Bottleneck Engineering and Optimal Technical and Non-Technical Approaches in Power Grid's Congestion Management: A Real Case Study

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The congestion phenomenon is one of the challenging problems during peak hours of power grids. With no management or scientific approach, it can cause severe and irreparable damage to the grid equipment and substantial financial losses to the network owners. Congestion management (CM) has been introduced as a critical solution to eliminate power transmission obstacles and prevent lines and transformers overloading and several grid damages. Some studies have been conducted with the aim of congestion management in recent years, which generally have a technical or non-technical approach using planning and optimizing methods on predetermined data. In this research, a 10-year analysis of monthly peak load snapshots of an actual power system using a powerful analyzer software, PowerFactory version 2022 (DIgSILENT), and recorded loads by the Supervisory Control and Data Acquisition (SCADA) system under different scenarios is investigated. This real case study includes the impacts of distributed generations (renewable or non-renewable), large-scale centralized power plant (PP) and the proposed optimal allocation of flexible ac transmission systems (FACTS) devices such as static VAR compensator (SVC), phase shifting transformer (PST) to the power grid using grey wolf optimization (GWO) algorithm. Also, expansion stages in the power lines, stations and increasing the capacity at the bottleneck points are simulated. The effectiveness of technical and non-technical proposed approaches for congestion management is confirmed in the result section.

keywords: *Congestion phenomenon, Blackouts, Congestion Management, Bottleneck, FACTS Devices, SCADA.*

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NOMENCLATURE

CM	Congestion management
SCADA	Supervisory control and data acquisition
PP	Power plant
FACTS	Flexible ac transmission systems
SVC	Static VAR compensator
PST	Phase shifting transformer
GWO	Grey wolf optimization
EHV	Extra high voltage
AVR	Automatic voltage regulator
TSO	Transmission system operator
DSO	Distribution system operator
DG	Distributed generations
THD	Total harmonic distortion
SPS	Special protection scheme
GR	Generators rescheduling
DR	Demand response
RESs	Renewable energy sources

PSO Particle swarm optimization
SC Single contingency
ATR Auto-transformers
SLD Single-line diagram
CT Current transformers
CB Circuit breakers
LT line trap
$ASTM$ American society for testing and materials
EAF Electric arc furnace
GPR Ground potential rise

1. INTRODUCTION

The development of smart cities requires a smart network in the electricity production, transmission, and distribution network to have a stable power supply and good power provision. Transmission lines and electric machines of the transmission network are the main elements of sustainable energy supply for smart cities through the smart grid. The development of smart cities has a positive effect on the environment. It reduces social costs due to the effective use of energy while increasing the capacity of renewable resources [1]. The development of power systems leads to the overloading of equipment in transmission networks and consequently causes the phenomenon of congestion in the power grid. Congestion has serious and destructive effects on power networks, including severe damage to transformers and conductors of transmission lines. Congestion phenomenon occurs when the transmission networks and equipment are not able to transmit the required electric power based on the load demand. These types of problems are controlled and managed through congestion management (CM) methods, which play a crucial role in power systems [2]. Congestion of the transmission line or transmission transformer is a major technical problem that must be managed as soon as possible to maintain the security and stability of the power systems. Today, the electricity industry in developed and developing countries is changing its structure and deregulation by replacing the previous public facilities with competitive electricity markets. By using CM in the network, overloaded lines are eliminated, or the overloading of electrical equipment is prevented. Many factors have been mentioned in technical texts for congestion in power grids [3]. In a competitive electric market, congestion occurs when the transmission networks cannot perform all the required energy exchanges and supply the consumer load due to the violation of the network's operational limits [4]. In other words, congestion refers to the overloading of a device while loading electrical energy, which exceeds its thermal boundaries and permitted capacities. Also, this phenomenon occurs when the electric current passing through the transmission equipment exceeds its permissible current, and its reliability decrease [5]. Physical and systemic limitations in the transmission grid are one of the main factors in the occurrence of congestion in transmission lines. Physical limitations such as equipment aging and thermal limitations of the transmission line or transformer are effective in the occurrence of congestion phenomenon. This adverse effect must be removed from the power systems in order to ensure the security of the system and to prevent further blocking and the expansion of blackouts [6]. The bottleneck phenomenon in the transmission lines occurs when the transmission systems operate at or beyond the range of their exchange capacity limits; in these cases, the congestion leads to preventing new contracts for power supply, making existing contracts infeasible, increase in price and market power abuse [7]. Congestion in the network can be due to reactive power flow because of low compensation in the downstream network or excessive compensation in the upstream network. The imperfect and non-sustainable development of the network against the load centers and the creation of deep points in the power network are also considered as other reasons. For example, in the case of low power, due to the large capacitance of extra high voltage (EHV) networks and improper compensation in shunt reactors, it can lead to the flow of reactive power through bottlenecks towards the downstream network and occupy the capacity of the equipment. For this purpose, automatic reactive power control based on the automatic voltage regulator (AVR) system (in transformers and generators), automatic control in flexible ac transmission systems (FACTS) devices, their operating modes, and smart control in network control centers (dispatching at distribution system operator (TSO) and distribution system operator (DSO) levels) and re-dispatching management in some lines are mandatory [8]. Congestion in the network can be caused by the flow of active power due to the geographical location of the production centers and consumption centers, their electrical distance from each other, and the electric torque of the load centers. Installing distributed generations (DGs) near the consumption centers can be a solution. In bottleneck engineering, the balance between active and reactive power flow should be observed. Analysis of other system indicators such as energy loss, grid load factor, grid loss factor, and point indicators (power factor and total harmonic distortion (THD)) should be considered. Also, the direction of harmonic power flow in the network and its consequences, including excessive heating of electric machines, is required to be considered. The voltage limitation, the transient stability of generators, and similar cases are examples of the limitations of the transmission grid that can lead to congestion. Also, due to possible unexpected occurrences and unplanned scenarios, such as shutdowns in generation units, an unexpected increase in load demand and equipment failure causes congestion. The classification of CM and its approaches are shown in figure1. The occurrence of congestion in power systems has led to disruptions and disturbances in the power network, which, if not managed, will cause outages of the equipment due to the operation of current overload relays and the operation of special protection scheme (SPS) in an interconnected system [9]. The effects of congestion in the power grid are damage to equipment, the occurrence of interruptions, the reduction of system reliability, and improper voltage quality[10]. In order to prevent damage to the power system equipment and increase the power quality, studies of FACTS devices and their role in power quality should be considered. CM is known as one of the critical issues in maintaining security and increasing the reliability of power networks, and reducing the financial losses caused by congestion. Ignoring the CM in the system leads to widespread blackouts, which are associated with negative social and economic consequences CM is a mechanism through which transmission congestion can be reduced by maintaining all exchanges within the safe range by deploying all scheduled operations for system lines[11]. CM can be done in two ways - technical and non-technical methods. Technical methods are costly methods. For example, assuming that some lines are blacked out, it is possible to reduce the congestion in the transmission lines by using electronic power devices (such as FACTS) and phase-shifting transformers (PST). Non-technical methods

