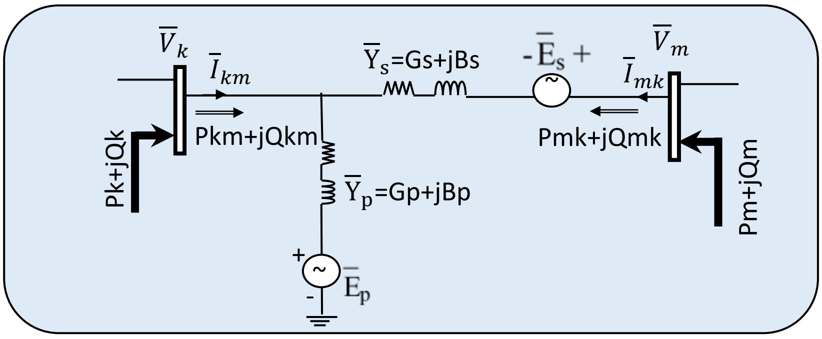


Figure 15. UPFC modeling circuit.

The power flow equations for an electrical network incorporating a UPFC remain unchanged for nodes other than nodes (k) and (m), compared to the equations for a network without the device. However, the power equations injected at the two specific nodes (k) and (m) are modified to account for the presence of the UPFC.

$$P_k = P_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} cos\left(\propto_k - \propto_j - \theta_{kj}\right) \tag{31}$$

$$Q_k = Q_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} sin\left(\propto_k - \propto_j - \theta_{kj}\right) \tag{32}$$

$$P_m = P_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} cos\left(\propto_m - \propto_j - \theta_{mj}\right) \tag{33}$$

$$Q_m = Q_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} sin\left(\propto_m - \propto_j - \theta_{mj}\right) \tag{34}$$

Equations (31 to 34) involve summation terms that represent the same equations as those for a system without a UPFC device, disregarding the line (km). However, to incorporate the effects of the UPFC and account for the transmitted powers, the equations for the transmitted powers P_{km}, Q_{km}, P_{mk} and Q_{mk} can be expressed as follows:

$$\begin{aligned} P_{km} = {} & \left(G_p + G_s\right) {V_k}^2 - V_k E_p Y_p cos\left(\propto_k - \propto_p - \theta_p\right) + V_k E_s Y_s cos\left(\propto_k - \propto_s - \theta_s\right) \\ & - V_k V_m Y_s cos\left(\propto_k - \propto_m - \theta_s\right) \end{aligned} \tag{35}$$

$$\begin{aligned} Q_{km} = {} & -\left(B_p + B_s\right) {V_k}^2 - V_k E_p Y_p sin\left(\propto_k - \propto_p - \theta_p\right) + V_k E_s Y_s sin\left(\propto_k - \propto_s - \theta_s\right) \\ & - V_k V_m Y_s sin\left(\propto_k - \propto_m - \theta_s\right) \end{aligned} \tag{36}$$

$$P_{mk} = G_s {V_m}^2 - V_m V_k Y_s cos\left(\propto_m - \propto_k - \theta_s\right) - V_m E_s Y_s cos\left(\propto_m - \propto_s - \theta_s\right) \tag{37}$$

$$Q_{mk} = -B_s {V_m}^2 - V_m V_k Y_s sin\left(\propto_m - \propto_k - \theta_s\right) - V_m E_s Y_s sin\left(\propto_m - \propto_s - \theta_s\right) \tag{38}$$

The power provided by the shunt component of the UPFC via the DC link is utilized by the series part. This relationship can be expressed as follows:

$$\begin{gathered} P_{Eps} = Real\left(\overline{E}_p . \overline{I}_p^*\right) - Real\left(\overline{E}_s . \overline{I}_s^*\right) \\ = -G_p E_p^2 - G_s E_s^2 + E_p V_k Y_p \cos\left(\propto_p - \propto_k - \theta_p\right) - E_s V_k Y_s \cos\left(\propto_s - \propto_k - \theta_s\right) + \\ E_s V_m Y_s cos\left(\propto_s - \propto_m - \theta_s\right) = 0 \end{gathered} \tag{39}$$

3.5. Electrical network with SVC

The SVC is a parallel compensator. It is used to adjust the voltage of the node where it is connected by varying its equivalent reactance. It basically consists of a TCR and a fixed capacitor (Xc). Generally, there are two configurations of the SVC [20] which are:

- (a) Start-up delay angle model: The equivalent reactance XSVC is a function of a variable firing angle. It represents a combination of a fixed capacitive reactance and a reactance controlled by a pair of head-to-tail thyristors (TCR) as shown in Figure 16a, this model provides information on the firing angle of the thyristors required to achieve a given level of compensation.
- (b) Total susceptance model: A variable susceptance BSVC, represents the equivalent susceptance at the fundamental frequency of all the shunt modules of the SVC, Figure 16b.

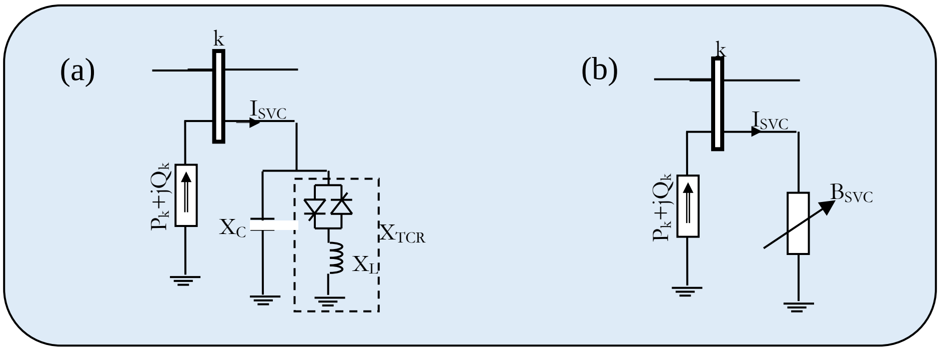


Figure 16. (a) Total susceptibility model (b) Start-up delay angle model.

The Equivalent Susceptance B_{SVC} at the fundamental frequency is expressed as a function of the firing angle ψ of the thyristors [19–21].

$$\text{BSVC} = 1\ \text{XC.XL}\ [\text{XL} - \text{XC}\pi\ 2\pi - \psi + \sin 2\psi\ ] \qquad (40)$$

where

$$X_L = L\omega \,\text{et}\, X_C = \frac{1}{C\omega} \qquad (41)$$

The active and reactive powers injected at node k where the SVC is connected are given respectively by Eqs (40) and (41):

$$P_k = P_{SVC} + \sum_{j=1}^{N} V_k V_j Y_{kj} cos(\propto_k - \propto_j - \theta_{kj}) \qquad (42)$$

$$Q_k = Q_{SVC} + \sum_{j=1}^{N} V_k V_j Y_{kj} sin(\propto_k - \propto_j - \theta_{kj}) \qquad (43)$$

where P_{SVC} and Q_{SVC} are the active and reactive powers consumed by the SVC. The studied SVC compensator does not contain any resistive component. Consequently, the SVC and the network do not exchange any active power. On the other hand, Q_{SVC} is a function of the voltage at node k and the equivalent susceptance of the SVC [19,20].

$$P_{SVC} = 0 \tag{44}$$

$$Q_{SVC} = -V_k^2 \, . B_{SVC} \tag{45}$$

3.6. Electrical network with TCSC

The TCSC compensator consists of a fixed capacitor in parallel with an inductor controlled by thyristors. This assembly enables a rapid and continuous variation of the transmission line impedance at the fundamental frequency of the network [19,20]. A module of a TCSC in series with the transmission line is shown in Figure 17.

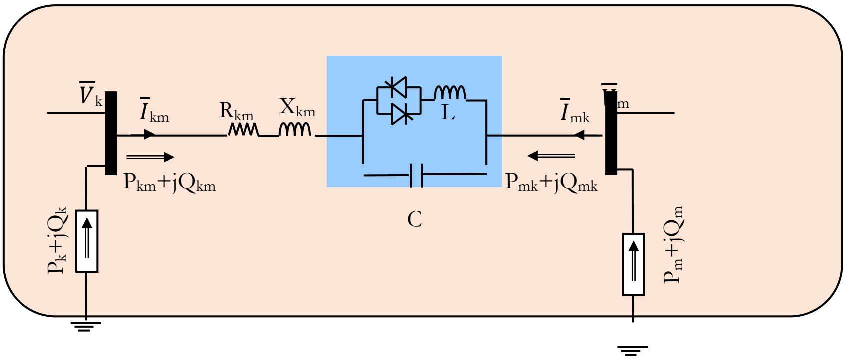


Figure 17. The TCSC Model.

The equivalent reactance of the TCSC at the fundamental frequency of the network is given by the following equation [19–21]

$$X_{TCSC} = -X_c + C_1[2\sigma + sin2\sigma] + C_2 cos^2\sigma[\varpi \tan(\varpi\sigma) - tan\sigma] \tag{46}$$

where

$$\sigma = \pi - \psi \quad , \varpi = \sqrt{\frac{X_c}{X_L}} \quad , X_{LC} = \frac{X_c . X_L}{X_c - X_L}, \; C_1 = \frac{X_c + X_{LC}}{\pi}, \quad C_2 = -\frac{{X_{LC}}^2}{\pi . X_L} \tag{47}$$

3.7. Electrical network with IPFC

The IPFC, with its unique capacity for series compensation, is a powerful unit that is able to controlling multiple transmission lines' power flow. For instance, Figure 18 shows an IPFC placed in series with two transmission lines (ij) and (ik) to control their parameters.

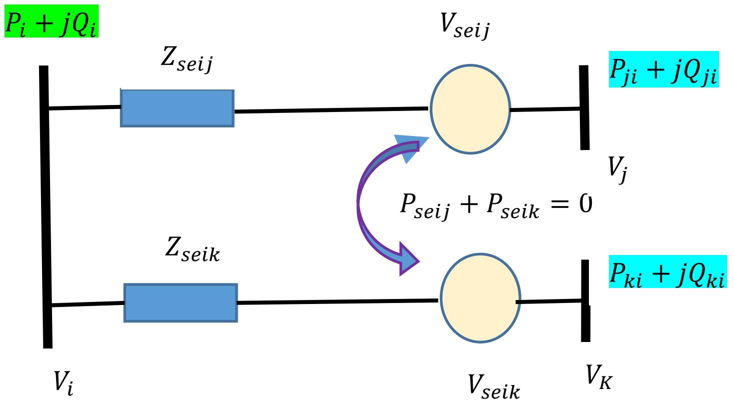


Figure 18. Simplified network of IPFC in a 3-bus system.

In Figure 18, *Vi*, *Vj* and *Vk* are voltages at buses i, j and k, respectively. V_{seij} and V_{seik} are complex controllable series injected voltage at buses j and k.

At bus i, the current is given by the following expression

$$I_i = I_{ij} + I_{ik} \tag{48}$$

thus,

$$I_i = \frac{V_i - V_{seij} - V_j}{Z_{seij}} + \frac{V_i - V_{seik} - V_k}{Z_{seik}} \tag{49}$$

The complex powers can be given as follows.

$$S_i = V_i I_{ij}^* = P_i + jQ_i \tag{50}$$

Note that the star $(\bullet)^*$ in Eq (50) and in the others denotes the complex conjugate.

