An On-Line Operational Optimization Approach for Open Unified Power Quality Conditioner for Energy Loss Minimization of Distribution Networks

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***Abstract*—This paper presents an on-line operational optimization approach to determine the optimal reactive power/volt-ampere reactive (VAr) set points for open unified power quality conditioner (UPQC-O) under varying load demand of a distribution network. The UPQC-O consists of series and shunt inverters. The modeling of UPQC-O is done to provide VAr support to a network, to mitigate supply voltage sag to the downstream buses, and to eliminate harmonics present in the line current. A non-linear optimization problem is formulated to determine the optimal VAr set points for the inverters of UPQC-O in each loading condition. The objective function is the minimization of energy loss. The limits on bus voltage magnitude, line current flow, and maximum VAr support capacities of inverters are considered to be the operational constraints. The optimization is performed with the data of hourly varying load demand for different seasons in a year. The optimization problem is solved using CONOPT solver of general algebraic modeling system. The cost-benefit analysis and the infrastructure required for the real time implementation of the proposed methodology are also provided. The simulation results show the effectiveness of the proposed approach in energy loss reduction.**

***Index Terms*—Distribution networks, energy loss, non-liner optimization, open UPQC, power quality, VAr set point.**

NOMENCLATURE

ρ	Set of all lines of the network.
μ	Set of all buses of the network except substation bus.
ϑ	Set of all downstream buses which are beyond bus ‘f’.
τ	Set of all downstream lines which are beyond bus ‘f’.
γ	Set of seasons in a year.
β	Set of day type (weekday/weekend) in a week.
Γ_{yw}	Set of load scenarios in day type ‘w’ of season ‘y’.
Δ	Set of all buses where shunt inverter is placed.
Λ	Set of all buses where series inverter is placed.
y	Index for seasons in a year.
w	Index for day type (weekday/ weekend) in a week.
d_{yw}	Index for load scenarios in day type ‘w’ of season ‘y’.
t_y	Total number of weeks in a year for which season ‘y’ occurs.
t_w	Total number of days in a week for which day type ‘w’ occurs.
t_{ywh}	Total number of hours of occurrence of load scenario ‘d_{yw}’ in day type ‘w’ of season ‘y’.
P_{ef}	Real power flow of line ‘ef’.
Q_{ef}	Reactive power flow of line ‘ef’.
P_g	Real power demand of bus ‘g’.
Q_g	Reactive power demand of bus ‘g’.
$\vec{I}_{ef}$	Current flow in line ‘ef’.
R_{ef}	Resistance of line ‘ef’.
X_{ef}	Reactance of line ‘ef’.
Z_{ef}	Impedance of line ‘ef’.
L_{ef}	Real power loss in line ‘ef’.
M_{ef}	Reactive power loss in line ‘ef’.
$\vec{V}_e$	Bus voltage at bus ‘e’.
V_{Se}^{Sag}	Series voltage injected by series inverter during voltage sag condition.
V_{Se}^{Hel}	Series voltage injected by the series inverter during healthy condition.
V_R	Magnitude of receiving end voltage in healthy condition.
V_R'	Magnitude of receiving end voltage during voltage sag condition.
S_U	Total VA-rating of UPQC-O.
S_{Se}	VA-rating of series inverter.
S_{Sh}	VA-rating of shunt inverter.
I_S	Amount of current flowing through the series inverter.
Q_{Se}	Rated VAr capacity of series inverter.
Q_{Sh}	Rated VAr capacity of shunt inverter.
I_{Sh}	Shunt compensating current (fundamental) injected by shunt inverter.
I_L	Line current at the point of connection of shunt inverter.
V_L	Bus voltage magnitude at the point of connection of shunt inverter.

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I_L^{dis}	Distortion component in line current I_L.
I_{Sh}^{dis}	Distortion component in shunt compensating current I_{Sh}.
Q_f^U	VAr support provided by series/shunt inverter at bus 'f'.
$V_{min}(V_{max})$	Minimum (maximum) bus voltage limit.
I_{max}	Thermal limit of all lines.
S_{base}	Base MVA of the distribution network.
$I_{efd_{yw}}$	Current flow in line 'ef' in during load scenario 'd_{yw}'.
C_E	Unit cost of energy (\$/kWh).
r_e	Annual energy price growth rate.
$K_{Se}(t)$	Ratio of series voltage injected by the series inverter in a particular loading condition $\{V_{Se}^{Hel}(t)\}$ to that of the healthy condition, i.e., V_{Se}^{Hel}.
$K_{Sh}(t)$	Ratio of shunt compensating current injected by the shunt inverter in a particular loading condition $\{I_{Sh}(t)\}$ to that of the rated value, i.e., I_{Sh}.
N_{Sh}	Number of shunt inverter(s) to be placed in distribution network.
I_{Sh}^{rms}	RMS value of shunt compensating current.
N	Number of total buses in a network.

I. Introduction

The optimal operation of power systems under varying load demand is a challenging research problem. In practical power systems, there are many compensating devices deployed so as to improve the steady-state operational performance, for example, capacitor bank, on-load tap changer, voltage regulators etc. The determination of the optimal set points of these devices under varying load demand needs the formulation of an on-line optimization approach. The power/energy loss reduction/minimization is one of the important objective functions used in the determination of the set points for the compensators [1]–[4]. Some of the approaches are capacitor placement [1], [2], network reconfiguration [3], distributed generation (DG) allocation [4] etc. Although all these techniques can help in power/energy loss minimization, there are some issues in deploying these technologies. The capacitor placement is a cheaper option for the energy loss reduction. But, since the load demand is continuously varying, the smooth control of capacitor is a complex task. Thus, a capacitor bank is traditionally controlled in few discrete steps [2]. Moreover, the change of set point from one value to other creates transient. The reconfiguration of a network can result in significant reduction in energy loss. But, it needs optimal operation of the tie-switches by solving a combinatorial optimization problem. In case of DG placement, the handling of intermittency of renewable generation is a challenging task. Moreover, all these approaches are not skilled to mitigate power quality (PQ) issues, such as, voltage sag/swell mitigation, harmonics elimination etc. The custom power devices [5] are a group of reactive power compensators. The placement of these in a distribution network helps in mitigating some of the PQ problems and it reduces energy loss of a network by providing the reactive power/volt-ampere reactive (VAr) support to it [5].