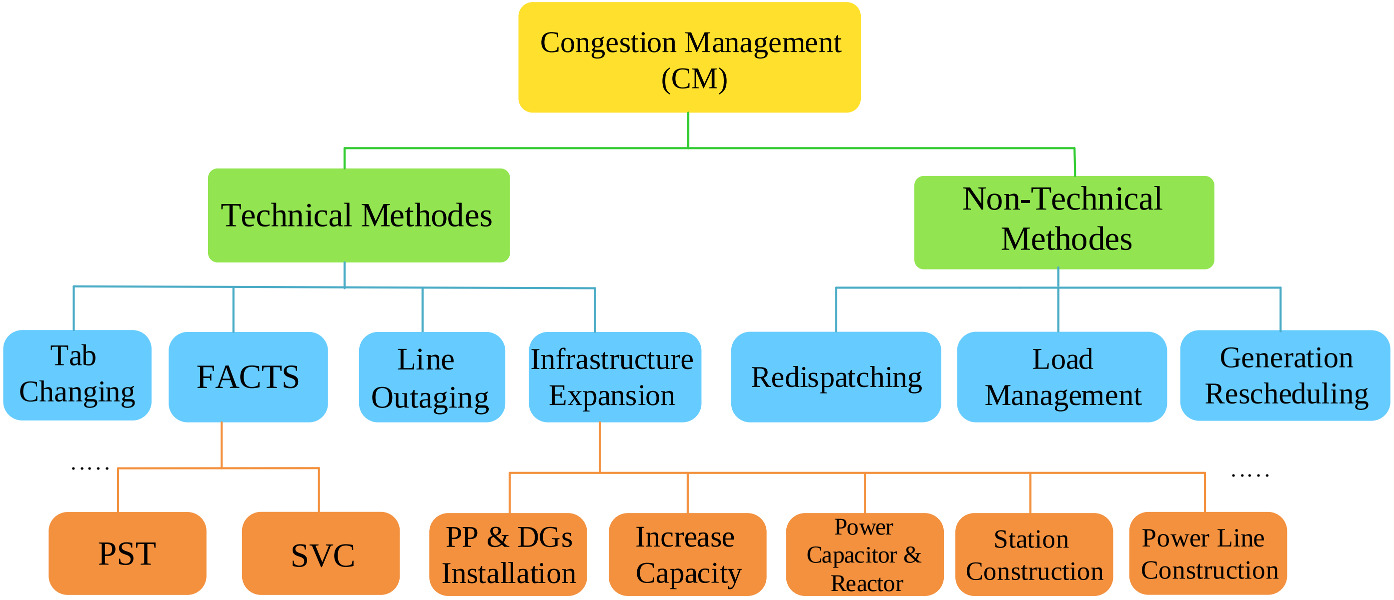

Fig. 1. Overview of congestion management and its technical, non-technical classification

or cost-free methods are optimal production management with economic load distribution, including security constraints, congestion pricing, and electricity market-based methods. Several management methods are as follows: generators rescheduling (GR) in congestion mode, reducing load, managing DGs, and demand response (DR)[12]. A comparison of the studied papers from different perspectives is provided in Table 1. Comprehensive studies have been carried out for the optimal placement of DGs to minimize power losses, increase voltage stability and improve voltage characteristics. Optimum placement of DGs is necessary to achieve maximum benefits with lower investment costs. Hence the optimal allocation of DG resources to solve problems related to the size and appropriate location of DGs with multi-objective constraints is studied in reference [13]. The optimal placement of FACTS devices in power networks has been mentioned in many references as an effective way to manage congestion. The optimal placement of serial FACTS devices in the power network where the penetration level of renewable energy sources (RESs) is high has been studied in reference [14]. It is possible to use a PST to limit the power flow from the low-capacity path and direct it to the high-capacity paths. Therefore, it is possible to reduce the limits of transmission in the operation services[14]. The combination of the demand response method and the FACTS devices in power grids is one of the standard methods of CM. The efficacy of this method is compared and simulated in many articles which studied different power systems with the presence of various types of FACT devices and the applying the DR method [15]. Different optimization algorithm and constraints aim to minimize the total costs of congestion and maximize reliability with meta-heuristic algorithms making it possible to increase the power system stability, reduce congestion and provide an uninterrupted power supply [16]. Also, in [17], a bi-level optimization is proposed regarding the placement of FACTS in the optimal points of the system, and studies have been conducted about the stability of the system and CM. In the aforementioned bi-level optimization, one level of the problem aims to reduce the costs of the FACTS devices, and the other level is to reduce congestion by making the constraints feasible. A review of recent studies with the approach of optimal placement of FACTS devices in power systems by particle swarm optimization (PSO) algorithm is given in [18]. In reference [19], non-technical methods of GR and load management in a 30-busbars power grid using a multi-objective PSO are mentioned to reduce the congestion of transmission lines. This article proposes the CM with both technical and non-technical approaches, under different scenarios with the expansion stage approach based on the load profile at the peak load point of the power network with real data recorded and collected by the SCADA system over a 10-year period and reviewed on a monthly basis in an actual power network. The effectiveness of the proposed optimal FACTS allocation using the grey wolf optimization (GWO) algorithm, infrastructure expansion method in the real power grid, and load managing technique is carried out in the PowerFactory version 2022 (DIgSILENT) software regarding the bottleneck points of the network. Finally, the simulation results and the comparison study confirmed the validity of the suggested optimal approaches under various scenarios in the result section. The main contributions are as follows:

- Overcoming the congestion phenomenon and contingency problems in the transmission systems by optimal installing of FACTS devices and generation rescheduling.
- Determining the optimum location of FACT devices using the GWO algorithm
- Employing a 10-year real case study in the PoweFactory version 2022 (DIgSILENT) to better understand congestion management

2. THEORETICAL DESCRIPTION: TECHNICAL AND NON-TECHNICAL APPROACHES FOR CONGESTION MANAGEMENT IN A REAL POWER NETWORK

In the studied grid, the capacity of the 230/63 kV transformer fleet is assumed to be 2640 MVA, and the capacity of the 400/230 kV auto-transformer fleet is assumed to be 600 MV at bottleneck