It can be also given in terms of voltages and impedances as follows.

$$S_i = V_i \left[\frac{V_i - V_{seij} - V_j}{Z_{seij}} + \frac{V_i - V_{seik} - V_k}{Z_{seik}}\right]^* \tag{51}$$

After simplification, the expressions of active and reactive powers can be found in [22]. If the losses in the converter are ignored, the active power exchange between the IPFC and the power network is considered equal to zero. This property is expressed by the following equation

$$P_i = \sum P_{sum} = 0 \tag{52}$$

Active and reactive powers flow by sending an end transmission line which is connected to bus j and k, including P_{ni} and $-Q_{ni}$, which are given by the following equations [23]

$$P_{ni} - P_{ni}^{spec} = 0; \quad n \in \{j, k\} \tag{53}$$

$$Q_{ni} - Q_{ni}^{spec} = 0; \quad n \in \{j, k\} \tag{54}$$

where P_{ni}^{spec} and Q_{ni}^{spec} represent the active and reactive powers flow control reference, respectively.

4. Problem formulation

4.1. Objective functions

4.1.1. Total active transmission losses

For an electrical power system of N buses, the total active losses in the transmission lines of electrical energy are given by the following objective function [24]

$$F_1 = \sum_{i=1}^{N}\sum_{i=1}^{N} Y_{ij}V_i\,V_j cos\left(\propto_i - \propto_j - \theta_{ij}\right) \tag{55}$$

where V_i and $\propto_i$ are modulus and phase of the voltage at bus i, respectively. Y_{ij} and θ_{ij} are modulus and argument of an element (i,j) of the complex nodal admittance matrix Y, respectively.

4.1.2. Deviation of the voltages at load buses

The total deviation of the voltages at the load buses from a reference voltage V_i^{ref}, is represented by the following objective function

$$F_2 = \sum_{i=1}^{N}\left(V_i - V_i^{ref}\right)^2 \tag{56}$$

4.1.3. Production cost function

To incorporate the VPLE into the quadratic equation for the generation fuel cost, the cost expression for the i-th generator can be represented by Eq (57) [25] as follows:

$$F_3(P_i) = a_i + b_iP_i + c_iP_i^2 + \left|e_i \cdot \sin\left(f_i * \left(P_i^{min} - P_i\right)\right)\right| \tag{57}$$

where a_i, b_i, and c_i are the cost coefficients of the i-th generator; ei and fi are the VPLE coefficients for the i-th generator and P_i^{min} is the smallest value of real power delivered by the i-th generator (in MW).

The cost characteristics with and without VPLEs are depicted in Figure 19. In this figure, five VPLEs (A, B, C, D, and E) are taken into consideration. This figure makes it clear that the cost function becomes non-convex when VPLEs are added.

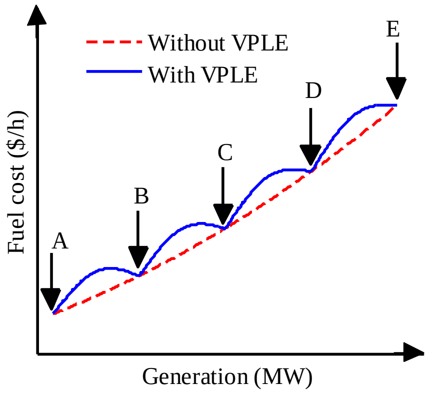


Figure 19. Cost curve with and without VPLE.

4.1.4. FACTS Devices installation cost

The cost installation is considered for the proper placement of FACTS controllers. This FACTS installation cost has been formulated mathematically by the following expression:

$$F_4(C_{FACTS}) = OIC = C * S * 1000 \tag{58}$$

where OIC is the Optimal FACTS Installation Cost in US$ and C is the FACTS Installation Cost in US$/KVAR.

The CI of some FACTS devices such as SVC, TCSC and UPFC, is given from Siemens database [26–28], STATCOM from [29], IPFC from [30] according to the following expressions:

$$C_{SVC} = 0.0003S^2 - 0.3051S + 127.38 \tag{59}$$

$$C_{TCSC} = 0.0015S^2 - 0.7130S + 153.75 \tag{60}$$

$$C_{UPFC} = 0.0003S^2 - 0.2691S + 188.22 \tag{61}$$

$$C_{STATCOM} = 0.000375S^2 + 0.3041S + 162.4 \tag{62}$$

$$C_{IPFC} = 0.00015S^2 - 0.01345S + 94.11 \tag{63}$$

where S is the operating range of FACTS Devices in MVAR and is given by the following equation

$$S = |Q_2| - |Q_1| \tag{64}$$

where Q_2 and Q_1 are the reactive power in MVAR respectively after and before the FACTS installation.

Expressions for the cost function of the SSSC FACTS device are given below [31]

$$C_{SSSC} = SSSC_{Capacity} \times \eta \times CRF \tag{65}$$

where η is the investment cost coefficient per MVA of the SSSC. CRF is the capital recovery factor, expressed as follows.

$$CRF = \frac{i(t+i)^n}{(1+i)^n - 1} \tag{66}$$

where i is the discount rate or present worth rate. n is the life time of the SSSC in years.

The annual capital payment (ACP) can be calculated as given by the following equation

$$ACP = P \times CRF \tag{67}$$

where P is the present project cost.

4.2. Constraints of the problem

The Optimal Power Flow (OPF) problem encompasses various constraints, including the energy balance, network security, and constraints specific to FACTS devices. These constraints can be formulated as follows:

4.2.1. Bus voltage and line flow

The suitable location and setting of FACTS controllers can be based on bus voltage stability and line flow limits. These two parameters can be combined in one function J which denotes the factor related to the bus voltage limits and line flow limits [28]. This function can be expressed as follows

$$J = \prod_{Bus} VS_{Bus} \times \prod_{Line} OVL_{Line} \tag{68}$$

where VS designates the voltage stability index for a bus and OVL denotes line overload factor for a given line [28].

$$VS = \begin{cases} 1; & if\ 0.9 \leq V_b \leq 1.1 \\ \exp(\mu|1 - V_b|)\,; & otherwise \end{cases} \tag{69}$$

$$OVL = \begin{cases} 1; & if\ P_{pq} \leq P_{pq}^{max} \\ \exp\left(\lambda\left|1 - \dfrac{P_{pq}}{P_{pq}^{max}}\right|\right); & otherwise \end{cases} \tag{70}$$

Here,

P_{pq}: Active power between p, q buses.

P_{pq}^{max}: Line's thermal limit between p, q buses.

V_b: Voltage at bus b and $\lambda = \mu = 1$, small positive constants.

4.2.2. Power flow constraints

The constraint of power flow is described by the following equation [28]

$$g(V, \theta) = 0 \tag{71}$$

where

$$g(V,\theta)=\begin{cases} P_t(V,\theta)-P_t^{net}\ ; \quad for\ each\ PQ\ bus\ t \\ Q_t(V,\theta)-Q_t^{net}\ ; \quad for\ each\ PQ\ bus\ t \\ P_m(V,\theta)-P_m^{net}\ ;\ for\ each\ PV\ bus\ m\ not\ incluant\ reference \end{cases} \tag{72}$$

Here,
P_t: Active power calculated for PQ bus.
P_m: Active power calculated for PV bus.
Q_t: Reactive power calculated for PQ bus.
P_t^{net}: Active power specified for PQ bus.
Q_t^{net}: Reactive power specified for PQ bus.
(V,θ): Voltage magnitude and phase angle at buses.

4.2.3. Constraints related to FACTS devices

Generally, the upper and lower limits of the various parameters characterizing most FACTS devices after placement are as follows.

- TCSC reactance Limit Values

$$X_{TCSCmin} \leq X_{TCSC} \leq X_{TCSCmax} \tag{73}$$

where X_{TCSC} is the reactance added to the line after the TCSC.

- SVC reactive power Limit Values

$$Q_{SVCmin} \leq Q_{SVC} \leq Q_{SVCmax} \tag{74}$$

where Q_{SVC} is the reactive power injected at the bus after placing the SVC.

- STATCOM Parameters Limit Values

$$E_p^{min} \leq E_p \leq E_p^{max} \tag{75}$$

$$\propto_p^{min} \leq \propto_p \leq \propto_p^{max} \tag{76}$$

where E_p^{max} and $\propto_p^{max}$ are voltage magnitude and phase angle limit values for the parallel voltage source, respectively.

- SSSC Parameters limit values

$$E_s^{min} \leq E_s \leq E_s^{max} \tag{77}$$

$$\propto_s^{min} \leq \propto_s \leq \propto_s^{max} \tag{78}$$

where E_s^{max} and $\propto_s^{max}$ are voltage magnitude and phase angle limit values for the series voltage source, respectively.

- UPFC Parameters limit values

The UPFC Parameters limits can be represented by constraints (75), (76), (77) and (78).

- IPFC Parameter limit values

$$V_{sein}^{min} \leq V_{sein} \leq V_{sein}^{max} \tag{79}$$

$$-\pi \leq \theta_{sein} \leq \pi \tag{80}$$

where V_{sein}^{min} and V_{sein}^{max} are voltage magnitude limits of the controllable series injected voltage. θ_{sein} is the phase angle of the controllable series injected voltage.

5. Overview of simulation-based approaches for FACTS device optimization challenges

The most suitable FACTS location was determined using simulation-based approaches in other references. In the following section, a variety of simulation software for education and research in the area of FACTS devices are discussed. Additionally, it provides a simulation software-based modeling and simulation of different FACTS controllers as presented in journal articles and conference proceedings like MATLAB/Simulink, ETAP, EMTP-RV, MatPower, Netomac, PSB, PSAT, PSCAD-EMTDC, PSIM, PSPICE, RTDS etc., given by Figure 20.

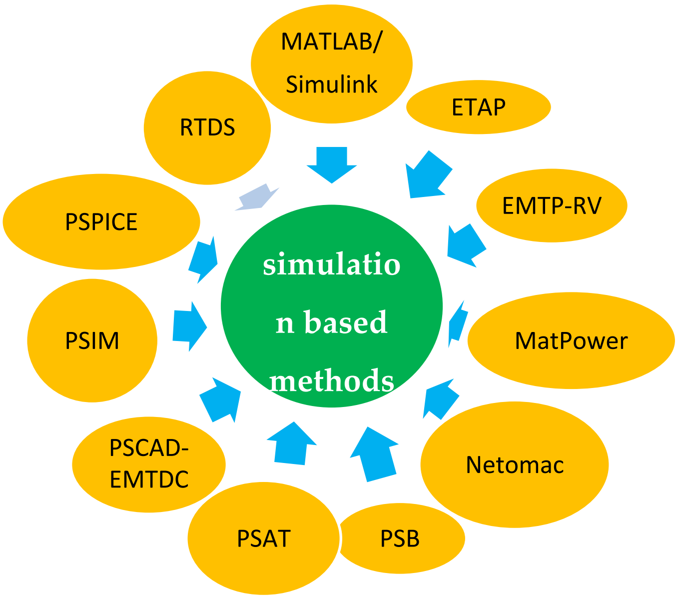


Figure 20. Simulation based methods related to the FACTS devices optimization problem.

5.1. MATLAB/SIMULINK

MATLAB/SIMULINK is a widely used software tool for modeling and simulating power systems, including FACTS devices. One common application of MATLAB/SIMULINK in the context of FACTS devices is the optimization of their control parameters to ameliorate the performance of the electric network.

The optimization problem can be framed as a constrained optimization issue, aiming to minimize a cost function while adhering to constraints on the system variables. The cost function may be defined in various ways based on the specific application; however, it generally incorporates terms related to power losses, voltage deviations, and other performance metrics of the power system.

To solve the optimization problem, MATLAB/SIMULINK can be used in combination with optimization techniques like GA and PSO. These algorithms can be implemented using MATLAB/SIMULINK's optimization toolbox, which provides a set of functions for solving optimization problems.

In addition to optimization, MATLAB/SIMULINK can also be used to model and simulate FACTS devices and their control systems. This can be useful for evaluating the performance of different control strategies, assessing the effects of FACTS controllers in the electric network, and designing new FACTS devices.

