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Optimal sizing and location of open-UPQC in distribution networks considering load growth

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A R T I C L E I N F O

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Power quality
Distribution network
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Planning

A B S T R A C T

Voltage and current deficiencies in distribution network (DN) necessitate the improvement of power quality (PQ). Custom power devices (CPDs) compensate for these deficiencies. Recently, in presence of communication infrastructure in smart distribution network, open unified power quality conditioner (OUPQC) is attracted the attention of DN researchers and operators. OUPQC is utilized in DN to improve voltage and current deficiencies by operation of its series unit (SEU) and shunt units (SHU), respectively. Simultaneous compensation capability of voltage and current in distribution network increase its utilization by network operator. In steady state condition, the operation of SHUs compensate the reactive power flow in distribution network and the operation of SEU improve the voltage deficiencies in installation location. Hence, the optimum utilization of OUPQC result in maximization of its benefit for voltage and current improvement. In this regard, the planning of distribution network is performed considering the utilization of OUPQC and load growth. The optimum location, size and installation time of OUPQC is determined for minimizing the cost of distribution network during the planning horizon. Power loss reduction and voltage profile improvement are considered as benefits of the proposed planning approach. On the other hand, the added costs to the distribution network include the installation and maintenance costs of SEU and SHUs of OUPQC. The proposed planning approach is utilized to be tested on both standard IEEE 69-bus and practical Iranian 95-bus distribution networks. The results show that the proposed planning method is effective in term of economic and technical parameters of distribution networks and is useful for network planners.

1. Introduction

Nowadays, with the increase in importance of power quality (PQ) in distribution networks (DNs), custom power devices (CPDs) attract the attention of network operator and researchers. The utilized power quality conditioners are categorized from capacitor as simple passive filter to hybrid active power filters such as unified power quality conditioner (UPQC) [1]. UPQC, comprises of series and shunt inverters sharing the same capacitor as DC link, is responsible to compensate the voltage and current deficiencies in installation bus of DN [2,3]. UPQC has achieved prominence in recent years as an alternative for solving the PQ problem, because of its simultaneous compensating capabilities for both the distributor and the load side [4–7]. After varieties of development in configuration and control strategies of UPQC [8–13], Open-UPQC (OUPQC) is proposed by Brenna and Faranda [14]. This new solution, starts from the UPQC configuration, removes the common DC connection and splits the shunt unit (SHU) into several shunted devices. OUPQC has more flexible modularity than traditional UPQC for field applications. For instance, one of the major advantages of OUPQC in comparison with conventional UPQC is the flexibility of installation of series unit (SEU) and SHU in different locations of the DN. The mentioned advantage makes it possible to install the SHU at most optimum location while the SEU is installed at different location. In addition, installation of SEU and SHUs in DN improves the OUPQC compensation capability in voltage sag condition. Cooperation of SEU and SHUs in compensation of voltage deficiencies is proposed in [15]. The capability of installation of SEU and SHUs in different location of DN enables the utilisation of roof-top Photovoltaic Systems in compensation of voltage and current deficiencies in DNs [16].

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Nomenclature

PQ	Power Quality
DN	Distribution Network
CPD	Custom Power Device
UPQC	Unified Power Quality Conditioner
OUPQC	Open-UPQC
SHU	Shunt Unit
SEU	Series Unit
LV	Low-Voltage
ICT	Information and Communications Technology
BFSLF	Backward-Forward Sweep Load Flow
PVSML	Percentage of Voltage Sag Mitigated Load
PV	Photovoltaic
PVHC	PV Hosting Capacity
BESS	Battery Energy Storage
V_{SEU}	Injected SEU voltage
I_{SR}	Sending to receiving branch current
V_{se}^{sag}	Injected SEU voltage in sag condition
I_{load}	Load current
I_{line}	Branch Current
S_{SHU}	SHU Rating
S_{SEU}	SEU Rating
PF_R	Power Factor in receiving end bus
V_S^{sag}	Sending end voltage at sag condition
V_R	Receiving end voltage at healthy condition
$V_R^{'}$	Receiving end voltage at sag condition
RRPI	Ratio of Reactive Power Injection
E_{Loss}^{OUPQC}	Total energy loss of the network after OUPQC installation
E_{Loss}^{orig}	Total energy loss of the original network
C_i	Load growth coefficient for each type of load at year i

2. Related works

OUPQC consists of two controlled pulse-width modulated shunt and series inverters that have no common DC link. Generally, SEU configuration is the same as known dynamic voltage restorer [17] and SHU configuration is as the same as DSTATCOM [1]. After proposing a new configuration and its control strategy in [14] a group of researchers started to focus on its application in electrical networks. The application of OUPQC in DN is studied in [18–20]. In [21] a detailed analysis of SEU and SHU of OUPQC and their capabilities are presented. In addition, a rating design study of SEU and SHU is presented. Hafezi et al in [19] utilized the OUPQC as a tool to improve the PQ level in low-voltage (LV) DN. In [22] an Information and Communications Technology (ICT)-based power control is proposed in order to manage cooperation between SEU and SHU of OUPQC. The cooperation is meant to improve system functionality and performance. In [23] OUPQC model is extended by considering the presence of storage units, which can be connected to the renewable energy sources. The OUPQC model is incorporated to the backward-forward sweep load flow (BFSLF) algorithm for DNs [23]. Both the SEU and SHU are placed in each bus of a DN, one at a time and their effect on improving the power loss and PQ indices of a DN is studied [23]. The rating requirement of the OUPQC at different locations in a DN is also determined [23]. In [24] different models for UPQC and OUPQC are developed for improving PQ and energy efficiency of DNs. In addition, a planning approach for the optimal placement of UPQC inverters by considering additional technical constraint, i.e., percentage of voltage sag mitigated load (PVSML) is proposed. Furthermore, a comparative study is presented about the impact of the placement of these UPQC models on DNs and their rating requirements. In [24] an OUPQC model with PV array and battery is developed for SHU to act as active and reactive power compensators of radial DNs. In addition, a planning approach is presented to optimise the energy loss of radial DNs with the optimal placement of OUPQC by maintaining a pre-set PQ criterion in terms of voltage sag mitigation and harmonic suppression. In [24] a steady-state model is proposed for OUPQC with storage units connected to renewable energy sources. In addition, an exhaustive search approach is presented to study the impact of OUPQC placement in different buses of a DN on power loss and PQ improvement. Lakshmi and Ganguly in [24] developed a multi-objective planning approach for the simultaneous optimization of PVHC and energy loss of DNs. In addition, they modelled and allocated the OUPQC in DNs, which can be used to improve the energy loss and PQ of the network. Then, they developed PV-BESS-OUPQC model for the peak load shaving of radial DNs while keeping a desired PQ level intact [25]. In [25] an operational optimization approach is proposed to determine the time varying VAr compensation set points for OUPQC with time varying load demand and impact of the placement of OUPQC with time varying set points is studied on the energy loss reduction of DNs.

Table 1
Summarization of related works.

Ref.	planning approach of DN	OUPQC/ UPQC	Load Growth	Geo-Referenced DN	Economical Evaluation
[5]	✓	UPQC			
[15]		OUPQC			
[16]		OUPQC			
[24]	✓	OUPQC			✓
[25]	✓	OUPQC			✓
[29]	✓	OUPQC			✓
Proposed Method	✓	OUPQC	✓	✓	✓

On the other hand, the DNs are always keeps growing due to increasing in load demand by the network costumers. The growth of DNs necessitates the planning studies to consider the load growth in planning horizon [26,27]. In [28] the load growth is considered at three stages while ref [27] multiplies the load of each year by a constant multiplier to obtain the load of the next year.

In order to present a comprehensive evaluation of the published paper, the main related works are summarized in the Table 1.