Table 1. Comparison of recent studies

References	Congestion Management		FACTS	Case Study	Considering RESs	Algorithm used
	Technical	Non-technical				
[2]	×	✓	-	IEEE-39 Bus System	×	Market-based congestion management
[3]	×	✓	-	New England-39 Bus System	×	PSO
[5]	×	✓	-	IEEE-39 Bus System	×	Distributed optimization-based dynamic tariff(DDT)
[9]	×	✓	-	IEEE-118 Bus System	✓	Stochastic optimization
[11]	×	✓	-	New England-39 Bus System	×	-
[14]	×	✓	-	IEEE-33 Bus System	✓	-
[16]	×	✓	-	IEEE-30 Bus System	×	Firefly Algorithm
[17]	✓	×	PST	IEEE-118 Bus System	✓	-
[20]	×	✓	-	German transmission grid	✓	-
This Study	✓	✓	PST-SVC	Real Data & Real Time	✓	Gray Wolf Optimization (GWO)

(1) and 630 MV at the bottleneck (2), which are shown in Figure 2. At bottleneck (1), the phenomenon of congestion with the occurrence of current overload in autotransformers has been observed. Due to the weak voltage in the 230 kV downstream link ring and the high consumption of reactive power in the downstream loads, which are mainly metal and iron smelting industries, the power factor is less than 0.7 at bottleneck (1). The studies carried out are based on the results of the analysis of load flow in the snapshots recorded in the monthly peak load, which is extracted from the SCADA system in the form of a peak load flow sheet. The single-line diagram of the power network under study is shown in Figure 2, with three bottleneck points. In all the scenarios, the network conditions are assumed normal from the point of view of the capacity and adequacy of equipment (The equipment are being loaded with the nominal capacity at the peak load operation point of the grid). For a better comparison, the single contingency (SC) condition and outage of the equipment are not considered. The maintenance and repair procedure and different outages (force, emergency, and planned) in peak load conditions have been ignored, and the system mode is considered to be in the steady state. It is obvious that in dynamic conditions such as generation units' shutdown and power lines and transformers outage, the conditions of the power network are marginal, and the results of these studies absolutely changes[21]. In the first step, the bottleneck points should be identified. The network and proper re-arrangement should be considered in order to save the bottleneck points from the undesirable congestion phenomenon with the growth of the loads in the future [22]. The CM requires a tactical management approach and technical engineering techniques. Therefore, various fields of engineering are dealing with the congestion phenomenon[23]. The CM, with appropriate guidelines and road maps, has attempted to reduce the destructive effects and negative consequences of congestion as much as possible [24]. With the growth of the load and the incomplete development of the network, one of the congestion consequences is the occurrence of load and electrical stress caused by this phenomenon, which brings additional stress on electrical equipment, compromising their insulation. One of the undesirable effects of this issue is the disturbances in the load performance and the equipment operations during this phenomenon [25].The main constraints and relationships of CM in transmission lines are stated below:

$$P_{flow}{}^{\min} \leq \Delta P_{flow} \leq P_{flow}{}^{max} \tag{1}$$

$$V_B^{\min} \leq V_B \leq V_B^{\max} \tag{2}$$

$$P_{Gen}{}^{\min} - P_{Gen}{}^{o} \leq P_{Gen} \leq P_{Gen}{}^{\max} - P_{Gen}{}^{o} \tag{3}$$

$$Q_i{}^{\min} \leq Q_i \leq Q_i{}^{max} \tag{4}$$

$$\Delta\varphi_{\min}{}^{PST} \leq \Delta\varphi^{PST} \leq \Delta\varphi_{\max}{}^{PST} \tag{5}$$

$$T^i_{\min} \leq T^i \leq T^i_{\max} \tag{6}$$

where $P_flow^m in$, $P_flow^m ax$ are the minimum and maximum power flow in the lines; $V_B^m in$, $V_B^m ax$ are the minimum and maximum voltages of bus bares; $P_Gen^m in$, $P_Gen^m ax$ are the minimum and maximum and generated power of generation units respectively, the P_Gen^o is initial active power set point of the generator; $Q_i^m in$, $Q_i^m ax$ are the minimum and maximum reactive power (generated or absorbed) in the power network equipment. $\Delta\phi^{pst}$ is the change in the phase shifting transformers in the acceptable range ($\Delta\phi^{pst}_{min}$,$\Delta\phi^{pst}_{max}$). T_i is the transformer taps constraint which have minimum and maximum setting limits (T^i_{min} , T^i_{max})[25]. The equality constraints (power balance) include active and reactive power balances are as follow:

$$P_{Gi} - P_{Di} = \sum_{j=1}^{n} \left(V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i \right) \quad \textbf{(7)}$$

$$Q_{Gi} - Q_{Di} = -\sum_{j=1}^{n} \left(V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i \right) \quad \textbf{(8)}$$

In the Eq. 7 ,8 i=1,. . . , n where n is the bus numbers, P_{Gi} , Q_{Gi} are the active and reactive power of generators at the i, P_{Di} ,Q_{Di} show the active and reactive load demands of the system, V, δ are the magnitude and angle of the voltage, θ_{ij} is the load angle. Figure 2 shows different parts of studied network including three PP with different generation capacity, three bottlenecks, FACTS devices (PST, SVC), and auto-transformers (ATR). In order to identify the static behavior of the studied power network, load flow calculations have been performed and repeated more than thousands of times. The aim is to refine the modeling and increase the quality of the simulation, which was firstly checked by collecting data and validating them using the PowerFactory software (DIgSILENT) for the implementation and establishment of power system studies and calculating the reality-based loading in equipment (lines and transformers) from 2008 to 2023, from versions 2013 to 2022 of the mentioned software. For peak load scale, the under-study network from 2015 to 2022 has been in the range of 1500 to 2000 MW. The comparison histogram of the ATRs loading at the first bottleneck with 96 cuts of 3D data in 12 months from 2015 to 2022 is given in Figure 3. In 2017, an ATR with a capacity of 315 MVA was connected to the network at the bottleneck (2). Then, in 2020, the second ATR has operated in the same bottleneck. In 2022, assuming a 6% increase in the average load, the loading percentage of ATRs has reached 80%. In figure 3, the loading percentage of the ATRs, its changes in the monthly peak load operating points, and the snapshots recorded during the peak load hours of the studied network are mentioned (assuming this state as the base scenario / first scenario).

