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ORIGINAL PAPER

Multi-objective-based reactive power planning and voltage stability enhancement using FACTS and capacitor banks

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Abstract

Reactive power planning (RPP) and voltage stability improvement (VSI) consider two of the most important problems to meet a major challenge of the power system. In this work, a multi-objective genetic algorithm (MOGA) for RPP with objectives of cost minimization of the power losses, new reactive power (VAR) sources, maximization of the VSI, and enhancement of total transfer capacity (TTC) is introduced. Different optimization variables are considered including generator voltages, transformer tap changers besides load, and different operational constraints. The best compromise solution is determined through a fuzzy min–max approach. Comparison studies among capacitor banks, flexible ac transmission systems (FACTS) or both as new VAR support sources to achieve better performance are explored. Moreover, the optimal allocations of switchable VAR sources are not determined in advance; instead, they are treated as control variables to improve the techno-economic operation of the network. Added to that many voltage stability indicators are presented, and their results are compared. The effectiveness of the proposed algorithm is examined on a modified IEEE 30-bus test system and South Egypt Electricity network where felicitous results have been acquired. The results expound on the effectiveness of the proposed approach compared with other optimization methods.

Keywords Reactive power planning · FACTS devices · Capacitor banks · MOGA optimization · Voltage stability

Abbreviations

Sets of indices

N_b	Total number of buses
N_cap	Number of a possible installed capacitor bank
N_d	Number of load level duration
N_g	Number of generators
N_L	Number of transmission lines
N_SVC	Number of a possible installed SVC devices
N_T	Number of installed transformers
N_TCSC	Number of a possible installed TCSC devices

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Constants and parameters

B_{ij}	Transmission line susceptance between bus i and bus j (p.u)
C_c	Per-unit cost of the capacitor bank ($/MVAR)
C_F	The fixed installation cost of capacitor bank in ($)
G_{ij}	Transmission line conductance between bus i and bus j (p.u)
h_l	Per-unit energy cost ($/MWh)
ir	The interest rate for VAR devices (%)
LT	The lifetime of VAR devices (years)
R_{ij}	Transmission line resistance between bus i and bus j (p.u)
X_{ij}	Transmission line reactance between bus i and bus j (p.u

Variables

$\mathrm{AIC}_\mathrm{VAR}$	Annual installing cost of new installed VAR sources ($)

$B_{c,I}$	Susceptance of newly installed capacitor bank at bus i (p.u)
$B_{\text{svc},l}$	Susceptance of newly installed SVC device at bus i (p.u)
$C_{\text{Cap},l}$	Cost of the newly installed capacitor bank ($)
$C_{\text{svc},I}$	Cost of installed SVC devices at bus i ($/MVAR)
$C_{\text{TCSC},L}$	Cost of installed TCSC devices at line l ($/MVAR)
$C_{\text{TCSC},L} d_l$	Duration of load level, L (Hour)
IC_{VAR}	Installing cost of added VAR sources ($)
P_{D}	Current operating value of active power delivered to the demand (MW)
$P_{D\max}$	Maximum possible active power consumed by the load (MW)
$P_{gi}\,Q_{gi}$	Active and reactive power generated at bus i (MW/MVAR)
$P_{li},\ Q_{li}$	Active and reactive load power at bus j (MW/MVAR)
$P_{\text{loss},L}$	Network active power loss during the period l (MW)
Q^{o}_{ci}	Inductive or capacitive power of exiting VAR source installed at bus i (MVAR)
$Q_{c,l}$	Operating range of newly installed capacitor bank at bus i (MVAR)
$S_{\text{svc},I}$	Power injections at bus i by newly installed SVC device (MVAR)
$S_{\text{TCSC},L}$	Power injections at line l by new installed TCSC device (MVAR)
$V_i,\ V_{ij}$	Voltage magnitude of bus i and j, respectively (p.u)
Wc	The cost of active power losses of the power system ($)
$X_{\text{TCSC},L}$	The reactance of new installed TCSC device at line l (p.u)
δ_{ij}	The phase angle between bus i and j (rad.)
θ_{ji}	The phase angle of the term F_{ji} (rad

1 Introduction

With the great difficulties faced by modern power system operation, it is important to meet constantly increasing load demand and contingencies while maintaining reliable power delivery to the customers and keeping bus voltage boundaries. Due to incremental load demand, the power system is being operated under extremely stressful conditions, and this makes the system works near its stability limit. Therefore, a relatively small disturbance can change its state and becomes unstable [1]. Thus, it is imperative to improve power system stability to prevent load shedding, system collapse, and improve its security and reliability.

Many control actions can be taken in order to relieve system stresses [2]. These include changing the voltage setpoints of voltage-controlled buses via controlling the generator's excitation or updating the setting of taps changing transformers and installing VAR sources with varying sizes and locations such as shunt capacitors, static VAR compensators, and FACTS devices. However, inadequate reactive power support may lead to voltage collapses and further to major power outages. So, it is essential to optimally allocate the new reactive power sources [3]. The techniques used for allocating the new reactive power sources can be generally divided into two methods. These are the index and optimization-based methods. The former depends on the priority list and sensitivity indexes to reduce solutions space, while in the latter, the conventional or heuristic optimization methods are used [4].

The target of RPP is the coordination of the existing VAR sources and optimally allocates the new sources taking into account the achievement of specific objective functions. These functions may include minimization of the costs of real power losses and additional reactive power supplies investment, enhancement of voltage stability, and improvement of voltage profile [4]. The new VAR sources could be used for enhancing system controllability resulting in the TTC enhancement [5]. Improving current electricity power production systems is far more reasonable than constructing new power plants, electrical power transmission, and distribution lines, which may take several years in addition to the high cost of installation and the difficulties of pollution control. Also, it may be claimed that the system congestion will be decreased, resulting in increased power system security. The transmission system will be more lucrative if current transmission assets are used to their full potential. The RPP problem is complicated due to overlapping objective functions, constraints, and control variables. In addition, there are a large number of uncertain parameters which are partially discrete and continuous.

Different conventional methods have been applied to solve the RPP problem. Among these methods are successive linear programming [6], mixed integer nonlinear programming [7], and branch and bound method [8]. However, due to the complex nature of the RPP problem, these methods are not feasible to find the global optimum solution. A variety of intelligence methods have been vastly applied to solve the RPP problem because of their robustness, effectiveness, and suitability to find out optimal solutions. Some researchers have been used these methods with the shunt capacitors as a reactive power source such as simulated annealing (SA) [9], genetic algorithm (GA) [10], evolutionary programming (EP) [11], particle swarm optimization (PSO) [12] and [13], differential evolution (DE) [14] and [15], ant colony optimization algorithm [16], the gravitational search algorithm (GSA) [17], modified DE [18], random drift PSO [19],

Table 1 Categorizes the reviewed literature and provides the novelties of the proposed model in comparison with other researches

Ref	Year	Optimization algorithm	Objective(s)	VAR sources		Stability index	Proposed multi-objective	Determine location	VAR cost	Transformer ratio
				Capacitor's bank	FACTS					
[6]	1988	Linear programming	Min. (Losses and VAR cost)	✓	×	–	–	Pre-defined	✓	✓
[9]	1993	SA	Min. (Losses and VAR cost)	✓	×	–	–	Pre-defined	✓	×
[11]	2004	EP	Min. (Losses and VAR cost and volt. deviation)	✓	×	–	–	Pre-defined	✓	✓
[13]	2008	Fuzzy adaptive PSO	Min. Losses / Min. volt. / Max stability	✓	×	L-index	–	Pre-defined	×	✓
[8]	2009	Branch-and-bound, mixed integer program	Min. VAR cost with a VSM constrained	✓	×	VSM	–	backward/forward Alg	✓	×
[10]	2010	GA	Min. (Losses and VAR cost and volt. deviation)	✓	×	–	–	Pre-defined	✓	✓
[16]	2011	Ant colony optimization	Min. Losses	✓	×	–	–	Pre-defined	×	×
[15]	2011	DE	Min. Losses / Min. volt. / Max stability	✓	×	L-index	–	Pre-defined	×	✓
[28]	2012	Modified non-dominated sorting GA	Min. (Losses and VAR cost) and Max stability	✓	×	L-index	Pareto optimal set	Pre-defined	✓	✓
[21]	2013	DE	Min. (Losses & volt. Deviation) & Max stability	×	✓	Static voltage stability index	Weighted method	Global best positions	×	✓
[17]	2014	Opposition-based GSA	Min. Losses / Min. volt. deviation / Max. stability	✓	×	L-index	–	Pre-defined	×	✓
[29]	2014	DE	Min. (Losses & VAR cost) & Max stability	✓	×	L-index	Pareto optimal set	Pre-defined	✓	✓
[22]	2015	New Improved DE	Min. (Losses and VAR cost)	✓	✓	–	–	New voltage stability index	✓	✓
[23]	2015	GSA	Min. (Losses and VAR cost)	×	✓	–	–	Pre-defined	✓	✓

Table 1 (continued)

Ref	Year	Optimization algorithm	Objective(s)	VAR sources		Stability index	Proposed multi-objective	Determine location	VAR cost	Transformer ratio
				Capacitor's bank	FACTS					
[12]	2016	Simple PSO	Min. (Losses and VAR cost)	✓	×	–	–	Weakest	✓	✓
[14]	2016	DE	Min. (Losses and VAR cost)	✓	×	–	–	Refined heuristic process	✓	✓
[24]	2016	Evolutionary PSO	Min. (Losses and VAR cost)	×	✓	–	–	Weakest	✓	✓
[25]	2018	Whale optimization algorithm	Min. (Losses and VAR cost)	×	✓	–	–	VCPI for SVC power flow analysis for TCSC	✓	✓
[18]	2019	DE	Min. (Losses and VAR cost & volt. deviation)	✓	×	–	–	Weak voltage bus	✓	✓
[30]	2019	Artificial physics optimization and PSO	Min. (Losses and VAR cost and volt. deviation) and Max stability	✓	×	L-index	Weighted method	Pre-defined	×	✓
[7]	2020	Successive linear programming and GA	Min. (Losses and VAR cost)	×	✓	–	–	Pre-defined	✓	✓
[20]	2020	Modified crow search algorithm	Min. (operating cost and VAR cost)	✓	×	L-index	–	Loss sensitivity analysis, power flow analysis, modal analysis	✓	✓
[19]	2020	Random drift PSO	Min. Losses	✓	×	–	–	Weakest	×	×
[26]	2021	Fractional-order Darwinian PSO	Min. (Losses and VAR cost)	×	✓	–	–	VCPI for SVC Power flow analysis for TCSC	✓	✓
[27]	2021	Quasi-oppositional and salp swarm algorithm	Min. (Losses and VAR cost)	✓	✓	–	–	Line stability index	✓	✓
This Work	2021	MOGA	Min. (Losses and VAR cost) and Max stability & Max TTC	✓	✓	VSM and multi-indices	Pareto optimal set and fuzzy decision maker	Optimal location by MOGA	✓	✓

and modified crow search algorithm in [20], while the RPP problem was solved with FACTS using DE algorithm [21], improved DE [22], GSA [23], GSA with PSO [24], whale optimization algorithm [25], fractional-order Darwinian PSO [26], and quasi-oppositional with salp swarm algorithm in [27]. A multi-objective problem is introduced in [28] and [29]. PSO is present in [30] to solve single- and multi-objective. The above literature considered the locations of new VAR sources that were directly simply estimated or assumed by locating the new VAR sources at the weakest bus. Table 1 categorizes the reviewed literature and provides the novelties of the proposed work in comparison with other research studies.

