This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Impact of Unified Power-Quality Conditioner Allocation on Line Loading, Losses, and Voltage Stability of Radial Distribution Systems

Sanjib Ganguly, *Member, IEEE*

***Abstract*—This paper presents an investigative study on the impact of unified power-quality conditioner (UPQC) allocation on radial distribution systems. A design approach for UPQC, called sag-based design for phase-angle control for UPQC (UPQC-SPAC) is proposed. The phase-angle shifting of the load voltage required to mitigate a given value of voltage sag is determined and the same is used during a healthy operating condition in order to provide the reactive power compensation of a distribution network. To study the impact of the UPQC-SPAC allocation on distribution systems, it is placed at each node, except the substation node, one at a time. The load-flow algorithm for radial distribution systems is suitably modified to incorporate the UPQC-SPAC model. The simulation results show that a significant amount of power-loss reduction, under voltage mitigation, and the enhancement of voltage stability margin can be obtained with an appropriate placement of the UPQC-SPAC in a distribution network. The performance comparison of the UPQC-SPAC with one previously reported design approach shows that it is more efficient in undervoltage mitigation. An appropriate allocation of the UPQC-SPAC is also found to be beneficial for the networks with distributed-generation units.**

***Index Terms*—Power distribution planning, power loss, unified power-quality conditioner (UPQC), voltage stability.**

NOMENCLTURE

$V_S(V_L)$	Voltage at the source (load) end of UPQC.
V_{So}	Source-end voltage during healthy condition.
$V_{Se}(\theta_{Se})$	Injected series voltage (its angle $w.r.t\ V_S$).
$k(k_{\text{sag}})$	Per-unit sag (p.u. source voltage during sag).
$S_{Sh}(S_{Se})$	VA rating of the shunt (series) inverter.
$I_S(I_L)$	Current at source (load) end of the UPQC.
$I_{Sh}(\theta_{Sh})$	Shunt compensating current (angle w.r.t. V_L).
ϕ	Phase angle of load current.
δ	Angle between the source and load-end voltage.
$\text{THD}_{Sh}(\text{THD}_L)$	THD of shunt compensating (load) current.
$P_L(Q_L)$	Active (reactive) power demand of the load.

Manuscript received May 21, 2013; revised December 16, 2013; accepted May 22, 2014. Paper no. TPWRD-00610-2013.

The author is with the Department of Electrical Engineering, National Institute of Technology, Rourkela 769008, India (e-mail: sanjib191@gmail.com).

Digital Object Identifier 10.1109/TPWRD.2014.2327154

I. INTRODUCTION

WITH THE advent of advanced power-electronics technologies, extensive research is going on around the globe to improve power quality (PQ). The flexible ac transmission systems (FACTS) are the outcomes of this research. These days, similar types of technologies are used in PQ improvement in distribution systems. The unified PQ conditioner (UPQC) is one of these types of advanced power-electronics devices. A UPQC is similar in construction to the unified power-flow controller (UPFC), one of the versatile flexible ac transmission systems (FACTS) devices used in transmission systems. The UPFC and UPQC provide simultaneous shunt and series compensations with a series and a shunt inverter, respectively. A UPFC works in transmission systems which are supposed to be balanced and relatively distortion free. However, a UPQC is made to operate in distribution systems which are relatively unbalanced and with higher harmonic contents due to the increasing trend of power-electronic interfaces. There is a considerably large volume of literature on UPQC and a state-of-art review can be obtained in [1].

With the two inverters, a UPQC can protect a customer/load from sag, swell in supply voltage, and it can also reduce the harmonic pollution created by the load. The shunt inverter injects a shunt compensating current to the load in order to provide load reactive compensation and to compensate the harmonic distortion created by the load. The series inverter is used to mitigate voltage-related problems, for example, sag and swell in supply voltage, etc. Basically, it injects a series voltage to the load. These two inverters are connected back to back with a dc link and this becomes the most common form of UPQC structure after its practical implementation reported in [2]. There are various UPQC models reported, and they are categorically presented in [1], such as UPQC-P, UPQC-Q, UPQC-S, UPQC-VA$_{\text{min}}$, etc. In UPQC-P, the series inverter handles only active power by injecting an in-phase voltage to the load in order to mitigate the voltage sag problem. In

UPQC-Q, the series inverter mitigates voltage sag/swell by providing reactive power which is done by injecting a voltage in quadrature with source voltage. A comparative performance assessment of these two UPQC models is given in [3]. The series inverter in UPQC-S can simultaneously inject real and reactive power [4]. In UPQC-VA$_{\min}$, a model based on the minimization of the VA rating of the UPQC is provided. This model is reported in [5], where the optimum phase angle of the injected voltage of the series inverter is determined.

There are a few different directions of research on UPQC and they are: 1) development of different series compensation schemes, for example UPQC-P, UPQC-Q, UPQC-S, etc.; 2) the development of different UPQC topologies/structures, for example, three-phase four-wire structure [6], interline UPQC [7] where the two inverters are placed in different feeders of a network, UPQC without a common dc link or OPEN UPQC [8] etc.; 3) development of a control strategy for UPQC, for example, phase-angle control [9], simultaneous voltage and current compensation scheme [10], particle swarm optimization-based feedback controller [11], etc.; and 4) minimization of the cost/VA rating of the UPQC [12], etc. Recently, an investigation on the combined operation with distributed-generation (DG) units is reported in [13] and [14]. In almost all works, UPQC is designed to protect a single load, which seems to be the most sensitive load that requires uninterrupted and a regulated power supply. Process industries with variable speed drives, critical service providers such as medical centers, airports, and broadcasting centers are examples of sensitive load. However, the impact of UPQC placement at a particular node of a network on the remaining nodes is not investigated except in [15], where the impact of UPQC allocation on undervoltage mitigation of distribution networks is studied. But the work is limited to a fixed shunt compensation for UPQC, and the impact of UPQC allocation on power-loss reduction as well as improvements in line loadability and voltage stability are not studied. The fixed shunt compensation irrespective of the load demand and the location of UPQC in a network is not a realistic approach.