Also, MATLAB/SIMULINK is a powerful simulation tool for optimizing and simulating electric networks with FACTS devices, and it is widely utilized by researchers and professionals in the area.

The researchers in [32] employed the technique of simulation for a power system with a voltage source converter (VSC) on MATLAB/SIMULINK to improve the stability of voltage. The advantage of this technique has been explored by incorporating the load injection modeling of various VSCs based on FACTS controllers, including UPFC, SSSC and STATCOM. The effectiveness of this developed technique has been performed on the new England system. The simulation results proved that the UPFC can provide the best results of the stability improvement. In [33], a comprehensive Simulink model of a IPFC FACTS device has been developed utilizing Switching level simulation modeling to obtain a flexible CPF on multi lines. An IEEE 30 bus test has been used under various loading conditions to demonstrated the capability of IPFC for ATC enhancement and voltage profile improvement. Models and simulations of STATCOM, UPFC, SSSC, FC-TCR, and TCSC were explored in [34] to improve electric network stability and enhance the PTC. Simulation results of all mentioned FACTS devices connected to a simple transmission line were acquired using the MATLAB/SIMULINK environment. It has been observed that the voltage profile and the power flow are improved with the use of all compensating devices.

5.2. ETAP

ETAP is another software tool commonly used for the analysis and design of an electric network, including the optimization of FACTS devices. ETAP has a range of features for modeling and simulating power systems, including FACTS devices, and it has capabilities for optimization and control system design.

To enhance the control parameters of FACTS controllers in ETAP, the user can define an optimization objective and constraints on the system variables and then use the built-in optimization algorithms to find the optimal solution. ETAP supports a variety of optimization algorithms, including GA, PSO, and SA, among others.

ETAP also has a range of tools for designing and simulating control systems for FACTS devices, including PID controllers, FL controllers, and model predictive controllers. These tools can be used to design controllers that optimize the performance of the electric network while considering the constraints and limitations of the FACTS devices.

In addition to optimization and control system design, ETAP can also be used for a range of other tasks related to FACTS devices, including transient stability analysis, voltage regulation, and power flow analysis. ETAP also has capabilities for modeling and simulating other electric network components, like generators, transformers, and transmission lines.

Therefore, ETAP is an effective simulation tool for modeling, simulating, and optimizing electric networks with FACTS devices, and it is widely used by engineers and researchers in the field.

The Load Flow Analysis in reference [35] focuses on a single-line diagram of a 132/11 kV substation. The computer simulation of the substation was conducted using the ETAP software environment. The analysis was performed under various conditions, including steady state, peak load, and balanced conditions, with and without an SVC device.

The Load Flow Analysis is a computational method used to determine the steady-state voltages, currents, and power flows within an electric network. In this study, examine the voltage profiles and power flow of the 132/11 kV substation.

The ETAP software environment is a widely utilized platform for conducting electrical network analysis and simulation. It provides capabilities for modeling the substation components, specifying load and generation profiles, defining system parameters, and performing load flow calculations.

The analysis considers different operating scenarios, including steady-state conditions that represent normal operating conditions, peak load conditions that represent the highest expected demand, and balanced conditions that ensure symmetrical load distribution.

Furthermore, we investigate the effect of the SVC device on the substation's performance. The SVC is a FACTS device that can regulate voltage levels and reactive power to enhance the stability and control of the electric network. By comparing the load flow results with and without the SVC, the study evaluates the effectiveness of the device in improving voltage stability of voltage and power factor correction within the substation.

By utilizing the single-line diagram, performing load flow analysis in the ETAP environment, and considering different operating conditions with and without the SVC, the study offers valuable insights into power flow and voltage behavior of the 132/11 kV substation.

Thus, the researchers in [35] conducted a Load Flow Analysis for a 132/11 kV substation, utilizing a single-line diagram and the ETAP software environment. The analysis encompassed steady-state, peak load, and balanced conditions, examining the performance of the substation with and without an SVC device.

In this context, the researchers in [36] investigated the SVC utilization to ameliorate the voltage profile and minimize the transmission losses under peak load conditions using ETAP software.

5.3. EMTP-RV

Electromagnetic Transients Program Restructured Version (EMTP-RV) is a software application for simulation and analysis of transient phenomena in electric networks, including the behavior of FACTS controllers. While EMTP-RV does not have built-in optimization capabilities, it can be used in conjunction with other tools, such as MATLAB or Python, to optimize the FACTS devices parameters.

To use EMTP-RV for FACTS device optimization, the user can first develop a detailed model of the electric networks in EMTP-RV, including the FACTS device and its control system. The user can then export the model to MATLAB or Python, where optimization algorithms can be used to optimize the control parameters of the FACTS device.

Once the optimization process is finished, the optimized control parameters can be imported back into EMTP-RV for further simulation and analysis. EMTP-RV has a range of features for simulating transient phenomena in electric networks, including fault analysis, switching transients, and lightning surges, among others. These features can be used to assess the performance of the electric network with the optimized FACTS device control parameters and identify any possible issues or fields for enhancement.

As a result, EMTP-RV is a robust tool for simulation and analysis of the behavior in electric network with FACTS devices, and it can be used in conjunction with other tools for optimization and control system design.

A model of SSSC using the EMTP-RV simulation package is presented in [37], employing a VSC to produce a high-quality waveform. For high-voltage applications, a 3-level NPC PWM VSC has been utilized to manage the impedance characteristics of a transmission line through both direct and indirect control techniques. The performance of the electric network equipped with a simulated model of the SSSC has been validated through three tests, allowing for simultaneous comparison of the direct and indirect types of controllers. It is observed that the proposed simulated models behave well in all cases. In [38], EMTP-RV chain link STATCOM (CLC) modeling, control, and simulation are described. Therefore, a 3-phase CLS having 3-links per phase connecting to AC side system by GTO thyristor converters has been presented. To drive the switches of the CLS, The SPWM technique has been used. The performance evaluation of the Closed-Loop Control System (CLS) was conducted through simulation using the Electromagnetic Transients Program Revised Version (EMTP-RV) software. The simulations were carried out to assess the system's behavior under steady-state and transient-state conditions. Notably, the transient tests demonstrated the CLS's commendable dynamic performance in regulating the electric network voltage.

EMTP-RV is a powerful software tool used for simulation and analysis of electromagnetic transients in electric network. By employing this software, researchers and engineers can model and simulate various system components and their dynamic responses to different operating conditions.

The evaluation of the CLS system involved examining its performance in both steady-state and transient conditions. scenarios. Steady-state conditions represent the system's stable operating state, while transient-state conditions encompass sudden changes or disturbances that can affect the system's dynamic behavior.

The transient tests specifically entailed evaluating the CLS's ability to regulate the electric network voltage. Voltage regulation is a crucial element of electric network operation, as it ensures that voltage levels remain within acceptable limits., thereby supporting the system's stability and optimal performance.

The results obtained from the simulations using EMTP-RV demonstrated that the CLS system exhibited robust performance in both steady-state and transient conditions. The system effectively regulated the electric network voltage, showcasing its ability to respond dynamically to changes and disturbances.

By utilizing simulation techniques and the EMTP-RV software, the performance evaluation of the CLS system offered valuable insights into its behavior under various conditions. The favorable results observed in the transient tests highlighted the system's strong dynamic performance, indicating its effectiveness in voltage regulation for power systems.

The results demonstrated the CLS's commendable performance and its suitability for voltage regulation applications within power systems.

In reference [39], the researchers investigated the same computer tool to modeling a STATCOM FACTS device using Hysteresis Current Controlled VSC. Simulation results have been elaborated for a test model with Control structure of STATCOM, and the advantages of this approach in dynamic response control are noted.

5.4. MATPOWER

MATPOWER is a freely available and open-source software package that is specifically designed for electric network analysis and optimization. This software package provides a comprehensive set of tools and algorithms to facilitate the modeling, simulation, and analysis of electrical power systems, including the optimization of FACTS device control parameters. MATPOWER includes a range of optimization algorithms, including interior point methods, Newton's method, and quasi-Newton methods, among others, that can be utilized to optimize the FACTS devices parameters control.

MATPOWER is built on MATLAB, a widely used computational software environment, and leverages its powerful mathematical and optimization capabilities. It offers a user-friendly interface and a flexible framework that allows engineers, researchers, and power system operators to perform a variety of tasks related to power system analysis and optimization.

The key features of MATPOWER include:

- Power Flow Analysis: MATPOWER enables users to perform power flow analysis, which calculates the steady-state voltages, currents, and power flows within a power system. This analysis helps in understanding the system's operating conditions and assessing its stability.
- Optimal Power Flow (OPF): The software package also provides tools for solving the Optimal Power Flow (OPF) problem. OPF is a mathematical optimization problem that aims to determine the optimal settings for control variables, such as generator outputs and transformer tap settings, to minimize the generation cost while satisfying various operational constraints.
- Network Visualization: MATPOWER offers visualization capabilities to display the power system's topology, including buses, lines, transformers, and generators. It allows users to interactively explore and analyze the network structure and operating conditions.
- Extensibility: MATPOWER is designed to be extensible, allowing users to incorporate their own custom models, algorithms, and optimization techniques. This extensibility enables researchers and developers to tailor the software to their specific needs and extend its capabilities.

MATPOWER is an open-source software package designed for electric network simulations and analysis, focusing on power flow and optimal power flow (OPF) studies. Built on MATLAB, it offers a user-friendly interface that allows users to perform standard and DC power flow calculations and optimize power system operations while considering various constraints. MATPOWER features a flexible data format for easy system modeling and includes a set of standard test cases for benchmarking. It supports advanced modeling capabilities, such as integrating renewable energy sources and storage systems, and is backed by extensive documentation and a vibrant community of users. As a valuable resource for researchers and educators, MATPOWER is widely used in academic settings for teaching concepts of power system analysis and for developing and testing new algorithms, making it a significant tool in the field of power systems engineering.

MATPOWER has become a popular choice among power system professionals due to its versatility, ease of use, and open-source nature. Its availability as an open-source software package promotes collaboration, innovation, and the sharing of knowledge within the power system community.

Therefore, MATPOWER is an open-source software tool specifically designed for power system analysis and optimization. It provides a range of tools and features to model, simulate, and analyze electric networks, containing power flow analysis, optimal power flow, network visualization, and flexible modeling capabilities. Its open-source nature fosters collaboration and customization, making it a valuable tool for power system engineers and researchers.

To use MATPOWER for FACTS device optimization, the user can first develop a detailed model of the electric network in MATPOWER, including the FACTS controllers and its control system. The user can then define an optimization objective and constraints on the system variables and use one of the built-in optimization algorithms to find the optimal solution.

MATPOWER also includes a range of tools for modeling and simulating power systems with FACTS devices, including load flow analysis, transient stability analysis, and contingency analysis, among others. These tools can be utilized to assess the performance of an electric network with the optimized FACTS device control parameters and assess the impact of the FACTS device on the system.

MATPOWER also supports the utilization of external optimization techniques, such as those implemented in MATLAB or Python, which can be used in conjunction with MATPOWER to optimize the FACTS device parameters control.

Thus, MATPOWER is a powerful and flexible tool for electric network analysis and optimization, including the FACTS device control parameters optimization, and it is widely used by researchers and professionals in the area.

The IPFC is a highly effective FACTS controllers that allows for power flow control on multiple transmission lines. Researchers have investigated the best location and parameter configuration of the IPFC using conventional power flow techniques, such as the Newton-Raphson (NR) method. However, incorporating the IPFC into existing software and automating the calculation of its parameters can be easily achieved. To this end, a new IPFC model was developed using MATLAB and subsequently integrated into the MATPOWER software package as described in reference [40].