In this work, a MOGA is utilized to solve the RPP problem, where the minimization of the costs of losses and newly installed VAR sources is the first objective and the second objective is the maximization of the voltage stability. Also, the VAR sources are used to enhance TTC. By improving the voltage stability, the distance from the current operating state to the voltage collapse point is increased leading to secure operation. Therefore, the voltage stability margin (VSM) is used in this study as an indicator to check the system voltage stability. The results of the VSM are compared with those of the L-index, fast voltage stability index (FVSI), line stability index (LSI), new line stability index (NLSI), and new voltage stability index (NVSI) indicators. Different VAR sources are applied to compensate of the lack of reactive power. In addition, in this paper, the new optimal VAR sources allocations are considered as control variables and are resolved via GA. A modified IEEE 30-bus system and South Egypt Electricity network are used to examine the accuracy of the proposed approach.

The main contributions of the present work are:

1. A new application of MOGA to solve the RPP problem for minimization of the costs of power losses and the new installing VAR sources, maximization of the VSM, and increasing TTC.
2. A VSM indicator is proposed and its results are compared with those of the L-index, FVSI, LSI, NLSI, and NVSI indicators.
3. Multi-type of VAR sources with a detailed model of each type are presented.
4. The optimal allocations of new VAR sources are considered as control variables instead of locating them at the weakest buses or lines.

The remnant of the paper is organized as follows: The modeling of the new VAR sources is described in Sect. 2. Section 3 describes the multi-objective RRP problem formulation. The multi-objective RPP solution algorithm proposed for solving the RPP is presented in Sects. 4 and 5. Section 6 provides test results and discussion. Section 6 conclusions are presented.

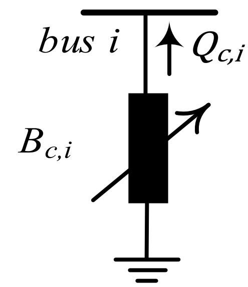

Fig. 1 Capacitor bank model

2 Modeling of new VAR sources

In this section, the models of different VAR sources used in this work are presented. For static applications, the VAR sources can be modeled by two methods: (i) impedance insertion model (IIM), and (ii) power injection model (PIM) [31].

2.1 Modeling of capacitor banks

Shunt capacitors are employed as VAR sources in the power system. In addition to the availability of fixed capacitor banks, there are also variable capacitor banks which are achieved using switched capacitors [32]. According to the mechanism of varying the values of variable capacitor banks, the achieved MVAR from them is in steps, and therefore, the VAR source size is represented as a discrete not continuously variable. Figure 1. shows the modeling of capacitor bank, while the injected power at bus i is:

$$Q_{c.i} = B_{c,i} V_i^2 \tag{1}$$

2.2 Modeling of FACTS devises

FACTS devices are used for controlling the power flow, voltage enhancement, decreasing the losses and enhancing transmission lines loadability [33]. There are many types of FACTS that can be installed in the power system. Static var compensator (SVC) and thyristor-controlled series compensators (TCSC) are two of the suitable approaches to be chosen according to our purpose, voltage stability, and reactive power support enhancement. In addition, they have low investment costs, fast control responses, and increment in system loadability [31, 34].

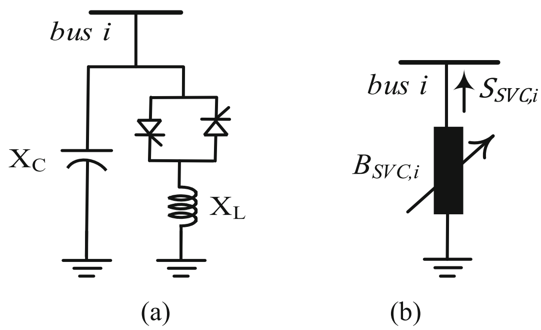

Fig. 2 Static var compensator, **a** basic structure, **b** power injection model

2.2.1 Modeling of SVC

The SVC is modeled as a shunt variable susceptance that injects reactive power added at variable bus locations [32]. Figure 2a shows the basic structure of the SVC, while the model of the SVC is shown in Fig. 2b and the injected power at bus i is:

$$S_{svc,i} = B_{svc,i} V_i^2 \tag{2}$$

2.2.2 Modeling of TCSC

The TCSC is a capacitive reactance compensator consisting of a series thyristor-controlled reactor shunted by a capacitor bank [35]. Figure 3a shows a schematic impersonation of a TCSC connected in a transmission line between bus i and j of the power system, while Fig. 3b shows the modeling of TCSC. The TCSC as a power injection model is shown in Fig. 3c.

According to Fig. 3c, four injected powers can be represented as [1]:

$$P_{TCSC,i} = |V_i|^2 \Delta G_{ij} - |V_i||V_j| \times [\Delta G_{ij}\cos(\delta_{ij}) + \Delta B_{ij}\sin(\delta_{ij})] \tag{3}$$

$$Q_{TCSC,i} = -|V_i|^2 \Delta B_{ij} - |V_i||V_j| \times [\Delta G_{ij}\sin(\delta_{ij}) - \Delta B_{ij}\cos(\delta_{ij})] \tag{4}$$

$$P_{TCSC,j} = |V_j|^2 \Delta G_{ij} - |V_i||V_j| \times [\Delta G_{ij}\cos(\delta_{ij}) - \Delta B_{ij}\sin(\delta_{ij})] \tag{5}$$

$$Q_{TCSC,j} = -|V_i|^2 \Delta B_{ij} + |V_i||V_j| \times [\Delta G_{ij}\sin(\delta_{ij}) + \Delta B_{ij}\cos(\delta_{ij})] \tag{6}$$

where $P_{TCSC,i}$, $Q_{TCSC,i}$, $P_{TCSC,j}$, and $Q_{TCSC,j}$ are power injections (positive or negative) due to installing the TCSC in a branch (i–j). Also, ΔG_{ij} and ΔB_{ij} depend on TCSC reactance and are given as [1]:

$$\Delta G_{ij} = \frac{-X_{TCSC} R_{ij}(X_{TCSC} - 2X_{ij})}{\left(R_{ij}^2 + X_{ij}^2\right)\left[R_{ij}^2 + (X_{ij} - X_{TCSC})^2\right]} \tag{7}$$

$$\Delta B_{ij} = \frac{X_{TCSC}\left(R_{ij}^2 - X_{ij}^2 + X_{TCSC} X_{ij}\right)}{\left(R_{ij}^2 + X_{ij}^2\right)\left[R_{ij}^2 + (X_{ij} - X_{TCSC})^2\right]} \tag{8}$$

3 Problem formulation

The RPP problem is a mathematical formulation, which can be simply considered as they endeavor to have an optimal solution for objective function through a set of controllable variables. MOGA is used in this study with different conflicting goals. These include the minimization of new VAR sources or losses costs, VSI, and TTC enhancement. The ultimate goal of a MOGA is to identify solutions in the Pareto optimal set [36].

3.1 Objective function

There are different objective functions that are handled in the RPP problem. These are:

3.1.1 Active power losses cost

The first objective is the minimization of active power losses cost (Wc) of the power system and is calculated as [28]:

$$Wc = \sum_{i \in N_d} h_l d_l P_{loss,i} \tag{9}$$

$$P_{loss,i} = \sum_{j \in N_L} G_{ij}\left[V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_{ij})\right] \tag{10}$$

3.1.2 VAR cost

The second goal in the RPP problem is the minimization of the new VAR sources investment costs (IC_{VAR}) and is formulated as:

$$IC_{VAR} = \sum_{i \in N_{SVC}} C_{svc,i} \times S_{SVC,i} + \sum_{l \in N_{TCSC}} C_{TCSC,l} \times S_{TCSC,l} + \sum_{i \in N_{cap}} C_{Cap,i} \tag{11}$$