The theme of this paper is to study the impact of a UPQC allocation on overall distribution systems. The strategy used in phase-angle control for UPQC (UPQC-PAC) [9] is followed in the series inverter design. In the UPQC-PAC, the series inverter is used to shift the phase angle of load voltage, keeping its magnitude the same. Due to this phase shift, the series inverter participates in reactive power compensation. This considerably reduces the VA rating of the shunt inverter and the overall VA rating of UPQC [9]. However, the design of the UPQC-PAC is aimed at the reactive power compensation of the single load in [9]. Thus, a modified design is carried out in this paper. The contributions of this work are summarized as follows:

- development of a UPQC model, called sag-based design for phase-angle control for UPQC (UPQC-SPAC), capable of mitigating a given value of voltage sag and providing the reactive power compensation of distribution networks during healthy conditions;
- the development of a distribution system load-flow algorithm incorporating the UPQC-SPAC model;
- study the impact of UPQC placement at a particular node on the remaining nodes of the distribution networks.

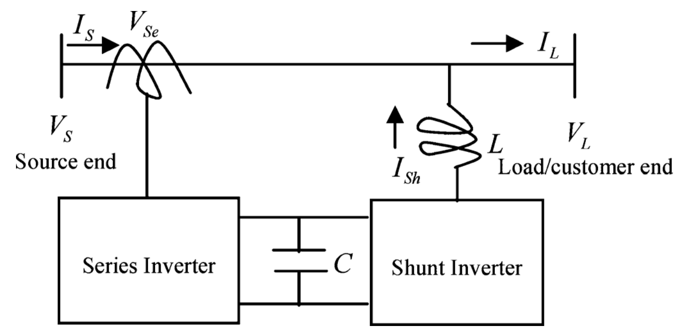


Fig. 1. Schematic of the UPQC.

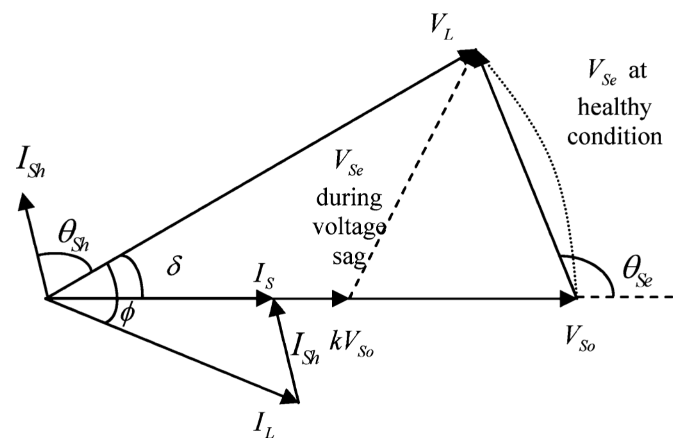


Fig. 2. Phasor diagram of shunt and series compensations of UPQC-SPAC at the normal/healthy voltage condition and during voltage sag.

The simulation study is performed on 33-node and 69-node test distribution systems. The performance of the proposed model is compared with an existing UPQC model and with two optimal reactive power compensation strategies. The effect of UPQC-SPAC allocation on a distribution network with DG is studied.

This paper is organized as follows. The UPQC-SPAC model and the distribution system load flow incorporating the UPQC-SPAC model are described in Sections II and III, respectively. In Section IV, an analysis of the VA rating of UPQC-SPAC is provided. The simulation study on the impact of the UPQC-SPAC allocation is presented in Section V and discussed. Section VI concludes this paper.

II. Modeling of the UPQC-SPAC

A UPQC consists of a series and a shunt inverter as shown in Fig. 1. The series inverter injects a series voltage (V_{Se}) in order to mitigate sag and a swell of supply voltage. The shunt inverter injects a shunt compensating current (I_{Sh}) in order to compensate the reactive component of load current and harmonic distortion created by the load. It is assumed that the UPQC is placed very close to the load end. The phasor diagram shown in Fig. 2 shows the voltage and current injections provided by the series and shunt inverters, respectively. In the proposed design approach, the series voltage is injected to the source at a healthy operating condition and during voltage sag.

The magnitude of V_{Se} depends on the maximum voltage sag to be mitigated. The injection of the series voltage V_{Se} creates a phase angle (δ) shift of the load-end voltage. In UPQC-PAC, the maximum phase angle shift, that is, the maximum value of δ is determined in view of the reactive power compensation required from the series inverter [9]. In the proposed scheme, it is determined according to a given maximum value of voltage sag mitigation required. This is the novelty of the UPQC-SPAC over the UPQC-PAC model. The VA ratings of the series and shunt inverters are determined in the following subsections. The overall VA rating of the UPQC-SPAC is the sum of the VA ratings of the series and shunt inverters.