In order to validate the precision and functionalities of the newly implemented IPFC steady-state model, a test network consisting of five buses was utilized. The IPFC's impact on optimal power flow (OPF) was discussed in reference [41], where both the TCSC and TCPAR were individually designed using the MATPOWER simulation package. Results of the Simulation were derived from the IEEE 30-bus test system, and the findings demonstrated a reduction in power losses and fuel costs when compared to the standard OPF solution for the IEEE 30-bus system.

5.5. NETOMAC

NETOMAC is a software tool for optimizing the control parameters of FACTS controllers in electrical systems. NETOMAC is specifically designed to address the problem of power oscillations in power systems, which can lead to stability issues and even blackouts under certain conditions.

NETOMAC uses a model of the electric network that includes the generators, transmission lines, and FACTS controllers and it employs an optimization algorithm to adjust the FACTS devices parameters control to minimize the power oscillations in the system. The optimization algorithm used in NETOMAC is based on linear matrix inequalities (LMIs), which provide a robust and efficient way to optimize the FACTS device parameters control.

In order to utilize NETOMAC, users must first develop a comprehensive model of the power system that includes FACTS devices and their corresponding control systems. Once the power system model is constructed, NETOMAC can be employed to optimize the FACTS device parameters control with the objective of minimizing power oscillations within the system.

NETOMAC offers simulation tools that enable users to assess the behavior of the power system using the optimized control parameters for the FACTS devices. It provides a variety of performance metrics to evaluate the effectiveness of the optimization process. These simulation tools facilitate the analysis of the effect of FACTS controllers on electric network stability and performance, as well as the identification of any potential issues or areas for improvement.

Therefore, NETOMAC serves as a powerful tool for optimizing the FACTS devices parameters control in electrical systems, with a specific focus on addressing power oscillation problems. It employs Linear Matrix Inequality (LMI) techniques to provide a robust and efficient optimization algorithm. Furthermore, it incorporates simulation capabilities to assess the performance of the electric network. once the control parameters of the FACTS devices have been optimized. NETOMAC is widely utilized by researchers and industry professionals in the area of electric network analysis and control.

The researchers in [42] describe the application of a nonlinear control scheme for the TCSC FACTS device. The TCSC device is utilized to mitigate power oscillations and enhance transient stability in the electric network. The TCSC modeling and power system simulations were performed using NETOMAC. The nonlinear control strategy for TCSC was examined on a one-machine-infinite bus test network and compared with a traditional control scheme. The results showcased notable enhancements in dynamic performance with the employment of the nonlinear control strategy.

In reference [43], an optimization and coordination approach for FACTS devices, comprising SVC and TCSC, was developed to mitigate power oscillations. NETOMAC was employed to optimize the TCSC damping controller in the transient condition, considering the operation of power system stabilizers and SVC. This optimization mode of NETOMAC facilitates the achievement of maximum oscillation damping by optimally coordinating all relevant controllers for FACTS controllers installed in the same electric network.

Additionally, the researchers in [44] discuss the development of a per-unit model for the UPFC using NETOMAC. The model is specifically designed for the implementation of a Phase-Octave-Damping (POD) controller. The developed UPFC model bears similarities to a Power System Stabilizer (PSS), and simulation results demonstrate the effective enhancement of system stability and POD system performance achieved through the proposed control strategy.

Therefore, NETOMAC is a powerful tool for optimizing the control parameters of FACTS devices in electric networks, specifically addressing power oscillation issues. It incorporates simulation capabilities and utilizes LMIs for robust optimization. References [42–44] demonstrate the applications of NETOMAC in the development and optimization of control schemes for TCSC, coordinated FACTS controllers (SVC and TCSC), and UPFC, respectively.

5.6. PSB

Power System Blockset (PSB) is a toolbox within the MATLAB/Simulink environment for modeling and simulating electric networks, including FACTS controllers. PSB includes a range of blocks for modeling electric network components, like transformers, transmission lines, and FACTS controllers, as well as blocks for implementing control systems and optimization algorithms.

To optimize the FACTS device parameters control in PSB, the user can first develop a detailed model of the power system, including the FACTS device and its control system, using the PSB blocks. The user can then use the built-in optimization algorithms in MATLAB/Simulink, such as gradient-based methods, GA, and PSO, to optimize the FACTS device parameters control.

PSB also includes tools for simulating the behavior of the power system with the optimized FACTS device control parameters, and it provides a range of performance metrics to evaluate the effectiveness of the optimization. These tools can be utilized to assess the effect of the FACTS devices on the stability, reliability, and efficiency of the electric network, and to identify any potential issues or areas for improvement.

In addition to optimization, PSB can be utilized for a range of other tasks related to FACTS devices, including transient stability analysis, voltage regulation, and power flow analysis. PSB also supports the utilization of external optimization techniques, such as those implemented in MATLAB or Python, which can be used in conjunction with PSB to optimize the control parameters of FACTS devices.

Hence, PSB is a powerful software for modeling, simulating, and optimizing power systems with FACTS devices, and it is widely used by researchers and professionals in the area. The integration with MATLAB/Simulink and the availability of a wide range of optimization algorithms and performance metrics make PSB a versatile and flexible tool for power system analysis and optimization.

In reference [45], the researchers investigated the best location and sizing of the SSSC in an electric network. The objective was to enhance the voltage profile and minimize transmission line losses. To analyze the dynamic performance and transient stability of a power system integrated with an SSSC device, they proposed a new model of a three-phase VSC tailored for series-connected FACTS controllers. The proposed model was thoroughly validated through simulations conducted using PSB and Simulink software.

The aim was to identify the optimal locations within the power system where the SSSC should be installed, as well as the appropriate size or rating of the device. By strategically placing the SSSC and determining the optimal size, the researchers sought to ameliorate the profile of voltage, thereby enhancing the overall system performance. Additionally, the objective was to minimize transmission line losses, which can contribute to improved system efficiency.

To evaluate the dynamic behavior and transient stability of the power system incorporating the SSSC, the researchers developed a new model of a three-phase VSC. This model was specifically tailored to accommodate series-connected FACTS controllers, such as the SSSC. It was essential to have an accurate and reliable model to simulate the behavior of the SSSC and its impact on the power system dynamics.

To validate the proposed model and assess the effectiveness of the SSSC in enhancing system performance, simulations were performed using both PSB and Simulink software. These software tools provide a platform for comprehensive power system simulations and enable the assessment of various performance metrics, such as voltage profiles and transmission line losses.

Thus, the researchers in [45] focused on the suitable location and sizing of the SSSC in electric networks to improve the voltage profile and minimize transmission line losses. The researchers proposed a new model of a three-phase VSC suitable for series-connected FACTS controllers, including the SSSC. The model was verified through simulations conducted using PSB and Simulink software. They aimed to enhance the understanding of the SSSC's dynamic performance and transient stability in power systems and provide insights into its effective integration for improved system operation.

On the other hand, this utilized a brand-new SSSC model to regulate the transmission line's power flow, which has been evaluated for the IEEE 14-bus test network under three conditions considering the impact of Step Change of Reference Value, Load Variation, and Balanced Fault, respectively. Modeling, control design, and detailed digital simulation of UPFC in the MATLAB/Simulink environment were proposed in [46] to enable flexible control of an electric network. Transmission lines and power systems have been simulated by PSB for more flexibility. The applied new model of UPFC to control the power flow in the power system has been performed on a simplified test system, including two generators, one transmission line, and a load. It can be observed that the integration of the UPFC in the network will not only enhance study state load flow but also improve network transient stability and accuracy. The dynamic operation of both STATCOM and SSSC based on a new full model, including a 48-pulse GTO thyristor voltage source converter, is presented in reference [47] for combined reactive power compensation and voltage stabilization of a power system. These two FACTS devices have been simulated within the power system and performed in MATLAB/simulation, where PSB has been used. Their controllers have modeled based on a decoupled voltage and current control strategy. These applied control schemes have been validated by digital simulation, when these FACTS controllers have been connected to the 500-kv electrical network under different load conditions, and it can be concluded an enhancement of the dynamic performance. Similarly, reference [48] has been presented for solving the same problem, a 6-pulse (GTO) model for STATCOM.

5.7. PSAT

PSAT is an open-source software package for electric network analysis and optimization, including the optimization of FACTS device parameter control. PSAT is developed in MATLAB and includes a range of tools for modeling and simulating power systems, including FACTS controllers.

To optimize the FACTS devices parameters control in PSAT, the user can first develop modeling of the electric network, containing the FACTS device and its control system, using the PSAT modeling tools. The user can then use one of the built-in optimization algorithms, such as GA, PSO, and SA, to optimize the control parameters of the FACTS device.

PSAT also includes tools for simulating the behavior of the power system with the optimized FACTS device control parameters, and it provides a range of performance metrics to evaluate the effectiveness of the optimization. These tools can be used to assess the impact of the FACTS controllers on the stability, reliability, and efficiency of the electric network, and to identify any potential issues or areas for improvement.

In addition to optimization, PSAT can be utilized for a range of other tasks related to FACTS devices, including transient stability analysis, voltage regulation, and power flow analysis. PSAT also supports the utilization of external optimization techniques, such as those implemented in MATLAB or Python, which can be used in conjunction with PSAT to optimize FACTS device parameter control.

Thus, PSAT is a powerful and flexible tool for electric network analysis and optimization, including the optimization of FACTS device control parameters. The open-source nature of PSAT makes it accessible to a wide range of users, and the availability of a wide range of optimization algorithms and performance metrics makes it a versatile tool for power system analysis and optimization.

The researchers in [49] utilized a CPF simulation approach based on the PSAT package to determine the best placement and parameter settings of the SVC. The objective was to enhance voltage stability within the power system. The proposed approach was implemented and tested on the IEEE 14-bus test system, and all the results presented in the study were generated using the PSAT package. The strategy was lauded for its simplicity, speed, and convenience in conducting voltage stability analysis.

In reference [50], Yap EM et al. demonstrated the application of the PSAT package for network analysis involving alternative methods to improve transmission capability using the UPFC FACTS device. They focused on the IEEE 14-bus test system, and simulation results illustrated the PSAT package's ability to provide quick solutions for steady-state power flow conditions.

In reference [51], PSAT/MATLAB was employed to investigate the effects of different FACTS controllers, including UPFC, SSSC, SVC, and STATCOM, on reactive power sustainability and voltage stability in the IEEE 9-bus test system during a symmetrical three-phase fault. Simulation results indicated that both SSSC and UPFC outperformed SVC and STATCOM in terms of their impact on system performance.

Therefore, the researchers in [49–51] utilized the PSAT package to analyze and optimize the performance of FACTS controllers in electric networks. The researchers in [49] focused on the placement and parameter setting of an SVC to ameliorate voltage stability, while the researchers in reference [50] explored alternative means of enhancing transmission capability using the UPFC. Last, the researchers in [51] investigated the effects of multiple FACTS controllers on reactive power sustainability and voltage stability.

5.8. PSCAD-EMTDC

PSCAD with EMTDC is a software tool for simulating and analyzing electric networks, including the behavior of FACTS devices. PSCAD-EMTDC provides a graphical interface for building and simulating power system models, including FACTS devices and their control systems.

To optimize the FACTS device parameter control in PSCAD-EMTDC, the user can first develop a detailed model of the electric network, including the FACTS device and its control system, using the PSCAD-EMTDC modeling tools. The user can then use external optimization algorithms, such as those implemented in MATLAB or Python, to optimize the FACTS device parameter control.

PSCAD-EMTDC also includes tools for simulating the behavior of the electric network with the optimized FACTS device control parameters, and it provides a range of performance metrics to evaluate the effectiveness of the optimization. These tools can be utilized to assess the effect of the FACTS devices on the stability, dependability and efficiency of the electric network, and to identify any potential issues or areas for improvement.