Unified power quality conditioner (UPQC) is type of custom power device. An UPQC consists of two inverters, namely, series and shunt inverters to provide VAr support and to mitigate some of the PQ issues, such as, voltage sag/swell, harmonics, voltage unbalance etc. [6]. In literature, there are many works reported on UPQC. A comprehensive review on UPQC can be found in [7]. The research on UPQC is of multi-directional with following attributes:

- (a) *Development of Control Strategy:* In [8], a control strategy is developed for the minimization of VA-loading of UPQC by injecting series voltage with an optimal phase angle. In [9], phase angle control (PAC) approach is proposed for UPQC to allow the series inverter to share the VAr compensation along with the shunt inverter. In [10], the fixed and variable PAC methods-based controllers are designed for UPQC. In [11], non-linear sliding mode control and switching dynamics control strategies are developed for UPQC to mitigate some PQ problems of distribution networks. In [12], [13], control strategies are developed for the series and shunt inverters of solar photovoltaic (PV) integrated UPQC. In [14], the design and control of transformer-less UPQC are presented.
- *(b) Optimal Sizing:* In [15], the variable PAC method based optimization algorithm is developed to optimize the VA-ratings of series and shunt inverters. A control algorithm is also developed to reduce the VA-loading of UPQC. The same methodology is used in [16] to optimize the VA-ratings of series and shunt inverters, and the series transformer. In [17], an approach is proposed to determine the minimum VA-rating of UPQC based on the different values of sag and swell. In [18], superconducting fault current limiters are used along with UPQC to reduce the overall VA-rating.
- *(c) Allocation to Distribution Networks:* The reactive power compensation capability of UPQC for the improvement of energy efficiency of distribution networks is investigated in [19]–[22]. In [19], the impact of allocation of UPQC on the line loading, network power loss, and voltage stability of distribution network is studied. In [20], the VA-rating and location for the placement of UPQC are determined using particle swarm optimization (PSO) by minimizing the network power loss and voltage drop. In [21], PSO-based multi-objective planning approach is developed to simultaneously minimize the VA-rating of UPQC, network power loss, and percentage of bus with under voltage problem. In [22], the location and size of UPQC are determined to minimize the cost of energy loss, cost of load interrupted due to voltage sag, and cost of UPQC. The impact of UPQC allocation on voltage unbalance, total harmonic distortion (THD), voltage sag etc., is also studied.
- *(d) Development of New Topology:* An open UPQC (UPQC-O) topology is reported in [23], in which the series and shunt inverters are placed in different locations and they do not share the common DC-link. In [24], modified

three-phase four-wire UPQC topology is provided. In [25], a three-phase three-wire UPQC topology is reported with ten switching devices. In [26], [27], the current-source inverter-based UPQC topologies are developed.

The placement of UPQC-O in distribution networks can simultaneously improve the energy efficiency and PQ [28]. The works reported on UPQC-O can be found in [28]–[32]. In [29], enhanced phase-locked loop and non-linear adaptive filter-based control schemes are designed for the inverters of UPQC-O. In [30], the performance of UPQC-O is demonstrated on a low voltage distribution network of city of Brescia (Italy). In [31], PV-integrated UPQC-O is presented for the improvement of energy efficiency and PQ of distribution networks. In [32], the capability of UPQC-O for the simultaneous improvement of PV hosting capacity and energy efficiency of distribution networks is studied. However, in [31], [32], the optimal location and rating of UPQC-O are determined considering the peak and off-peak loading conditions. But, practically, load demand varies with time, day, and seasons. Hence, the injection of rated VAr during light load condition may increase the energy loss in distribution networks. Thus, this needs an approach which can be used to determine time varying VAr set points for the inverters of UPQC-O during time varying load demand. But, in none of these works on UPQC-O, this is addressed. This is the motivation behind the proposed approach.

In this work, an operational optimization approach for the determination of VAr compensation/injection set points for UPQC-O with time varying load demand is proposed. The objective function is the minimization of the energy loss of distribution networks under the operational constraints, such as, bus voltage limit, line thermal limit, and maximum VAr support capacity limits of the inverters. The optimization problem is modelled to fit into General Algebraic Modelling System (GAMS) software. The CONOPT solver is used to solve the optimization problem. The infrastructure required for the real-time implementation of the proposed methodology is also discussed. The cost-benefit analysis of proposed methodology in view of saving from the energy loss reduction is provided. The contributions of this work are:

- The formulation of an operational optimization approach to determine the time varying VAr compensation set points for UPQC-O with time varying load demand
- To study the impact of the placement of UPQC-O with time varying set points on the energy loss reduction of distribution networks

The simulation study is carried out using a 33-bus radial distribution network.

This paper is organized as follows. In Section III, the problem formulation for the operational optimization of UPQC-O is given. Section IV describes the infrastructure required for real time implementation of proposed methodology. Section V provides the simulation results. Section VI concludes the work.

II. Problem Formulation for the Operational Optimization of UPQC-O

This section describes the problem formulation. The steady-state models of radial distribution networks and UPQC-O are also provided.

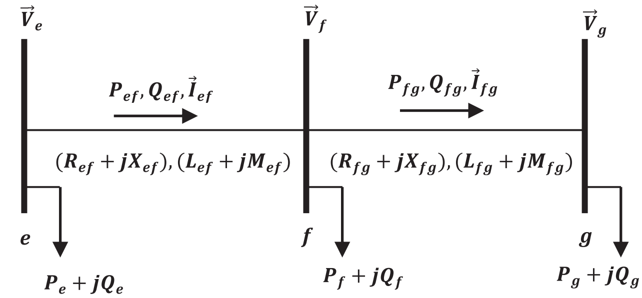

Fig. 1. A typical 3-bus radial distribution network.

A. Steady-State Model of Balanced Radial Distribution Networks

A 3-bus radial distribution network, as shown in Fig. 1, is considered to discuss the steady-state operational model of a radial distribution network [33]. The real and reactive power flow in any line, say, 'ef' can be computed by applying the load balance at bus 'f' as:

$$P_{ef} = \sum_{g \in \vartheta} P_g + P_f + \sum_{fg \in \tau} L_{fg} \quad \forall f \in \mu \tag{1}$$

$$Q_{ef} = \sum_{g \in \vartheta} Q_g + Q_f + \sum_{fg \in \tau} M_{fg} \quad \forall f \in \mu \tag{2}$$

The receiving end bus voltage magnitude (V_f) of any line, say, 'ef' can be computed by using Eq. (3),

$$V_e^2 = V_f^2 + 2\left(R_{ef}P_{ef} + X_{ef}Q_{ef}\right) + Z_{ef}^2 I_{ef}^2 \quad \forall ef \in \rho \tag{3}$$

The magnitude of current flow in any line, say, 'ef' can be computed as:

$$I_{ef}^2 = \frac{P_{ef}^2 + Q_{ef}^2}{V_f^2} \quad \forall ef \in \rho \tag{4}$$

The different operational parameters of a distribution network, such as, bus voltage magnitude, line current flow, network power loss can be computed by using Eqs. (1)–(4).

B. Steady-State Model of UPQC-O for Radial Distribution Networks

An UPQC-O consists of two voltage-sourced inverters: (i) series inverter and (ii) shunt inverter. The series inverter is designed to provide VAr support to a network during healthy condition and to mitigate supply voltage sag during voltage sag condition [32]. On the other hand, the shunt inverter is modelled to provide VAr support to a network and to eliminate harmonics present in line current [32]. A 7-bus radial distribution network, as shown in Fig. 2, is considered to describe the steady-state model of UPQC-O. The phasor diagrams for the series and shunt inverters are shown in Figs. 3(a) and 3(b), respectively.