According to the reviewed researches in the previous section, the mentioned literatures lack an optimum planning of DN considering OUPQC and time varying loads. In addition, the effect of load growth in study period affect the optimization process, which consists the aim of this paper. Mentioned points are organized the contributions of this paper. Daily, seasonal and yearly load profiles are considered in this paper to provide an effective and acceptable planning approach of DN. Furthermore, technical and economic objectives are devised to achieve the best results in the optimization problem. Moreover, in order to present a comprehensive evaluation of the proposed method, four different DNs are utilized as case studies. Utilized DNs comprises of IEEE standard DNs (69 and 119 bus), a 95-bus practical DN and a geo-referenced DN. Evaluation of the DN studies in geo-referenced DNs are conducted previously in published papers. Shahnia et al in [1] utilized a geo-referenced DN to evaluate the proposed expansion planning approach. Valenzuela et al in [30] proposed a planning approach for resilient underground DN using geo-referenced data. Transformer and tie point allocation are studied in the mentioned reference. Nahman et al in [31] proposed a reliability point of view planning of DN considering the uncertainty of power consumption, line failure rates, and of power supplied by distributed generators. They evaluates their proposed

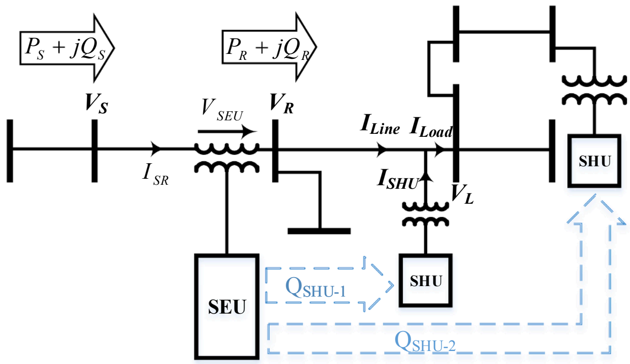

Fig. 1. Configuration of OUPQC in DN.

planning approach in geo-referenced DN. Valenzuela et al in [32] proposed a DN planning approach which considers both transformer loadings and voltage drop simultaneously. The planning approach is tested in a geo-referenced DN and the optimum results revealed on a geo-referenced map. Wilson et al in [33] developed an optimization problem to find the optimal routing of an ungrounded electrical DN while taking into account the characteristics of terrain using geo-referenced information of the grid. Inga et al in [34] presented a model of optimal sizing of electrical DN using geo-referenced information. As it is inferred from the reviewed works, optimal allocation of OUPQC in practical and non-practical DNs is not yet studied. Hence, the contributions of the paper are briefly as follow:

- Proposing a comprehensive planning approach of DN considering OUPQC,
- Consideration of hourly time varying loads in the proposed planning approach to achieve an effective and acceptable planning results,
- Consideration of the effect of load growth (comprises of current loads and joining new users to the geo-referenced DN) in the proposed planning procedure
- Consideration of technical (Harmonics, Voltage sag) and economic constraints in proposed planning procedure.

The rest of the paper is as follows. Section 2 describes the modelling and operation of OUPQC. Afterwards, the planning approach is proposed in Section 3. Simulation of the proposed method in DNs is performed and explained in fourth section. Finally, Section 5 contains the paper's conclusion.

3. Formulation of the problem

3.1. Mathematical model of OUPQC

SEU and SHU compensate the network requirements using communication channel. Mainly, the SEU is designed to compensate for voltage deficiencies and SHUs are designed for current improvements. Voltage improvement by the SEU is adopted by injection of series voltage while shunt compensation of current deficiencies is adopted by current injection. Therefore, utilization of these units in DN, depends on their locations and consequently required compensations.

3.1.1. Modelling of series unit

The SEU is compensating the PCC voltage deficiencies by injection of an in quadrature series voltage through series transformer which is fed by filter circuit and DC link. Fig. 1 shows the SEU and SHUs configuration in DN. As shown in Fig. 1, the SEU determines the required reactive power injection of SHUs and then sends the information of required reactive power through the communication link. The SEU injects an in quadrature voltage so as to compensate the voltage of installation location by injection of reactive power. The vector diagram of SEU is presented in Fig. 2. As shown in the Fig. 2, (V_{SEU}) is applied in quadrature to the current vector (I_{SR}) so as to inject only reactive power to the network.

3.1.2. Performance of series unit

The purpose of installation of SEU is to compensate the voltage deficiencies of upstream network. Maximum series voltage for compensation of source voltage deficiency is required in voltage sag condition. Hence, SEU is being designed to be capable of compensation of most severe pre-defined voltage sag condition. Therefore, the rating of SEU must be determined in most severe pre-defined voltage sag which the series voltage is injected so as to maintain the receiving end voltage at 1pu by applying reactive power to the network. As shown in the Fig. 2, the sending end voltage is smaller than 1 pu, therefore the series voltage improves the magnitude of receiving end voltage. According to Fig. 2, the magnitude of series voltage is:

$$V_{se}^{sag} = \sqrt{V_R^2 + V_R' - 2V_R V_R' cos(\delta'' - \delta')} \tag{1}$$

From the Fig. 2,

$$\varphi' = \varphi - (\delta'' - \delta') \tag{2}$$

Also we have:

$$\begin{aligned} V_R cos\delta'' &= V_R' cos\delta' + V_{se}^{sag} sin\varphi' \\ V_R sin\delta'' &= V_R' sin\delta' + V_{se}^{sag} cos\varphi' \end{aligned} \tag{3}$$

By mapping the V_R and V_R' on I_{SR}':

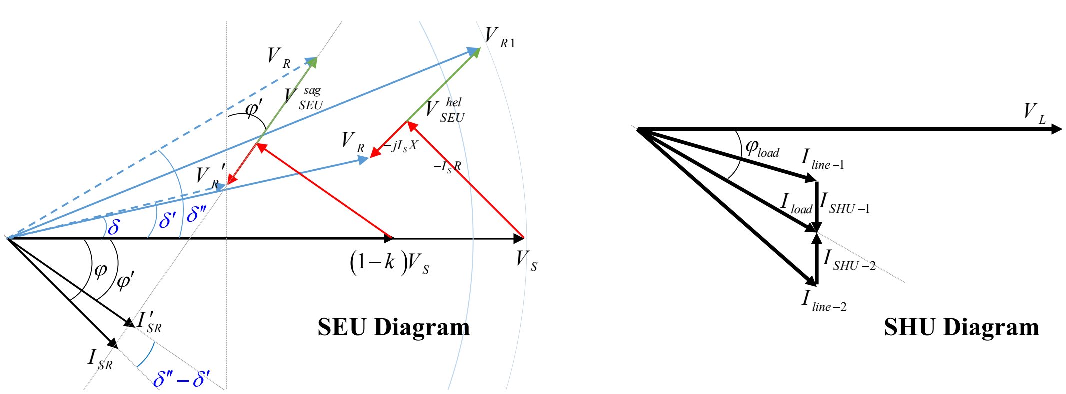

Fig. 2. Vector Diagram of SEU and SHU Operation.

$$V_R cos(\varphi + \delta') = V'_R cos(2\delta' + \varphi - \delta'') \tag{4}$$

Therefore, δ'' can be calculated by:

$$\delta'' = cos^{-1}\left\{\frac{V_R}{V'_R}cos(\varphi + \delta')\right\} + \varphi + 2\delta' \tag{5}$$

In healthy condition where the sending end voltage is greater than 0.9 pu [35], the injected series voltage (by (1)) only improve the receiving end voltage shortage which is resulted from voltage drop on network impedances. In this condition, the required series voltage is smaller than that of required in most severe voltage sag.

3.1.3. Modelling of shunt unit

SHU of OUPQC is designed to compensate for branch current deficiencies such as power factor and harmonics. Hence, vector diagram of SHU is represented in Fig. 2, where I_{load} and I_{line} is branch current before and after shunt injection. I_{SHU} is SHU current and is calculated to be capable of total reactive compensation of load as:

$$I_{SHU} = I_{Load} \times sin(\varphi_{Load}) \tag{6}$$

where φ_{Load} is the angle between bus voltage of installed SHU (V_L) and I_{Load}. Also, each SHU is responsible to compensate the harmonics of line current. So, the required shunt harmonic current is equal to line harmonic current:

$$I^{dist}_{Load} = I^{dist}_{SHU} \tag{7}$$

Hence, the injected current of each SHU is as follow:

$$I_{SHU} = I^{fund}_{Load}\sqrt{\left(sin(\varphi_{Load})^2 + THD^2_{Load}\right)} \tag{8}$$

Therefore, rating of each SHU is calculated as:

$$S_{SHU} = V_{Load} \times I_{SHU} \tag{9}$$

3.1.4. Operation of OUPQC in distribution network

SEU of OUPQC is placed in DN aiming to compensate voltage deficiencies such as voltage sag. Furthermore, in healthy condition ($V_S > 0.9$) SEU is capable of improving voltage profile by injecting quadrature series voltage. In other word, SEU of OUPQC injects reactive power to the network to improve voltage magnitude at installation bus. However, compensation capability of SEU is dependent to the angle of branch current referred to angle of PCC voltage (e.g. power factor of branch current [36]). On the other hand, operation of SHUs in the network, affect the power factor at SEU installation location. For more explanation, injection of reactive power by SHUs, improve the power factor in SEU location. Therefore, in voltage sag condition which is detected by SEU, SHUs can operate in such a way that they decrease the power factor in SEU installation location. This method of SHUs performance, decrease the power factor in SEU location and consequently increase the compensation capability of SEU. For more explanation, assume that sending end voltage in location of SEU experiences a voltage sag of:

$$V^{sag}_S < PF_R \tag{10}$$

where PF_R is the network power factor at receiving end of installed bus of SEU. Therefore, this magnitude of voltage sag cannot being compensated by the quadrature injection of series voltage [36]. Hence, it is required to decrease the PF_R to V^{sag}_S as follow:

$$PF^{new}_R = V^{sag}_S = \frac{P_{SR}}{\sqrt{P^2_{SR} + Q^2_{SR-new}}} \tag{11}$$

where P_{SR} and Q_{SR-new} are active and new reactive power flowing from sending to receiving end buses of installed SEU. New value of PF^{new}_R is achievable by absorption of reactive power by SHUs. Using (11), the new value of flowing reactive power can be calculated as:

Pseudo-code for rating design of OUPQC in DN	
	Begin
1	Define network data parameters: Network data, Load data
2	Define Installation Locations for SEU and SHUs SEU Location, SHU Location
3	Determine Maximum Voltage Sag Compensation Capability: $V_S^{sag-max}$
4	Determine Maximum THD Compensation Capability THD^{max}_{Load}
5	$[V_{profile}, I_{profile}] = LoadFlow\,(Network\ data,\ Load\ data,\ SEU\ Location,\ SHU\ Locations)$
6	Calculate I_{SHU} for each SHUs using: $I_{SHU} = I^{fund}_{Load} \times sqrt\left(\sin(\varphi_{Load})^2 + THD_{Load}{}^2\right)$
7	Calculate rating of each SHU by: $S_{SHU} = V_{Load} \times I_{SHU}$
8	Calculate φ for SEU using Maximum Voltage Sag Compensation Capability: $\varphi = \cos^{-1}\left(V_S^{sag-max}\right)$
9	Calculate Maximum Series Injection using: $V^{sag}_{Se} = \sin(\varphi)$
10	Calculate rating of SEU by : $S_{Se} = V^{sag}_{Se} \times I$

Fig. 3. Pseudo-code for rating design of OUPQC in distribution network.

$$Q_{SR-new} = \sqrt{\frac{P^2_{SR}}{(V^{sag}_S)^2} - P^2_{SR}} \tag{12}$$

Therefore, the required injection of reactive power by SHUs is determined as:

$$Q_{SHUs} = Q_{SR} - Q_{SR-new} \tag{13}$$

where Q_{SHUs} is the required injection of reactive power by SHUs. Sharing of required reactive power injection between SHUs is determined according to their ratings. The ratio of reactive power injection to the SHU rating is defined as Ratio of Reactive Power Injection (RRPI).

$$RRPI = \frac{Q_{SHUs}}{Total\ SHUs\ Ratings} \tag{14}$$

Therefore, the index of RRPI is between −1 and 1. In case of large voltage sag (more severe than power factor), it is required to decrease the power factor of branch current or increase the flowing reactive power. Therefore the new reactive power is more than the initial one ($Q_{SR-new} > Q_{SR}$ and therefore $Q_{SHUs} < 0$). This objective is being achieved by absorption of reactive power by the SHUs.

In case of normal undervoltages which $V_S > PF_R$, compensation of receiving voltage is possible even with bigger power factor. Therefore, it is possible to allow the SHUs to inject the reactive power to the network and consequently increase the power factor at SEU location. Hence, $Q_{SR-new} < Q_{SR}$ and therefore $Q_{SHUs} > 0$.

Accordingly, based on the maximum compensable voltage sag ($V^{sag-max}_S$), required V_{Se} is determined using (2):

$$V^{sag}_{Se} = sin(\varphi) \tag{15}$$

where φ is the power factor in maximum compensable voltage sag while the SHUs contribute to improve the compensation capability of SEU. Therefore, φ is calculated as:

$$\varphi = cos^{-1}(V^{sag-max}_S) \tag{16}$$

By using (15) the rating of SEU is calculated as:

$$S_{SEU} = V^{sag}_{Se} \times I \tag{17}$$

Fig. 3 shows the developed algorithm for rating design of OUPQC in DN. In addition, the operational algorithm for OUPQC performance is

Pseudo-code for Operational approach for OUPQC Performance

1 Input V_S , I_{SR} at the installation location
2 Calculate Active and Reactive Power
$P_{SR}+jQ_{SR}=V_S I_{SR}^*$
3 Calculate required reactive power in SEU location
$Q_{SR-new}=\sqrt{\frac{P_{SR}^2}{(V_S)^2}-P_{SR}^2}$
4 Calculate Total Reactive Power by Shunt Units
$Q_{SHUs}=Q_{SR}-Q_{SR-new}$
5 Calculate *RRPI* index
$RRPI=\frac{Q_{SHUs}}{Total\ SHUs\ Ratings}$
6 Calculate power factor angle (φ)
$\varphi=\cos^{-1}\left(\frac{P_{SR}}{\sqrt{P_{SR}^2+Q_{SR}^2}}\right)$
7 Calculate series injection of SEU
$V_{Se}=\sin(\varphi)$

Fig. 4. Pseudo-code for Operational approach for OUPQC Performance.

developed as Fig. 4. Integration principle of OUPQC in backward/forward load flow is presented in [15].

3.2. Planning approach for distribution network

The proposed model of OUPQC is utilized to install in DN in such a way that the most beneficial would be achieved during the planning period. In the study of OUPQC installation in DN for a planning period, its shorter time-scale capabilities are being represented by appropriate indexes. The mentioned method of study guaranties the compensation of voltage/current deficiencies during the planning period.

3.2.1. Optimization procedure

It should be mentioned that the main problem for finding the optimal location and size of OUPQC units is a Mixed Integer Non-linear Programming (MINLP), non-convex, and the meta-heuristic algorithms like GA and PSO can be very useful for solving these types of problems [37,38]. In this paper, the genetic algorithm is utilized for obtaining the optimum planning procedure [39]. Hence, optimization procedure is devised in such a way that the DN costs being minimized during the planning period.

The objective of the planning is minimization of OUPQC related costs of DN consist of:

- Reduction of network energy losses which affect the purchased energy from upstream network,

$$Benefit: E_{Loss}^{OUPQC}-E_{Loss}^{orig} \tag{18}$$

where E_{Loss}^{OUPQC} is the total energy loss of the network after OUPQC installation. E_{Loss}^{orig} is the total energy loss of the original network without any installation of compensation devices.

o The real power losses of DN (P_{Loss}) is defined by the following equation

$$P_{Loss}=\sum_{i=1}^{n_b}P_{Loss_i}^{(1)}+\sum_{i=1}^{n_b}\sum_{h=h_0}^{h=h_{max}}P_{Loss_i}^{(h)} \tag{19}$$

where n_b is number of branches and h_{max} is upper limit of the considered harmonic orders. As shown in (19) the fundamental and harmonic losses of DN are considered as total network power loss. Therefore, in order to calculate the energy losses of the network during the planning horizon, first, it is required to calculate the energy losses of each year. Then, a summation of energy losses of planning horizon is calculated for determining the *Benefit* of the planning problem. In this paper, the consuming load of the network is considered to be increase during the planning horizon. The load curve for each year is obtained by multiplying the initial load curve by the load growth coefficient for each type of load in the mentioned year as follows:

$$S_{Load}^i=C_i*S_{Load}^{initial} \tag{20}$$

where S_{Load}^i is the load curve at i^{th} year, C_i is the load growth coefficient for each type of load, and $S_{Load}^{initial}$ is the initial load curve.

- Installation cost of SEU and SHUs of OUPQC and their maintenance cost.

The cost of SEU and SHUs of OUPQC is considered as follow [29]. The considered cost is the life cycle cost of OUPQC comprises of installation and maintenance costs.

$$C_{OUPQC}=0.0003S_{Tot}^2-0.2691S_{Tot}+188.2(\$/kVA) \tag{21}$$

where S_{tot} is the total OUPQC rating in kVA. Therefore, in order to achieve the most beneficial plan for DN, the ratio of cost to benefit is considered as objective function as follow:

$$OF=\mathrm{Cost}/_{Benefit} \tag{22}$$

Each chromosome consists of four different parts as follow (see Fig. 5):

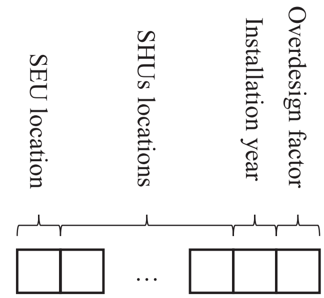

Fig. 5. Chromosome structure consists of 4 sections: SEU location, SHU locations, Installation year and Overdesign factor.