In addition to optimization, PSCAD-EMTDC can be used for a range of other tasks related to FACTS devices, including transient stability analysis, voltage regulation, and power flow analysis. PSCAD-EMTDC also has capabilities for modeling and simulating other electric network components, such as generators, transformers, and transmission lines.

Therefore, PSCAD-EMTDC is a powerful simulation tool for simulating and analyzing electric networks with FACTS devices. While it does not have built-in optimization capabilities, it provides a flexible and user-friendly environment for building and simulating power system models, and it can be used in conjunction with external optimization algorithms to optimize the control parameters of FACTS devices. PSCAD-EMTDC is widely used by researchers and practitioners in this field of electric network analysis and design.

In reference [52], it was observed that the conventional UPFC has limitations in simultaneously controlling the active and reactive power of two-machine systems due to the limited number of control variables. To address this issue, a new UPFC topology called the center node UPFC (C-UPFC) was introduced. The C-UPFC was placed at the midpoint of the transmission line to overcome the limitations. The impedance of the transmission line was considered in the impedance of the two machines for clearer illustrations. Simulation results were presented on a two-machine test network using the PSCAD/EMTDC package. The results demonstrated that the C-UPFC could dynamically regulate the FACTS control devices in multiple operations of the receiving and sending ends, enabling simultaneous control of the midpoint voltage magnitude and the DC link voltage.

In reference [53], a control system adapted to the STATCOM with reduced switching frequency was investigated for reactive power compensation. The control scheme for the STATCOM was implemented using a current-regulated PWM inverter with a SVM-based hysteresis current controller (HCC) technique. Simulation results showed a significant reduction in the switching frequency with the proposed technique, combining the advantages of SVM and HCC techniques in reactive power compensation mode.

In reference [54], a proposed STATCOM based on the CSC topology was simulated using the PSCAD/EMTDC package. The nonlinear model of the CSC, which posed challenges in controller design, was transformed into a linear model using a novel modeling technique. Simulation results indicated that the CSC-based STATCOM could achieve all the objectives of a STATCOM.

The researchers in [55] introduced a power flow control scheme based on a VSC-based IPFC FACTS device. The relationship between the injected voltage and the resulting power flow in the line was utilized to design two power flow control schemes. The performance of the developed control schemes was examined using the PSCAD/EMTDC simulation package.

5.9. PSIM

Power Simulator (PSIM) is a software tool for simulating and analyzing power electronics and power systems, including FACTS devices. PSIM includes a range of modeling tools for electric network components, like transformers, generators, transmission lines, and FACTS controllers, and it includes tools for designing and evaluating control systems for FACTS devices.

To optimize the FACTS device parameter control in PSIM, the user can first develop a detailed model of the electric network, including the FACTS controllers and its control system, using the PSIM modeling tools. The user can then use external optimization algorithms, such as those implemented in MATLAB or Python, to optimize the control parameters of the FACTS device.

PSIM also includes tools for simulating the behavior of the power system with the optimized FACTS device control parameters, and it provides a range of performance metrics to evaluate the effectiveness of the optimization. These tools can be used to assess the effect of the FACTS controllers on the stability, reliability, and efficiency of the electric network, and to identify any potential issues or areas for improvement.

In addition to optimization, PSIM can be used for a range of other tasks related to FACTS devices, including transient stability analysis, voltage regulation, and power flow analysis. PSIM also has capabilities for modeling and simulating other power electronics components, such as inverters, converters, and motor drives.

Then, PSIM is a powerful software for the simulation and analysis of an electric network with FACTS devices and power electronics components. While it does not have built-in optimization capabilities, it provides a flexible and user-friendly environment for building and simulating power system models, and it can be used in conjunction with external optimization algorithms to optimize the FACTS device parameter control. PSIM is widely used by researchers and professionals in the area of power electronics and power system analysis and design.

The dynamic performance of FACTS control devices during various operations has been discussed in [56]. Therefore, a schematic and basic control of reconfiguration Techniques by PSIM/MATLAB of FACTS Control Devices, including STATCOM, SSSC, and UPFC, have been presented. Each device has been described by the corresponding differential equations and the power balance equations for the terminal buses.

5.10. PSPICE

PSPICE is a software tool for simulating and analyzing electronic circuits, including power electronics circuits used in power systems, including FACTS devices. PSPICE includes a range of modeling tools for electronic components, such as diodes, transistors, and operational amplifiers, and it also includes tools for designing and evaluating control systems for power electronics circuits.

To optimize the FACTS device parameter control in PSPICE, the user can first develop a detailed model of the power electronics circuit, including the FACTS device and its control system, using the PSPICE modeling tools. The user can then use external optimization algorithms, such as those implemented in MATLAB or Python, to optimize the control parameters of the FACTS device.

PSPICE also includes tools for simulating the behavior of the power electronics circuit with the optimized FACTS device control parameters, and it provides a range of performance metrics to evaluate the effectiveness of the optimization. These tools can be used to assess the effect of the FACTS controllers on the stability, reliability, and efficiency of the electric network, and to identify any potential issues or areas for improvement.

In addition to optimization, PSPICE can be used for a range of other tasks related to power electronics circuits, including transient analysis, frequency analysis, and noise analysis. PSPICE also has capabilities for modeling and simulating other electronic components, such as sensors, actuators, and communication systems.

Therefore, PSPICE is a powerful software for simulation and analysis of power electronics circuits, including FACTS devices. While it is primarily designed for electronic circuits than power systems, it can be used to model and optimize the FACTS device parameter control in the context of electric networks. PSPICE provides a flexible and user-friendly environment for building and simulating electronic circuits, and it can be used in conjunction with external optimization algorithms to optimize the control parameters of FACTS devices. PSPICE is widely used by researchers and professionals in the field of electronic circuit design and analysis.

In reference [57], the authors focused on developing new and cost-effective converter-based FACTS device topologies that leverage existing equipment while providing improved control performance. Specifically, two novel power flow controller topologies for the IPFC were proposed. The IPFC was utilized to improve power balance and power flow in a transmission system. The proposed topologies were simulated using the PSPICE software package. The simulation results demonstrated the ability of the IPFC controller topologies to regulate the transmission line impedance in the power system.

In reference [58], the researchers designed an average model of a STATCOM based on the exact state equations. The design process involved utilizing PSPICE simulations. The main focus was on controlling the phase difference between the converter voltage and the AC system voltage within a small range to achieve nearly linear reactive power control. A comparison of simulation results between the average model and an approximate model, which was simulated using MATLAB and PSPICE, was performed to assess the sufficiency of the average model.

As a result, the researchers [57] introduced two novel power flow controller topologies for the IPFC to improve power balance and power flow in a transmission system. The simulations conducted using the PSPICE software package demonstrated the effectiveness of these topologies. Reference [58] focused on designing an average model of a STATCOM based on exact state equations. PSPICE simulations were utilized, and the study compared the simulation results of the average model with an approximate model simulated using MATLAB and PSPICE to verify its adequacy.

5.11. RTDS

RTDS is a hardware-in-the-loop simulation tool designed for power systems., including FACTS devices. RTDS uses a real-time simulation platform to simulate the behavior of power systems in real-time, allowing for the testing and evaluation of control systems for FACTS devices in real-world conditions.

To optimize the FACTS device parameter control in RTDS, the user can first develop a detailed model of the electric network, including the FACTS controllers and its control system, using the RTDS modeling tools. The user can then use external optimization algorithms, such as those implemented in MATLAB or Python, to optimize the control parameters of the FACTS device.

RTDS also includes tools for simulating the behavior of the power system with the optimized FACTS device control parameters, and it provides a range of performance metrics to evaluate the effectiveness of the optimization. These tools can be used to assess the effect of the FACTS controllers on the stability, reliability, and efficiency of the electric network, and to identify any potential issues or areas for improvement. In addition, RTDS allows for the testing and evaluation of control systems for FACTS devices in real-time, which can provide valuable insights into the performance of the control system under real-world conditions.

Thus, RTDS is a powerful tool for simulating and analyzing power systems with FACTS devices. While it is primarily designed for real-time simulation rather than optimization, it can be used in conjunction with external optimization algorithms to optimize the FACTS device parameter control. RTDS provides a high-fidelity simulation environment that can accurately model the behavior of power systems, and it allows for the testing and evaluation of control systems for FACTS devices in real-world conditions. RTDS is widely used by researchers and practitioners in the field of power system analysis and design, particularly for testing and validating control systems for FACTS devices in real-time.

In reference [59], the impact of series compensation using TCSC on the performance of impedance-based protection relays was analyzed under normal operation and fault conditions at different load power flows. The electric network and protective relays were simulated in detail using RTDS. Simulation results validated the effectiveness of using a commercial relay for the analysis.

In reference [60], the researchers employed real-time testing of a SVC controller using the RTDS simulator to improve the accuracy of the firing angle for Thyristor-Controlled Reactors (TCR). The real-time simulation technology using the RTDS has been successfully applied to various commercial projects, providing positive results and experience.

The effect of SVC and STATCOM on the mid-point voltage control performance of distance relays in transmission lines using FACTS devices was studied in reference [61]. Three cases were considered to achieve this objective: An analytical study containing simulations using the transient simulation software EMTDC, and testing a commercial distance relay using the RTDS. The simulation results obtained during the testing of the commercial relay validated the findings of the analytical and simulation studies.

In reference [62], the authors investigated the use of nonlinear PID control to design the top-level controller of a SSSC for optimizing power flow and enhancing power system stability by rapidly controlling the line impedance. The feasibility of this modeling and control approach was validated using the RTDS software to dampen power system oscillations.

Table 1 provides an overview of simulation-based methods used in research works related to the optimization of FACTS devices. The table includes information on the simulation tools used, the objectives of the studies, and the specific FACTS devices considered for addressing the problem of optimization.

Table 1. Overview of simulation-based approaches for FACTS device optimization challenges.