- *Steady-State Model of the Series Inverter:* For a k p.u. amount of voltage sag in supply voltage, the receiving end

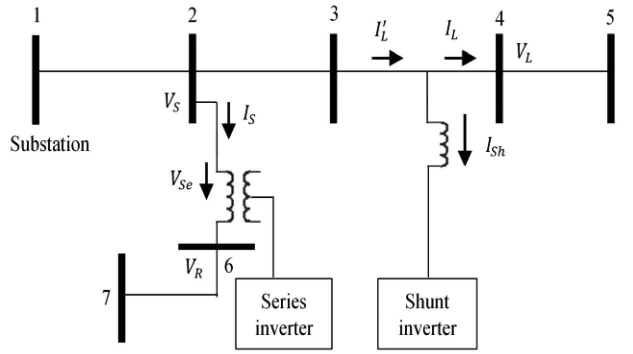

Fig. 2. A typical 7-bus radial distribution network with UPQC-O.

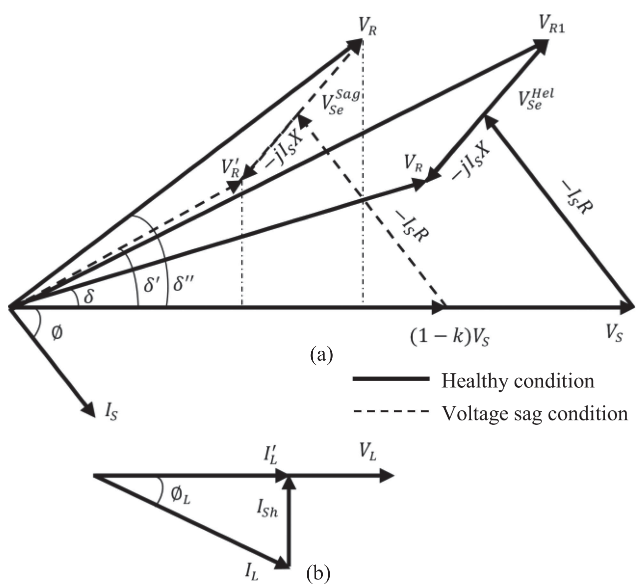

Fig. 3. Phasor diagrams for: (a) series and (b) shunt inverters of UPQC-O.

voltage is reduced from V_R to V'_R. The receiving end voltage during voltage sag condition can be computed as:

$$\overrightarrow{V'_R} = (1-k)\ \overrightarrow{V_S} - \overrightarrow{I_S}\,(R+jX) \tag{5}$$

The series inverter injects V_{Se}^{Sag} amount of series voltage to mitigate k p.u. amount of voltage sag in supply voltage V_S. The series injected voltage V_{Se}^{Sag} can be computed as:

$$V_{Se}^{sag} = \sqrt{V_R^2 + {V'_R}^2 - 2V_R{V_R}'\cos(\delta'' - \delta')} \tag{6}$$

From Fig. 3(a), δ'' can be found as:

$$\delta'' = \cos^{-1}\left\{\frac{{V_R}'}{V_R}\cos(\delta' + \emptyset)\right\} - \emptyset \tag{7}$$

In the healthy condition, the series inverter can inject maximum $\boldsymbol{V_{Se}^{Hel}}(=\boldsymbol{V_{Se}^{\mathrm{Sag}}})$ amount of series voltage to provide the rated VAr support to a network. The VA-rating of series inverter can be computed as:

$$S_{Se} = V_{Se}^{Hel}\ I_S \tag{8}$$

The rated VAr capacity of the series inverter (Q_{Se}) is equal to S_{Se}.

- *Steady-State Model of the Shunt Inverter:* The magnitude of shunt compensating current (fundamental) to be injected by the shunt inverter can be computed from Fig. 3(b),

$$I_{Sh} = I_L\ \sin\emptyset_L \tag{9}$$

One of the functions of the shunt inverter is to eliminate the harmonics present in the line current. This is modelled by Eq. (10) [32]:

$$I_L^{dis} = I_{Sh}^{dis} \tag{10}$$

Thus, the RMS value of shunt compensating current including total harmonic distortion (THD) is computed as:

$$I_{Sh}^{rms} = I_L\ \sqrt{(\sin\emptyset_L)^2 + {THD_L}^2} \tag{11}$$

The VA-rating of shunt inverter is computed with the RMS value of shunt compensating current as:

$$S_{Sh} = V_L\ I_{Sh}^{rms} \tag{12}$$

Since the optimization model proposed in this work is to minimize the energy loss with UPQC-O allocation, the VAr injection of shunt inverter(s) is computed with the fundamental shunt current as given below.

$$Q_{Sh} = V_L\ I_{Sh} \tag{13}$$

The total VA-rating of UPQC-O is shown in Eq. (14).

$$S_U = S_{Se} + S_{Sh} \tag{14}$$

C. Operation of UPQC-O During Time Varying Load Demand

The variation in load demand of a network changes the line currents and bus voltages of a network. The operation of UPQC-O under time varying load demand is described below.

- *Operation of Series and Shunt Inverters during Healthy Condition:* The series inverter injects a fraction $\{K_{Se}(t)\}$ of rated series voltage (V_{Se}^{Hel}) and the shunt inverter injects a fraction $\{K_{Sh}(t)\}$ of rated shunt current (I_{Sh}) in different loading conditions to provide the optimal VAr compensation to a network. i.e.,

$$V_{Se}^{Hel}(t) = K_{Se}\ (t)\, V_{Se}^{Hel} \tag{15}$$

$$I_{Sh}(t) = K_{Sh}\ (t)\, I_{Sh} \tag{16}$$

Since both the inverters of UPQC-O are designed to inject only reactive power to a network, the phase angle between $V_{Se}^{Hel}(t)$ and $I_S(t)$ is exactly maintained at 90° for the series inverter in all the loading conditions. For the shunt inverter, the phase angle between the $V_L(t)$ and $I_{Sh}(t)$ is also maintained at 90° for the same reason.

- *Operation of Series Inverter during Voltage Sag Condition:* One of the functions of the series inverter is to mitigate the voltage sag occurring at the upstream network. The amount of sag mitigated by the series inverter in different loading conditions is computed as:
  1) The VA-rating of the series inverter (S_{Se}) is computed by considering a given amount of voltage sag in supply voltage V_S and the peak load demand of the base-case

network. The current flowing through the series inverter, i.e., $I_S(t)$ would change with the change in load demand. The amount of series voltage to be injected by the series inverter in a particular loading condition can be computed by using Eq. (8) as:

$$V_{Se}^{Sag}(t) = \frac{S_{Se}}{I_S(t)} \tag{17}$$

2) The amount of sag $k(t)$ to be mitigated by the series inverter in a particular loading condition can be computed by solving Eqs. (5)–(7).