As shown in the above figure, the GA chromosome consists of four different parts as follow:

- SEU location
  - o The location of SEU in DN. Since the OUPQC comprises of one SEU, therefore one gene is utilized to represent the location of SEU.
- SHUs locations
  - o The locations of SHUs in DN. Since the OUPQC is capable to utilize multiple SHUs, therefore the corresponding gene numbers are considered for their locations. Hence, the considered chromosome length is different in each SHUs number.
- Installation year
  - o The installation year of OUPQC in case study DN. One gene is considered to represent the installation year.
- Overdesign factor
  - o The capability of overdesign in ratings of OUPQC is considered in the planning approach. Since the ratings of SEU and SHUs are determined based on their location and the network power flow, therefore, the capability of overdesign is considered to install the overrated OUPQC. This capability

Pseudo-code for planning approach

Objective min $OF(x) = \frac{Cost(x)}{Benefit(x)}$, $x = x_1, x_2, \ldots, x_d$
(x represents a GA *chromosome*)
Define optimization aspects (input data): Network data, Load data, OUPQC data, Optimization Constraints.
Initialize *population* of *GA* comprises of installation location and installation year for OUPQC plus overdesign factor,
while iter < = *population*
  $C_{OUPQC} = 0.0003S_{Tot}^2 - 0.2691S_{Tot} + 188.2(\$/kVA)$
  $[V_{profile}, I_{profile}] = LoadFlow(x)$
  if min ($V_{profile}) < V_{min}^{allowed}$ || max ($I_{profile}) > I_{max}^{allowed}$
    go to next chromosome; iter = iter +1;
  else
    $[V_{profile}^{sag}, I_{profile}^{sag}] = LoadFlow^{sag}(x)$
    if $PVSML < PVSML^{allowed}$
      go to next chromosome; iter = iter +1;
    else
      $[V_{profile}^{H}, I_{profile}^{H}] = HarmonicLoadFlow(x)$
      if max $(V_{profile}^{H}) < V_{profile}^{H-allowed}$
        go to next chromosome; iter = iter +1;
      else
        Calculate power losses in the study period,
      end if
    end if
  end if
end while
while *convergence* ≠ 1
  Perform *mutation* and *crossover* of GA
  Check for GA convergence
end while
Output Results

Fig. 6. Proposed algorithm of planning approach.

leads to make the OUPQC suitable for design parameters like voltage sag compensation capability and THD compensation capability.

The planning approach is utilized in DNs based on the devised algorithm (Fig. 6).

3.2.2. Operational constraints

The operation of DN must satisfy the operational constraints such as voltage and current limits. Therefore, in this paper the following constraints are considered that must be satisfied in each year of operation.

A. Steady State Operation

Two sets of constraints are assumed on bus voltages for their RMS and THD. Constraints on RMS values are defined with the lower and upper bounds, V^{min} and V^{max} respectively, as follows:

$$V^{min} \leqslant \sqrt{\sum_h [V_i^{(h)}]^2} \leqslant V^{max}, \text{ for } i = 1, \ldots, n \tag{23}$$

where $V_i^{(h)}$ is the RMS value of voltage at bus i for harmonic h. The voltage distortion constraint is considered by specifying the maximum THD of voltages denoted with THD^{max}:

$$THD_i = \left(\frac{\sqrt{\sum_{h \neq 1} [V_i^{(h)}]^2}}{V_i^{(1)}} \times 100\right) \leqslant THD^{max}, \text{ for } i = 1, \ldots, n \tag{24}$$

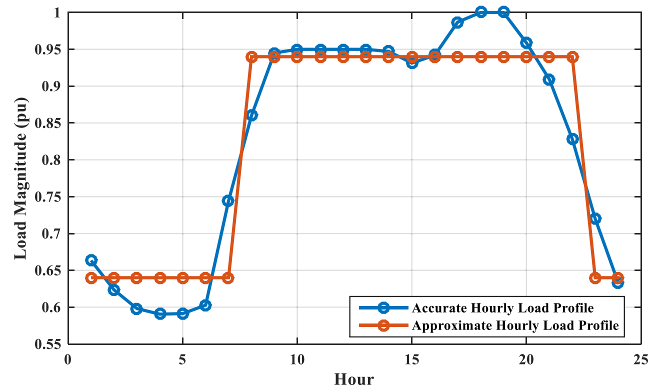

Fig. 7. Accurate daily load profile and its approximate curve.

The bounds for (25) and (26) are specified by the IEEE-519 standard [40], and they are $V^{min} = 0.9$ pu, $V^{max} = 1.1$ pu and $THD^{max} = 5\%$.

In addition, the current ampacity of network branches are considered as follow:

$$I_i \leqslant I_i^{max}, \text{ for } i = 1, \ldots, m \tag{25}$$

where I_i is branch current and I_i^{max} is maximum allowed current of branch. Current carrying capacity of branches 1–9 is 400 A, 46–49 and 52–64 is 300 A and for all other branches are 200 A [41].

B. Voltage Sag Operation

In order to evaluate the effectiveness of the selected ratings of OUPQC in voltage sag condition, the PVSML index is considered. PVSML is the percentage of load protected by the SEU from a given value of voltage sag [24]:

$$PVSML = \frac{Re\left\{\overline{V}(m)\overline{I}^*(nm)\right\}}{P_D + P_L} \tag{26}$$

where $\overline{V}(m)$ is the voltage at bus m, $\overline{I}^*(nm)$ is the line current flowing from buses n to m, P_D is total active power demand of the network and P_L is the uncompensated DN power loss.

4. Analysis of the results

The effectiveness of the proposed planning approach is evaluated in four DNs. To achieve the optimum size and location of OUPQC, the genetic algorithm is implemented in MATLAB software. In this paper planning period is chosen 20 years. In addition, the cost of energy loss is considered 0.08 $/kWh [29]. The devised planning approach considers the following aspects:

4.1. Network components

4.1.1. Load model

The loads in the DN are composed of linear and nonlinear loads. The linear loads are modeled as a constant power while non-linear loads are applied as harmonic current sources. The nonlinear loads contain three types of load including PWM-ASD, variable frequency drive (VFD) and six-pulse loads [42].

In addition, the peak and off-peak level are considered for daily load curve. In order to compromise between the optimization speed and the study accuracy, each 24-h load curve is represented as two load levels. Fig. 7 shows the approximation of 24-h load curve with peak and off-peak load levels.

As shown in above figure, the daily load profile is replaced by peak level with duration of 15 h and off-peak level with duration of 9 h. In

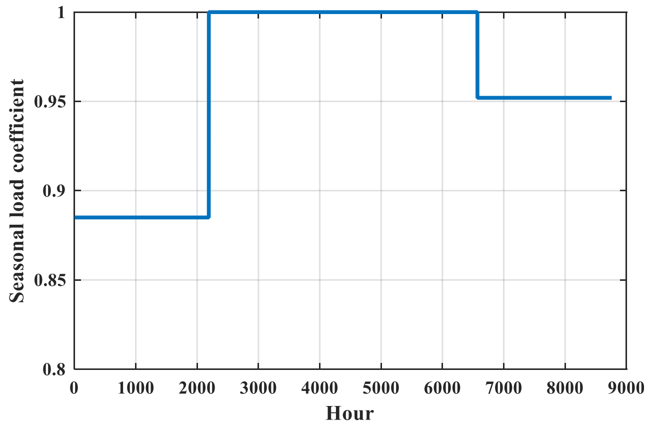

Fig. 8. Seasonal load profile.

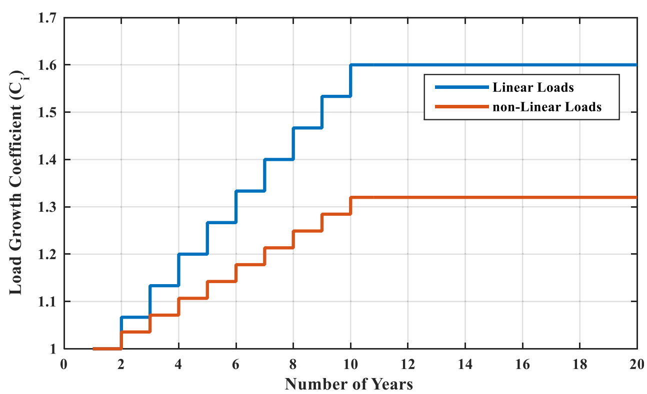

Fig. 9. Load growth curves for linear and non-linear loads.

addition, the seasonal load profile is considered based on IEEE 8760 h load profile [26,27]. The load profile of each season is considered to calculate the maximum level. Fig. 8 shows the calculated load level for each season.

4.1.2. Load growth modelling

Many factors such as population growth and construction of new industrial plants would increase the electricity demands in networks. Therefore, it is more important to consider the load growth factor at the beginning of the network planning [43]. To achieve this goal, we consider load growth for available loads in the DN. As it is state previously, the load curve for each year is obtained by multiplying the initial load curve by the load growth coefficient for each type of load in the mentioned year. The considered load growth curve is presented in Fig. 9. As shown in the figure, two curves are considered for linear and non-linear loads [26,27]. The considered load growth curves are different for linear and non-linear loads.

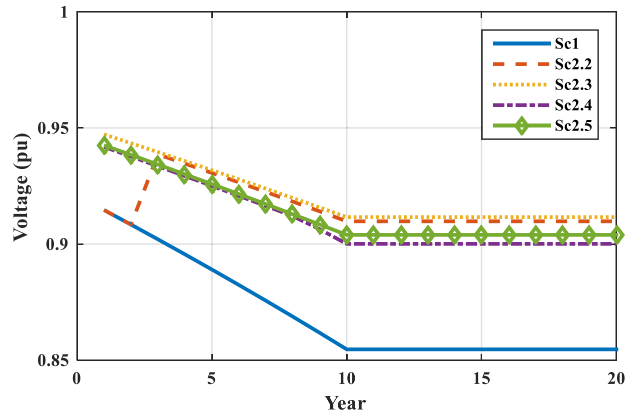

Fig. 10. Minimum voltage of the network in planning years for different scenarios – 69-Bus distribution network.