A. Determination of VA Rating for the Series Inverter

The VA rating of the series inverter depends on the injected voltage (V_{Se}) and the compensated source-end current (I_S) as given

$$S_{Se} = V_{Se} I_S. \tag{1}$$

At healthy condition, the source voltage is $V_S = V_{So}$. But during voltage sag, the source voltage magnitude is reduced to $V_S = kV_{So}\{k_{\text{sag}} = (1-k)$: per-unit sag in source voltage$\}$. Therefore, the series voltage injection required to mitigate k_{sag} p.u. amount of voltage sag can be determined by

$$V_{Se} = \sqrt{V_L^2 + (kV_{So})^2 - 2V_L(kV_{So})\cos\delta}. \tag{2}$$

Since the load-end voltage magnitude is kept constant at any condition, i.e., $(V_L = V_{So} = V_S)$, (2) is rewritten as

$$\begin{aligned} V_{Se} &= \sqrt{V_S^2 + (kV_S)^2 - 2V_S(kV_S)\cos\delta} \\ &= V_S\sqrt{1 + k^2 - 2k\cos\delta}. \end{aligned} \tag{3}$$

Assuming that the UPQC is lossless, the active power demanded by the load is equal to the active power drawn from the source [16]. Hence

$$kV_S I_S = V_L I_L \cos\phi \tag{4}$$

$$I_S = \frac{I_L\cos\phi}{k}. \tag{5}$$

From (1), (3), and (6), the VA rating of the series inverter is obtained as

$$S_{Se} = \frac{V_S I_L \cos\phi}{k}\sqrt{1 + k^2 - 2k\cos\delta}. \tag{6}$$

B. Determination of the VA Rating for the Shunt Inverter

The VA rating of the shunt inverter depends on the load-end voltage (V_L) which is equal to the source voltage (V_S) and the compensating shunt current (I_{Sh}) provided by the shunt inverter as given

$$S_{Sh} = V_S I_{Sh}. \tag{7}$$

According to Fig. 2, the compensating current can be determined as

$$I_{Sh} = \sqrt{I_S^2 + I_L^2 - 2I_S I_L\cos(\phi - \delta)}. \tag{8}$$

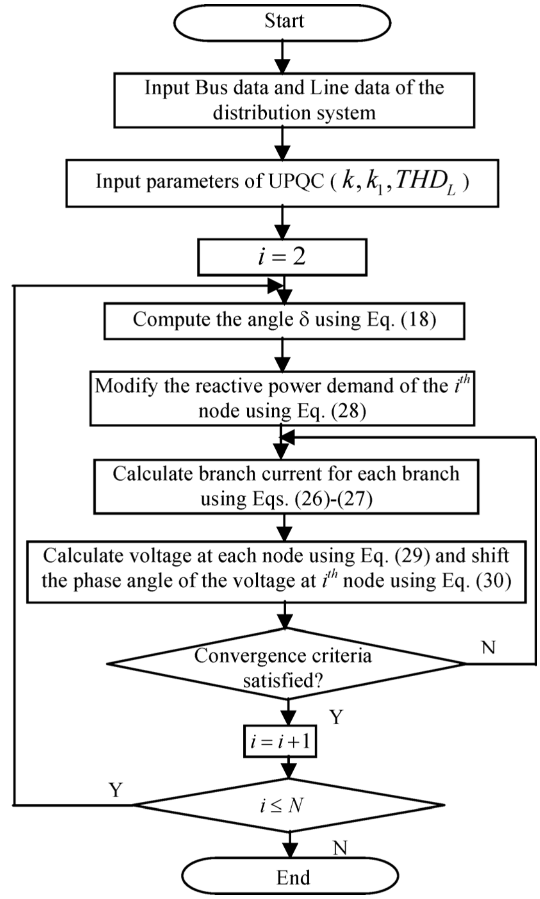


Fig. 3. Flowchart of the load-flow algorithm incorporating the UPQC-SPAC model (N = total number of nodes).

From (5) and (8)

$$I_{Sh} = I_L\sqrt{1 + \frac{\cos^2\phi}{k^2} - \frac{2\cos\phi\cos(\phi - \delta)}{k}}. \tag{9}$$

Due to the increasing use of nonlinear loads, the load current consists of harmonics. Thus, one of the functions of UPQC is harmonic elimination. The harmonic content in load current is measured by the total harmonic distortion (THD). It is defined as the ratio of distortion component of the current (I^{dis}) to the fundamental component (I^f) as given

$$\text{THD} = I^{\text{dis}}/I^f. \tag{10}$$

The shunt inverter of UPQC is controlled in such a way that it (I_{Sh}^{dis}) can compensate the distortion component of the load current (I_L^{dis}) [5], i.e.,

$$I_L^{\text{dis}} = I_{Sh}^{\text{dis}}. \tag{11}$$

From (10) and (11)

$$\text{THD}_L I_L^f = \text{THD}_{Sh} I_{Sh}^f \tag{12}$$

$$\text{THD}_{Sh} = \text{THD}_L \Big/ \sqrt{1 + \frac{\cos^2\phi}{k^2} - \frac{2\cos\phi\cos(\phi - \delta)}{k}}. \tag{13}$$

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Therefore, the rms value of the shunt current is obtained as

$$I_{Sh} = I_{Sh}^{f}\sqrt{1+\mathrm{THD}_{Sh}^{2}}. \quad (14)$$

From (13) and (14), the shunt compensating current provided by the shunt inverter can be determined as

$$I_{Sh} = I_{L}^{f}\sqrt{1+\frac{\cos^2\phi}{k^2}-\frac{2\cos\phi\cos(\phi-\delta)}{k}+\mathrm{THD}_{L}^{2}}. \quad (15)$$

Thus, the VA rating of the shunt inverter is

$$S_{Sh} = V_S I_{L}^{f}\sqrt{1+\frac{\cos^2\phi}{k^2}-\frac{2\cos\phi\cos(\phi-\delta)}{k}+\mathrm{THD}_{L}^{2}}. \quad (16)$$

C. Determination of Phase Angle δ

Let there be sag in source voltage and its magnitude be reduced to $kV_S\{k = (1-k_{\text{sag}})$: per-unit source voltage during sag$\}$. From Fig. 2, it can be written that

$$V_{Se}^2 = V_L^2 + (kV_S)^2 - 2V_L(kV_S).\cos\delta \quad (17)$$

Let the minimum series voltage that should be injected to restore load voltage be $V_{Se} = k_1 V_S$. Therefore, putting this to (17), the angle δ can be determined as

$$\cos\delta = (1+k^2-k_1^2)/2k. \quad (18)$$

Since $\cos\delta \le 1, (1+k^2-k_1^2) \le 2k$, this yields $(1-k) \le k_1$, i.e., $k_1 \ge k_{\text{sag}}$. This provides an important design constraint that the per-unit voltage rating of the series inverter is to be greater than equal to the per-unit sag in source voltage.