D. Operational Optimization Problem

The optimization problem is formulated to determine the optimal VAr compensation set points for the inverters of UPQC-O in each loading condition. The minimization of hourly energy loss of distribution network is considered to be the objective function. The mathematical formulation of the proposed optimization problem is given below.

$$\min EL = \sum_{ef\in\rho} I_{ef}^2 R_{ef} \tag{18}$$

subjects to the following constraints:

$$P_{ef} = \sum_{g\in\vartheta} P_g + P_f + \sum_{fg\in\tau} L_{fg} \quad \forall f \in \mu \tag{19}$$

$$Q_{ef} + Q_f^U = \sum_{g\in\vartheta} Q_g + Q_f + \sum_{fg\in\tau} M_{fg} \quad \forall f \in \mu \tag{20}$$

where, Q_f^U is the amount of reactive power provided by the series inverter (Q_f^{Se}) or shunt inverter (Q_f^{Sh}) located at bus 'f'.

$$V_e^2 = V_f^2 + 2\left(R_{ef}P_{ef} + X_{ef}Q_{ef}\right) + Z_{ef}^2 I_{ef}^2 \quad \forall ef \in \rho \tag{21}$$

$$I_{ef}^2 = \frac{P_{ef}^2 + Q_{ef}^2}{V_f^2} \quad \forall ef \in \rho \tag{22}$$

$$V_{min} \le V_f \le V_{max} \quad \forall f \in \mu \tag{23}$$

$$I_{ef} \le I_{max} \quad \forall ef \in \rho \tag{24}$$

$$Q_f^{Sh} \le Q_{Sh} \quad \forall f \in \Delta \tag{25}$$

$$Q_f^{Se} \le Q_{Se} \quad \forall f \in \Lambda \tag{26}$$

Eq. (18) represents the objective function for the energy loss minimization. Eqs. (19)–(24) represent the steady-state operational constraints of a radial distribution network with UPQC-O. The constraints (25) and (26) are to limit the VAr injection below the Volt-Ampere capacities of the shunt and series inverters, respectively.

III. Infrastructure for the Real Time Implementation of Proposed Methodology and Solution Strategy

This section briefly describes the solution approach along with the infrastructure required for the real time implementation of the proposed methodology. A 5-bus radial distribution network

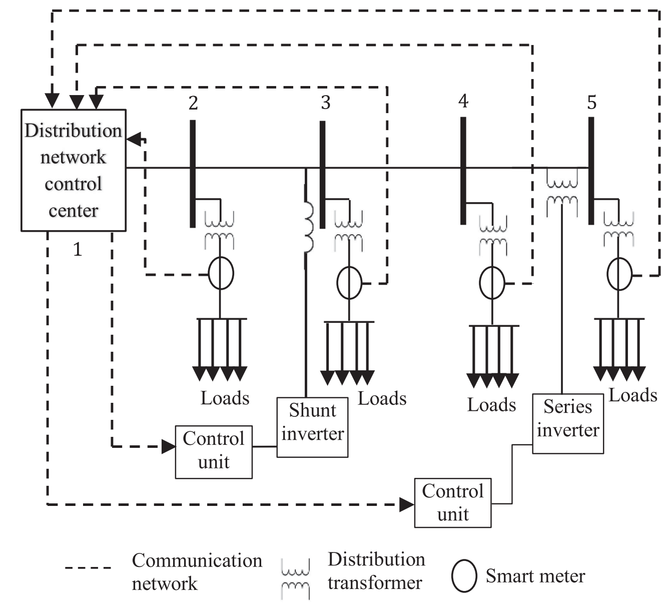

Fig. 4. Schematic for the infrastructure required for the real time implementation of the proposed approach.

with smart grid technologies, as shown in Fig. 4, is used. Smart-grid technologies, such as, smart meters, communication network, information technology, advance control systems etc., are required for the implementation of proposed methodology. The respective functions of these technologies are explained below.

- *Smart Meter (SM):* It is an electronic device which is used to measure the electricity usage and to send the information to the energy supplier. The SMs located near to the distribution transformers (DTs) measure the time varying load demand under a DT and send the information to the distribution network control center (DNCC).
- *Communication Network (CN):* It is required to send the load demand data from each SM to the DNCC and also to send the optimal VAr injection set points obtained with the operational optimization from the DNCC to each inverter. The type of CN used for the communication of information can be decided based on the geographical area of network, distance between the load centers and DNCC, operating range of CN, data transfer rate of CN etc. Optical fibers or wireless communication can be used.
- *Control Infrastructure:* It is used to control/regulate the behavior of devices/systems. In this work, it is required to receive the optimal VAr injection set points from the DNCC and to tune the operations of the inverters.
- *Other Accessories:* The information of electricity usage recorded by a SM is firstly encoded using an encoder to transmit the information to the DNCC. The information received by the receiver at the DNCC is to be decoded with a decoder. The data aggregator unit is to be used to collect the information of hourly average load demand of all the buses. The load data can also be collected in a user-defined time interval. This information is to be transferred to the computer for the determination of optimal VAr injection set points for the inverters of UPQC-O. The information of

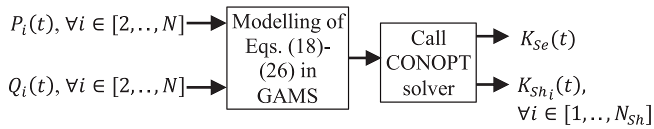

Fig. 5. Block diagram for the determination of set points of the inverters.

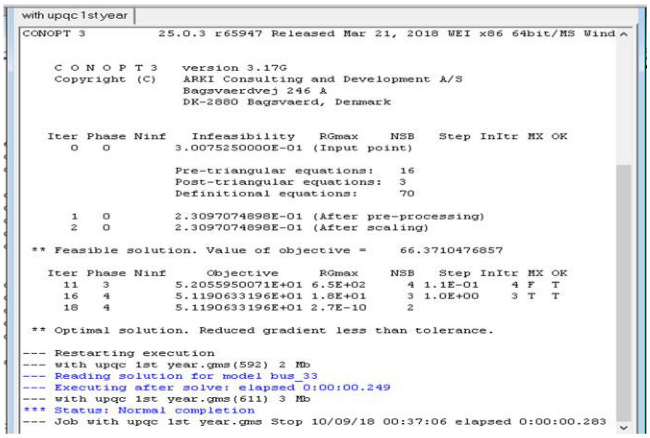

Fig. 6. Snapshot for a solution obtained with CONOPT solver of GAMS.

the optimal VAr injection set points needs to be encoded with an encoder to transmit to the respective control units of the inverters. The information received in the control units is to be again decoded with a decoder to tune the set points, i.e., $K_{Se}(t)$ and $K_{Sh}(t)$ of the inverters.

- *Solution Strategy:* The proposed optimization model is fitted into GAMS, a high level modelling software used to solve different kind of optimization problems. Since the problem is a kind of non-linear optimization, CONOPT solver of GAMS is used. It takes less than two seconds to solve the proposed optimization problem. Hence, it can reliably be used in solving the problem online for real distribution networks. The determination of the set points for the inverters of UPQC-O using GAMS is pictorially shown in Fig. 5. The snapshot for a solution obtained with CONOPT solver of GAMS is shown in Fig. 6.

IV. Simulation Results

The proposed methodology of operational optimization of UPQC-O with time varying load is validated on a 33-bus radial distribution network. It is of single feeder network as shown in Fig. 7. The total peak real and reactive power demand of the network are 3.7150 MW and 2.3 MVAr, respectively. The base VA and base voltage are 100 MVA and 12.6 kV, respectively. The bus data and line data of the network can be found in [34]. The circled area in the Fig. 7 is considered to be an industrial area. The voltage sag occurred in upstream network may severely affect the performance of many adjustable speed drives used in industries [35]. Hence, a series inverter is judiciously located at bus 19 to protect all the industrial loads from voltage sag. Two case studies are provided based on the number and different locations of shunt inverters.