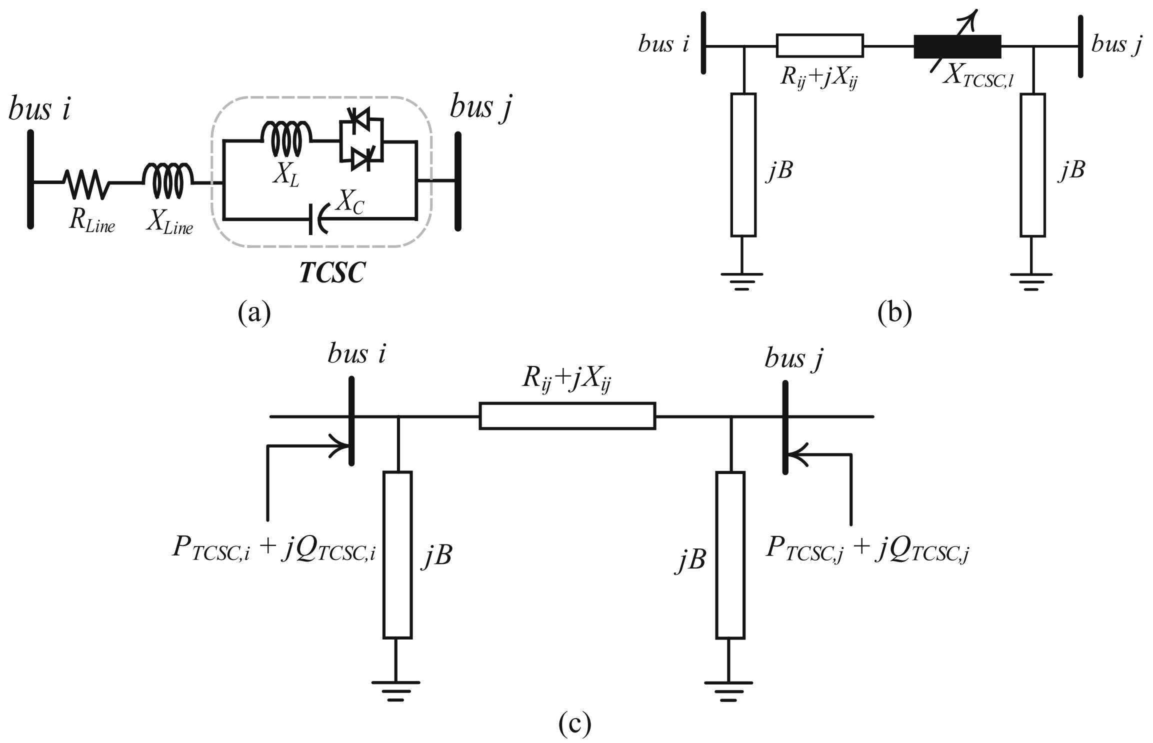

Fig. 3 Thyristor series compensator TCSC **a** basic structure, **b** steady-state model and **c** power injection model

Equation (9) consisting of three parts represents the costs of the SVC, TCSC, and capacitor banks [31], respectively, where

$$C_{svc} = 0.0003S_{SVC}^2 - 0.3051S_{SVC} + 127.38 \tag{12}$$

$$C_{TCSC} = 0.0015S_{TCSC}^2 - 0.7131S_{TCSC} + 153.57 \tag{13}$$

$$C_{Cap} = C_F + C_c Q_c \tag{14}$$

where $C_F = 1000\$$ and $C_c = 3 \times 10^4\$/\text{MVAR}$ [28].

The annual installing cost of VAR sources is given by [31]

$$AIC_{VAR} = IC_{VAR}\frac{ir(1+ir)^{LT}}{(1+ir)^{LT}-1} \tag{15}$$

3.1.3 Enhancement of power system voltage stability

Voltage stability is related to the "ability of a power system to maintain acceptable voltages at all buses under normal conditions and after being subjected to a disturbance" [3]. The P–V curves are used to determine the loading margin of a power system and can be built at a base case by increment the power system load gradually until reaching the voltage collapse point, the nose of the PV curve, as shown in Fig. 4. The per-unit loading distance between the base case and voltage collapse loading is called the VSM, which can be calculated as [37]:

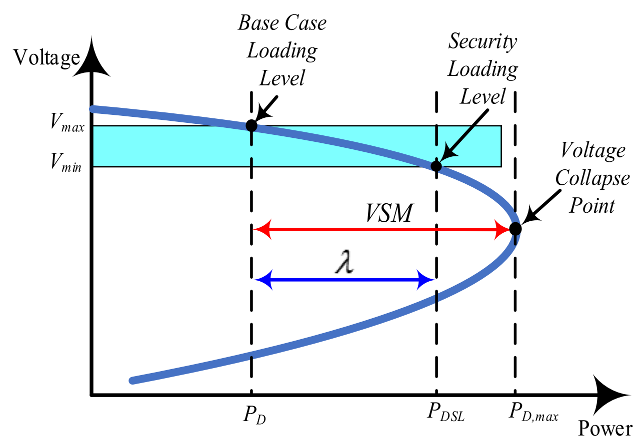

Fig. 4 Reaction between loading and bus voltage

$$VSM = P_{D,max} - P_D \tag{16}$$

A greater VSM implies a more secure power system and therefore guarantees that not any relatively small disturbance leads to instability of the system and the system is operating far from the voltage instability margin.

Moreover, the L-index is determined to be another approximate measure of the voltage stability. Its value is ranging from zero to one and is based on load flow analysis. The bus with the highest L-index value is the weakest bus in the system. It is calculated according to equations [28]:

$$\begin{vmatrix} I_G \\ I_L \end{vmatrix} = \begin{vmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{vmatrix} \begin{vmatrix} V_G \\ V_L \end{vmatrix} \tag{17}$$

where I_G,V_G: The currents and voltage at generator buses, respectively,

I_L,V_L: The currents and voltage at load buses, and Y_{GG}, Y_{GL}, Y_{LG}, Y_{LL}: The elements of Y_{bus} admittance matrix.

Rearranging Eq. (17), we get

$$\begin{vmatrix} V_L \\ I_G \end{vmatrix} = \begin{vmatrix} Z_{LL} F_{LG} \\ K_{GL} Y_{GG} \end{vmatrix} \begin{vmatrix} I_L \\ V_G \end{vmatrix} \tag{18}$$

where

$$F_{LG} = -|Y_{LL}|^{-1}|Y_{LG}| \tag{19}$$

The L-index of bus j_{th} is given as [28]:

$$L_j = \left|1 - \sum_{i=1}^{N_g} F_{ji} \frac{V_i}{V_j} \angle\left(\theta_{ji} + \delta_{ij}\right)\right| \tag{20}$$

where F_{ji} is the elements of F_{LG} matrix.

By minimizing L-index, the system will be a more secure system, and the system becomes able to overcome any disturbance that occurs on the system as much as possible.

In addition, FVSI, LSI, NLSI, and NVSI can be used as an indicator of voltage stability. FVSI is based on the concept of power flow through a single line. For a typical transmission line, the FVSI is calculated by [2]:

$$FVSI_{ij} = \frac{4Z_{ij}^2 Q_j}{V_i^2 X_{ij}} \tag{21}$$

where Z_{ij} is the line impedance, Q_j is the total reactive power flow at the receiving end.

The line that gives the index value closest to 1 will be the most critical line of the system and may lead to the whole system instability. If FVSI goes beyond 1, a sudden voltage drop leading to the collapse of the system will be occurred at one of the buses connected to this line.

LSI is derived based on power transmission line concepts. The expression for the index is given as [3]:

$$LSI_{ij} = \frac{4X_{ij} Q_j}{V_i^2 \sin^2(\emptyset - \delta)} \tag{22}$$

where $\emptyset$ is the transmission line angle.

$$\emptyset = \tan^{-1}\frac{X_{ij}}{R_{ij}} \tag{23}$$

A line in the system is said to be close to instability when the LSI value is close to 1. On the other hand, if the LSI value is less than 1, the system is said to be stable.

NLSI is proposed to monitor voltage stability conditions and/or for voltage collapse prediction. The NLSI is given as [3]:

$$NLSI_{ij} = \frac{4Q_j}{V_i^2}\left[\frac{Z_{ij}^2}{X_{ij}}\varepsilon - \frac{X_{ij}}{\sin^2(\emptyset - \delta)}(\varepsilon - 1)\right] \tag{24}$$

where ε is a switching function whose value depends on whether the angle difference, δ, is very small or not.

$$\varepsilon = \begin{cases} 1 \text{ if } \delta < \delta_c \\ 0 \text{ if } \delta \geq \delta_c \end{cases} \tag{25}$$

When NLSI is less than 1, the voltage is stable. When its value comes closer to 1, the voltage comes nearer to collapse. The NLSI combines two existing voltage stability indices, the LSI and FVSI, taking advantage of the accuracy of the LSI and the fastness of the FVSI.

The NVSI provides a complete description of the system's performance. NVSI is mathematically explained as follows [4]:

$$NVSI_{ij} = \frac{2X_{ij}\sqrt{Q_j^2 + P_j^2}}{2X_{ij} Q_j - V_i^2} \tag{26}$$

where P_j is the total active power flow at the receiving end.

The value of NVSI must be less than 1 in all transmission lines to achieve a secure system operation. And, the closer its value is to zero, the system becomes more stable. The advantage of this index is that it relates both real and reactive power, whereas other indices relate only to the reactive power of the system.

3.1.4 Enhancemessnt TTC using new VAR sources

To identify the best allocation of VAR sources for TTC enhancement, the third objective function is stated as maximizing of P_m value, which is computed as the sum of real power load at all buses and given as follows:

$$P_m = \sum_{i=1}^{N_b} P_{Di} \tag{27}$$

3.2 Constraints

To ensure that the system operates in a stable and reliable state, many constraints must be satisfied. Also, these constraints guarantee that the obtained optimal solution is feasible for practical power system operation. They can be classified as equality and inequality constraints.

Active power balance and reactive power balance

$$P_{gi} - P_{Di} - V_i \sum_{j=1}^{N_b} V_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij}) = 0, \quad i \in N_b \tag{28}$$

$$Q_{gi} - Q_{Di} + Q_{ci} + Q_{ci}^o - V_i \sum_{i=1}^{N_b} V_j \left(G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}\right) = 0 \quad i \in N_b \tag{29}$$

Voltage constraints

$$V_i^{\min} \le V_i \le V_i^{\max}, \quad i \in N_b \tag{30}$$

where v_i^{min} and v_i^{max} are 0.95 and 1.05 p.u, respectively.

Generator reactive power limit

$$Q_{Gi}^{\min} \le Q_{gi} \le Q_{Gi}^{\max}, \quad i \in N_g \tag{31}$$

Slack bus active power generation limit

$$P_s^{\min} \le P_s \le P_s^{\max} \tag{32}$$

Transmission line flow limit

The apparent power which flows in transmission lines must be less than the maximum allowable limit in order to avoid any damage in transmission lines.

$$|S_l| \le S_l^{\max}, \quad l \in N_L \tag{33}$$

Transformer tap setting limit

The limit of the transformer tap setting is presented as:

$$T_K^{\min} \le T_K \le T_K^{\max}, \quad k \in N_T \tag{34}$$

where $T_K^{\min}$ and $T_K^{\max}$ are 0.9 and 1.1 p.u with the step size 0.025.