3. SYSTEM MODELING AND OPTIMAL LOCATING OF FACTS DEVICES

In the case of inter-regional exchange at the voltage level of 230 kV, with the maximum generation in ISO conditions and power injection to the 230 kV busbar at the PP (2) location, congestion and destructive overload are possible in the A17-A16 line, especially when the network is using single-bundle conductors (Canary) age of more than 50 years. The characteristic impedance value of the A17-A16 transmission line is 380 Ohms and 140 MW nominal power at the rated voltage. The permitted transmission power by conductor, which remains the system in safety margin, is 210 to 252 MW. The maximum transmission power with the thermal limits of the new conductor in the peak load of the day is 365 MW. The critical part of the line includes conductors, connections (connectors), jumpers, fittings, clamps, other old accessories, repair points, communication joints, and other interface equipment such as current transformers (CT), circuit breakers (CB), the existing line trap (LT) in the lines with limitations, reduce the amount of transmission capacity. Also, the mentioned line is prone to the congestion phenomenon at the bottleneck in peak hours. It should be noted that according to the technical catalog, the ampacity of the canary conductor at a temperature of 25 degrees Celsius (°C) is 970 A. In the summer season, at the peak load hours at a temperature of 40 (°C), the ampacity of the conductor has been announced as 812 A according to the ASTM. It should be mentioned that for the high land with a height of 1700 meters above mean sea level (AMSL) at a temperature of 40 (°C), the day ampacity of the new conductor is 917 A and the night ampacity is 1060 A can be calculated according to the standard IEEE std. 738 (2012). The aging coefficient and the age of the conductor should also be considered in these calculations. In this regard, the numbers and figures announced by the manufacturer are used for the technical calculations. The physical limitation of the conductor and mechanical strength reduction is due to excessive heat, which occurs for aluminum at a temperature of more than 93 (°C), the normal thermal limit of the conductor current, if there are technical documents of the line design, is determined based on the mentioned temperature level in the design (between 75 and 85 (°C)) otherwise, it is considered at 75 (°C). If the use of the default temperature of 75 (°C) causes any new restrictions, blackouts under normal conditions, it is necessary to carry out additional investigations to determine the appropriate temperature or corrective actions (such as; conductor replacement, online monitoring) to be included in the agenda of the line owner. In the safe and intelligent operation of line conductors' mode, a smart procedure should be adopted by using online equipment monitoring of the line and warning systems in dispatching centers, so that the operating temperature of the conductor in dynamic conditions do not excess 90 (°C). This issue requires the development of the structure and advanced software and hardware systems, online measurement, monitoring points, the development of a secure telecommunication, data transmission system, and an increase in network security indicators [26]. To manage the congestion phenomenon in the mentioned transmission line with thermal limitations and conductors, one of the procedures is to use FACTS devices, especially the PST, which is installed and operated in series with the line. This equipment can increase or decrease the series equivalent reactance in the overloaded link and consequently decrease or increase the transmission power in the congestion lines [27].

A. Grey wolf Optimization (GWO)

GWO is a brand-new optimization algorithm, presented in 2014. The GWO algorithm was developed to answer the optimization problems with the nonlinear behavior, which the outcomes demonstrated that the presented algorithm possesses an efficient performance and finds the solutions precisely due to its good local search criteria that performs exceptionally well for different problems and optimal solutions. Furthermore, population-based optimization methods are now a trend and has created many modern and developed techniques to solve many engineering issues. Compared with traditional optimization algorithms such as PSO and GA, GWO has the advantages of fewer parameters, simple principles, implementing easily and reduced operational time[28]. GWO is inspired by social hierarchy and the smart hunting system of grey wolves. Grey wolves usually live in a group of 6–11 singular. The head of a group (alpha) has the responsibility to make decisions. Other members of the group have to obey the settlements made by alpha. Handling the group is the main role of the alpha. The next role in the social hierarchy of grey wolves is beta which is to help alpha in making orders. Beta is a good alternative for alpha in specific circumstances. The beta enhances the alpha's commands and returns the feedbacks. Omega plays the weakest level of the group as the scapegoat. All the commands of other members must be obeyed by the omega who they are the last allowed to consume meal. Omega can prevent internal fight and other problems which can be find