4.2. Case study distribution networks

First, IEEE 69-bus DN is implemented as benchmark. In addition, the effectiveness of the proposed method is evaluated in practical Iranian DN.

In order to evaluate the effectiveness of the proposed planning approach, the following scenarios are considered to provide the comprehensive comparison study.

- Scenario1: Basic distribution network without OUPQC installation.
- Scenario2: Distribution network with OUPQC placement consisting one SEU and multiple SHUs.
  - o Single SHU,
  - o Two SHUs,
  - o Three SHUs,
  - o Four SHUs,
  - o Five SHUs.

A. IEEE Standard 69-Bus DN

First, well-known IEEE standard 69-bus DN is utilized as case study [41,44]. The voltage level of the network is 12.66 kV. The system has a single supply point with 69-buses, 7 laterals, and 68 branches. Current ampacity of network branches 1–9 is 400 A, 46–49 and 52–64 is 300 A and for all other branches is 200 A [41]. The total load of the network is 3802.19 kW and 2694.6 kVAr. Table 2 shows the results of the DN in predefined scenarios.

Table 2 shows the planning results for installation of OUPQC in 69-bus DN. The first scenario (Sc.1) represents the operation of current form of the DN during the planning period. Voltage profile of the scenario Sc.1 in 20 years plotted in Fig. 10. As shown in the Table 2 and Fig. 10, operation of the DN without installation of any compensation devices violate the IEEE limits in fourth year. However, since the voltage limit is considered in planning procedure, the minimum voltage of the network is kept larger than 0.9 pu in all years of operation by installation

Table 2
Planning results of 69-bus distribution network.

	SEU			SHU(s)			Planning Parameters			
Scenario	Location	Rating (kVA)	Installation Year	Location(s)	Rating(s) (kVA)	Installation Year	Energy Loss (MWh) (Reduction w.r.t. Sc-1)	OUPQC costs (×1000$)	V_{min} in planning period	OF
Sc-1	–	–	–	–	–	–	4621.2 (0%)	–	0.855	–
Sc-2.1	There is no possible solution due to the technical constraints.									
Sc-2.2	3	9789.1	3	21 60	4844.2	3	3993.1 (13.7%)	283	0.9084	5.58
Sc-2.3	3	8631.1	1	13 45 61	4808.5	1	3584.8 (22.5%)	239	0.912	2.87
Sc-2.4	3	5185.5	1	10 21 38 61	3846.0	1	3078.6 (33.6%)	107	0.9001	0.858
Sc-2.5	3	8073.9	1	12 32 37 60 63	5930.5	1	3344.2 (27.7%)	259	0.904	2.53

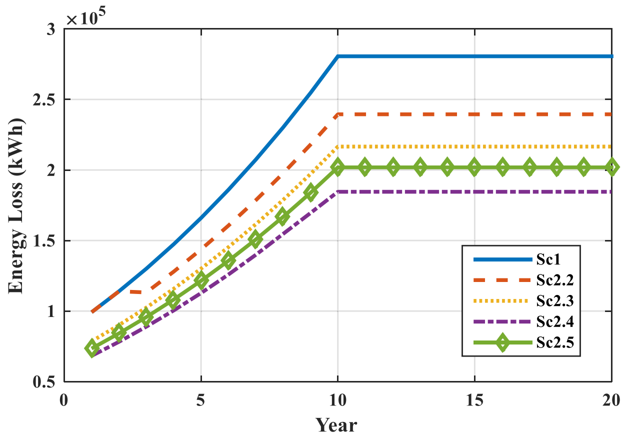

Fig. 11. Energy loss of the network in planning years for different scenarios – 69-Bus distribution network.

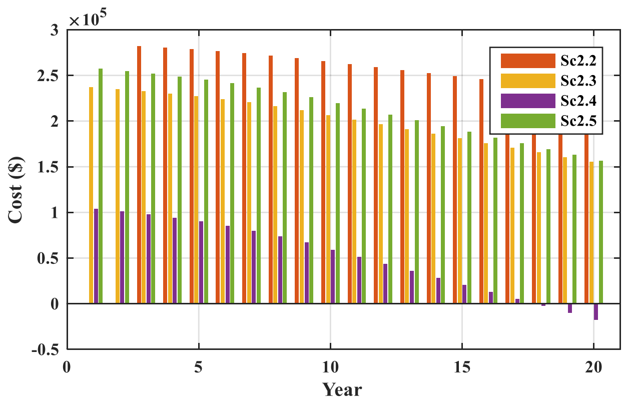

Fig. 12. Cumulative cash difference between the base scenario and the other feasible scenarios- 69-bus distribution network.

of different OUPQCs in different scenarios except for Sc2.1. As explained before, voltage constraint is considered for planning procedure. So, the second scenario (Sc2.1) is not converged to a feasible solution. Minimum voltage of the DN during 20 years of operation is plotted in Fig. 10.

As shown in the figure, installation of OUPQC in scenarios 2.2–2.5 improve the minimum voltage of the network to the allowable limit. Furthermore, as shown in the table, the scenario 2.4 leads to best OF value. In addition, the network energy loss during the 20 years of operation for each scenario are shown in Fig. 11.

As concluded from the table and the above figures, the proposed planning approach minimizes the DN costs for 20 years while maintaining the technical network constraints in allowable limits. As shown in Fig. 11, Sc2.4 results in better energy loss profile in comparison to the other scenarios. For providing a comprehensive economical comparison between the feasible scenarios, the cash flow during the planning period is plotted in Fig. 12.

Fig. 12 shows the cumulative cash difference between the base scenario (Sc1) and the other feasible scenarios. As shown in the figure, the Sc2.2 starts with zero values which represent the equal values of cash flows between this scenarios and base scenario. After three years, the cash flow of Sc2.2 starts which indicates the installation cost of OUPQC in this year. On the other hand, for example, the Sc2.4 cash flows during the planning period starts with $+1 \times 10^5$ value which represents the installation cost of OUPQC in the first year in comparison to the base scenario. At the end of 20th year, the cumulative cash flow of the Sc2.4 ends with -0.18×10^5 value which represents the lower cumulative cost in comparison to the base scenario (Sc1). The plotted figure shows the priority of Sc2.4 to be implemented in comparison to the other scenarios.

Table 3
comparison results of proposed method and previously published method in 69-bus DN.

	Installation location		Loss Reduction (w.r.t base case)	Planning cost (×1000 $)	Minimum Voltage (pu)
	SEU	SHU (s)			
[45]	7	7	9.59 (%)	936.2	0.91
Proposed method-GA	1	10 21 38 61	33.6 (%)	107	0.90
Proposed method-DPSO	1	10 21 38 61	33.6 (%)	107	0.90

In order to provide a statistical comparison between the proposed method and previously published papers, the results of planning approach of UPQC-Q is obtained from [45]. In the mentioned reference, the planning problem of UPQC-Q is performed in 33-bus and 69-bus DNs. Moreover, in order to validate the optimisation results, a different optimization algorithm is utilised. The planning problem of installation of OUPQC in 69-bus DN in Sc-2.4 is performed with Discrete Particle Swarm Optimisation (DPSO) algorithm [46]. Table 3 shows the comparison results of proposed method and previously published method in 69-bus DN.

According to the Table 3, installation of OUPQC in which SEU and SHUs are installed at different locations, in comparison to UPQC-Q installation results in better statistical achievement. As shown in the table, implementation of OUPQC with lower planning cost, results in more loss reduction while approximately maintain the minimum voltage of the DN. In addition, the optimization results of DPSO algorithm validates the obtained results with GA.

B. Practical 95-bus Iranian distribution network

In order to evaluate the effectiveness of the proposed planning approach in practical DN, 95-bus practical Iranian DN is implemented. Detail information of the DN can be found in [47]. The DN voltage is 20 kV and the total load is 6511.5 kW and 3153.67 kVar.

As explained previously, the ratings of OUPQC units are determined based electrical parameters of installation location. Table 4 shows the results of OUPQC installation in practical DN.

As shown in the table, installation of single and two shunted OUPQCs are not feasible for planning procedure due to voltage limit constraint. It is concluded from the table that between the Sc2.3-Sc2.5, the fifth scenario is capable to achieve the best objective function value.

In the Sc2.5 installation of smaller OUPQC in comparison to the Sc2.3 and Sc2.4 leads to large amount of loss reduction. Fig. 13 shows the energy loss of four feasible scenarios during the planning period. As shown in Fig. 13, the Sc2.3 leads to better loss profile during the planning period in comparison to the other scenarios. However, the implemented OUPQC in Sc2.3 has larger ratings in comparison to the scenarios. On the other hand, the Sc2.5 which the installation of OUPQC is done in the first year, achieves the best objective function value. The voltage profile of planning procedure is plotted in Fig. 14. As shown in Fig. 14, the best voltage profile is achieved in Sc2.3. However, the Sc2.4 and Sc2.5 achieved acceptable voltage profiles, too. In order to provide a comprehensive economical comparison between the feasible scenarios, the cash flow of the planning period is plotted in Fig. 15.