Reactive power generation limit of VAR source

The new capacitor bank has a minimum and maximum limit, and it is expressed as:

$$Q_{C,i}^{\min} \le Q_{C,i} \le Q_{C,i}^{\max}, \quad i \in N_{cap} \tag{35}$$

where $Q_{C,i}^{\min}$ and $Q_{C,i}^{\max}$ are 0 and 5 MVAR with the step size of 1 MVAR.

The limits of SVC and TCSC

$$S_{SVC,i}^{\min} \le S_{SVC,i} \le S_{SVC,i}^{\max}, \quad i \in N_{SVC} \tag{36}$$

$$-0.8X_{ij} \le x_{TCSCi} \le 0.2X_{ij}, \quad i \in N_{TCSC} \tag{37}$$

where $S_{SVC,i}^{min}$ and $S_{SVC,i}^{max}$ are -100 and 100 MVAR and have a continuous control, while the range of TCSC is between -0.8 and 0.2 of the reactance of the installation line.

4 Multi-objective RPP solution

RPP is a nonlinear optimization problem and can be formulated as:

$$\text{Minimizing/Maximizing} \quad f_i(x, u) \quad i = 1, 2, \ldots N_{obj} \tag{38}$$

Subject to $g(x, u) = 0$ Equality constraints.

$h(x, u) \le 0$ Inequality constraints.

where $f(x, u)$ is the objective function; x is the set of the controllable variable; u is the set of the state variable.

In general, there are two ways to solve multiple-objective optimization problems. The first way is done by combining the individual objective functions into a single composite function. Many methods have been used to solve the composite single objective problem such as weighted sum and ε-constraint. As an example in (32), the multi-objective optimization problem is converted to a single objective optimization problem by generating a composite objective F from a linear sum of multiple objective functions $f_i(x, u)$.

$$\text{Minimizing/MaximizingF} = w_1F_1 + w_2F_2 \quad where \begin{cases} w_1, w_2 \ge 0 \\ w_1 + w_2 = 1 \end{cases} \tag{39}$$

The existing single-objective optimization algorithms can be used to optimize the above objective function, and the weights (w_1, w_2) must be pre-set. This way may have undesirable consequences that were explicitly setting the weights, which introduces the designer's preconceived capability about the relative trade-off between objectives. This may have a profound impact on design decisions.

The second way for solving the multi-objectives optimization problem is to search directly to determine the entire Pareto optimal set. The principle of an ideal multi-objective optimization technique is to define multiple tradeoff optimal solutions, which have a wide range of values for objective functions, and then select one of the solutions according to the requirement of the system operator. In this paper, MOGA has been used to solve RPP problem. The GA has many advantages, such as the ability to deal with complex problems and parallelism, use probabilistic transition rules not deterministic rules, support multi-objective optimization and work well on mixed discrete/continuous problems. Additionally, multiple offspring in a population act as independent agents, allowing the population to explore the search space in many directions at the same time [41]. A set of points are provided on the Pareto optimal front. The first objective is to minimize losses cost and installed VAR sources cost. The second objective is to improve voltage stability by increasing the VSM. The solution of the MOGA procedure is a set of points; at each point, we have a value for each objective. In the present paper, the fuzzy min–max approach is used to determine the best compromise solution. The fuzzy membership function MS_i of i^{th} objective function can be expressed as:

$$MS_i = \begin{cases} 1 & \text{if } F_i \le F_i^{min} \\ \frac{F_i^{max} - F_i}{F_i^{max} - F_i^{min}} & \text{if } F_i^{min} < F_i < F_i^{max} \\ 0 & \text{if } F_i \ge F_i^{max} \end{cases} \tag{40}$$

where F_i^{min} and F_i^{max} are the minimum and maximum values of the i^{th} objective function among all non-dominated solutions, respectively. For each non-dominated solution k, the normalized membership function (MS^k) is determined using:

$$MS^k = \frac{\sum_{i=1}^{N_{obj}} MS_i^k}{\sum_{k=1}^{M_s} \sum_{i=1}^{N_{obj}} MS_i^k} \tag{41}$$

where N_{obj} is the total number of objective functions, and M_s is the number of available solutions. The best compromise solution is the one having a maximum value of MS^k.

5 Proposed solution algorithm

The proposed RPP algorithm based on MOGA is summarized in the following steps:

- *Step 1:* Read the system data (bus, generator, branch, demand, etc.).
- *Step 2:* Run power flow
- *Step 3:* Check if there is an RPP problem in the network, if yes, identify the control variables. If no go to stop.
- *Step 4:* Select the MOGA parameters: population size, number of generations, etc.
- *Step 5:* Randomly initialize the population and set the generation count.
- *Step 6:* Update system data according to RPP solving method and run power flow again.

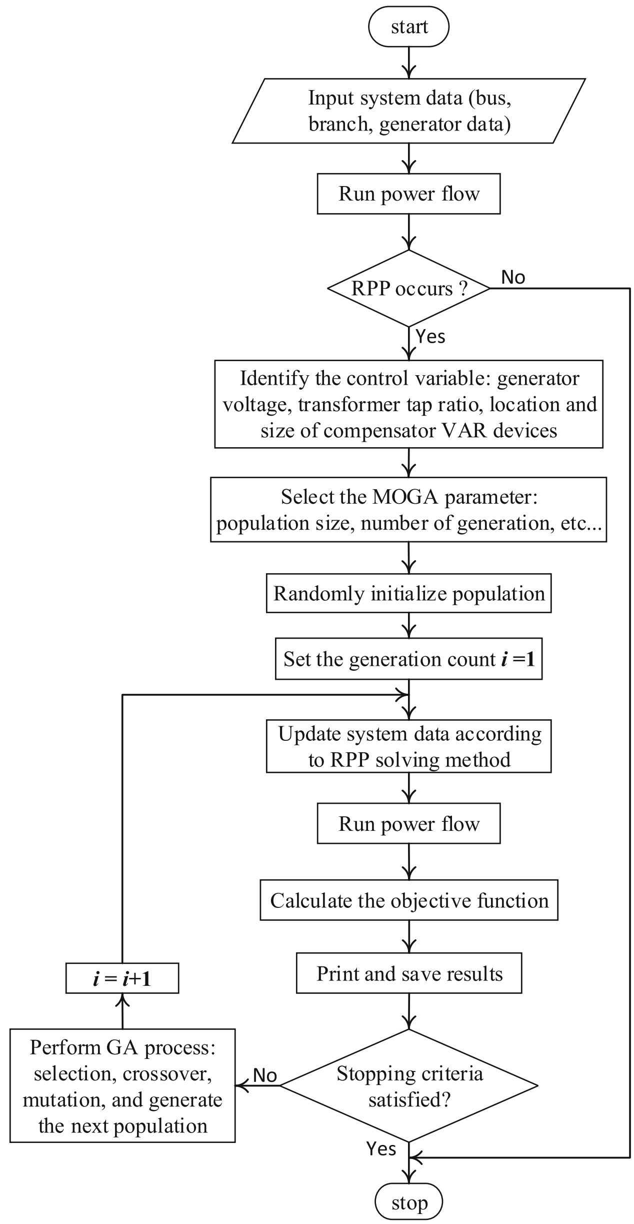

Fig. 5 Flowchart for the proposed algorithm

- *Step 7:* Evaluate the objective functions and check the system constraints.
- *Step 8:* Perform GA process selection, crossover, and mutation and generate the population for the next generation.
- *Step 9:* Repeat the steps from 6 to 8 and increment the generation count until the count reaches the maximum number of generations.
- *Step 10:* If the stopping criteria are satisfied, stop and print the results.

The flowchart for the proposed algorithm is shown in Fig. 5.

Table 2 Controller setting for the initial case and pre-VAR source added

Item	Initial case	Pre-using new VAR source
v_{g1}	1.05	1.049
v_{g2}	1.04	1.048
v_{g5}	1.01	1.025
v_{g8}	1.01	1.00
v_{g11}	1.05	1.049
v_{g13}	1.05	1.05
T_1	1.078	1.025
T_2	1.069	0.925
T_3	1.032	0.950
T_4	1.068	0.900
Losses (MW)	10.31	8.987
Cost of losses ($)	5.419×10^6	4.723×10^6
L-index	0.4557	0.3255
VSM	0.1047	0.12
Min voltage	0.736 (30)	0.898 (30)

6 Results and discussion

To present the effectiveness of the proposed approach, it is applied to the modified IEEE 30-bus system and South Egypt Electricity network.

6.1 Modified IEEE 30-bus test system

The modified IEEE 30-bus system [42] has six generators, 24 load buses, and 41 transmission lines, of which four branches (6–9), (6–10), (4–12), and (28–27) are with the tap changing transformer, and the system will be supported by eight new VAR source [43]. The initial value of generator voltage and setting of taps changing transformer are shown in Table 2. Due to the incremental loading of the system, the system suffers from stress. The results shown in Fig. 6 are gained by applying the power flow and assume this as the base case. From the figure, it is remarked that the voltage is violated on many buses. Bus 30 is the weakest bus, which has a voltage of 0.736p.u.

The problem is addressed with the possibilities available, i.e., changing the voltage setpoints of voltage-controlled buses and modulating the taps setting of taps changing transformers. The results are given in Table 2. Figure 7 shows the voltage at each bus in this case. It is observed also that the voltage is out of the limit at many buses, where the value of minimum voltage equals 0.898 p.u. at bus 30. So, there is an urgent need to strengthen the system with additional VAR sources.

Different cases are carried out including either using capacitor banks, FACTS, or a mixture between them for solving the RPP problem. In addition, there is a detailed view of the use of each case if the RPP is handled as a single objective using GA or multi-objective problems using MOGA.

6.1.1 Case 1: capacitor banks

Table 3 shows the control variables and results when the minimization of the cost or VSI is employed as a single objective and when they are adopted together as multi-objective. Figure 8 depicts the Pareto optimal front of total annual cost and VSM with a population size of 50 and 300 iterations.