D. Active and Reactive Power Provided by the Inverters at the Healthy Operating Condition

The UPQC-SPAC operates in phase-angle control mode during healthy conditions. Therefore, the active (P_{Se}) and reactive power (Q_{Se}) delivered by the series inverter can be determined as

$$P_{Se} = S_{Se}\cos\theta_{Se} \quad (19)$$
$$Q_{Se} = S_{Se}\sin\theta_{Se}. \quad (20)$$

Similarly, the active (P_{Sh}) and reactive power (Q_{Sh}) delivered by the shunt inverter can be obtained as

$$P_{Sh} = S_{Sh}\cos\theta_{Sh} \quad (21)$$
$$Q_{Sh} = S_{Sh}\sin\theta_{Sh}. \quad (22)$$

The angles θ_{Se} and θ_{Sh} are determined [9] by

$$\theta_{Se} = 180^0 - \tan^{-1}\left(\frac{\sin\delta}{1-\cos\delta}\right) \quad (23)$$
$$\theta_{Sh} = \tan^{-1}\left\{\frac{\cos(\phi-\delta)-\cos\phi}{\sin(\phi-\delta)}\right\} + 90^0 - \delta. \quad (24)$$

The total reactive power delivered by the UPQC-SPAC is

$$Q_{\text{UPQC}} = Q_{Se} + Q_{Sh}. \quad (25)$$

III. Incorporation of the UPQC-SPAC Model in Distribution System Load Flow

To study the impact of UPQC allocation in a distribution network, the UPQC-SPAC model is incorporated in the forward-backward sweep load-flow algorithm [17], a simple but efficient algorithm for radial distribution systems. The algorithm consists of two major steps:

Step 1) *Backward sweep*: In this step, the load current of each node of a distribution network is determined as

$$\bar{I}_L(m) = \left\{\frac{P_L(m) - jQ_L(m)}{\bar{V}^*(m)}\right\} \quad (26)$$

where $P_L(m)$ and $Q_L(m)$ represent the active and reactive power demand at node m. Therefore, the current in each branch of the network is computed as follows:

$$\bar{I}(mn) = \bar{I}_L(n) + \sum_{m\in\Gamma}\bar{I}_L(m) \quad (27)$$

where the set Γ consists of all nodes which are located beyond node n [17]. To incorporate the shunt inverter model, the reactive power demand at the candidate node at which a UPQC is to be placed, i.e., η_{UPQC} is modified as

$$Q_L(\eta_{\text{UPQC}}) = Q_L(\eta_{\text{UPQC}}) - Q_{Sh}. \quad (28)$$

Step 2) *Forward sweep*: This step is used after the backward sweep in order to determine the voltage at each node of a distribution network as follows:

$$\bar{V}(n) = \bar{V}(m) - \bar{I}(mn)Z(mn) \quad (29)$$

where nodes m and n represent the sending and receiving end nodes, respectively, for branch *mn*, and $Z(mn)$ is the impedance of the branch.

The series inverter model is incorporated by advancing the phase angle of the voltage of the candidate node at which a UPQC is to be placed by angle δ as given

$$\bar{V}(\eta_{\text{UPQC}}) = V_{\text{LD}}\angle(\alpha_{\eta_{\text{UPQC}}} + \delta) \quad (30)$$

where $\alpha_{\eta_{\text{UPQC}}}$ is the phase angle of the voltage at the node at which a UPQC is placed and V_{LD} is the load voltage.

The flowchart of the load-flow algorithm incorporating the UPQC-SPAC model is shown in Fig. 3. In this flowchart, each node except the substation node (i.e., node 1) is considered as a candidate location for the UPQC-SPAC allocation and separate load flow is performed for each location. This helps to understand the impact of the UPQC-SPAC allocation during healthy conditions.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

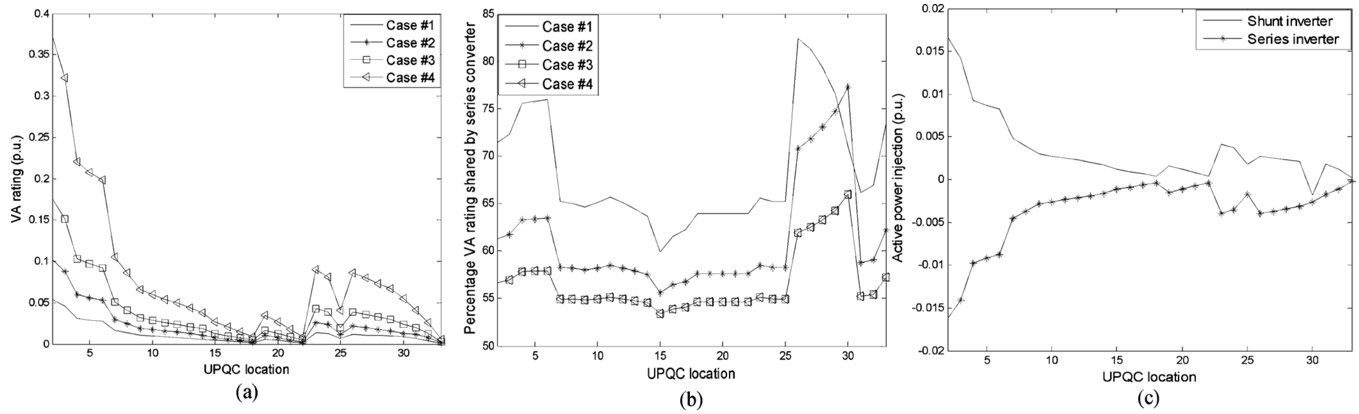


Fig. 4. UPQC-SPAC allocation at different nodes of the 33-node system: (a) VA rating, (b) percentage of VA shared by the series inverter, and (c) active power injection of series and shunt inverters.