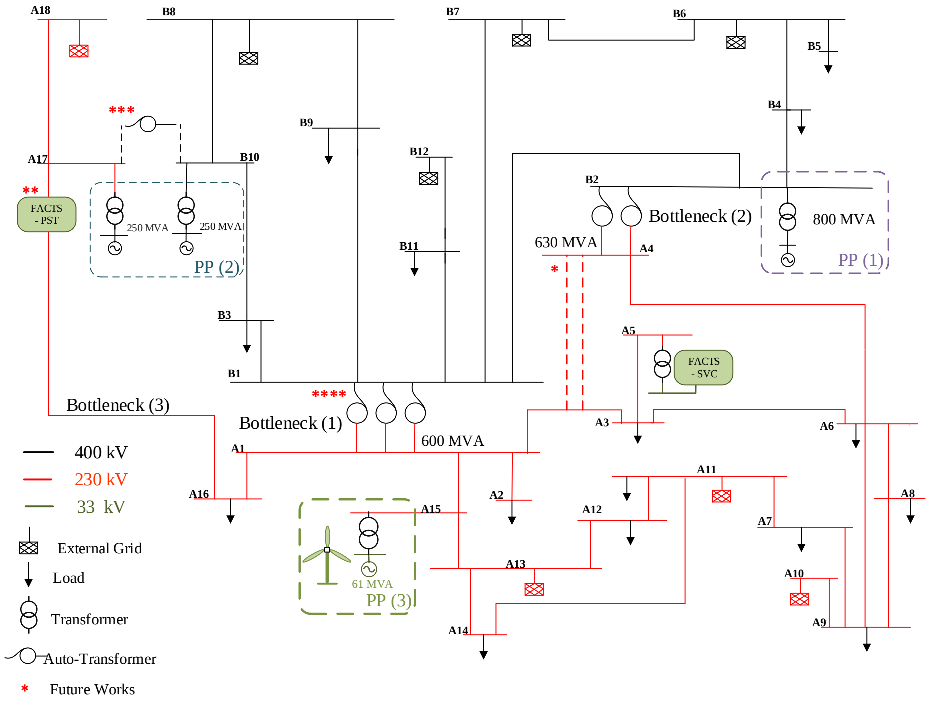

Fig. 2. Single-Line Diagram (SLD) of the under-study power grid

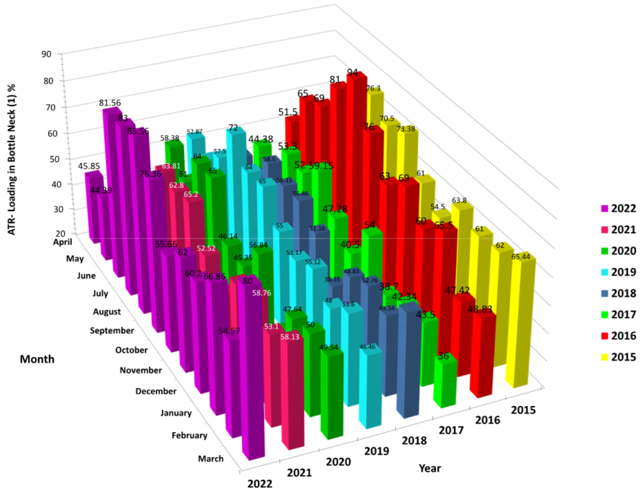

Fig. 3. 3D bar diagram with a comparative approach between the loading indexes of ATRs at the first bottleneck for the monthly peak load operating point from 2015 to 2022

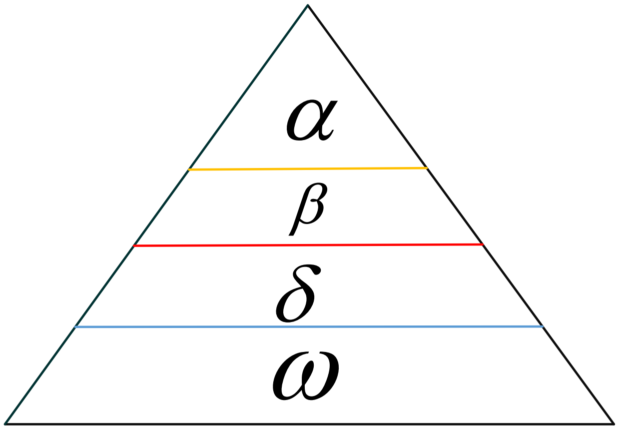

Fig. 4. 3D bar diagram with a comparative approach between the loading indexes of ATRs at the first bottleneck for the monthly peak load operating point from 2015 to 2022

in the group of grey wolves. Other than alpha, beta, and omega, are called subordinate (delta). They obey the alpha and beta wolves and prevail the omega wolves The hunting method of grey wolves, which includes models of the hierarchy, tracking, encircling, and attacking prey are mathematically described. In this model the best answer is assumed as α, the second and third levels of fitness are β and delta (δ), respectively. The rest of the candidate answers called omega (ω).

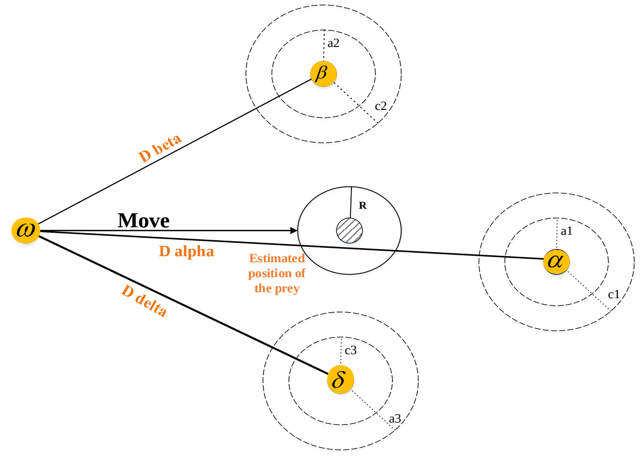

Fig. 5. Updating positions in GWO algorithm

B. Mathematical Model of the GWO Algorithm

As aforementioned, grey wolves in the hunting, encircle a prey. This behavior is described as:

$$\vec{D} = \left|\vec{C}.\vec{X}_p - \vec{X}(t)\right| \tag{9}$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A}.\vec{D} \tag{10}$$

Where t = iteration time, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{X}_p$ is the prey's position, $\vec{X}$ is the grey wolf's position and $\vec{D}$ is to determine a new position of the grey wolf. $\vec{A}$ and $\vec{C}$ are described as follow:

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \tag{11}$$

$$\vec{C} = 2.\vec{r}_2 \tag{12}$$

Where $\vec{a}$ is the vector set to decrease linearly over iteration; $\vec{r}_1$ and $\vec{r}_2$ are random vectors in [0,1]. Therefore, a grey wolf can be in each random place near the pray which was described in equation (5). Figure 5 demonstrates the update process of alpha, beta and delta in a 2D search space. As depicted in this figure, the best place (answer) is middle of a circle that is in the decision space based on the position of α, β and δ. To put it another way, α, β and δ calculate the position of prey and update their latest position near the prey. The mentioned process is depicted as a flowchart in fig.6.

C. Optimal Implementing of FACT Devices

By adding the PST in the 230 kV section and developing the communication, interconnection section between the bus bares A_{17}, B_{10} via ATR feeder and also, forming a power cascade between the two 400 kV and 230 kV sections in the PP (2) through installing an ATR with a suitable capacity (315 MVA), it is possible to control the exchange power flow between areas in the high-load transmission line and manage the congestion. The existence of congestion lines from energy and power loss point of view has unusual conditions and greatly affect the energy loss index. In this paper, the total loss of the power grid is attained via the load distribution, before and after locating FACTs in the studied system and it is used as one of the factors for the target function as follow:

$$Active\ Losses = \left(\frac{|v|^2}{R_{Z_i}}\right)_{after} - \left(\frac{|v|^2}{R_{Z_i}}\right)_{before} \tag{13}$$

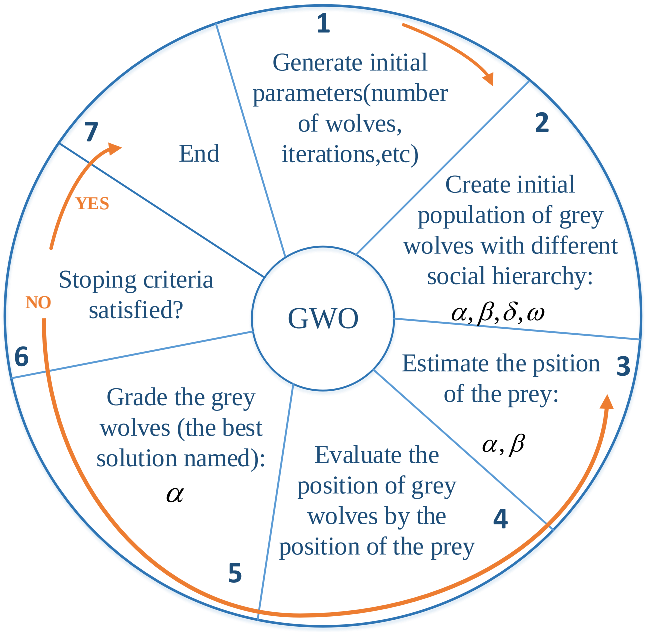

Fig. 6. Flowchart of the proposed GWO algorithm

$$Reactive\ Losses = \left(\frac{|v|^2}{X_{Z_i}}\right)_{after} - \left(\frac{|v|^2}{X_{Z_i}}\right)_{before} \tag{14}$$