When the optimization problem is handled with considering the cost, losses plus capacitor banks costs, as a single objective, the results show that the total cost is decreased from 5.419×10^6 \$ to 4.02×10^6 \$ with a net saving of 25.82%, while the voltage at all buses is within permissible limits, and the minimum voltage is 0.97 p.u at bus 19. Moreover, it is observed that the stability has been improved, and the VSM is increased from 0.1047 to 1.2158 after installing capacitor banks.

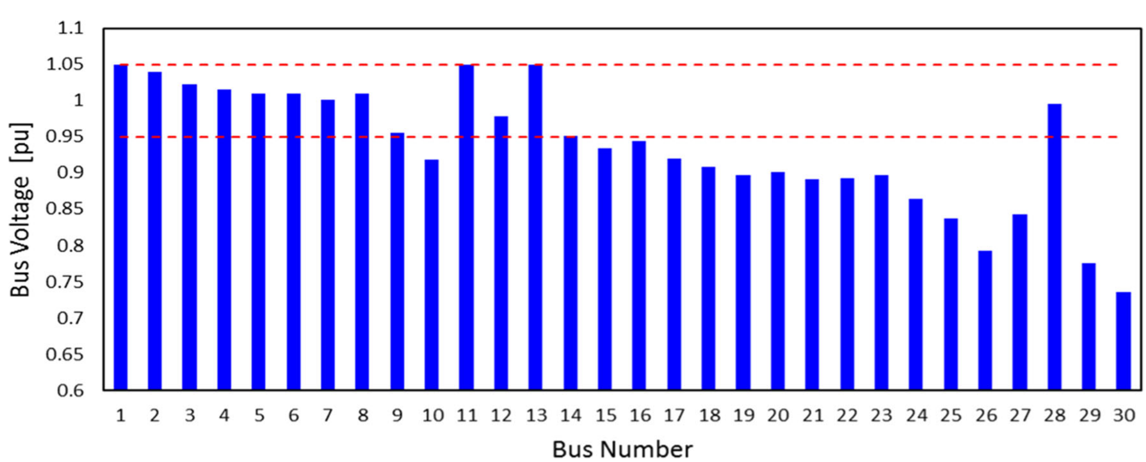

Fig. 6 Initial voltage buses

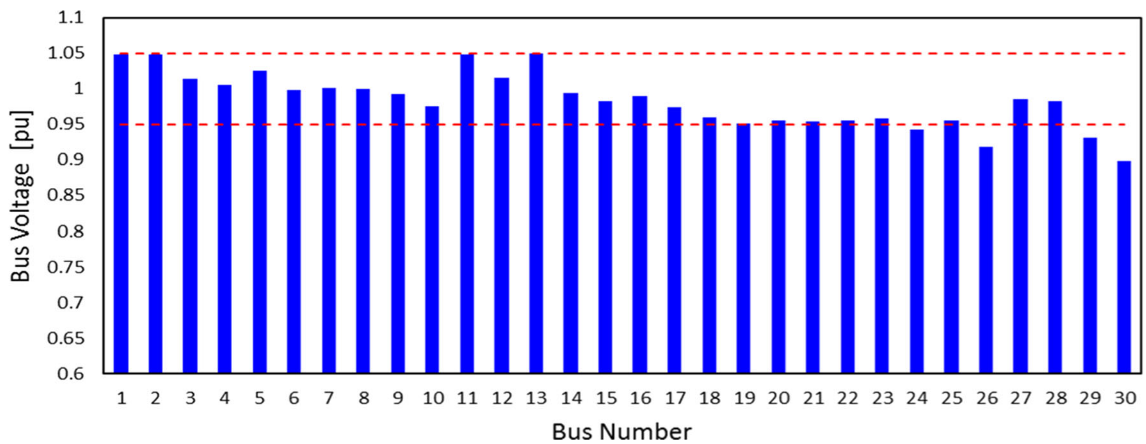

Fig. 7 Pre-installation of new VAR sources voltage buses

Table 3 Control variables setting for case 1

Item	Initial case	Cost is an objective	Stability is an objective	Multi-objective (cost + stability)
v_{g1}	1.05	1.050	1.018	1.046
v_{g2}	1.04	1.044	1.007	1.035
v_{g5}	1.01	1.021	0.978	1.007
v_{g8}	1.01	1.018	0.970	1.003
v_{g11}	1.05	1.050	1.050	1.050
v_{g13}	1.05	1.050	1.050	1.050
T_1	1.078	1.000	0.900	0.975
T_2	1.069	0.925	0.925	0.925
T_3	1.032	1.025	0.925	0.975
T_4	1.068	0.925	0.900	0.900
Q_1	–	5 (21)	5 (30)	5 (26)
Q_2	–	4 (24)	5 (24)	5 (24)
Q_3	–	5 (28)	5 (23)	5 (29)
Q_4	–	5 (26)	4 (22)	5 (30)
Q_5	–	5 (22)	5 (29)	5 (19)
Q_6	–	4 (23)	5 (27)	5 (21)
Q_7	–	5 (29)	5 (25)	5 (22)
Q_8	–	5 (30)	5 (26)	5 (23)
Losses (MW)	10.31	7.296	7.852	7.307
Cost of losses ($)	5.419×10^6	3.83×10^6	4.13×10^6	3.84×10^6
Cost of VAR ($)	–	1.87×10^5	1.92×10^5	1.97×10^5
Total annual cost ($)	5.419×10^6	4.02×10^6	4.32×10^6	4.04×10^6
L-index	0.4557	0.2964	0.2941	0.2887
VSM	0.1047	1.2158	1.7839	1.6529
Net saving	–	25.82%	20.28%	25.44%
Min voltage	0.736 (30)	0.97 (19)	0.961 (28)	0.991 (28)

By comparing the value of the L-index in the case of using the total cost as an objective (0.2964) with the case of using the stability as an objective (0.2941), it has a very small change and therefore another indicator, VSM, is used to measure the voltage stability. For best VSM when the stability is the objective function, as shown in Table 3, the VSM has been increased to 1.7839, the minimum voltage is 0.961 at bus 19. It is noted that the losses are decreased to 7.852

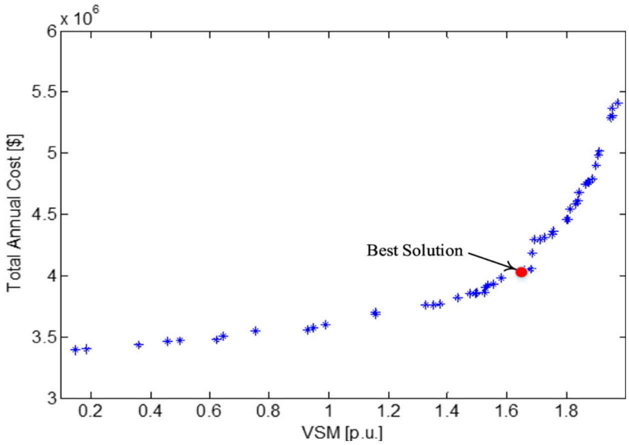

Fig. 8 Best Pareto optimal front of total annual cost and VSM

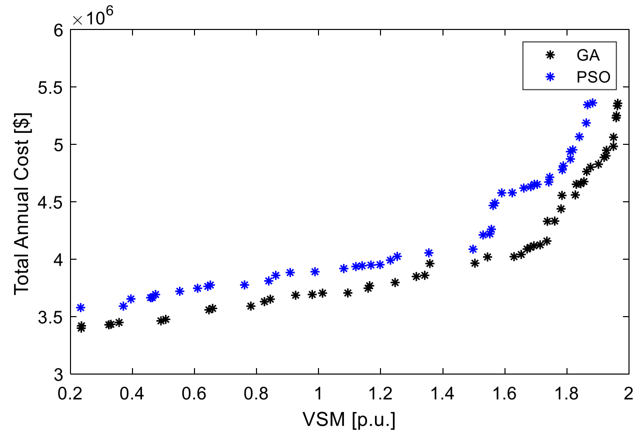

Fig. 10 Comparison between GA and PSO for multi-objective case

from the initial value and the net saving is 20.28%. In a multi-objective case, a 25.44% net saving has been gained with the VSM equals 1.6529.

A comparison between GA and PSO for the total annual cost and VSM with respect to iterations is shown in Fig. 9 in the case of using capacitor banks only. As appear in this figure, although PSO achieves faster results, GA gives better results. It can also be noted that the single-objective optimization technique gives better results than the multi-objective technique, but at the expense of the other goal. Figure 10 shows a comparison between GA and PSO in the multi-objective case.

6.1.2 Case 2: FACTS

In this case, the FACTS devices are used as VAR sources instead of capacitor banks. Two different FACTS devices are installed. Four SVC and four TCSC are installed in the network, which satisfies the system stability. Table 4 presents the optimal allocations of installed FACTS devices and the control variables.

With the cost is an objective, the net saving is about 17.14%, while when the objective is just to improve the voltage stability, the results demonstrate that the network is operated at high VSM (3.8241) and the total annual cost is very high (8.24×10^6 \$). For the multi-objective case, the VSM is increased to 2.7348 with a net saving of 16.77%. It is remarked that this method is more expensive than using capacitor banks but the system is more secure.