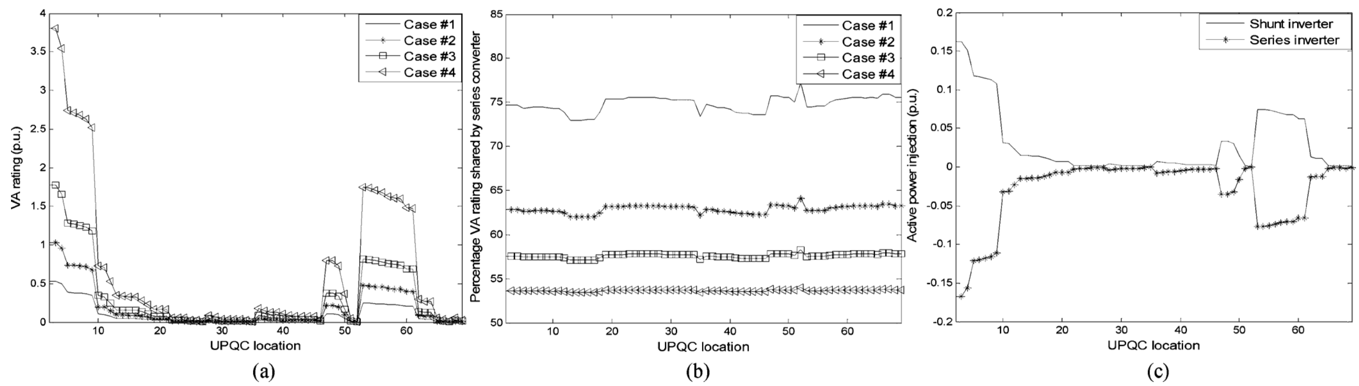


Fig. 5. UPQC-SPAC allocation at different nodes of the 69-node system: (a) VA rating, (b) percentage of VA shared by the series inverter, and (c) active power injection of series and shunt inverters.

IV. Analysis of the VA Rating of UPQC-SPAC

In this section, an analysis of the VA rating of the series and shunt inverters for UPQC-SPAC is provided. The two test distribution systems used in the study are: 1) 33-node and 2) 69-node systems. The system data are available in [18] and [19], respectively. Both systems have one substation located at node 1 and all other nodes are load nodes. The substation voltage is specified to be $1\angle 0$ p.u. The effect of a UPQC-SPAC allocation at each node of the test networks, one at a time, during healthy condition is studied by considering that the UPQC-SPAC is designed to mitigate:

- *Case* #1: 20% of voltage sag, that is, $k_{\rm sag} = 0.2,\ k = 0.8$.
- *Case* #2: 40% of voltage sag, that is, $k_{\rm sag} = 0.4,\ k = 0.6$.
- *Case* #3: 60% of voltage sag, that is, $k_{\rm sag} = 0.6,\ k = 0.4$.
- *Case* #4: 80% of voltage sag, that is, $k_{\rm sag} = 0.8,\ k = 0.2$.

The THD of the load current is considered to be 0.2. The results of a UPQC-SPAC allocation at each node of the 33-node and 69-node distribution systems, one at a time, are shown in Figs. 4 and 5, respectively. The VA rating for the UPQC-SPAC at different locations for the two test systems is shown in Figs. 4(a) and (b). The results illustrate that higher-rated UPQC-SPAC is required if it is to be placed closer to the substation. It is expected because the branches located closer to the substation carry higher load current. It is also observed that higher-rated UPQC-SPAC is required to mitigate a higher amount of voltage sag. The reason is that higher series-injected voltage is required to mitigate a higher value of voltage sag. The percentage of VA shared by the series inverter at different UPQC-SPAC locations in the two test systems is shown in Figs. 4(b) and 5(b). The result illustrates that the percentage VA sharing of the series inverter is more than that of the shunt inverter. However, this becomes less with the Case #3 and #4 designs. The reason is that angle δ increases with a higher value of $k_{\rm sag}$.

Thus, the difference between the angles φ and δ increases. This results in a higher amount of shunt compensating current required in the reactive power compensation. Hence, the VA rating of the shunt inverter increases. Active power injection by both inverters of the UPQC-SPAC with *Case* #2 design is shown in Figs. 4(c) and 5(c) for the two test systems. The result shows that both inverters inject an equal and opposite amount of active power which circulates between the two inverters. Actually, the series inverter consumes a certain amount of active power. This increases the dc-ink voltage. Therefore, to keep the dc-link voltage constant, the shunt inverter injects a compensating current in such a way that the active power consumed by the series inverter is fed back to the supply. Thus, a certain amount of active power always circulates between the series and shunt inverters [9].