Fig. 15 shows the cumulative cash difference between the base scenario (Sc1) and the other feasible scenarios. As shown in the figure, the Sc2.5 cash flows during the planning period starts with $+2 \times 10^4$ value which represents the installation cost of OUPQC in the first year in comparison to the base scenario. On the other hand, the Sc2.3 and Sc2.4 start with zero values which represent the equal values of cash flows

Table 4
Planning results of 95-bus distribution network.

Scenario	SEU			SHU(s)			Planning Parameters			
	Location	Rating (kVA)	Installation Year	Location(s)	Rating(s) (kVA)	Installation Year	Energy Loss (MWh) (Reduction w.r.t. Sc-1)	OUPQC costs (×1000$)	V_{min} in planning period	OF
Sc-1	–	–	–	–	–	–	3190.9 (0%)	–	0.874	–
Sc-2.1	There is no possible solution due to the technical constraints.									
Sc-2.2	There is no possible solution due to the technical constraints.									
Sc-2.3	3	2993.3	3	25 34 83	1703.9	3	2567.4 (19.5%)	55.96	0.9086	1.1220
Sc-2.4	3	2668.2	4	10 56 77 95	1198.3	4	2576.3 (19.2%)	37.43	0.9049	0.7613
Sc-2.5	3	2126.4	1	35 44 73 76 95	830.7	1	2595.5 (18.66%)	21.41	0.9003	0.4494

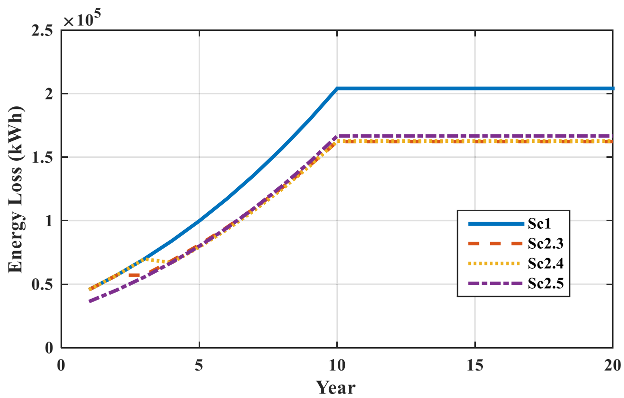

Fig. 13. Energy loss of the network in planning years for different scenarios – 95-Bus distribution network.

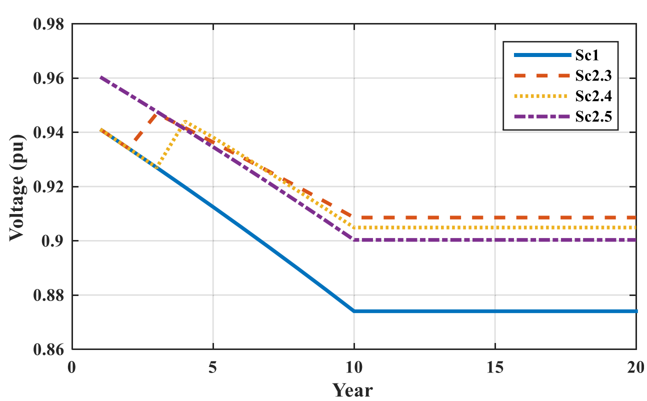

Fig. 14. Minimum voltage of the network in planning years for different scenarios – 95-Bus distribution network.

between these scenarios and base scenario. At the end of 20th year, the cumulative cash flow of the Sc2.5 ends with -2.6×10^4 value which represents the lower cumulative cost in comparison to the base scenario (Sc1).

C. Large-Scale IEEE 119-bus RDS

In order to evaluate the effectiveness of the proposed planning approach in a very large-scale DN, IEEE 119 bus radial DN is utilised. The network is an 11 kV DN with total power loads of 22709.7 kW active power and 17041.1 kvar reactive power. The network data including branch impedances and network loads are obtained from study [48,49]. Single line diagram of IEEE 119-Bus DN is shown in Fig. 16. Table 5 shows the results of the DN in predefined scenarios. (See Table 6)

Table 5 shows the planning results for installation of OUPQC in 119-bus DN. The first scenario (Sc-1) represents the operation of current form

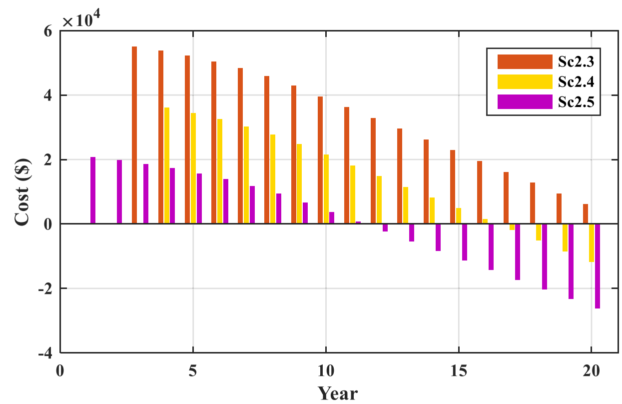

Fig. 15. Cumulative cash difference between the base scenario and the other feasible scenarios.

of the DN during the planning period. As shown in the table, three different locations are obtained as optimum locations for installation of SEUs instead of single SEU for whole of the network due to exponential behaviour of OUPQC cost.

Voltage profile of the scenario Sc-1 in 20 years plotted in Fig. 17. As shown in the Table 5 and Fig. 17, operation of the DN without installation of any compensation devices violate the IEEE limits in fifth year. However, since the voltage limit is considered in planning procedure, the minimum voltage of the network is kept larger than 0.9 pu in all years of operation by installation of different OUPQCs in different scenarios except for Sc-2.1 and Sc-2.2. As explained before, voltage constraint is considered for planning procedure. Hence, the second and third scenarios (Sc-2.1 and Sc-2.2) is not converged to a possible solution. Minimum voltage of the network during 20 years of operation is plotted in Fig. 17.

As shown in the figure, installation of OUPQC in scenarios Sc-2.3 to Sc-2.5 improve the minimum voltage of the network to the allowable limit. Furthermore, as shown in the table, the scenario 2.4 leads to best OF value. In addition, the network energy loss during the 20 years of operation for each scenario are shown in Fig. 18.

As concluded from the table and the above figures, the proposed planning approach minimizes the DN costs for 20 years while maintaining the technical network constraints in allowable limits. As shown in Fig. 18, Sc2.5 results in better energy loss profile in comparison to the other scenarios.

In order to provide a comprehensive economical comparison between the feasible scenarios, the cash flow during the planning period is plotted in Fig. 19.

Fig. 19 shows the cumulative cash difference between the base scenario (Sc-1) and the other feasible scenarios. As shown in the figure, the Sc-2.4 and Sc-2.5 cash flows during the planning period starts with value of $+2.2 \times 10^5$ and $+2.5 \times 10^5$ respectively, which represents the installation cost of OUPQC in the first year in comparison to the base scenario. On the other hand, the Sc2.3 starts with zero values, which

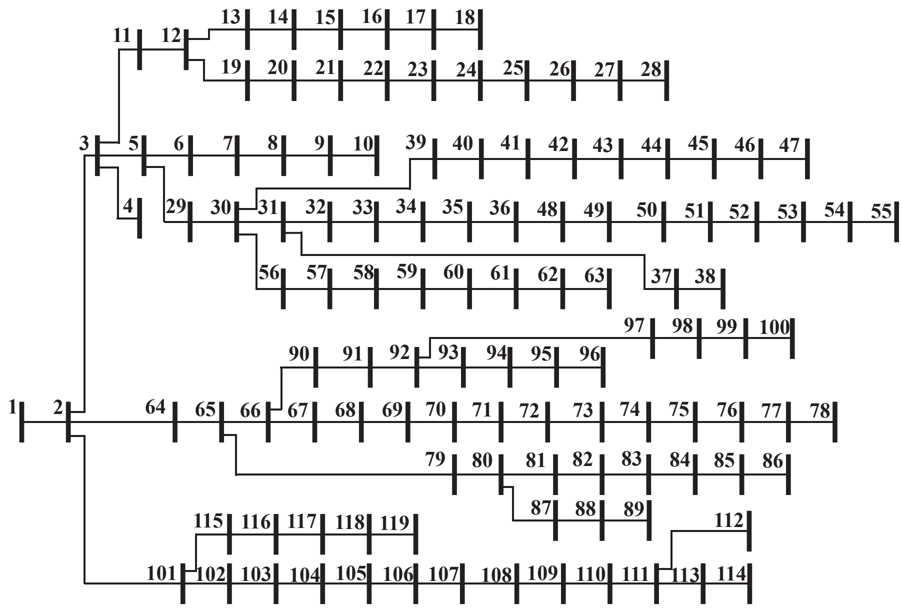

Fig. 16. Single line diagram of IEEE 119-Bus DN (bus numbers reordered).

Table 5
Planning results of 119-bus distribution network.