R_{Zi} and X_{Zi} are resistance and reactance of the power system parameters respectively. To find the best location(busbar) for the implementation of FACT devices in this article, the objective function is minimized using GWO algorithm as follow:

$$OF = Min\{ATR\ Loading(\%) + L_{TL} + L_a + C\} \tag{15}$$

Where OF, L_{TL}, L_a,C stand for objective function, transmission line overloading, active losses and congestion respectively. The optimum size and location for the implementation of FACTs such as PST, SVC in this bottleneck and CM study is obtained and described below: Studies such as load flow calculation, short-circuit analysis, dynamic stability, transient states caused by switching and protection coordination are also needed[29]. For example, if the lines in the under-study network are not transposed, then unbalanced load distribution studies should also be performed. Other studies may focus on the effect of harmonic load flow or the occurrence of sub synchronous oscillations. In the protection of lines equipped with PST, the settings of impedance relays such as distance relays in faulty zone (reach) detection have special considerations and special complexity. In order to solve the overloads problem for lines with limited operation in ring and transmission networks. In this study, a PST with the voltage of 245/245 kV, an electrical angle of ±20 degrees, capacity of 500 MVA and an impedance of 13% in cascade form with the A_{17}-A_{16} transmission line is considered. It should be mentioned that the 400 kV transmission lines have a higher carrying capacity and a greater resiliency due to the use of a conductor with two or more bundles and a larger current ampacity. For example, in EHV lines (400 kV) with Flat (horizontal) geometric arrangement, using a twin bundle arrangement with Curlew conductor, an ampacity of (2×1060) A, has a characteristic impedance of 300 ohms, the natural power of the line is in the range of 530 MW, and the rated power of the

Table 2. Description of the scenarios on the loading of ATRs of the 1st bottleneck point

Scenario	Scenario description
Base (1)	Effect of PP (1) with the development of it 230 kV stage
2	Effect of PP (1) and installation of SVC (at the A_5 busbar)
3	Considering the developments in 230 kV of PP (1), PP (2) in bottleneck (2)
4	Effect of PP (1), (2) considering SVC
5	Effect of PP (1), (2) considering SVC with inlet and outlet A_1-A_3 230 kV line at the A_4 busbar
6	Considering scenario 5 with the presence of series PST with A_17-A_16 line and making an interconnection between 230 kV and 400 kV feeders of PP (2)

line is assumed to be in the range of 800 MW to 950 MW. The thermal limit capacity with a new conductor at a temperature of 20 (°C) is considered to be around 1500 MW. In determining the current of the line, the instability of the power system must be considered.

4. SIMULATION RESULTS

In order to make a logical and reality-based comparison between different options and implemented and proposed scenarios and alternatives, the network topology with the load conditions of 2022 has been considered as a study reference. Table 2 describes 6 different CM's scenarios on ATRs loading in bottleneck 1.

A. The second scenario: Effect of PP (1) and SVC

In this scenario, the effect of the produced reactive power in a specific station equipped with an SVC with a voltage of 33 kV and a fixed capacitor bank of 150 MVAr in the role of a 2nd, 3rd, and 4th order harmonic current filter during shutdown and low load times of the electric arc furnace (EAF) at the ATRs of bottleneck 1 is given in figure 7.

B. The third scenario: Effect of PP (1) & (2) without SVC

In the third scenario, by considering expansion stages in the second scenario, the effect of the 230 kV part of the PP (2) with the generation capacity of 180 MW, 50 MVAr and the communication arrangement of inlet/outlet single-circuit line (A_{18}- A_{16}) in the busbar A_{17} without the presence of SVC at the ATRs in bottleneck 1 is given in figure8.

C. The fourth scenario: Effect of PP (1) & (2) with SVC

The effect of the 230 kV part of the PP (2) with generation capacity (180 MW, 50 MVAr), including the SVC in the specific station, on the loading of ATRs in the bottleneck 1 is given in figure 9.

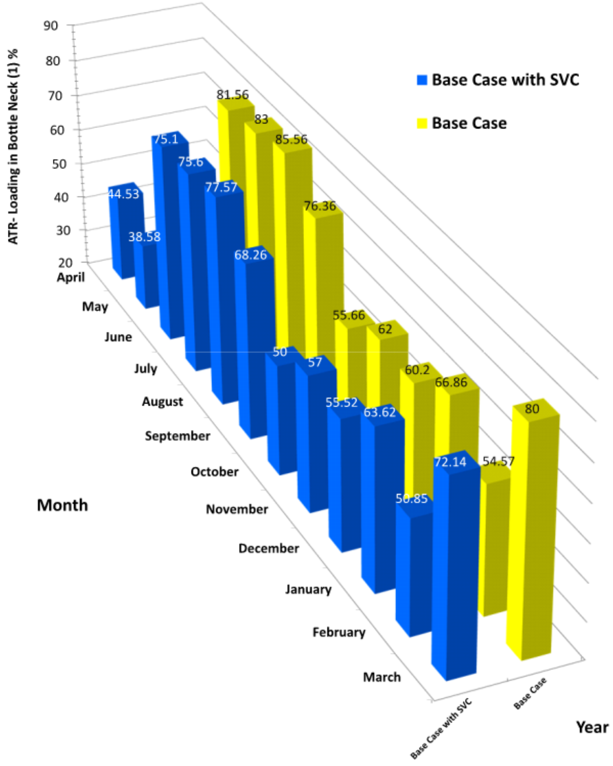

Fig. 7. ATR loading index at the first bottleneck point, including the effect of the SVC at A_5 busbar and comparing it with the base case