6.1.3 Case 3: capacitor banks with FACTS

FACTS are playing an effective role in VSI of the system in an excellent way but the total cost is increased significantly. On the contrary, the voltage stability is improved to some extent at a lower cost using capacitor banks. Therefore, a hybrid assortment of capacitor banks and FACTS devices

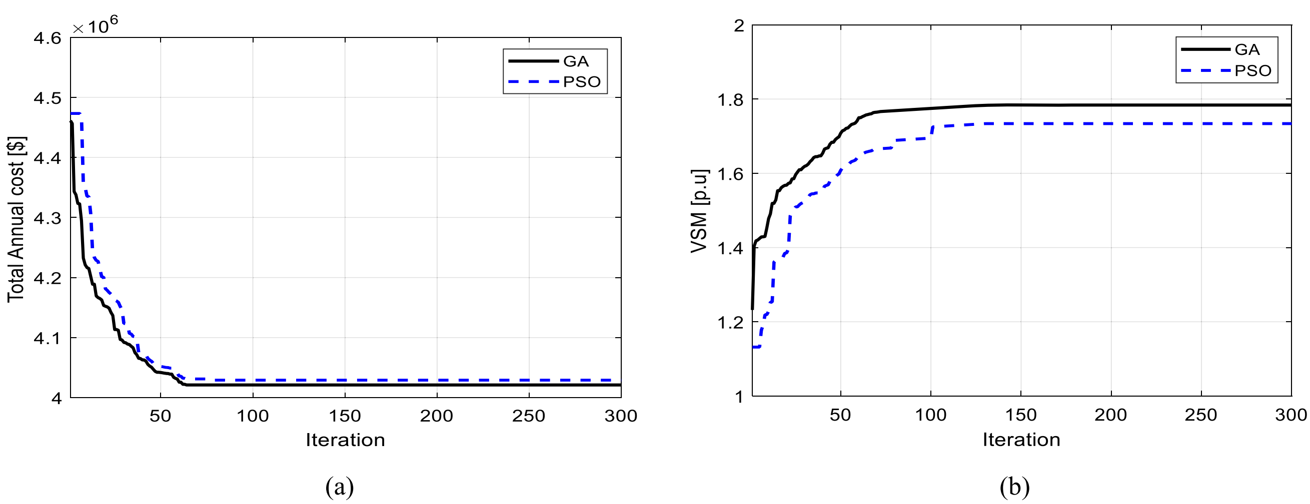

Fig. 9 Comparison between GA and PSO for solving RPP problem, **a** for the best cost, **b** for the best VSM

Table 4 Control variables setting of case 2

Item	Initial case	Cost is objective	Stability is objective	Multi-objective
v_{g1}	1.05	1.050	0.984	1.050
v_{g2}	1.04	1.049	0.974	1.045
v_{g5}	1.01	1.030	0.964	1.022
v_{g8}	1.01	1.018	0.955	1.011
v_{g11}	1.05	1.050	0.996	1.050
v_{g13}	1.05	1.050	0.998	1.050
T_1	1.078	1.075	1.025	1.000
T_2	1.069	0.925	0.925	0.925
T_3	1.032	1.025	0.900	1.025
T_4	1.068	1.000	0.925	0.975
SVC_1	–	0.444 (2)	15.3393 (30)	7.996 (30)
SVC_2	–	9.259 (24)	24.8394 (19)	1.086 (29)
SVC_3	–	4.622 (30)	25.2724 (24)	4.137 (26)
SVC_4	–	3.565 (10)	74.1720 (10)	0.025 (25)
$TCSC_1$	–	0.0114 (21)	0.0316 (10)	0.0332 (10)
$TCSC_2$	–	0.0031 (3)	0.3084 (36)	0.0003 (13)
$TCSC_3$	–	0.2534 (34)	0.3066 (37)	0.2754 (36)
$TCSC_4$	–	0.0173 (23)	0.1617 (13)	0.2457 (37)
Losses (MW)	10.31	7.895	8.405	7.66
Cost of losses ($)	5.419×10^6	4.15×10^6	4.42×10^6	4.03×10^6
Cost of SVC	–	3.32×10^5	2.17×10^6	2.46×10^5
Cost of TCSC	–	5.19×10^3	1.65×10^6	2.4×10^5
Cost of FACTS	–	3.37×10^5	3.82×10^6	4.86×10^5
Total annual cost	5.419×10^6	4.49×10^6	8.24×10^6	4.51×10^6
L-index	0.4557	0.3036	0.1609	0.1875
VSM	0.1047	1.2959	3.8241	2.7348
Net saving	–	17.14%	− 57.04%	16.77%
Min voltage	0.736 (30)	0.950 (19)	0.95 (7)	0.95 (19)

are used to solve the RPP problem to achieve a good level of voltage stability at a lower cost. The allocations of new VAR sources and other control variables are shown in Table 5. The net saving of 23.79% is gotten in case of the cost is a single objective with the VSM equals1.4239. When the objective is to just improve voltage stability, the VSM equals 3.7023 with a total cost of 8.67×10^6 \$. In a multi-objective problem, the net saving is 18.25% with a good VSM at 2.9505.

6.1.4 Using VAR sources to increase TTC

The different types of the new VAR source device are applied to solve the RPP problem with objectives of minimizing costs of losses and VAR sources, maximizing the voltage stability, and maximizing the total TTC.

Results are shown in Table 6. It is noted that increasing the TTC requires a greater cost. It is shown that before installing any VAR sources, the maximum TTC which could be achieved with allowable voltage at all buses is 291.16 MW. The total annual cost is 4.13×10^6, 5.2×10^6, and 4.46 $\times 10^6$ for three options of capacitors, FACTS, and hybrid assortment, respectively, where the TTC is 363.86, 566.97, and 516.85 respectively, and the VSM is 1.1697, 2.4, and 1.9284, respectively. It appears that employing the capacitor bank option alone is more acceptable from a purely economic sense because it provides the highest possible net savings. However, it is not a better option for increasing TTC or VSI, while using FACTS devices is the most effective technique to enhance TTC and VSI, but it comes with a high cost. It also indicates that employing a hybrid mix of capacitor banks and FACTS gives good results for enhancing TTC and VSM at a reasonable cost.

6.1.5 Comparison between fixed and optimal locations

Table 7 shows a comparison between the results in the case of assuming fixed locations of new VAR sources with those in case they are optimally located. If the locations of the

Table 5 Control variables setting of case 3

Item	Initial case	Cost is objective	Stability is objective	Multi-objective
v_{g1}	1.05	1.050	0.966	1.050
v_{g2}	1.04	1.045	0.956	1.045
v_{g5}	1.01	1.022	0.953	1.023
v_{g8}	1.01	1.019	0.952	1.020
v_{g11}	1.05	1.050	1.013	1.050
v_{g13}	1.05	1.050	0.991	1.050
T_1	1.078	1.025	1.000	1.000
T_2	1.069	0.925	0.900	0.950
T_3	1.032	1.050	0.900	1.025
T_4	1.068	0.975	0.900	1.000
Q_{c1}	–	5 (23)	4 (29)	5 (30)
Q_{c2}	–	5 (26)	4 (30)	3 (29)
Q_{c3}	–	5 (24)	4 (27)	4 (26)
SVC_1	–	10.812 (30)	99.277 (6)	6.362 (25)
SVC_2	–	0.222 (19)	62.661 (21)	8.448 (27)
$TCSC_1$	–	0.1553 (36)	0.3139 (36)	0.3126 (36)
$TCSC_2$	–	0.0022 (40)	0.0731 (14)	0.230 (37)
$TCSC_3$	–	0.0035 (28)	0.3156 (37)	0.0335 (10)
Losses (MW)	10.31	7.301	8.868	7.486
Cost of losses ($)	5.419×10^6	3.84×10^6	4.66×10^6	3.93×10^6
Cost of Q_c	–	7.37×10^4	5.91×10^4	5.91×10^4
Cost of TCSC	–	1.05×10^4	1.733×10^6	1.33×10^5
Cost of SVC	–	2.06×10^5	2.22×10^6	2.99×10^5
Cost of VAR source	–	2.95×10^5	4.01×10^6	4.91×10^5
Total annual cost	5.419×10^6	4.13×10^6	8.67×10^6	4.43×10^6
L-index	0.4557	0.2623	0.169	0.1723
VSM	0.1047	1.4239	3.7023	2.9505
Net saving	–	23.79%	− 59.99%	18.25%
Min voltage	0.736 (30)	0.953 (19)	(7)	0.95 (19)

new VAR sources are assumed to be fixed, then they will be located at the weakest buses which are 30, 29, 26, 25, 27, 24, 19, and 23, respectively, and the weakest line are 36, 13, 38, and 16, respectively.

From the table, it is remarked that in the case of the optimal locations of the new VAR sources, the results are better than initially assumed. For example, when the capacitor banks are used, the net saving is the same but the value of the VSM is better. In the case of using FACTS devices, both the net saving and VSM are better with values of 16.77% and 2.7348, respectively.

6.1.6 A comparison between multi-voltage stability indices

The MOGA is applied to solve the RPP problem with an objective to achieve a higher level of stability using capacitor banks, FACTS devices, or both of them. Table 8 illustrates comparison results using the VSM, L-index, FVSI, LSI, NLSI, and NVSI as an indicator of voltage stability.

6.1.7 Contingency analysis

The performance of the IEEE 30 bus system is studied under contingency. In this case, the stresses are represented by a three-phase fault, as the most severe fault. Table 9 shows the simulation results when the MOGA is applied to solve the RPP problem when a fault at line #30 and line #41 are considered. From the table, it is evident that in the case of line#30 outage and without installing new VAR sources, lines #27, #31, and #41 are overloaded not to mention that the voltage is below the limit in more than one bus and the minimum voltage is 0.863 p.u. at bus 30. After installing the new VAR sources, flow in all lines is at a limit, and the voltage at all buses and the VSM are improved. The same is true in the

Table 6 Control variables setting solving RRP problem and TTC enhancement

Item	Without VAR devices	Using capacitors	Using FACTS	Using hybrid
Cost of losses	5.21×10^6	3.98×10^6	3.87×10^6	3.92×10^6
Cost of new VAR	–	1.53×10^5	1.32×10^6	0.54×10^6
Total annual cost	5.21×10^6	4.13×10^6	5.2×10^6	4.46×10^6
VSM	0.9536	1.1697	2.4	1.9284
Installation VAR	–	4(24) 4(30) 3(21) 5(26) 4(9) 3(6) 4(29) 4(15)	SVC1, 6.22(12) SVC2, 13.95(30) SVC3, 17.82(21) SVC4, 22.63(19) TCSC1, 0.0138(10) TCSC2, 0.146(12) TCSC3, 0.003(23) TCSC4,0.0342(14)	CAP1, 5(30) CAP2, 3(21) CAP3, 4(9) TCSC1, 0.1482(10) TCSC2, 0.1232(36) TCSC3, 0.0331(23) SVC1, 12.54(24) SVC2, 19.78(29)
TTC	291.16	363.86	566.97	516.85
Min voltage	0.95 (30)	0.956 (30)	0.95 (23)	0.955 (29)