Refs	Objectives	Devices	Simulation tools
[32]	to enhance the voltage stability system.	STATCOM, SSSC and UPFC	MATLAB/Simulink
[33]	to obtain a flexible control of power flow on a multi transmission line.	IPFC	
[34]	Improve power flow and voltage profile.	FC-TCR, TCSC,STATCOM, SSSC and UPFC	
[35]	Minimization of power losses and deviation voltage.	SVC	ETAP
[36]	enhance the voltage profile, minimize the transmission loss under peak load conditions.	SVC	
[37]	Improve the transited power by control of the impedance characteristic of a transmission line.	SSSC	EMTP-RV
[38]	Ameliorate the dynamic performance of the CLS for the electric network voltage regulation.	STATCOM	
[39]	Enhance the voltage profile.	STATCOM	
[40]	power flow control of multiple transmission lines.	IPFC	MATPOWER
[41]	minimization of fuel cost and transmission losses.	TCSC, TCPAR	
[42]	damping power oscillations and enhancing transient stability.	TCSC	NETOMAC
[43]	to dampen power oscillation.	TCSC, SVC	
[44]	enhancement of stability system and POD system	UPFC	
[45]	voltage profile improvement, transmission line loss minimization.	SSSC	PSB
[46]	to control the power flow in the power system.	UPFC	
[47]	Management of Combined Reactive Power Compensation and Voltage Stabilization in Power Systems.	STATCOM	
[48]	Reactive power compensation for improvement of the voltage profile.	STATCOM	
[49]	to improve voltage stability system.	SVC	PSAT
[50]	improving the existing transmission capability of power system.	UPFC	

Continued on next page

Refs	Objectives	Devices	Simulation tools
[51]	to obtain reactive power sustainability and voltage stability under a symmetrical three phase fault.	STATCOM, SSSC, SVC, UPFC	
[52]	control simultaneously the line active and reactive power of two machine systems.	UPFC	PSCAD-EMTDC
[53]	compensation of reactive power.	STATCOM	
[54]	Eliminates the difficulties of the nonlinear model of the CSC.	STATCOM	
[55]		IPFC	
[56]	Enhance the dynamic performance of FACTS control devices across various operations.	STATCOM, SSSC, UPFC	PSIM
[57]	improved control performance and cost-effective converter-based FACTS devices.	IPFC	PSPICE
[58]	to obtain a nearly linear reactive power control.	STATCOM	
[59]	Impact of FACTS on the performance of impedance-based protection relays.	TCSC	RTDS
[60]	improve the precision of the tiring angle for TCR.	TCR	
[61]	evaluate the performance of distance relays on transmission lines with FACTS devices applied for midpoint voltage control.	STATCOM, SVC	
[62]	to optimize power flow and enhance power system stability.	SSSC	

5.12. Other simulation software

There are several other simulation software options, including SIMFACTS, SABER, and MIPOWER. SIMSEN, EUROSTAG, UWPFLOW, Power Flow Analysis and Control (PFAC) software, PSASP, and NEPLAN for the simulation of FACTS devices. Here is some additional information about these simulation software tools:

- SIMFACTS: SIMFACTS, is a simulation software tool used for the analysis of FACTS devices. However, it should be noted that SIMFACTS is not widely recognized or commonly discussed in the literature. Without further information, it is challenging to provide specific details about its features or capabilities.
- SABER: SABER is a comprehensive simulation tool developed by Synopsis that allows for the modeling and analysis of power electronic systems. While SABER is primarily used for circuit-level simulations, it can also be utilized for studying FACTS devices and their impact on power system performance.
- MIPOWER: MIPOWER is a simulation software tool developed by Power World Corporation. It is primarily used for power system analysis, including power flow, contingency analysis, and transient stability analysis. MIPOWER provides capabilities for modeling and simulating FACTS devices and assessing their impact on power system behavior.
- SIMSEN: SIMSEN (Simulation System for Electrical Networks) is a simulation software tool developed by Siemens. It is designed for modeling and analyzing electrical networks, including transmission and distribution systems.

- EUROSTAG: EUROSTAG is a widely used simulation software tool developed by Siemens PTI (Power Technologies International). It is designed for power system analysis, including transient stability, dynamic simulation, and voltage stability analysis.
- UWPFLOW: UWPFLOW (Unified Power Flow Controller Analysis Tool) is a simulation software tool developed by the University of Wisconsin-Madison. It is specifically focused on the analysis of Unified Power Flow Controllers (UPFCs) and their impact on power system operation and control.
- Power Flow Analysis and Control (PFAC) software: PFAC software is a generic term used to refer to various simulation tools that enable power flow analysis and control studies. Different software tools may have specific names or be developed by different organizations, but they serve the purpose of simulating power flow and control scenarios, including the incorporation of FACTS devices.
- PSASP: PSASP is a widely used power system simulation software developed by Washington State University. It provides comprehensive capabilities for electric network analysis, including the modeling and simulation of FACTS controllers and their impact on system performance.
- NEPLAN: NEPLAN is a popular simulation software tool developed by BCP (Business Computer Projects) for electrical power system analysis and planning. NEPLAN provides a range of features for power system simulation, including the modeling and analysis of FACTS devices.

These software tools, including SIMFACTS, SABER, MIPOWER, SIMSEN, EUROSTAG, UWPFLOW, PFAC software, PSASP, and NEPLAN, offer a variety of features and capabilities for studying FACTS devices and their impact on transmission system performance. The selection of software is based on specific requirements, availability, and familiarity within the research or electrical power setting.

Table 2 presents a comprehensive summary of other simulation-based approaches employed in research studies focusing on the optimization of FACTS devices. The table encompasses details regarding the simulation tools utilized, the objectives pursued in the studies, and the specific FACTS devices investigated to address various optimization challenges.

Table 2. A comprehensive summary of other simulation-based approaches for optimizing FACTS devices.

Refs	Objectives	Devices	Simulation tools
[63]	Power losses minimization	UPFC	TOPSIS
[64]	TTC	SVC, STATCOM	NEPLAN
[65]	PTC Enhancement	UPFC	PSASP
[66]	PTC Enhancement	SVC	PFAC
[67]	Static Voltage Stability: Influence of Wind Farm Integration and FACTS Devices	SVC, STATCOM	UWPFLOW
[68]	dynamic stability	UPFC, SVC, STATCOM	EUROSTAG
[69]	Steadystate and transient behavior	UPFC	SIMSEN
[70]	Interaction of wind farm with FACTS	UPFC, SVC, TCSC	SABER
[71]	Transient Stability Analysis	Series FACTS devices	MIPOWER
[72]	Power Flow Equation	STATCOM,SVC, TCSC, SSSC, UPFC	SIMFACTS

5.13. Simulation tools and real-time simulation

Real-time simulation plays a crucial role in analyzing and optimizing the operation of electrical power systems with FACTS devices. The "what, where, and why" of real-time simulation in the context of simulation-based methods for optimizing FACTS devices in electrical power systems as shown in Figure 21.

Therefore, real-time simulation is a valuable tool for optimizing FACTS devices in electrical power systems. By providing time-critical analysis, enabling performance improvement, mitigating risks, and saving costs, real-time simulation contributes to the effective operation and optimization of power systems incorporating FACTS devices. Overall, real-time simulation provides a powerful tool for analyzing and understanding the behavior of dynamic systems, enabling researchers and engineers to study and optimize system performance in time-critical scenarios.

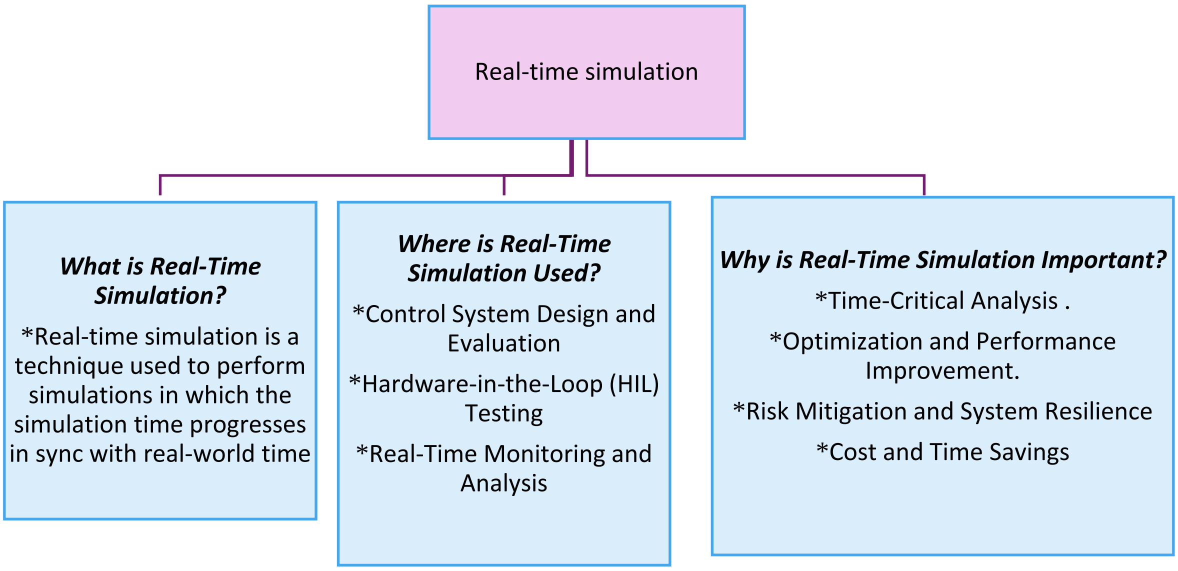


Figure 21. Simulation tools and real-time simulation.

6. Simulation results of FACTS devices in power systems

A 9-bus Western System Coordinating Council (WSCC) system [73] is used as a test case, with all data sourced from existing literature. Six cases of power flow analysis are conducted, focusing on the impact of FACTS devices on system performance. From the Figure 22, initially, the network operates without FACTS devices, successfully converging in 5 iterations, which establishes a baseline for performance metrics. The introduction of a STATCOM at bus 6 to maintain a voltage of 1.04 pu results in improved voltage magnitudes and phase angles as shown in Figure 23. The SSSC positioned between buses 1 and 2 increases the power flow from 0.743 pu to 0.820 pu, reflecting a 10% enhancement. A UPFC installed between lines 3 and 5 manages both active and reactive power flows, boosting them from 0.2626 pu and 0.0385 pu to 0.2900 pu and 0.0420 pu, respectively. Additionally, an SVC connected to bus 2 stabilizes the voltage at 1.0 pu, as shown in Figure 24, while a TCSC between buses 3 and 5 enhances power flow from 0.2626 pu to 0.2772 pu. Table 3 demonstrates that the integration of FACTS devices significantly improves the WSCC network's performance, enhancing voltage stability, increasing power flow, and optimizing reactive power management, highlighting the critical role of FACTS technology in modern power systems.

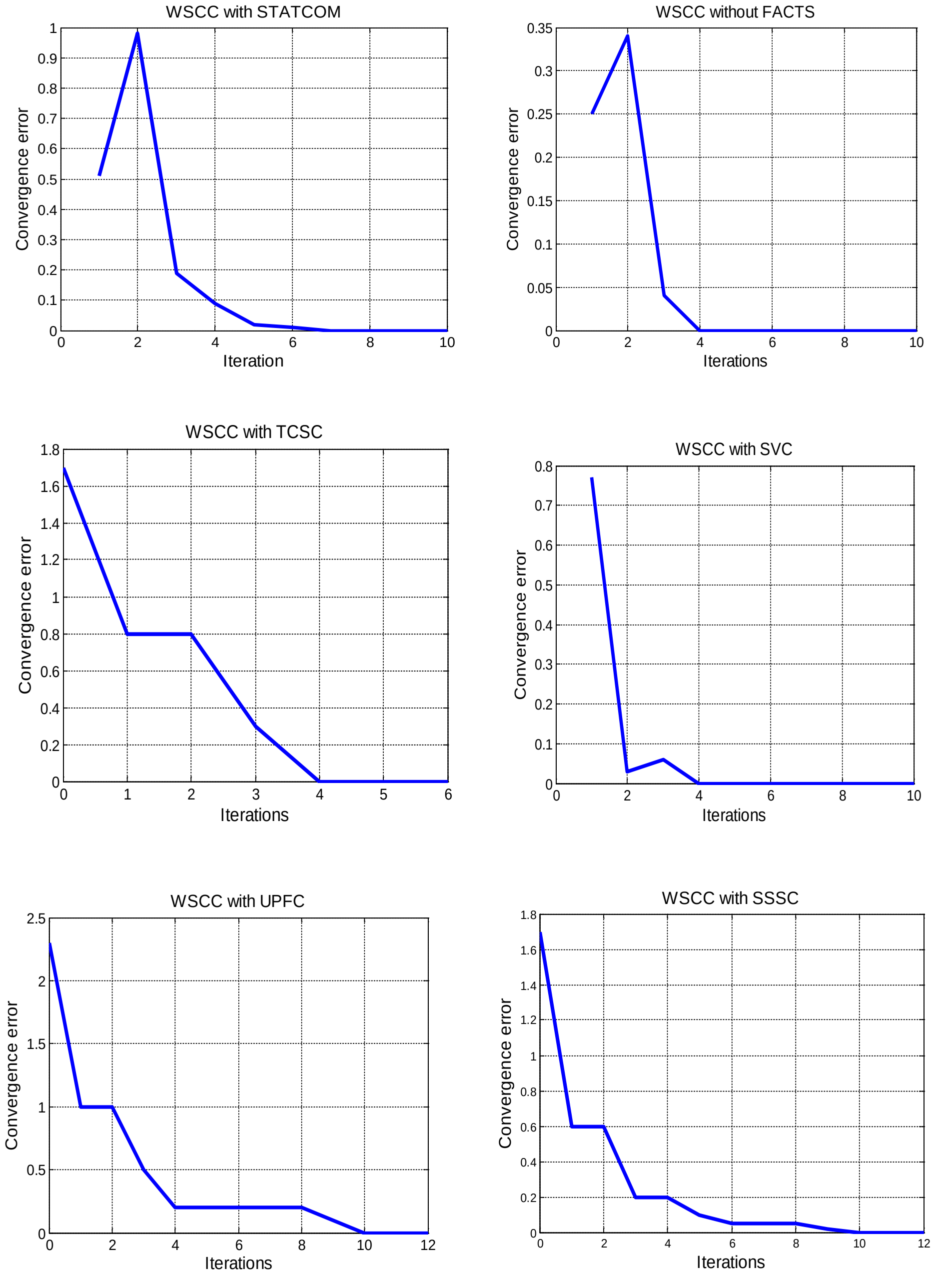


Figure 22. The convergence characteristic for the WSCC system with and without FACTS.