Scenario	SEU Location	SEU Rating (kVA)	SEU Installation Year	SHU(s) Location(s)	SHU(s) Rating(s) (kVA)	SHU(s) Installation Year	Planning Parameters Energy Loss (GWh) (Reduction w.r.t. Sc-1)	OUPQC costs (×1000$)	V_{min} in planning period	OF
Sc-1	–	–	–	–	–	–	1117.8 (0%)	–	0.8405	–
Sc-2.1	There is no possible solution due to the technical constraints.									
Sc-2.2	There is no possible solution due to the technical constraints.									
Sc-2.3	3 64 101	4301	2	24 43 51 73 85 97 106 110 118	7458	2	983,664 (12%)	151.51	0.9243	0.46
Sc-2.4	3 64 101	4469	1	23 42 49 61 68 74 83 97 103 108 113 117	8141	1	913,243 (18.3%)	220.50	0.9301	0.29
Sc-2.5	3 64 101	4637	1	15 23 35 43 60 67 72 82 88 99 103 107 110 117 112	8976	1	843,939 (24.3%)	252.12	0.9412	0.38

Table 6
Geo-referenced distribution network characteristics.

Network Characteristic	Value
Voltage Level	20 kV
Total Active Loads	37120 kW
Total Reactive Loads	14,671 kVar
Network geographical wideness	2800 × 5960 m
Areas	5
Load Points	56
Total number of Customers	8076

represent the equal values of cash flows between these scenarios and base scenario. At the end of 20th year, the cumulative cash flow of the Sc-2.4 ends with -1.2×10^5 , which represents the lower cumulative cost in comparison to the base scenario (Sc1).

D. Geo-referenced Distribution Network

The proposed planning approach of OUPQC implementation in DN is also applied in a DN with a different condition. The network is geo-referenced DN which is provided by DIgSILENT PowerFactory as a MV

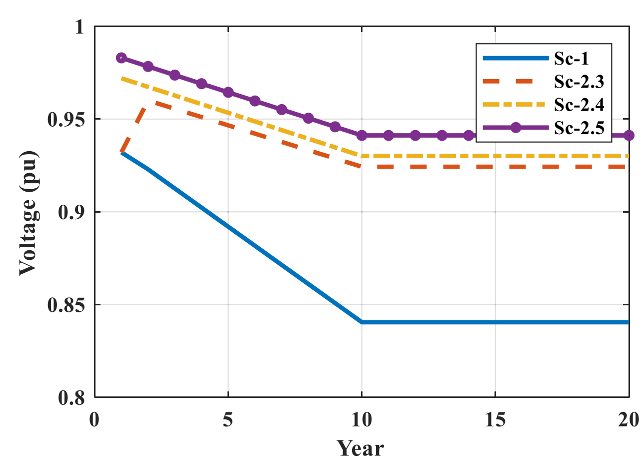

Fig. 17. Minimum voltage of the network in planning years for different scenarios – 119-Bus distribution network.

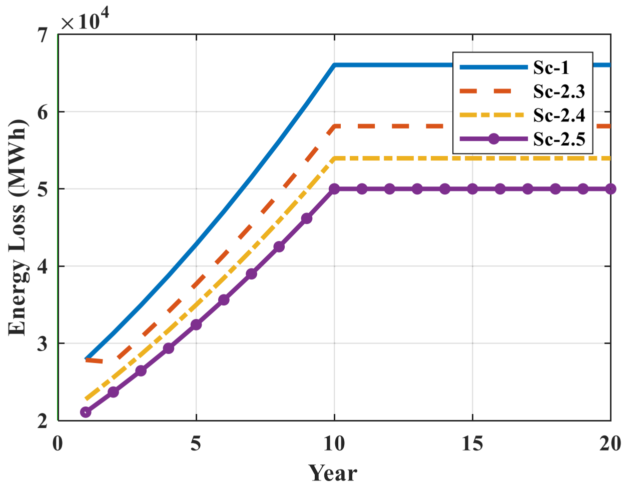

Fig. 18. Energy loss of the network in planning years for different scenarios – 119-Bus distribution network.

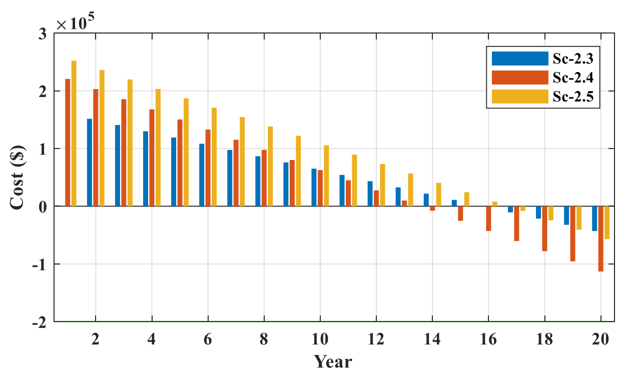

Fig. 19. Cumulative cash difference between the base scenario and the other feasible scenarios-119-bus RDS.

example network. The base network characteristics are as follow. Geo-referenced single line diagram of the network is presented in Fig. 20.

As shown in Table 7, the network consists of five areas. Detail information of number if load points, number of customers and the sharing of active/ reactive power of the network in different areas are shown in Table 7.

In this network, load growth is modelled in two aspects:

– Joining new users in LV DN which results in growth in the load powers of current load points. In this study, different load growth rate is considered for network areas as presented in Table 8 [28].
– The growth in the number of network bus-bars. In order to represent the network growth during the planning horizon, new network bus-bars are added to the network in two stages. Table 9 shows the new bus-bars (load points) and their adding time.

Recently, due to high penetration of distributed generation units in DNs, it is valuable to consider them in the planning problem of OUPQC. Hence, in this scenario, it is assumed that two DG units are installed in the DN during the planning horizon. In general, DG units are divided into two main categories: dispatchable and non-dispatchable units. Non-dispatchable units are those category of DG units which their output power value is dependent to some non-predictable parameters. For instance, the output power of photovoltaic DG units depend on solar radiation during the day (i.e. their output power is intermittent and unpredictable). In this paper, two dispatchable DG units are considered in the planning problem. Table 10 shows the technology and installation

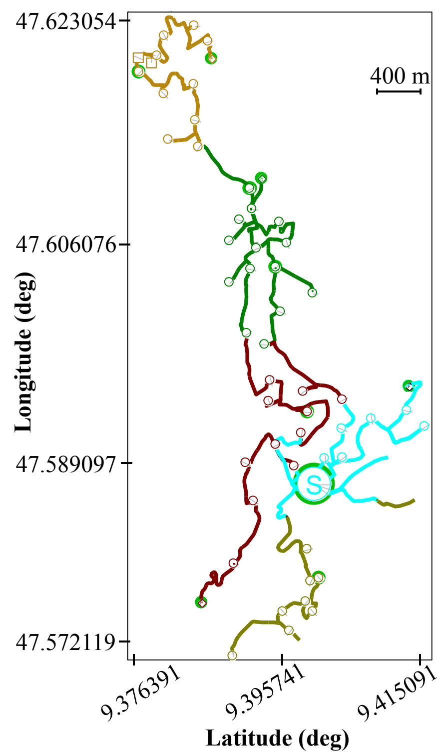

Fig. 20. Single line diagram of geo-referenced distribution network.

Table 7
Detail information of geo-referenced distribution network.

	Load Points	Customers	Load	
			Active (kW)	Reactive (kVar)
Area_01	9	1182	7920	3130
Area_02	8	1588	5485	2166
Area_03	12	1720	7125	2815
Area_04	15	2094	9085	3590
Area_05	12	1492	7505	2970
Total	56	8076	37,120	14,671

Table 8
Load growth model of geo-referenced distribution network.

	Load growth with respect to the first year		
	End of the 3rd year	End of the 7th year	End of the 13th year
Area_01	110 (%)	120 (%)	140 (%)
Area_02	104 (%)	111 (%)	133 (%)
Area_03	117 (%)	130 (%)	157 (%)
Area_04	123 (%)	135 (%)	166 (%)
Area_05	114 (%)	127 (%)	144 (%)

Table 9
New load point information of geo-referenced distribution network.

New load point	Installation Year	Area	Connect to	Load	
				Active (kW)	Reactive (kVar)
59	4	3	053	173	68
60	4	3	019	141	56
61	9	4	040	210	83
62	9	4	056	149	59
63	9	4	039	174	69

year of DG units during the planning horizon. The present scenario is

Table 10
Installation of DG units in geo-referenced distribution network.

DG unit	Installation ear	Area	Connect to	Rating (kW)
1	3	3	017	1500
2	7	4	035	2000
3	16	2	14	2500

different with previous scenarios. The main difference in present scenario and previous ones is the increase of load points during the planning horizon. In previous scenarios, in order to apply the proposed method for optimum installation of OUPQC in DN, there was a constant number of candidate locations (load points).