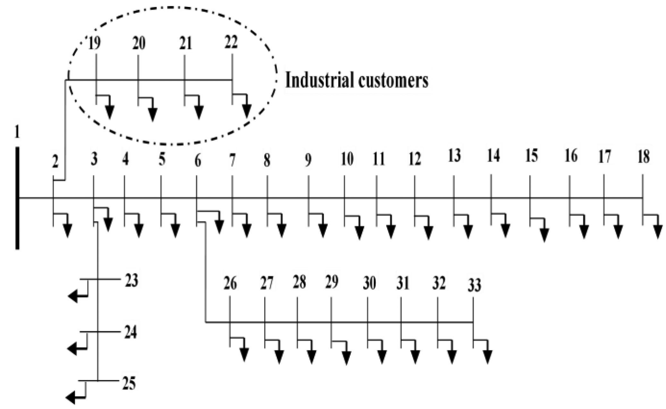

Fig. 7. Single line diagram of the 33-bus radial distribution.

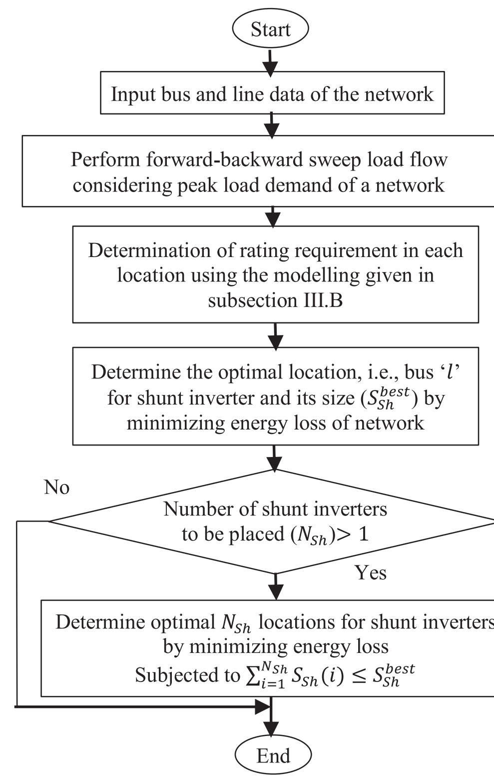

Fig. 8. Flowchart for the determination of locations and sizes of shunt inverter for single-point and multi-point compensations.

- *Case 1:* Single-point compensation with a shunt inverter located at bus 6.
- *Case 2:* Three-point compensation with three shunt inverters located in buses 7, 8, and 9.

The flow chart for the determination of the locations and sizes of shunt inverters for single-point and multi-point compensations is shown in Fig. 8. It is to be noted that the locations of the shunt inverters for multi-point compensation are selected such that the sum total of the sizes of all the inverters does not exceed the size of the inverter obtained in single point compensation. This is to have a fair comparison in between the single and multi-point compensations.

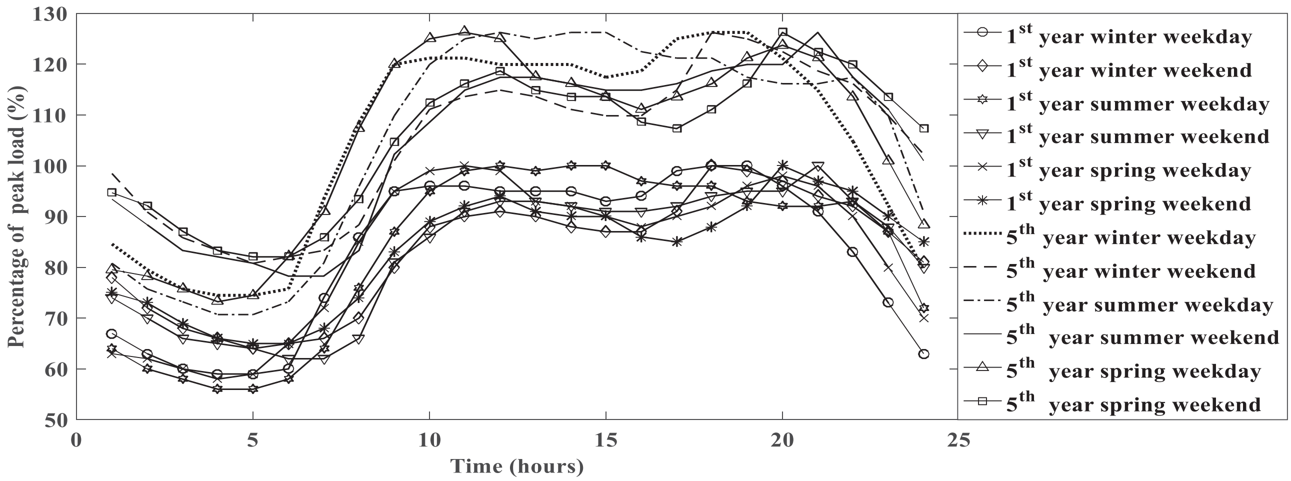

Fig. 9. Load curves for different seasons in the1st and 5th years of planning horizon.

The VA-ratings of inverters are computed by considering 30% voltage sag to be mitigated, 20% THD in line current, and peak load demand of the base-case network [31], [32]. The modelling provided in Section III-B is followed to set the VA-ratings of the inverters. It is assumed that the same amount of THD is present in all the loading conditions. Due to unavailability of standard short interval load data, the seasonal hourly average load variation, given in IEEE reliability test system [36], is considered to have the daily variation in load demand. The rate of annual load growth and energy price growth are assumed to be 6% [37] and 4% [38], respectively. The unit cost of energy is assumed to be 0.08$/ kWh [22].The planning horizon for the cost benefit analysis is considered to be 5 years. The load curves for different seasons of the 1st and 5th years are shown in Fig. 9. The minimum and maximum bus voltage magnitude limits are considered to be 0.9 p.u. and 1.05 p.u., respectively. The maximum line current flow limit for all lines are set as 300 A [39]. The CONPOT solver of GAMS is used to solve the problem. The simulation study is performed on Intel Core™ i5-4570 CPU @ 3.2 GHz processor.

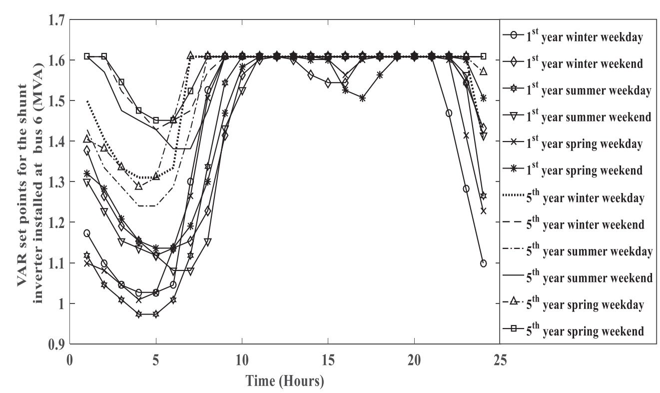

Fig. 10. Optimal VAr set points for the shunt inverter located at bus 6 in different seasons in the 1st and 5th years.