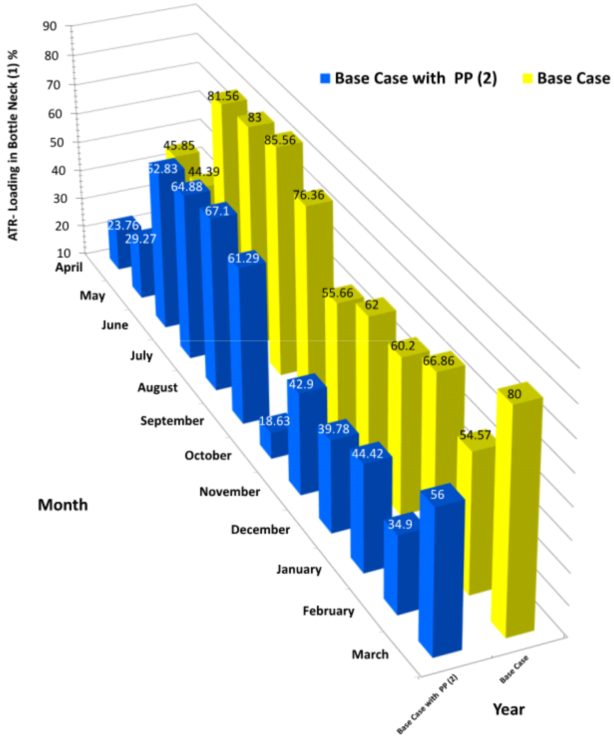

Fig. 8. ATR loading index at the first bottleneck point, considering the effect of the 230 kV section of the PP (2) at busbar A_{17}

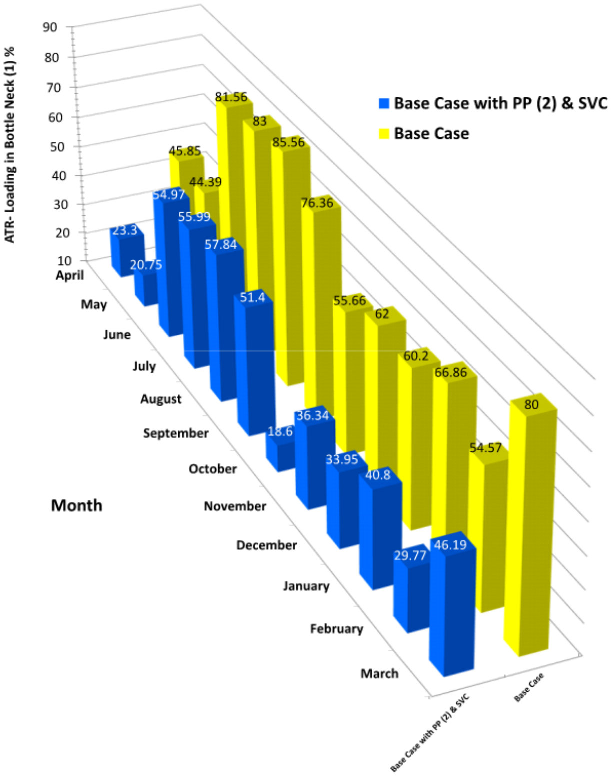

Fig. 9. Diagram of ATR loading index at the 1st bottleneck point, including simultaneous effects of the 230 kV part of the PP (2) at busbar A_{17} and the SVC at the busbar A_5

D. The fifth scenario: Effect of PP (1) & (2) with SVC and A_1-A_3 line

In the fifth scenario, the simultaneous effects of the SVC at busbar A5 and the 230 kV section of the PP (2) at busbar A_{17}, and the inlet/outlet 230 kV (A_1-A_3) line at the busbar A_4 in the bottleneck 2, on the loading of the ATRs in the bottleneck 1 is given in figure 10. The carried-out study indicates the need to develop one and half Breaker in the 230 kV section at the busbar A_4 in the second bottleneck point. Finally, in Figure 11, the comparison between the base scenario and other scenarios is shown in aggregate form.

E. The sixth scenario: Considering scenario 5 with series PST and A_{17}-A_{16} line

Assuming the sixth scenario is focusing on congestion control and management in the A17-A16 transmission line (the third bottleneck point), it is possible to install a series PST with the transmission line and develop the interconnection feeder in the PP (2) by installation of a 400/230 kV ATR with suitable capacity at the PP site, by reducing and increasing the leakage reactance (impedance %), the equipment of the PST can control the power flow in the 230 kV section and managed the congestion phenomenon in the transmission line until the conductor of the mentioned line experiences overload. Otherwise, without the PST and the development of the 400/230 kV section in the PP (2), emergency shutdowns of the line A17-A16 would be necessary to manage congestion in the bottleneck (3). Figure 12 shows the comparison between the fifth the sixth scenario (including a PST in series with the transmission line) and its role in the loading index of the installed ATR in the first bottleneck. It should be

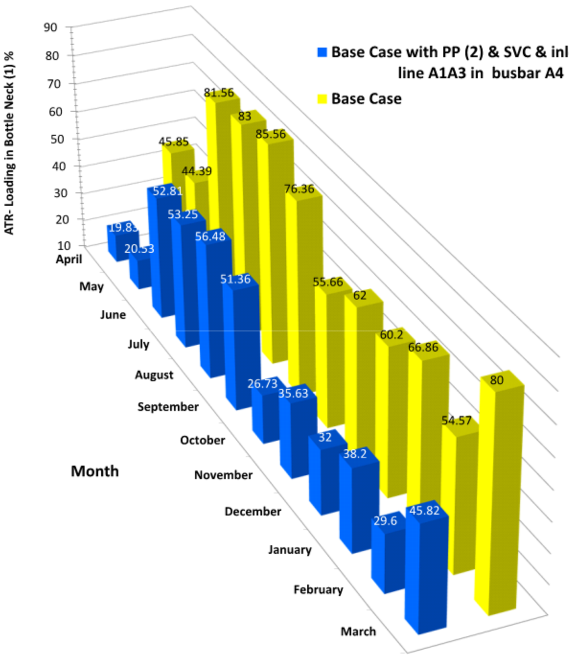

Fig. 10. ATR loading index at the first bottleneck point, considering the simultaneous effects of the 230 kV part of the PP (2), the SVC and the inlet / outlet the A_1-A_3 line in the busbar A_4