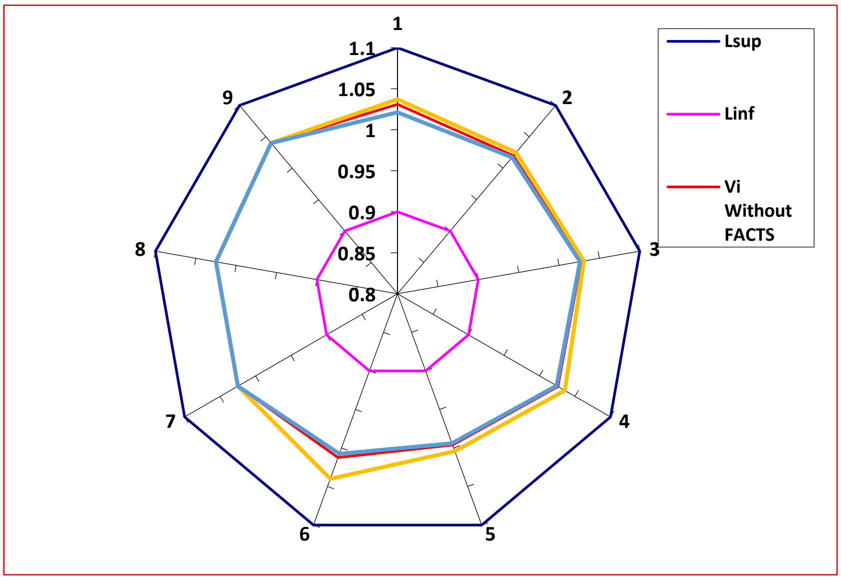


Figure 23. Voltage magnitudes for the system with (STATCOM, SSSC) and without FACTS devices.

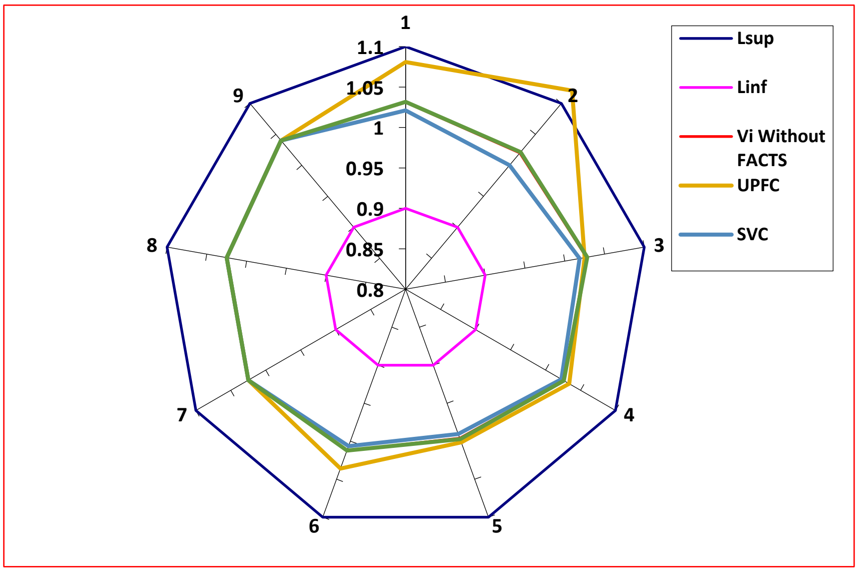


Figure 24. Voltage magnitudes for the system with (UPFC, SVC, TCSC) and without FACTS devices.

Table 3. Active and reactive powers transmitted for the system with and without FACTS devices.

		Multiple FACTS											
		Without FACTS		SVC		STATCOM		TCSC		*SSSC*		*UPFC*	
Lines		P	Q	P	Q	P	Q	P	Q	P	Q	P	Q
1	2	0,743	0,1677	0,7472	0,3616	0,7421	0.1904	0.6863	0,1613	0.820	0,0800	0,6821	−0,8854
1	6	0,5874	0.0066	0,5832	−0,0176	0.5883	−0.1219	0,6440	0,0033	0.5620	−0,0204	0,6483	0,1655
1	7	−0,8500	0.1271	−0,8500	−0,0484	−0.8500	0.2365	−0,85	0,1371	−0,8500	−0,0449	−0,8500	1,0511
3	5	0,2626	0.0385	0.2599	0,1957	0,2635	0,0140	0,2772	0,0372	0,2372	0,0570	0,29	0,0420
3	2	0,8870	0.0834	0,8897	0,0631	0.8861	0.0538	0,8300	0,0860	0,9124	0,0864	0,8100	0,0395
3	8	−1,6300	0.1182	−1,6300	−0,0227	−1.6300	0.1738	−1,6300	0,1335	−1,6300	0,0960	−1,6300	0,0792
4	5	0,3894	0.3191	0,3874	0,3458	0.3902	0.3440	0,4438	0,3037	0,3654	0,3232	0,4632	0,3461
4	6	0,3271	0.0943	0,3316	0,1228	0.3266	−0.1027	0,2725	0,1060	0,3520	0,1222	0,2678	−0,0707
4	9	−0,7165	−0.2376	−0,7190	−0,2939	−0.7168	−0.0621	−0,7163	−0,2339	−0,7174	−0,2703	−0,7310	−0,0970

7. Discussion

In this review, we aim to highlight the objectives, major applications, advantages, adaptability to varying operating conditions of electrical systems, and the potential for improving existing installations as the primary motivations for integrating FACTS devices into the electrical system. It has been identified that different FACTS systems can control several parameters of electrical networks, which are summarized in Table 4.

Table 4. Advantages of FACTS devices, controlled parameters, and primary applications.

FACTS Devices Benefits	*Enhancement of power transfer capability *Improvement of system stability *Increase of system security *Operation with high-speed response
FACTS Devices Controlled parameters	*TCSC provides impedance variation *SVC provides reactive power compensation *STATCOM provides reactive power control *SSSC provides real and reactive power management in the line *UPFC provides the control of both real and reactive power *IPFC provides power flow control of multiple lines
FACTS Devices Most applications	*Regulation of voltage: TCSC, UPFC, SVC, TCPST/PST, and STATCOM. *Stability and collapse of Voltage: SVC, UPFC, STATCOM, and TCSC. *Assets Optimization: TCPST/PST, TCSC, SVC, UPFC, SSSC, and STATCOM *Line Overload Limiting: UPFC, TCSC and TCPST/PST. *N-1 Contingency criteria fulfillment: TCSC, UPFC, STATCOM, and SVC. *Avoid congestion and re-dispatch: SVC, TCSC, and UPFC. *Transmission cost minimization: TCPST/PST, UPFC,STATCOM, TCSC, SVC, and SSSC. *Angle stability: UPFC, TCSC, SVC, and SSSC.

Simulation software and programs are effective and powerful tools, their application offers a contribution to technologically improving the field of electrical and electronic engineering quickly by modeling and simulating different FACTS device controllers. Based on a research paper published in IEEE Explorer with Simulation Software, MATLAB is the most widely used software for research and education. Indeed, its performance can be extended by adding Simulink. In some other references, simulation-based techniques were used to determine the best location for the FACTS. Various simulation tools have been considered as simulation-based methods for solving FACTS devices optimization problem. However, in several research works, these simulation software's and programs are considered a means of implementation of certain optimization techniques like Genetic Algorithms and Particle Swarm Optimization [74], differential evolution [75], etc., to solve this FACTS devices optimization problem. In a recent paper [76], Mohamed Ebeed et al. present a thorough survey of various modeling methods for combined series-shunt VSC-based FACTS devices within power flow solutions. The survey covers several models, including the power injection model, extended model, developed model, indirect model, simplified model, decoupled model, and π injection model. Furthermore, the authors provide a comparative analysis highlighting the advantages and disadvantages of each method.

Comparison between all these Simulation Software and some criticisms are as follows:

MATLAB/Simulink is a widely used simulation software that is particularly useful for modeling and simulating dynamic systems. It is known for its ease of use and versatility, as it can be used for a wide range of applications, including control systems, signal processing, and power systems. However, one criticism of MATLAB/Simulink is that it can be quite expensive to use, especially for large-scale projects.

ETAP is another popular simulation software that is specifically designed for power systems analysis. It offers a wide range of features, including load flow analysis, short-circuit analysis, and transient stability analysis. However, some users have criticized ETAP for being difficult to use and for lacking certain advanced features.

EMTP-RV is a simulation software that is primarily used for analyzing electromagnetic transients in power systems. It is known for its accuracy and versatility, but some users have found it to be complex and difficult to use.

MATPOWER is a simulation software that is designed for power system optimization and simulation. It is open-source, which makes it a popular choice for researchers and academics. However, some users have criticized MATPOWER for being less user-friendly than some of the commercial simulation software options.

NETOMAC is a simulation software that is used for analyzing and optimizing power system networks. It is known for its speed and accuracy, but some users have found it to be difficult to use.

PSB is a simulation software that is used for power system balancing and optimization. It offers a range of features, including load flow analysis and fault analysis. However, some users have criticized PSB for its limited capabilities compared to other simulation software options.

PSAT is a simulation software that is designed for power system analysis and optimization. It is known for its user-friendly interface and versatility, but some users have found it to be less accurate than some of the other simulation software options.

PSCAD-EMTDC is a simulation software that is used for analyzing electromagnetic transients in power systems. It is known for its accuracy and advanced features, but some users have criticized it for being difficult to use and for having a steep learning curve.

PSIM is a simulation software that is primarily used for power electronics simulation and design. It is known for its user-friendly interface and advanced features, but some users have found it to be less accurate than some of the other simulation software options.

PSPICE is a simulation software that is widely used for electronic circuit simulation and design. It is known for its accuracy and versatility, but some users have criticized it for being less user-friendly than some of the other simulation software options.

RTDS is a simulation software that is used for real-time power system simulation and testing. It is known for its accuracy and reliability, but some users have criticized it for being expensive and difficult to use.

Table 5 provides an overview of the strengths and weaknesses of each tool in the context of FACTS device applications, aiding in the selection of appropriate tools based on the specific needs of electrical systems.

Table 5. An overview of the strengths and weaknesses of each tool in the context of FACTS device applications.