Table 7 Comparison between fixed and optimal locations of new VAR sources

Item		Using capacitors	Using FACTS	Using hybrid
The case of fixed locations	Cost of losses	3.84×10^6	3.93×10^6	3.93×10^6
	Cost of new VAR	1.92×10^5	6.21×10^5	4.83×10^5
	Total annual cost	4.04×10^6	4.55×10^6	4.41×10^6
	VSM	1.5223	2.6104	2.7004
	L-index	0.2976	0.1865	0.1818
	Net saving	25.44%	16.04%	18.38%
	min. voltage	0.981 (19)	0.961 (19)	0.95 (19)
The case of optimal locations	Cost of losses	3.84×10^6	4.03×10^6	3.93×10^6
	Cost of new VAR	1.97×10^5	4.86×10^5	4.91×10^5
	Total annual cost	4.04×10^6	4.51×10^6	4.43×10^6
	VSM	1.6529	2.7348	2.9505
	L-index	0.2887	0.1875	0.1723
	Net saving	25.44%	16.77%	18.25%
	min. voltage	0.991 (28)	0.95 (19)	0.951 (19)

case of line #41 outage as well, without new VAR devices the line 27 is overloaded and the minimum voltage is 0.833 at bus 30. After the installation of new VAR sources, all constraints have been satisfied and the system becomes more secure. Moreover, it is noted that using capacitor banks and FACTS devices gives the best results as the cost is moderate and the stability is fairly good.

Table 8 Comparison between different stability indicators

Item		Using a capacitor bank	Using FACTS	Using hybrid
The case of using VSM	Cost of losses	3.84×10^6	4.03×10^6	3.93×10^6
	Cost of new VAR	1.97×10^5	4.86×10^5	4.91×10^5
	Total cost	4.04×10^6	4.51×10^6	4.43×10^6
	VSM	1.6529	2.7348	2.9505
	L-index	0.2887	0.1875	0.1723
	FVSI	0.1624	0.1477	0.1468
	LSI	0.1689	0.1498	0.1499
	NLSI	0.1624	0.1477	0.1468
	NVSI	0.9655	0.8998	0.8898
The case of using L-index	Cost of losses	3.89×10^6	3.8×10^6	3.78×10^6
	Cost of new VAR	1.82×10^5	9.07×10^5	6.63×10^5
	Total cost	4.07×10^6	4.5×10^6	4.44×10^6
	VSM	1.4196	2.6967	1.903
	L-index	0.2884	0.175	0.196
	FVSI	0.1728	0.1501	0.1598
	LSI	0.1801	0.1528	0.1623
	NLSI	0.1801	0.1528	0.1623
	NVSI	0.9628	0.9001	0.9123
The case of using FVSI	Cost of losses	3.94×10^6	3.99×10^6	3.95×10^6
	Cost of new VAR	1.58×10^5	9.92×10^5	5.52×10^5
	Total cost	4.1×10^6	4.98×10^6	4.5×10^6
	VSM	1.2585	1.2666	1.2454
	L-index	0.3117	0.3007	0.3002
	FVSI	0.1628	0.1427	0.1498
	LSI	0.1681	0.1447	0.0.1523
	NLSI	0.1681	0.1447	0.1498
	NVSI	0.9886	0.9989	0.9885
The case of using LSI	Cost of losses	4.03×10^6	3.98×10^6	3.96×10^6
	Cost of new VAR	1.48×10^5	1.08×10^6	5.63×10^5
	Total cost	4.18×10^6	5.06×10^6	4.52×10^6
	VSM	1.2007	1.2205	1.2112
	L-index	0.3158	0.2995	0.3025
	FVSI	0.1212	0.1572	0.1302
	LSI	0.1246	0.1620	0.1421
	NLSI	0.1212	0.1620	0.1421
	NVSI	0.9882	0.9773	0.09779

Table 8 (continued)

Item		Using a capacitor bank	Using FACTS	Using hybrid
The case of using NSLI	Cost of losses	3.97×10^6	3.93×10^6	3.93×10^6
	Cost of new VAR	1.53×10^5	1.32×10^6	6.11×10^5
	Total cost	4.12×10^6	5.26×10^6	4.54×10^6
	VSM	1.236	1.2787	1.2689
	L-index	0.3126	0.2892	0.2912
	FVSI	0.1601	0.1838	0.1789
	LSI	0.1652	0.1861	0.1811
	NLSI	0.1652	0.1861	0.1811
	NVSI	0.9882	0.9727	0.9789
The case of using NVSI	Cost of losses	4.1×10^6	3.9×10^6	3.95×10^6
	Cost of new VAR	1.23×10^5	1.27×10^6	5.66×10^5
	Total cost	4.22×10^6	5.18×10^6	4.52×10^6
	VSM	1.1758	1.3953	1.322
	L-index	0.3005	0.2727	0.2881
	FVSI	0.2947	0.158	0.1628
	LSI	0.2989	0.1597	0.1698
	NLSI	0.2989	0.158	0.1628
	NVSI	0.9610	0.7035	0.844

6.1.8 Comparison of simulation results

The results obtained by the proposed approach are compared to those reported in the literature. They are compared with the results of the opposition-based gravitational search algorithm (OGSA) [17], DE [14], and simple particle swarm optimization (SPSO) [12] when the cost has been formulated as a single objective function as seen in Table 10. It is observed that the net saving of the proposed method reaches 25.82%, while the corresponding value of OGSA equals 18.25%. The table also shows comparison results when the stability has been formulated as a single-objective function with those using DE [15], OGSA [17] and GA [11]. In addition, it demonstrates the results of MOGA compared to fuzzy adaptive particle swarm optimization (FAPSO) [13]. From the table, it is remarked that the proposed method gives better results and superior performance than other methods.

6.2 South Egypt Electricity network

The proposed method is applied to the South Egypt transmission network [44]. A single line diagram is shown in Fig. 11. The power system in the south of Egypt is heavily loaded with load 4778.5 MW and 2801.8 MVAR. Before installing the new VAR sources, the voltages at several buses are out of the limit and the minimum voltage is 0.665 at Oyanat. Due to the heavy system loading, the new capacitance bank setting reached 80 MVAR. By installing the new VAR sources with optimal setting and location as given in Table 11, the network buses voltage becomes suitable for a secure operation.

As shown from the results the use of any capacitor bank, FACTS or a hybrid assortment between them can compensate for the lack of reactive power in the system. When capacitors are only used to compensate for the lack of reactive power, this gives us more economical operation, but at the expense of increasing stability of the system. On the other hand, using FACTS gave us a more stable network, but of course, it is more costly than the previous option, whereas the use of a hybrid of capacitors and FACTS gave us the advantage of obtaining a network that greatly has good stability and at the same time a relatively reasonable cost.

7 Discussion

In view of the above results, it is clear that the use of any capacitor bank, FACTS, or a hybrid assortment between them fulfills the purpose required to compensate for the lack of

Table 9 Results of MOGA optimization for two severe contingencies in the IEEE 30 bus system

Item		Without VAR	Using capacitors	Using FACTS	Using hybrid
The case of line 30 outage	Cost of losses	5.15×10^6	3.99×10^6	4.45×10^6	4.19×10^6
	Cost of new VAR	–	1.92×10^5	1.01×10^6	9.8×10^5
	Total annual cost	5.15×10^6	4.19×10^6	5.45×10^6	5.17×10^6
	VSM	0.9536	1.4944	2.7129	2.0284
	L-index	0.3708	0.3074	0.1865	0.2468
	Installation VAR	–	5(30) 5(29) 4(24) 5(26) 5(23) 5(22) 5(21) 5(19)	SVC1, 5.22(30) SVC2, 8.55(29) SVC3, 17.18(26) SVC4, 4.53(25) TCSC1, 0.2885(36) TCSC2, 0.2524(37) TCSC3, 0.0323(10) TCSC4,0.0311(13)	CAP1, 4(30) CAP2, 1(29) CAP3, 3(26) TCSC1, 0.1482(36) TCSC2, 0.1232(37) TCSC3, 0.0331(10) SVC1, 2.96(25) SVC2, 33.78(27)
	Over loaded lines	27,31,41	–	–	–
	Min voltage	0.863 (30)	0.983 (19)	0.95 (23)	0.951 (23)
The case of line 41 outage	Cost of losses	5.22×10^6	4.25×10^6	4.6×10^6	4.36×10^6
	Cost of new VAR	–	1.97×10^5	1.02×10^6	5.43×10^5
	Total annual cost	5.22×10^6	4.45×10^6	5.63×10^6	4.9×10^6
	VSM	0.8298	1.3042	1.5656	1.4997
	L-index	0.3948	0.3372	0.2833	0.2962
	Installation VAR	–	5(30) 5(29) 5(24) 5(26) 5(23) 5(22) 5(21) 5(19)	SVC1, 3.98(30) SVC2, 7.72(29) SVC3, 0(26) SVC4, 30.22(25) TCSC1, 0.1839(36) TCSC2, 0.1572(37) TCSC3, 0.0012(10) TCSC4, 0.02(13)	CAP1, 5(30) CAP2, 2(29) CAP3, 5(26) TCSC1, 0.1453(36) TCSC2, 0.137(37) TCSC3, 0.0001(10) SVC1, 0.79(25) SVC2, 19.6(27)
	Overloaded lines	27	–	–	–
	Min voltage	0.833 (30)	0.958 (28)	0.95 (30)	0.95 (30)

reactive power in the system. It turns out that the use of the capacitor bank only is more appropriate from a purely economic point of view where it achieves the highest possible net save. But it is not a better option to improve voltage stability or TTC enhancement, while the use of FACTS devices is the best in terms of improving the stability and increasing the TTC of the system, but it is done at a very high cost. It also shows that the use of a hybrid assortment of capacitor banks and FACTS gives good results to improve network voltage stability and TTC with a fairly cheap cost. Given the advantage of relying on predefined locations to place new VAR sources or leaving this option as a control variable when solving the problem, it turns out that leaving this option as a control variable when solving the issue gives better results. Moreover, it is worth relying on the VSM as a voltage stability indicator in the objective function to improve voltage stability than using the L-index or other indices.