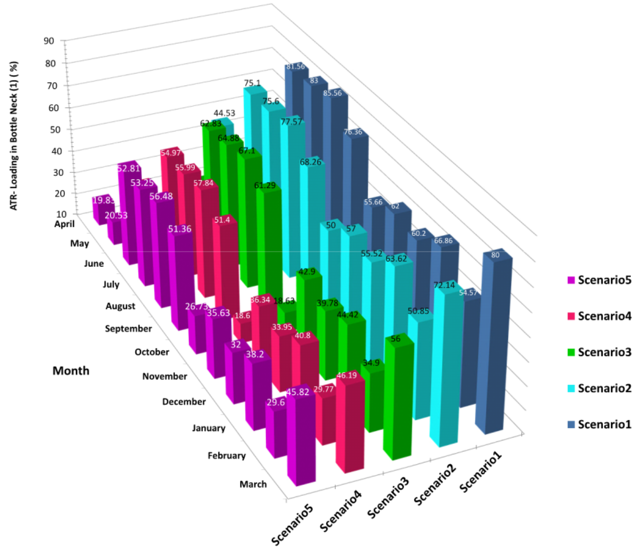

Fig. 11. ATR loading index at the 1st bottleneck point and comparison of the base state (scenario 1) with scenarios 2, 3, 4 and 5

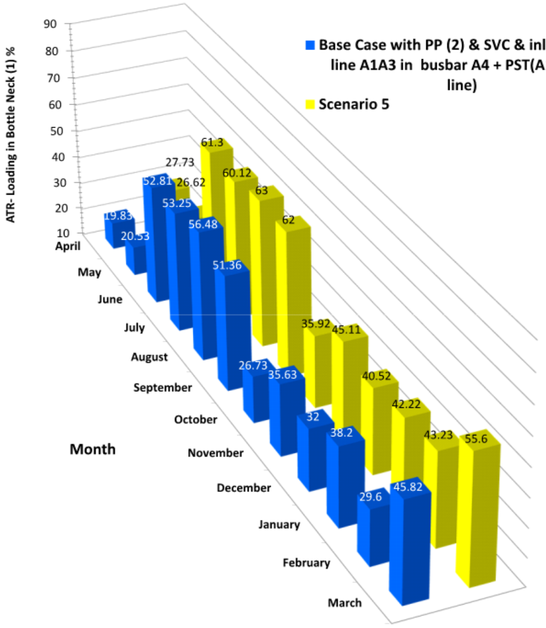

Fig. 12. ATR loading index at the 1st bottleneck point and comparison of scenario 5 and 6 with the effective presence of PST

mentioned that, in the bottleneck engineering with changes in the circuit topology network architecture and changes in configuration, communication arrangement, network development and increasing the capacity at the bottleneck points, the issue of increasing the level of short circuit in the busbars should be taken into consideration by reviewing limitations[20][30]. Necessary feasibility studies should be carried out in the phase study. With the increase of fault levels (FL) and fault currents, must be the resilience issues, breakers withstand capability, and other equipment ability such as CB, CT, and busbars strength should be checked from the point of view of fault electrodynamic forces until they are not exceeding their withstand limits. Also, the earthing system of bottleneck stations and the effect of asymmetric fault currents carrying (zero component) and its destructive effects on the mesh conductors of the ground system, touch and step voltages and rate of increase of ground potential rise (GPR) should be reviewed from a safety point of view[31]. In the studies of short-circuiting and power level measurement of three-phase short-circuiting to each other and single-phase to ground in 230 kV busbar A_1, 5 scenarios have been considered as described in table 3. Figure 13 shows the levels of three-phase and single-phase short circuit to the ground for five scenarios. This figure shows that in different scenarios with the change of the capacity and the change of the network configuration, the level of single-phase short circuit to the ground and 3-phase has changed and physical limitations should be taken into account from the point of view of bottleneck engineering. In order to reduce the cost of projects, scenarios and their role in increasing the level of short circuit should be considered so that the investment cost does not increase. In short circuit analysis, the basis is to measure the resilience of the existing equipment against the short circuit level (FL) increase. In this regard, redesigning and rearranging the network architecture with the approach of limiting the level of short circuit is helpful. Also, by planning, budgeting and optimization projects, the low-capacity existing

Table 3. Description of the considered scenarios regarding the penetration level of short circuit in the 230 kV busbar of the 1st bottleneck point

Scenario	Scenario description
1	Without considering the developments in 230 kV of PP (1) in bottleneck (2)
2	Considering the developments in 230 kV of PP (1) in bottleneck (2)
3	Considering the developments in 230 kV of PP (1), PP (2) in bottleneck (2)
4	Considering scenario 3 with inlet/outlet 230 kV A_1-A_3 transmission line at the busbar A_4
5	Effect of PP (1), (2) considering SVC with inlet and outlet A_1-A_3 230 kV line at the A_4 busbar
6	Considering scenario 4 with a capacity increase in bottleneck (1) from 600 MVA to 945 MVA

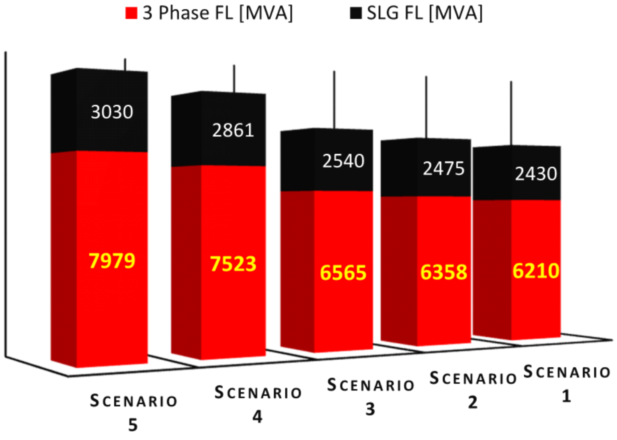

Fig. 13. Comparison diagram between three-phase and single-phase short circuit levels in five scenarios

equipment should be replaced with the high breaking capacity equipment.

5. CONCLUSION

The development of the network and the implementation of all projects have huge financial costs, which require the analysis of financial engineering and compliance with the approaches of engineering economics. Unfinished and incomplete development outside the demand period leads to blackout development, commercial losses, and irreparable social and political effects. Therefore, in bottleneck engineering, other financial, social, political, and economic dimensions and cost benefit analysis should also be considered. In this article, the CM of a power network with real data at peak load points for a period of 10 years on a monthly basis, which was recorded and collected by the SCADA system in the PowerFactory software version 2022 (DIgSILENT) has been simulated in different scenarios. The main finding can be summarized as below:

- The impact of the optimal presence of FACTS devices such as PST and SVC in CM
- The effect of small and large-scale PP units with several scenarios in ATRs loading
- The effectiveness of the non-technical methods such as generation rescheduling and redispatching to remove congestion and manage it in bottleneck points

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