Tool	FACTS Devices	Ease of Use	Simulation Capabilities	Accuracy	Efficiency	Comments
MATLAB/Simulink	SVC, STATCOM, UPFC	High	Advanced	Very High	Very Efficient	Good integration with other tools and libraries.
ETAP	SVC, TCSC	Medium	Good	High	Efficient	Primarily used for power flow analysis.
EMTP-RV	SVC, STATCOM, UPFC.	Medium	Very	Very High	Efficient	Excellent for transient simulations.
MATPOWER	SVC, STATCOM	High	Good	High	Efficient	Ideal for optimization and power flow analysis.
NETOMAC	SVC, STATCOM	Low	Good	Medium	Average	Less commonly used but useful for stability studies.
PSB	SVC, STATCOM	High	Good	High	Efficient	User-friendly interface, good for small-scale simulations.
PSAT	SVC, STATCOM	High	Good	High	Efficient	Open-source tool with strong optimization capabilities.
PSCAD-EMTDC	SVC, STATCOM, UPFC	Medium	Very Advanced	Very High	Very Efficient	Excellent for EMT simulations.
PSIM	SVC, STATCOM	High	Good	High	Efficient	Used for circuit simulations and power analysis.
PSPICE	SVC, STATCOM	High	Good	High	Efficient	Primarily used for electronic circuit simulation.
RTDS	SVC, STATCOM, UPFC	Medium	Very Advanced	Very High	Very Efficient	Used for real-time simulations, ideal for system testing.

According to the user's desired objectives and the nature of the application of FACTS systems, the appropriate tool can indeed be selected. Each tool offers distinct features and capabilities that cater to specific needs within the realm of FACTS device management and optimization.

The best tool for real-time simulations of FACTS devices is RTDS. RTDS is specifically designed for real-time simulations, enabling rapid and accurate modeling of dynamic systems, which makes it ideal for testing and analyzing FACTS devices under various operating conditions. It provides very high accuracy in simulating electrical systems, a crucial factor for evaluating the performance of FACTS devices in real-world scenarios. Additionally, RTDS supports a wide range of configurations and can simulate various FACTS devices, including Static VAR Compensators (SVCs), Static Synchronous Compensators (STATCOMs), and Unified Power Flow Controllers (UPFCs).

One of the standout features of RTDS is its ability to integrate with hardware-in-the-loop (HIL) testing, enabling the validation of control systems and algorithms in real-time. Its user-friendly interface facilitates the setup and execution of simulations, making it accessible for engineers and researchers alike. Furthermore, RTDS is widely adopted in both industry and academia for research and development in power systems, establishing itself as a trusted choice for real-time simulations. Thus, RTDS is exceptionally well-suited for applications requiring real-time performance evaluation of FACTS devices, providing reliable results that can significantly inform decision-making and system design.

The best tool for analyzing electrical power systems stability using FACTS devices is PSCAD-EMTDC. This tool excels in simulating electromagnetic transients, making it highly effective for studying the dynamic behavior of electrical power systems under various conditions. PSCAD-EMTDC allows for detailed modeling and simulation of various FACTS devices, such as Static VAR Compensators (SVCs), Static Synchronous Compensators (STATCOMs), and Unified Power Flow Controllers (UPFCs), enabling engineers to assess their impact on system stability.

One of the key advantages of PSCAD is its user-friendly graphical interface, which facilitates the construction of complex power system models and allows for realistic representations of system dynamics and interactions. The tool offers comprehensive analysis capabilities, including voltage stability, transient stability, and dynamic performance under fault conditions, which are critical for evaluating the effectiveness of FACTS devices in enhancing system performance. Additionally, PSCAD can be integrated with other simulation tools and hardware, enabling comprehensive studies that encompass various aspects of power system behavior. With a strong user community and extensive documentation, PSCAD-EMTDC provides valuable support for engineers and researchers. Therefore, it is highly regarded for its capabilities in power system stability analysis, making it an excellent choice for evaluating the role of FACTS devices in enhancing the reliability and efficiency of electrical systems.

The best tool for placing FACTS devices in electrical networks is MATLAB/Simulink. This software provides a highly flexible environment, allowing users to customize models and algorithms for specific optimization problems related to FACTS device placement. MATLAB/Simulink includes a robust optimization toolbox that effectively solves complex placement issues, enabling users to determine the optimal location, type, and size of FACTS devices within the network.

One of the key advantages of MATLAB/Simulink is its ability to integrate simulation and analysis seamlessly, enabling users to evaluate the performance of FACTS devices in the context of the entire electrical network. The user-friendly graphical interface in Simulink simplifies the modeling of electrical systems and helps visualize the effects of different placements. Additionally, users can implement advanced techniques such as genetic algorithms, particle swarm optimization, or other heuristic methods to optimize FACTS device placement based on specific criteria.

The extensive documentation and large user community associated with MATLAB/Simulink provide valuable resources for troubleshooting and sharing best practices. Then, MATLAB/Simulink stands out as an excellent choice for the placement of FACTS devices in electrical networks, offering the necessary tools and flexibility to effectively address complex optimization challenges.

The key strength of PSAT for FACTS devices in electrical networks lies in its robust optimization capabilities and user-friendly interface tailored for power system studies. As an open-source tool, PSAT offers flexibility, allowing users to customize and extend its functionalities to suit various research and practical applications involving FACTS devices. It provides a comprehensive range of analysis options, including power flow calculations, optimal power flow, and stability analysis, specifically designed to evaluate the impact of FACTS devices on system performance.

One of the notable advantages of PSAT is its integration with the MATLAB environment, which enables users to leverage MATLAB's extensive computational and visualization capabilities, enhancing the analysis of FACTS device performance. The toolbox includes effective optimization algorithms that allow users to determine the optimal placement and sizing of FACTS devices, ultimately improving network performance and stability. Additionally, PSAT features an intuitive graphical user interface that simplifies the modeling and simulation of power systems, making it accessible to both experienced engineers and newcomers.

Moreover, being part of the academic and research community, PSAT benefits from contributions and feedback from users, which helps in continually improving its features and functionalities. So, PSAT is a powerful tool for analyzing and optimizing FACTS devices in electrical networks, providing essential capabilities for effective power system management and enhancement.

Table 6 summarizes the utility of each tool for controlling FACTS devices to reduce congestion in overloaded power lines, particularly in the context of deregulated energy markets and the increasing penetration of renewable energy sources. Therefore, each tool offers unique capabilities that are essential for managing FACTS devices and reducing line congestion, particularly in the evolving landscape of deregulated energy markets and the integration of renewable energy sources.

Table 6. Summary of the utility of each tool for controlling FACTS devices.

Tool	Utility for FACTS devices control	Key features
MATLAB/Simulink	Custom modeling and simulation for FACTS optimization	Advanced optimization tools; flexibility to model renewable energy fluctuations.
ETAP	Analyzes power flow and congestion management	Advanced power flow analysis evaluates FACTS' impact on transfer capacity.
EMTP-RV	Simulates transients and dynamic responses	Excellent for anticipating congestion due to rapid renewable generation changes.
MATPOWER	Optimizes power systems in deregulated environments	Models market dynamics; assesses FACTS effectiveness in reducing congestion.

Continued on next page

Tool	Utility for FACTS devices control	Key features
NETOMAC	Studies stability and FACTS effects.	Useful for analyzing stability impacts in renewable integration scenarios.
PSB	Quick simulations of FACTS configurations.	Ideal for rapid testing in markets requiring swift decision-making.
PSAT	In-depth analysis of FACTS impact on congestion.	Open-source; focuses on performance studies in deregulated markets.
PSCAD-EMTDC	Analyzes dynamic performance under transient conditions.	Excellent for simulating the effects of FACTS on congestion from renewables.
PSIM	Simulates circuits and systems including FACTS.	Analyzes optimization of energy flow in congested networks.
PSPICE	Circuit simulation for FACTS integration.	Models FACTS for improved network integration; supports congestion management.
RTDS	Real-time testing of FACTS impacts.	Ideal for fast-paced market environments; tests immediate effects on congestion.

To effectively apply the methods discussed in this paper to real power grids, several prerequisites must be met. First, a solid understanding of electrical engineering principles, including circuit theory, power flow analysis, and control systems, is essential, along with familiarity with the operational dynamics of power grids, encompassing generation, transmission, and distribution processes. Additionally, high-quality data on the power system's configuration such as network topology, load characteristics, and generation capacities is necessary to create accurate models, complemented by historical performance data to inform the optimization process.

Proficiency in simulation tools like MATLAB/Simulink, EMTDC/PSCAD, and PSAT is crucial, as users must know how to implement models and algorithms effectively while understanding each tool's strengths and limitations. Knowledge of various optimization methodologies, including mathematical programming, evolutionary algorithms, and heuristic techniques, is also vital for selecting the right approach for FACTS device placement and sizing. Familiarity with soft computing techniques, such as neural networks and fuzzy logic, is necessary for optimizing FACTS controller locations, along with the ability to integrate these approaches with traditional methods for enhanced effectiveness.

Moreover, awareness of local regulatory standards governing power system operations is essential to ensure compliance with legal requirements, and coordination with grid operators and stakeholders is necessary to align optimization strategies with operational practices and grid reliability needs. By meeting these prerequisites, engineers and researchers can successfully apply the methods from the paper to real power grids, optimizing performance and enhancing the reliability of electrical systems. This careful preparation will facilitate the effective integration of FACTS devices and the application of simulation tools to address the challenges faced by modern power grids.

8. Conclusions

In conclusion, we provide a comprehensive overview of the role of FACTS (Flexible AC Transmission Systems) devices in enhancing the performance and reliability of electrical power systems, particularly in the context of increasing demand, deregulated energy markets, and the integration of renewable energy sources. By evaluating various simulation tools, including MATLAB/Simulink, PSAT, and PSCAD-EMTDC, we have highlighted the strengths and capabilities necessary for optimizing the placement and operation of FACTS devices to mitigate congestion and improve voltage stability.

The analysis underscores the importance of selecting appropriate tools based on the specific objectives and nature of the application, whether for transient simulations, optimization, or real-time testing. Through simulations and case studies, it becomes evident that FACTS devices can significantly enhance the efficiency of power systems, enabling better management of variable renewable energy inputs and facilitating a more robust grid infrastructure.

Therefore, this study not only contributes to the existing body of knowledge on FACTS technology but also serves as a guide for practitioners and researchers aiming to leverage these devices effectively. As the energy landscape continues to evolve, the integration of advanced simulation tools and the strategic deployment of FACTS devices will be crucial in addressing the challenges of modern power systems and ensuring a sustainable energy future.

Future extensions of this work could focus on the integration of FACTS devices in Distribution Systems (D-FACTS) that incorporate renewable energy sources such as solar, wind, and hydropower using other simulation tools. There are other simulation tools available for D-FACTS (Distribution Flexible AC Transmission Systems) as well. While some simulation tools primarily focus on transmission-level FACTS devices, there are others that can be used for modeling and analyzing D-FACTS devices in distribution systems. These tools allow for the simulation of D-FACTS devices and their impact on distribution system performance, including power flow, voltage regulation, fault management, and congestion mitigation such as OpenDSS (Open Distribution System Simulator), DIgSILENT Power Factory, etc. Therefore, the integration of D-FACTS devices with renewable energy sources in distribution systems holds significant potential for improving grid performance, enabling higher renewable energy penetration, and enhancing overall system resilience. However, addressing the associated challenges requires further research, technological advancements, and collaboration among industry stakeholders, researchers, and policymakers.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, M.A. and I.M.; methodology, I.M..; software, I.M.; validation, M.A. and I.M.; formal analysis, IM.; investigation, I.M. and M.A.; resources, S.A., H.H.A. and S.R.; writing—original draft preparation, I.M.; supervision, I.M. and M.A.; authors have read and agreed to the published version of the manuscript.

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