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

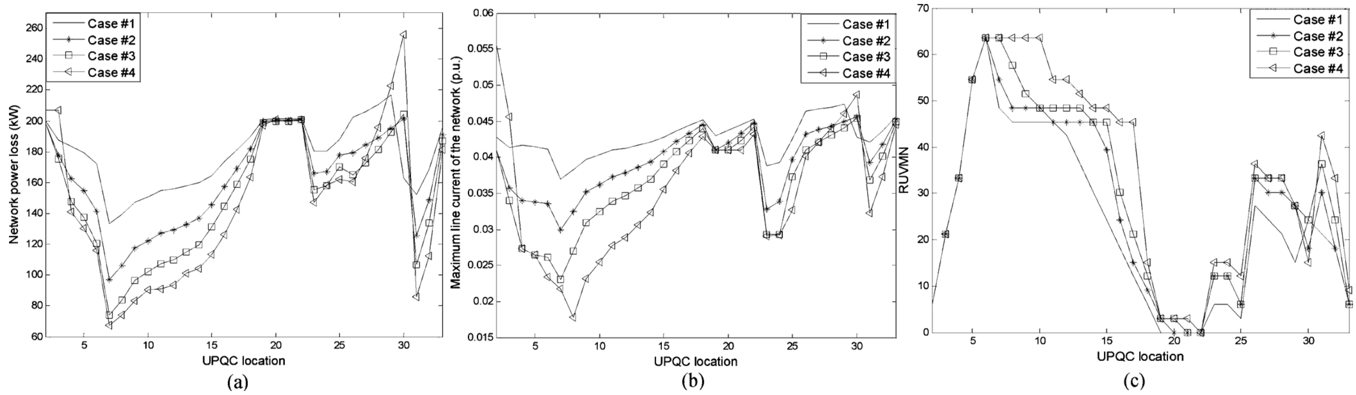


Fig. 6. Impact of UPQC-SPAC allocation at different nodes of the 33-node distribution system in view of: (a) network power loss, (b) the maximum line current of the network, and (c) RUVMN.

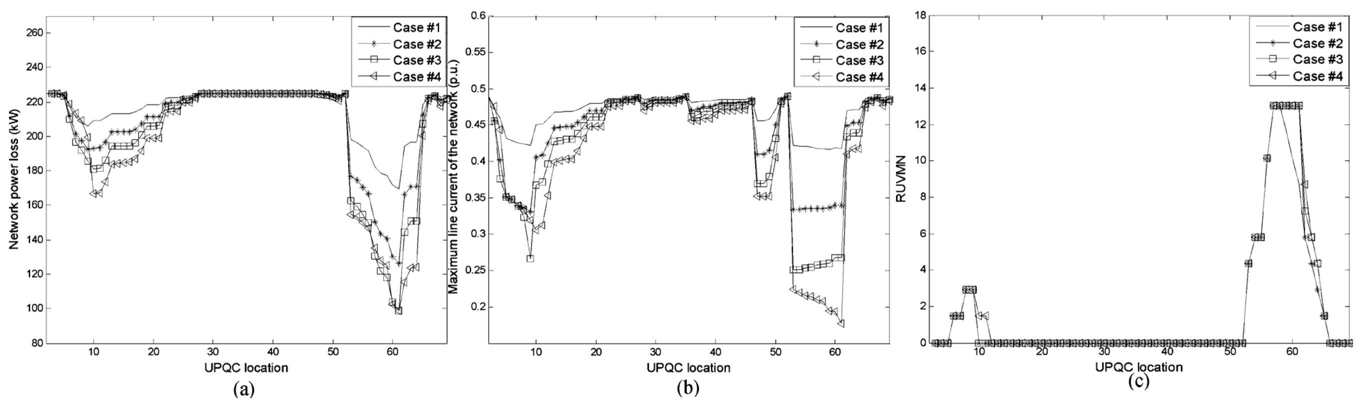


Fig. 7. Impact of UPQC-SPAC allocation at different nodes of the 69-node distribution system in view of: (a) network power loss, (b) the maximum line current of the network, and (c) RUVMN.

V. Simulation Study on the Impact of the UPQC-SPAC Allocation

This section provides the simulation study to show the impact of UPQC-SPAC allocation on different operational aspects of distribution systems during healthy condition, for example, power loss, undervoltage mitigation, etc. The results are shown in Figs. 6 and 7 for the 33- and 69-node systems, respectively. Four test case designs for the UPQC-SPAC, mentioned before, are used in the simulation study.

A. Impact on Network Power Loss

The effect of network power loss due to the UPQC-SPAC allocation at different nodes is shown in Figs. 6(a) and 7(a) for the two test systems. The power losses of the network without UPQC-SPAC are 202.67 kW and 224.98 kW for the 33-node and 69-node systems, respectively. The result shows that substantial loss reduction can be achieved with UPQC-SPAC if it is properly designed and suitably located in the network. This happens due to the load reactive power compensation provided by the UPQC-SPAC. A UPQC-SPAC designed to mitigate a higher amount of voltage sag provides better reactive power compensation. The solution corresponding to the lowest power loss for the 33-node system is obtained at node 7 with the Case #2 design. Similarly, the location corresponding to the lowest power loss at node 61 for the 69-node system is obtained with the Case #3 design. However, it is also seen that the Case #3 design increases the power loss for both networks if it is located at some specific nodes.

B. Impact on Maximum Line Current

The effect of the UPQC-SPAC allocation on maximum line current for the two networks is shown in Figs. 6(b) and 7(b). The maximum line current of the networks without UPQC-SPAC are 0.0461 p.u. and 0.4903 p.u. for the 33- and 69-node systems, respectively. The results illustrate that the maximum line current is reduced with UPQC-SPAC allocation. It is also observed that better results are obtained if the UPQC-SPAC is designed to mitigate a higher amount of voltage sag.

C. Impact on Undervoltage Mitigation

A UPQC can efficiently be used in undervoltage mitigation if it is used in healthy operating conditions as shown in [15]. In this paper, the upper and lower voltage limits are set to be 1.05 p.u. and 0.95 p.u., respectively. If the voltage at any node is less than the lower limit, it is said that it suffers from the undervoltage problem. In the 33-node system, 21 out of 33 nodes (i.e., 63.63%) have an undervoltage problem. Similarly, 9 out of 69 nodes (i.e., 13.04%) suffer from an undervoltage problem in the 69-node system. To quantify the effect of the UPQC allocation on undervoltage mitigation, an index called the rate of undervoltage mitigated nodes (RUVMN) [15] is used.