A. Optimal VAr Injection Set Points Obtained for the Inverters of UPQC-O in Case 1 and Case 2

The optimal VAr injection set points obtained with CONOPT for the shunt inverters during 24-hour load variation are shown in Fig. 10 and Figs. 11(a) and 11(b) for planning Cases 1 and 2, respectively. The Figs. 10 and 11 show that the optimal VAr injection set points obtained for the shunt inverters are varying with the variation in load demand, except the one placed at bus 7 which is found to be same irrespective of different loading conditions (not shown in the figure). This illustrates that different amount of VAr injection is required in different loading condition to minimize the overall energy loss. The results also show that higher amount of VAr injection is required at higher load demand so as to minimize the overall energy loss. Thus, the shunt inverters need to set at the respective rated VAr capacity during higher loading conditions. The VAr compensation set points also need to be tuned with the future growth of load. The VAr compensation set points obtained for the series inverter of UPQC-O during hourly load variation are found to be same in both the planning Cases 1 and 2. These are found to be set at the rated VAr capacity of the series inverter.

B. Minimum Bus Voltage Magnitude

The minimum bus voltage magnitudes obtained without UPQC-O and with UPQC-O (Case 1 and Case 2) are shown in Figs. 12(a)–(c) for different seasons considering 6% of annual load growth. The results of the 1st year and 5th year after the UPQC-O installation are shown. The results show that the minimum bus voltage magnitude of network is varying with the variation in load demand. For the obvious reason, the minimum bus voltage magnitude of network is found to be less in the 5th year as compared to the 1st year. In the 5th year, the minimum bus voltage magnitude obtained without UPQC-O are violating the limit set. However, with the UPQC-O (in Case 1 and Case 2) the bus voltage magnitudes are found to be well above the limit. It implies to the fact that the VAr support provided by the UPQC-O in both the cases improve the bus voltage magnitude of the

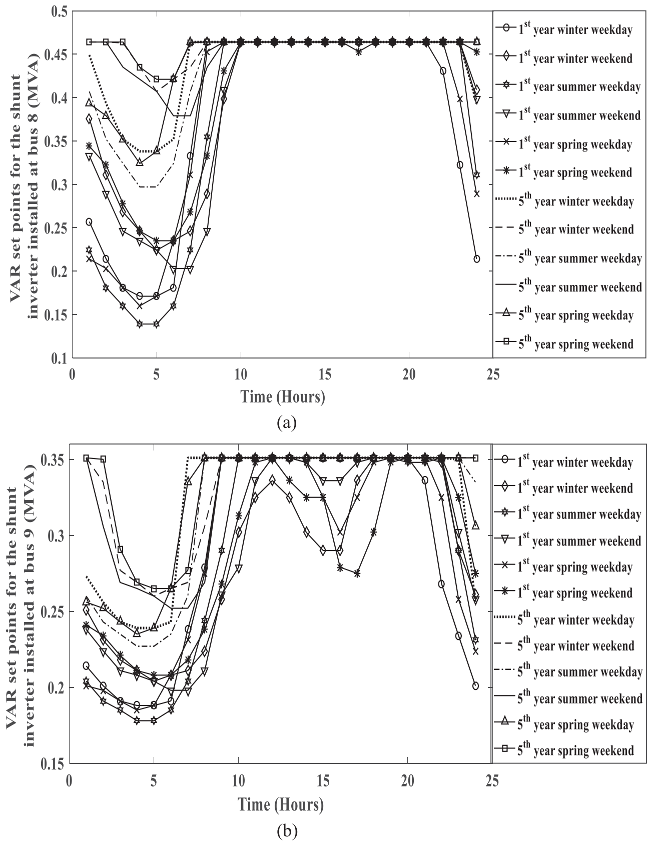

Fig. 11. Optimal VAr set points obtained for the shunt inverters located at: (a) bus 8 and (b) bus 9 in different seasons in the 1st and 5th years.

network. The results also show that the minimum bus voltage magnitude obtained with Case 2 is slightly better than that of the Case 1. The reason is that the UPQC-O provides three-point compensation in Case 2. However, in Case 1, UPQC-O provides single point compensation by a shunt inverter.

C. Voltage Sag Mitigation by the Series Inverter

As mentioned above, the series inverter is placed at bus 19 to protect the industrial customers of buses 19-22 from voltage sag. The maximum amount of voltage sag that the series inverter can mitigate with load variation is shown in Fig. 13 for different seasons of 1st and 5th years. This shows that the amount of voltage sag mitigation by the series inverter is decreasing with the increase in load demand. This is because the increase in load demand decreases the bus voltage magnitude and increases the line current flow in a network. This decreases the amount of series voltage to be injected by the series inverter to supply the rated VAr to mitigate voltage sag. The decrease in amount of series voltage to be injected by the series inverter decreases the amount of voltage sag mitigation. Hence, the amount of voltage sag mitigation obtainable using the same series inverter in 5th year is lower as compared to the 1st year.

D. Cost Benefit Analysis

The cost benefit analysis is provided considering two cost components: (i) cost of placement of UPQC-O, and (ii) saving

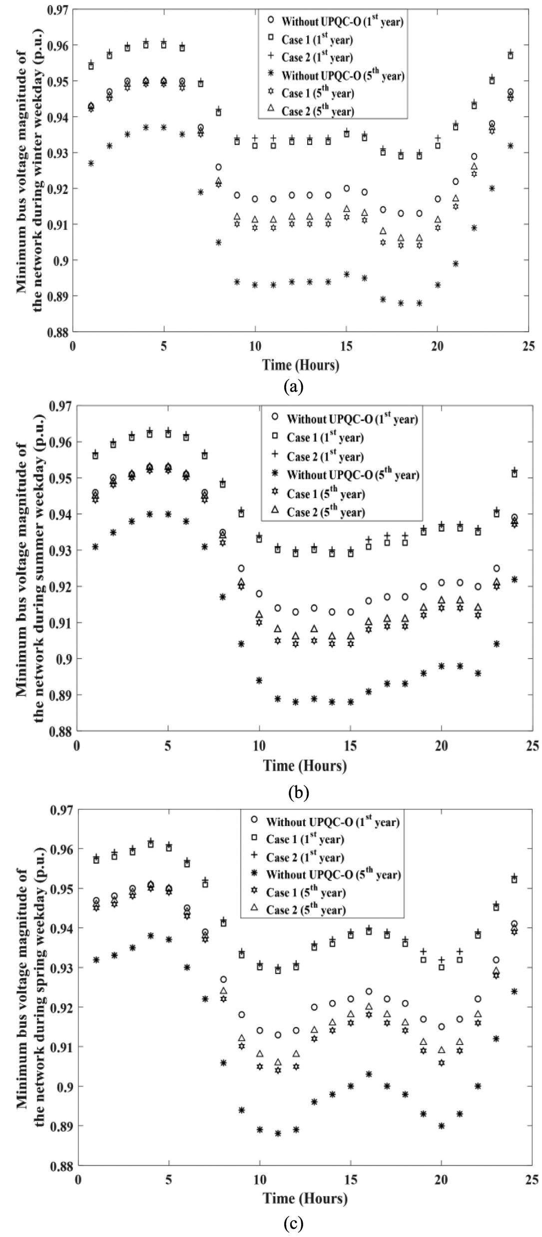

Fig. 12. Minimum bus voltage magnitude of the network obtained for: (a) winter weekday, (b) summer weekday, and (c) spring weekday for the 1st and 5th year for without UPQC-O, Case 1, and Case 2.