However, as shown in the Table 9 in the present scenario, the number of candidate locations (i.e. load points) would be increased in two steps; forth year and ninth year. For more explanation, there are 58 candidate location for installation of OUPQC units before the fourth year. Between the fourth and ninth year, there are 60 load points which are possible to install the SEU and SHUs of OUPQC. Then, after the ninth year, 63 candidate locations are exist for installation of OUPQC units. Therefore, it is not possible to define a constant domain of genetic algorithm for candidate locations. In order to overcome the explained issue, the genetic algorithm is utilized in three time-periods: period 1 from first year to forth year, period 2 form fifth year to ninth year and period 3 from tenth year to twentieth year. Then, the optimum results of objective function is compared between the defined periods and the best objective function value is considered as the final decision for installation of OUPQC in DN. Table 11 show the optimization results.

Table 11 shows the optimization results for planning of OUPQC in geo-referenced DN. According to the previous explanation, the optimization procedure are performed in three defined periods in which the installation location candidates are different. Best optimization results of each period is chosen and presented in the above table. As shown in the table, optimum location for installation of SEU for each scenario in

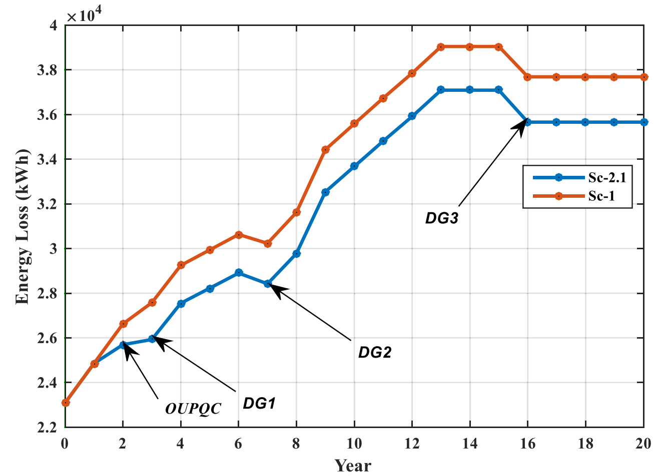

Fig. 21. Energy loss variations during the planning horizon- geo-referenced DN.

Table 11
Planning results of geo-referenced distribution network.

Scenario	SEU			SHU(s)			Planning Parameters			
	Location	Rating (kVA)	Installation Year	Location (s)	Rating (s) (kVA)	Installation Year	Energy Loss (MWh) (Reduction w.r.t. Sc-1)	OUPQC costs (×1000$)	V_{min} in planning period	OF
Sc-1	–	–	–	–	–	–	38,315 (0%)	–	0.891	–
Sc-2.1	SEL*	2389.5	2	33	2744.7	2	32,529 (15.1%)	58.71	0.932	0.014
	SEL*			37						
	SEL*			20						
	SEL*			6						
	SEL*			14						
Sc-2.2	SEL*	2840.1	3	44 50	3128.4	3	31,916 (16.7%)	62.27	0.935	0.018
	SEL*			32 40						
	SEL*			23 53						
	SEL*			4 8						
	SEL*			13 16						
Sc-2.3	SEL*	3247.0	2	28 45 52	3614.1	2	31,610 (17.5%)	69.50	0.946	0.023
	SEL*			30 36 40						
	SEL*			22 27 53						
	SEL*			4 7 41						
	SEL*			13 14 16						
Sc-2.4	SEL*	3351.9	2	33 45 48 55	4125.6	2	30,882 (19.4%)	78.95	0.949	0.025
	SEL*			26 35 37 40						
	SEL*			17 22 23 53						
	SEL*			3 6 7 41						
	SEL*			12 13 14 16						
Sc-2.5	SEL*	3587.1	2	24 31 42 45 51	4736.4	2	30,231 (21.1%)	95.73	0.961	0.029
	SEL*			18 30 34 37 40						
	SEL*			17 22 23 27 53						
	SEL*			3 5 6 7 41						
	SEL*			11 12 13 14 16						

* Sending End Location of feeder.

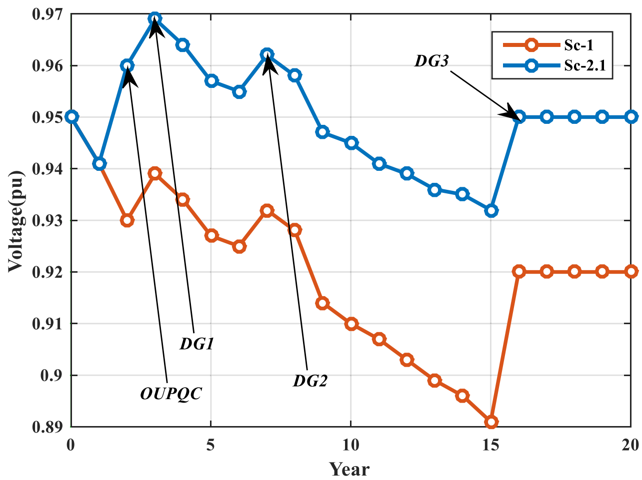

Fig. 22. Minimum voltage variations during the planning horizon- geo-referenced DN.

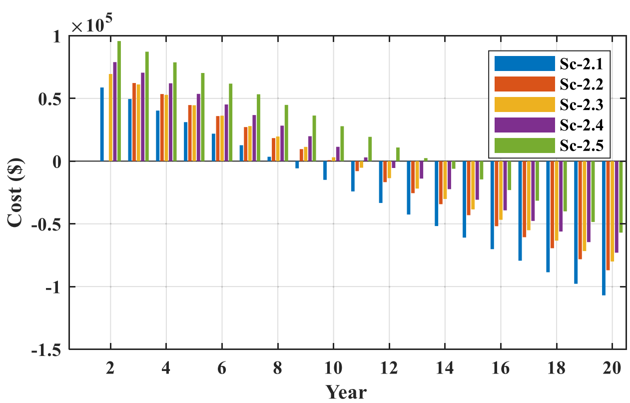

Fig. 23. Cumulative cash difference between the base scenario and the other feasible scenarios-geo-referenced RDS.

achieved at sending end location of feeder. Since the case study network comprises five distribution feeders, hence the SEU of OUPQC is installed in each feeder separately. According to the OF values for different scenarios which is presented in the table, the second scenario (Sc-2.1) in which a single SHU is installed in each feeder, has the best OF value. As shown in the above table, installation of more SHUs in the DN results in higher minimum voltage of the network (i.e. voltage profile). Furthermore, installation of more SHUs results in more reduction in the energy loss of the network. However, installation of more SHUs in the network requires more installation and maintenance cost in comparison to the Sc-2.1 which leads to larger OF value. Fig. 21 shows energy loss of the network during the planning horizon in the optimum scenario versus the first scenario in which no OUPQC is installed.

As shown in the above figure, installation of OUPQC in second year results in loss reduction in comparison to the first scenario. In the energy loss comparison figure, the effect of DG unit installation is also demonstrated. Fig. 22 shows the comparison between the base and optimum scenarios in terms of minimum voltage of the DN.

As shown in the above figure installation of OUPQC in the second year, highly improve the voltage profile. In addition, according to the figure, installation of three DG units also improve the voltage profile in the third, seventh and sixteenth years. In order to provide a comprehensive economical comparison between the feasible scenarios, the cash flow during the planning period is plotted in Fig. 23.

Fig. 23 shows the cumulative cash difference between the base scenario (Sc-1) and the other feasible scenarios. As shown in the figure, the Sc-2.1, Sc-2.3, Sc-2.4, and Sc-2.5 cash flows during the planning period starts with non– zero values, which represents the installation cost of OUPQC in the first year in comparison to the base scenario. On the other hand, the Sc2.2 starts with zero values, which represent the equal values of cash flows between these scenarios and base scenario. At the end of 20th year, the cumulative cash flow of the Sc-2.1 ends with -1.2×10^5 value, which represents the lowest cumulative cost in comparison to the base scenario (Sc1).

5. Conclusion

Distribution Networks (DNs) always face with voltage and current deficiencies due to different reasons. Connection of large variety of loads (e.g. electric drives, harmonic loads, etc.) and high R/X ratio of network branches, result in voltage and current deficiencies in the DNs. In order to overcome the deficiencies, Custom Power Devices (CPDs) are installed in the DNs. Open UPQC (OUPQC) which consists of single series unit (SEU) and multiple shunt units (SHUs) is attracting the attention of network planners due to its capabilities in compensation of voltage and current deficiencies together. In this paper, for the first time, a planning approach is proposed to implement the OUPQC in DN while considering time varying and growing loads in the planning horizon. Technical constraints of the network such as voltage and current limitations, are considered in the planning procedure. The optimization process is performed to achieve the best objective function value which represents the cost to benefit ratio. The proposed planning procedure it utilized to be evaluated in the four different DNs: IEEE 69-bus, practical 95-bus Iranian DN, IEEE large scale 119 bus DN, and geo-referenced DN. The results show the effectiveness of the proposed method to overcome the voltage and current deficiencies of the DNs while achieving the best economical solutions. The proposed method can be utilized as a useful tool by the network planner in practical DN.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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