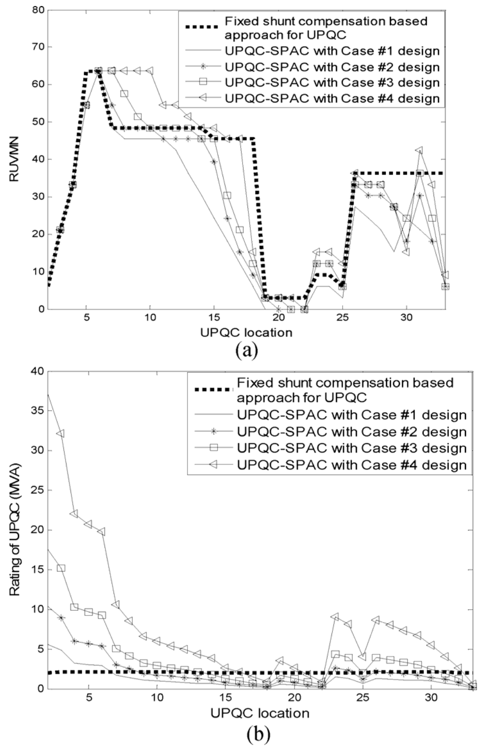


Fig. 8. Performance comparison between the fixed shunt compensation-based approach [15] and the UPQC-SPAC based on: (a) RUVMN of the network and (b) rating of the UPQC.

It is defined as the percentage of nodes that comes out from the undervoltage problem. For example, $\text{RUVMN} = 10\%$ implies that 10% of nodes, having an undervoltage problem, come out from it. The RUVMN is obtained due to the UPQC-SPAC allocation in different locations of the two test networks, which is shown in Figs. 6(c) and 7(c). These illustrate that better RUVMN can be obtained if the UPQC-SPAC is appropriately placed in the network. It is also observed that a UPQC-SPAC designed to mitigate a higher amount of voltage sag has the ability for better undervoltage mitigation. A performance comparison of the UPQC-SPAC is also carried out with the fixed shunt compensation-based approach of UPQC reported in [15]. The shunt inverter rating is kept constant to 2 MVA irrespective of its location in the network in [15]. The comparative results, in terms of RUVMN and the rating of the UPQC obtained with the 33-node system, are shown in Figs. 8(a) and (b), respectively. Better performance in terms of RUVMN is obtained with the UPQC-SPAC with the Case #4 design. But the ratings of the solutions obtained with the Case #4 design are found to be higher. According to the rating, the solutions obtained with the Case #2 design are better. But the RUVMN in most locations is poor. The intermediate results are obtained with Case #2 and #3 designs. As a compromise solution, the UPQC-SPAC obtained with the Case #2 design at node 7 yields the same RUVMN with a lower MVA rating (i.e., 1.69 MVA) compared to the approach reported in [15].

D. Impact on Maximum Loadability and Voltage Stability

To study the impact of the UPQC-SPAC allocation on voltage stability, the load demand of each node is increased and the effect of it on the node voltage is studied. This is done by using a multiplying factor called the loading factor (λ), defined as the ratio of increased load demand to the nominal/base-case load demand [20], i.e.,

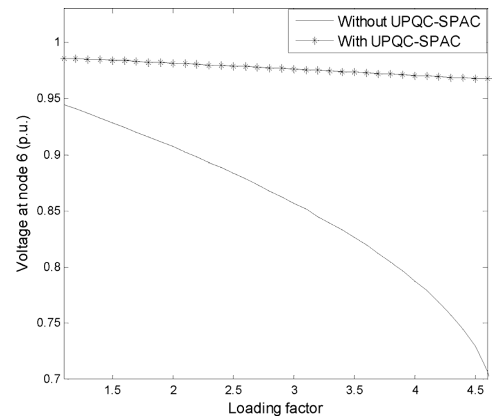


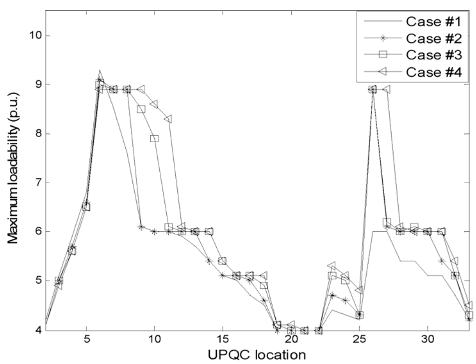
Fig. 9. Effect of loading on node voltage with and without UPQC-SPAC allocation.

$$P_L(m) = \lambda P_{LO}(m)$$
$$Q_L(m) = \lambda Q_{LO}(m) \tag{31}$$

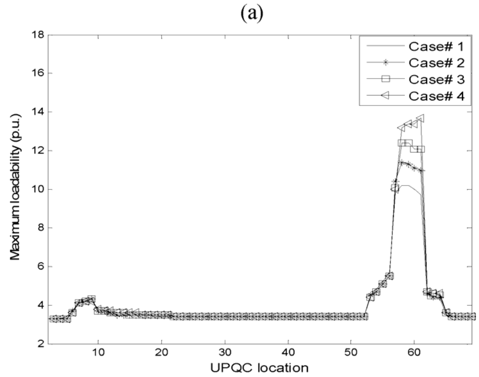
where $P_{LO}(m)$ and $Q_{LO}(m)$ represent the nominal/base-case active and reactive power demands, respectively, for node m. The maximum loadability of a network is the maximum value of the loading factor until the voltage at any node of the network starts collapsing. The higher value of maximum loadability implies better voltage stability margin [20]. Fig. 9 shows the voltage at node 6 with and without UPQC-SPAC allocation of the 33-node system. The result shows that there is significant improvement in the voltage stability margin with the UPQC-SPAC allocation. The maximum loadability obtained with the UPQC-SPAC at different nodes is shown in Fig. 10. The result illustrates that significantly higher maximum loadability can be obtained if a UPQC-SPAC is located at some specific nodes, for example, at nodes 6, 7, 8, 26, 27, etc. for the 33-node system and at nodes 58, 59, 60, 61, etc. for the 69-node system. The results obtained with Case #3 and Case #4 designs show better loadability.