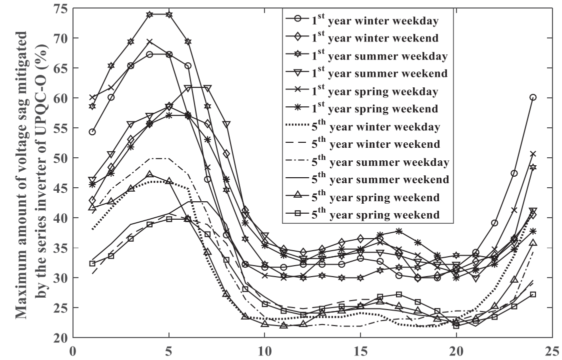

Fig. 13. Maximum amount of voltage sag can be mitigated by the series inverter located at bus 19 in different seasons in the 1st and 5th years.

TABLE I
COST BENEFIT ANALYSIS WITHOUT AND WITH UPQC-O

Costs and operational parameters	Without UPQC-O	Case 1	Case 2
Annual energy loss in the 1st year (MWh)	1233.2115	943.4183	950.4731
Reduction in annual energy loss with UPQC-O in 1st year (%)	-	23.4991	22.9270
Saving from energy loss reduction in 1st year ($)	-	23092.544	22619.072
VA-rating of UPQC-O (MVA)	-	1.7991	1.5811
Installation cost of UPQC-O ($\times 10^5$$)	-	3.3793	2.9740
Annual energy loss in the 5th year (MWh)	2038.5334	1570.4532	1583.6506
Reduction in annual energy loss with UPQC-O in 5th year (%)	-	22.9616	22.3142
Saving from energy loss reduction in 5th year ($)	-	43807.0103	42571.8830
Average of 1st and 5th years saving ($)	-	33449.7772	32595.4775
Return of investment after completion of 5 years (%)	-	49.4922	54.8007

TABLE II
ANNUAL ENERGY LOSS OF DISTRIBUTION NETWORK WITH VARIABLE AND CONSTANT VAR SET POINTS OF UPQC-O

Annual energy loss of the network	Case 1	Case 2
Without UPQC-O (MWh)	1233.2115	1233.2115
With variable set points of UPQC-O (MWh)	943.4183	950.4731
% reduction with respect to without UPQC-O	23.4991	22.9270
With constant set point of UPQC-O (MWh)	954.0300	958.8389
% reduction with respect to without UPQC-O	22.6386	22.2486
Saving of energy with variable set points of UPQC-O with respect to constant set point of UPQC-O (kWh)	10611.7000	8365.8000

from energy loss reduction. The unit cost for the placement of UPQC-O is computed as [18]:

$$C_U = 0.0003{S_U}^2 - 0.2691 S_U + 188.2\,(\$/\text{kVA}) \tag{27}$$

where, S_U is the total VA-rating of UPQC-O in MVA.

This does not include the cost of smart grid technologies, such as, costs of communication network, smart meters, high speed computers, control systems. The annual energy loss in kWh of distribution network is computed as:

$$AEL = 1000 S_{base} \sum_{y\in\gamma} t_y \sum_{w\in\beta} t_w \sum_{d_{yw}\in\Gamma_{yw}} t_{ywh} \sum_{ef\in\rho} I^2_{efd_{yw}} R_{ef} \tag{28}$$

The saving from energy loss reduction in the 1st and 5th years are computed as:

$$C_{AEL1} = C_E\ (AEL_{base1} - AEL_{U1}) \tag{29}$$

$$C_{AEL5} = C_E\ (1 + r_e)^4 (AEL_{base5} - AEL_{U5}) \tag{30}$$

where, AEL_{base1} and AEL_{base5} are the annual energy loss of base-case network without UPQC-O in the 1st and 5th years, respectively; AEL_{U1} and AEL_{U5} are the annual energy loss of network with UPQC-O in 1st and 5th years, respectively. Average annual saving from energy loss reduction is computed as:

$$C^{Avg}_{AEL} = \frac{C_{AEL1} + C_{AEL5}}{2} \tag{31}$$

The return of investment (%) after completion of the planning horizon (T_{ph}) is computed as:

$$IR = 100 \frac{T_{ph} C^{Avg}_{AEL}}{1000 C_U S_U} \tag{32}$$

Table I shows the different parameters related to the cost-benefit analysis. The results show that the return of investment in planning Case 2 is more as compared to Case 1 because of the less VA-rating requirement of UPQC-O in Case 2. It is noteworthy that the numerical value provided in Table I for return of investment is only in view of saving due to the energy loss reduction. There is another important benefit of planning Cases 1 and 2. The deployment of UPQC-O in distribution networks defers the network upgrade cost to the future years. The inclusion of this would further increase the percentage of return of investment.

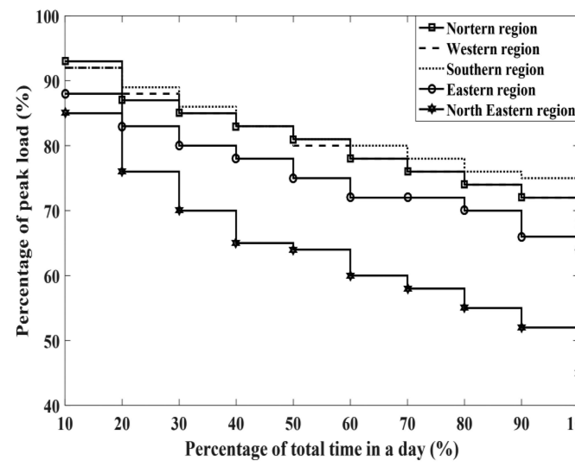

Fig. 14. Load demand duration curves for different regions of India [40].