8 Conclusion

MOGA has been applied to solve the RPP problem with the objectives of minimizing the cost of losses and new VAR sources devices, improving system voltage stability, and increasing TTC. The proposed approach has been tested on the modified IEEE 30 bus test system and South Egypt transmission network. It is evident that the use of any capacitor banks, FACTS, or a hybrid assortment between them fulfills the purpose required to compensate for the lack of reactive

Table 10 Comparison between the results of the proposed method and those reported in the literature

Item	Single objective function (cost)				Single objective function (stability)				Multi-objective	
	Ref. [17][a]	Ref. [14][b]	Ref. [12][c]	Proposed Method	Ref. [15][a]	Ref. [17][a]	Ref. [11][a]	Proposed Method	Ref. [13][a]	Proposed Method
Solution technique	OGSA	DE	SPSO	MOGA	DE	OGSA	GA	MOGA	FAPSO	MOGA
v_{g1}	1.05	1.1	–	1.050	1.0993	1.0951	1.05	1.018	1.073	1.046
v_{g2}	1.041	1.0942	–	1.044	1.0967	1.0994	1.0256	1.007	1.07	1.035
v_{g5}	1.0154	1.0745	–	1.021	1.0990	1.0991	1.0063	0.978	1.041	1.007
v_{g8}	1.0267	1.0765	–	1.018	1.0346	1.0991	0.9895	0.970	1.049	1.003
v_{g11}	1.0082	1	–	1.050	1.0993	1.0995	1.0584	1.050	1.066	1.050
v_{g13}	1.05	1	–	1.050	0.9517	1.0994	1.0806	1.050	1.072	1.050
T_1	1.0585	1.0844	0.9	1.000	0.9038	0.9728	1.05	0.900	1.02	0.975
T_2	0.9089	0.9	0.9	0.925	0.9029	0.9	0.9	0.925	0.99	0.925
T_3	1.0141	0.9924	0.9019	1.025	0.9002	0.9534	0.925	0.925	0.99	0.975
T_4	1.0182	0.9653	0.9	0.925	0.9360	0.9501	0.95	0.900	1.03	0.900
Capacitor Bank (Bus) (MVAR)	3.3 (10) 2.49 (12) 1.77 (15) 5 (17) 3.34 (20) 4.03 (21) 2.69 (23) 5 (24) 1.94 (29)	18.93 (10) 4.29 (24)	3.30 (7) 5.27 (15)	5 (21) 4 (24) 5 (28) 5 (26) 5 (22) 4 (23) 5 (29) 5 (30)	0.69 (10) 4.72 (12) 4.49 (15) 4.51 (17) 4.48 (20) 4.61 (21) 3.88 (23) 4.29 (24) 3.25 (29)	0.21 (10) 2.65 (12) 0.06 (17) 0.09 (24)	5 (30) 5 (29) 5 (26) 1 (25) 3 (24)	5 (30) 5 (24) 5 (23) 4 (22) 5 (29) 5 (27) 5 (25) 5 (26)	20 (10) 5 (15) 45 (19) 15 (24)	5 (26) 5 (24) 5 (29) 5 (30) 5 (19) 5 (21) 5 (22) 5 (23)

Table 10 (continued)

Item	Single objective function (cost)				Single objective function (stability)				Multi-objective	
	Ref. [17][a]	Ref. [14][b]	Ref. [12][c]	Proposed Method	Ref. [15][a]	Ref. [17][a]	Ref. [11][a]	Proposed Method	Ref. [13][a]	Proposed Method
VAR cost ($)	1.46×10^5	0	0	1.87×10^5	1.72×10^5	1.53×10^4	9.36×10^4	1.92×10^5	4.16×10^5	1.97×10^5
Losses (MW)	4.50	4.67	6.84	7.30	7.07	5.92	10.55	7.85	4.95	7.31
Losses cost ($)	2.36×10^6	2.45×10^6	3.60×10^6	3.83×10^6	3.72×10^6	3.11×10^6	5.55×10^6	4.13×10^6	2.60×10^6	3.84×10^6
Total demand	283.4	–	–	343.2	283.4	283.4	–	343.2	–	343.2
Total cost ($)	2.51×10^6	2.45×10^6	3.60×10^6	4.02×10^6	3.89×10^6	3.13×10^6	5.64×10^6	4.32×10^6	3.02×10^6	4.04×10^6
Net saving	18.25%	16.56%	3.80%	25.82%	− 26.69%	− 1.82%	0.29%	20.28%	− 4.19%	25.44%
L-index before opt	–	–	–	–	0.2144	0.2144	0.1978	0.4559	0.1579	0.4559
L-index after opt	0.1407	–	–	0.2887	0.1246	0.1230	0.1807	0.2941	0.1238	0.2887
VSM	–	–	–	1.6529	–	–	–	1.7839	–	1.6529

[a] For all previous references, the voltage limits of the generators are 0.9 to 1.1. Also, the transformer tap-ratio setting and size of the capacitor are continuous variable control.
[b] Ref [14] depends on using the initial capacitor bank at buses 10, 24 with values 19, 4.3, respectively.
[c] Ref [12] Although there is value for the capacitor, it was not calculated within the total cost and the value of the losses was calculated only

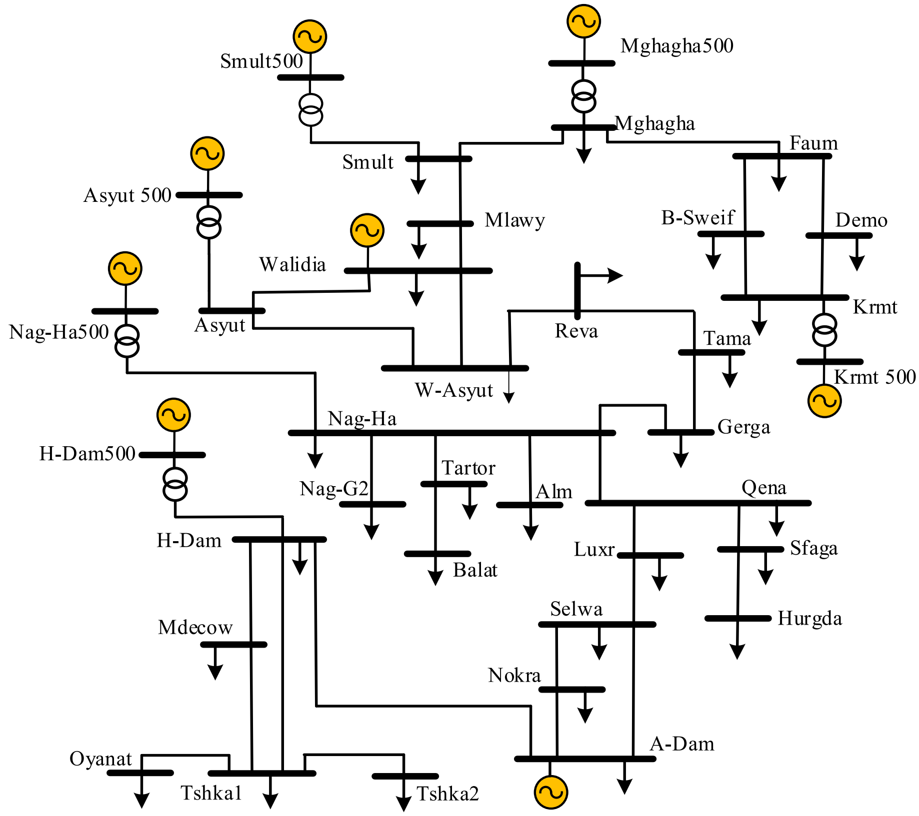

Fig. 11 South Egypt Electricity network

Table 11 Results of MOGA optimization for South Egypt Electricity network

Item	Without VAR devices	Using capacitors	Using FACTS	Using hybrid
Cost of losses	8.25×10^7	6.27×10^7	6.13×10^7	6.03×10^7
Cost of new VAR	–	2.17×10^6	9.64×10^6	6.03×10^6
Total annual cost	8.25×10^7	6.48×10^7	7.09×10^7	6.633×10^7
VSM	–	1.2744	1.854	1.726
Installation VAR	–	41 (Balat) 35 (Sfaga) 72 (Hurgda) 16 (Luxr) 79 (Mdecow) 59 (Tshka-1) 63 (Oyanat) 78 (Tshka-2)	SVC1, 89.4 (Balat) SVC2, 90.3 (Hurgda) SVC3, 86.7 (Tshka-1) SVC4, 89 (Tshka-2) TCSC1, 0.0069 (from Reva to Tama) TCSC2, 0.0165 (from Gerga to Nag-Ha) TCSC3, 0.0534 (from H-dam to Mdecow) TCSC4,0.1416 (from H-dam to Tshka-1)	CAP1, 80(Tama) CAP2, 73(Balat) CAP3, 75(Tshka-2) TCSC1, 0.0161(from Tama to Gerga) TCSC2, 0.0589(from H-dam to Mdecow) TCSC3, 0.1613(from H-dam to Tshka-1) SVC1, 96.2(Hurgda) SVC2, 99(Tshka1)
Min voltage	0.665 (Oyanat)	0.953 (Mdecow)	0.975 (Sfaga)	0.999 (Sfaga)

power in the system. It turns out that the use of the capacitor banks only is more appropriate from a purely economic point of view where they achieve the highest possible net save. However, they are not the best options to improve voltage stability or TTC enhancement, while the use of FACTS devices is the best in terms of improving the voltage stability and increasing the TTC of the system but results in a very high cost. The results presented in this work have proved that the hybrid assortment of capacitor banks and FACTS gives good results to improve network voltage stability and TTC with a fairly cheap cost. They also clarified the importance of optimally allocating the VAR sources instead of locating them at the weakest buses or weakest lines. Moreover, it is worth relying on the VSM as a voltage stability indicator in the objective function to improve voltage stability than using the L-index or others indices. The comparison results of the proposed approach with those reported in the literature have shown the robustness of the proposed approach to solve the RPP problem.

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