E. Comparison of Annual Energy Losses Obtained With Variable and Constant/Rated VAr Set Points of UPQC-O

This section provides the comparison between two approaches of energy loss minimization with UPQC-O. These are: (i) UPQC-O with variable set points and (ii) UPQC-O with constant/rated set point of UPQC-O. The annual energy losses obtained in the 1st year of planning horizon with variable and constant VAr set points of UPQC-O are shown in Table II for planning Cases 1 and 2. The results show that the UPQC-O with variable VAr injection set points yields lower energy loss as compared to the UPQC-O with constant/rated VAr injection. The integration of UPQC-O with variable VAr injection set points results in 10611.7 kWhr and 8365.8 kWhr of energy saving for the planning Cases 1 and 2, respectively. Another case study is provided by varying the load demand of the same network according to the load demand duration curves for different regions of India [40], as shown in Fig. 14. The single point compensation

TABLE III
ANNUAL ENERGY LOSS OBTAINED BY VARYING THE LOAD DEMAND ACCORDING TO THE DEMAND DURATION CURVES OF DIFFERENT REGIONS OF INDIA WITH VARIABLE AND CONSTANT VAr SET POINTS OF UPQC-O

Annual Energy loss of the network with UPQC-O with variable set point	Load demand variation according to the load demand duration curve of different regions in India				
	Northern region (LF=0.8570)	Western region (LF=0.8641)	Southern region (LF=0.8826)	Eastern region (LF=0.85)	North Eastern region (LF=0.7412)
Without UPQC-O (MWh)	1104.4853	1098.9245	1145.3691	966.8841	691.8902
With variable set points of UPQC-O (MWh)	846.4569	842.2293	877.4489	742.2120	532.7079
% reduction with respect to without UPQC-O	23.3619	23.3588	23.3916	23.2367	23.0069
With constant set point of UPQC-O (MWh)	853.9861	850.0108	883.0378	755.3617	569.8538
% reduction with respect to without UPQC-O	22.6802	22.6507	22.9036	21.8767	17.6381
Saving of energy with variable set points of UPQC-O with respect to constant set point of UPQC-O (kWh)	7529.2	7781.5	5588.9	13149.7	37145.9

TABLE IV
COMPARISON AMONG DIFFERENT COMPENSATION APPROACHES OF ENERGY LOSS REDUCTION

Solution obtained with different types compensation approaches	Without UPQC-O	UPQC-O Allocation				DSTATCOM allocation (Case C)	Capacitor allocation (Case D)
		Case A		Case B			
		Case A(a)	Case A(b)	Case B(a)	Case B(b)		
Annual energy loss (MWh)	1233.2115	943.4183	954.0300	942.5683	963.9156	943.7999	965.0003
VA-rating of shunt compensator (MVA)	-	1.6078	1.6078	1.778	1.778	1.792	1.792
VA-rating of series compensator (MVA)	-	0.1913	0.1913	0.359	0.359	-	-
Total VA-rating	-	1.7991	1.7991	2.137	2.137	1.792	1.792

using a shunt inverter (i.e., Case 1) is chosen for this study. The total energy losses obtained with the 1st year of planning horizon with variable and constant/rated VAr set points of UPQC-O are shown in Table III. The load factor (LF) corresponding to each load demand duration curve is shown in Table III. The results clearly show that the variable VAr injection set points of UPQC-O result in higher energy loss reduction and greater saving in energy as compared to the constant/rated VAr injection. It is also observed that the energy saving with the variable VAr injection set points of UPQC-O is more if the load factor of the demand duration curve is less. Hence, the proposed approach of energy loss minimization is more effective in those areas where load factor is low as the north eastern region of India.

F. Comparison Among Different Compensation Approaches for the Energy Loss Reduction of Distribution Network

In the literature, several approaches are reported for energy loss reduction in distribution networks. In this section, a case study is presented for the comparison of the solutions obtained with the proposed approach with two similar approaches. The following approaches of energy loss minimization are considered:

- Case A: In this case, the sizes of series and shunt inverters of UPQC-O in a location are determined using the modelling provided in Section III-B.
- Case B: In this case, the sizes of series and shunt inverters of UPQC-O are determined through optimization by setting a minimum and maximum set values for the VA-ratings.

The Case A and Case B have two subcases:
  - In Cases A(a) and B(a), the energy loss is minimized with variable VAr injection set points of UPQC-O.
  - In Cases A(b) and B(b), the energy loss is minimized with constant/rated VAr injection of UPQC-O.

- Case C: In this case, the energy loss is minimized with the allocation of DSTATCOM. The size of DSTATCOM is determined through optimization by setting a minimum and maximum set values for the VA-rating of DSTATCOM for energy loss minimization in peak load condition.
- Case D: In this case, the energy loss is minimized with the allocation of a fixed capacitor bank. The size of the capacitor bank is also determined through the optimization for energy loss minimization in peak load condition.

The single point compensation is chosen for this case study. The results obtained with these three cases are shown in Table IV. The results show that the variable VAr set points of UPQC-O in Case A(a) and B(a) provide better compensation to obtain higher energy loss reduction as compared to Cases A(b) and B(b), respectively. The solutions obtained with Cases A(a) and Case B(a) show similar annual energy loss reduction. However, the VA-rating requirement for UPQC-O for solution obtained with Case B(a) is higher as compared to Case A(a). The allocation of DSTATCOM in Case C provides similar annual energy loss reduction as obtained with the solutions of Cases A(a) and B(a). The size of DSTATCOM is also found to be similar as UPQC-O obtained with Case A. Among all the above mentioned approaches, the allocation of fixed capacitor bank results in comparatively lesser energy loss reduction in network because of the constant VAr injection in Case D. Although the installation of capacitor bank for VAr compensation is an economical option, it is not skilled to mitigate any of the PQ issues. UPQC-O with its series inverter can protect the downstream load from voltage sag occurring in upstream section. The voltage sag mitigation can be done with a DSTATCOM installed in a similar strategic location as the series inverter of UPQC-O. However, this needs additional DSTATCOM and it will increase the total VA rating.

V. CONCLUSION

In this paper, an online operational optimization approach for energy loss minimization for distribution networks with load variation has been proposed. The UPQC-O is modeled to provide time varying VAr compensation for the energy loss reduction and for voltage sag mitigation, whenever required. The infrastructure required for the real-time implementation of the proposed methodology has also been provided. The simulation results obtained with proposed approach provide the following:

- The variation in load demand and annual load growth need the tuning of the set points of the inverters of UPQC-O to have optimal operation. Hence, the optimal VAr compensation set points for the shunt inverter(s) are found to be varying with the time varying load demand and load growth.
- The amount of supply voltage sag mitigation that a series inverter can provide also varies with the time variation of load demand and the load growth. A series inverter with a given capacity can mitigate higher amount of voltage sag during light load condition as compared to the peak load condition.
- The deployment of any of the planning cases can reduce significant amount of the annual energy loss which typically lies 20–25% for the system studied. It also significantly improves the bus voltage magnitude of distribution networks.
- The planning Case 2, being a three-point compensation, is the economical option than the Case 1 (i.e., single point compensation) in view of higher return of investment and less VA-rating of UPQC-O. But, it requires more investment to establish the communication network and control infrastructure.
- The deployment of any of the planning cases defers the network upgrade cost to future years, as well.
- The UPQC-O with variable VAr set points can provide better compensation in terms of higher loss reduction as compared to the constant VAr set point approach. The deployment of proposed approach in the areas where load factor is low can save more energy as compared to the constant/rated VAr compensation.

Although the approach is applicable online with the advent of smart grid technologies which may result in better precision of the set points, it could be applicable offline if the day ahead load prediction can correctly be done. The operational optimization of UPQC-O during stochastic variation of renewable generation and daily load variation can be a possible extension of this work.

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