E. Impact on Distribution System With DG

A UPQC can provide reactive power support to a DG unit during voltage sag as shown in [14]. To study its impact on a network at healthy condition, an induction generator unit is placed at each node of the 69-node system, one at a time. Its active power rating is 1 MW and it consumes reactive power from the system at a power factor of 0.8. The network power loss due to the UPQC-SPAC allocation at the presence of DG at each node of the network is shown in Fig. 11. The result illustrates that the network power loss is reduced at few locations, for example, at nodes 57–61 and it increases at most of the locations. The solution corresponding to the minimum power loss is shown in Table I. The result shows that the rating of the UPQC-SPAC is considerably reduced because the line current at most of the



(a)



(b)

Fig. 10. Maximum loadability of the network due to UPQC-SPAC allocation at different nodes studied on the: (a) 33-node and (b) 69-node systems.

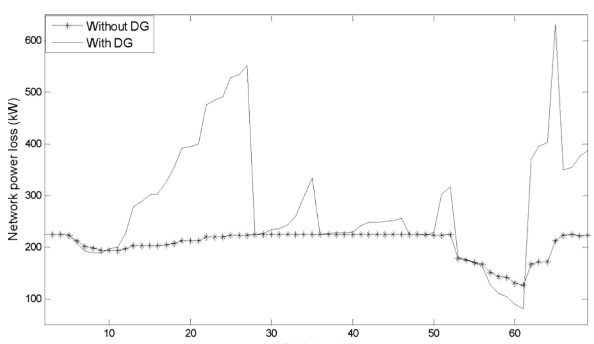


Fig. 11. Network power loss of the 69-node system with combined DG and UPQC-SPAC allocations.

TABLE I
SOLUTIONS CORRESPONDING TO THE LOWEST POWER LOSS

Operational aspects	UPQC-SPAC allocation		DSTATCOM allocation	Capacitor allocation
	Without DG	With DG		
Location(s)	61	61	61	20, 50, 53
Power loss (kW)	126.52	80.28	158.6136	146.33
Minimum node voltage (p.u.)	0.9677	0.9567	0.9245	0.932
MVA rating	4.014	1.924	0.924	1.59

branches is reduced due to the presence of DG at node 61 of the network.

F. Performance Comparison with DSTATCOM and Capacitor Allocations

The performance of the UPQC-SPAC with Case #2 design is compared with two optimal reactive power compensation strategies, that is, DSTATCOM [21] and capacitor allocations [22]. The solutions corresponding to the lowest power loss obtained with the 69-node system are given in Table I. A better solution in terms of power loss and node voltage is obtained with the UPQC-SPAC. But its rating is higher compared to DSTATCOM because the voltage sag mitigation is not considered in the design of DSTATCOM in [21].

VI. CONCLUSION

An investigative study has been carried out to bring out the impact of the UPQC allocation on distribution systems. A new design approach for UPQC to mitigate a given value of voltage sag is proposed. A modified load-flow algorithm including the UPQC-SPAC model is devised. The salient observations from the results obtained are summarized as follows.

- The series inverter of the UPQC-SPAC is used in a major role in reactive power compensation of a distribution network during healthy operating conditions.
- A UPQC-SPAC located at a particular node can protect all of the downstream loads of the feeder from the voltage sag occurring upstream. Hence, the best location for the UPQC-SPAC is supposed to be the node closest to the substation. But this increases the MVA rating of the UPQC-SPAC because it has to handle higher load current. Thus, it requires more investment cost.
- The performance of the UPQC-SPAC is location specific. If it is located at some specific nodes, significant improvements in power loss, undervoltage mitigation, and voltage stability margin can be obtained.
- If a UPQC-SPAC is designed to mitigate a higher amount of voltage sag, its phase angle δ increases. Thus, it can provide more reactive power compensation.
- Due to the UPQC-SPAC placement at a particular node, the customers of the other nodes also benefit.
- The UPQC-SPAC can provide reactive power support to DG and its rating is reduced during the presence of DG.

This paper focuses on the study of the impact of UPQC allocation on distribution systems. A design optimization with the formulation of suitable objective functions may provide the optimal location and rating for UPQC in a network. This requires further investigation.

REFERENCES

[1] V. Khadkikar, “Enhancing electric power quality using UPQC: A comprehensive overview,” *IEEE Trans. Power Electron.*, vol. 27, no. 5, pp. 2284–2297, May 2012.

[2] H. Fujita and H. Akagi, “The unified power quality conditioner: The integration of series- and shunt-active filters,” *IEEE Trans. Power Electron.*, vol. 13, no. 2, pp. 315–322, Mar. 1998.

[3] M. Basu, S. P. Das, and G. K. Dubey, "Comparative evaluation of two models of UPQC for suitable interface to enhance power quality," *Elect. Power Syst. Res.*, vol. 77, pp. 821–830, 2007.

[4] V. Khadkikar and A. Chandra, "UPQC-S: A novel concept of simultaneous voltage sag/swell and load reactive power compensations utilizing series inverter of UPQC," *IEEE Trans. Power Electron.*, vol. 26, no. 9, pp. 2414–2425, Sep. 2011.

[5] D. O. Kisck, V. Navrapescu, and M. Kisck, "Single-phase unified power quality conditioner with optimum voltage angle injection for minimum VA requirement," in *Proc. IEEE Power Electron. Specialists Conf.*, Bucharest, Romania, 2007, pp. 574–579.

[6] V. Khadkikar and A. Chandra, "A novel structure for three-phase four-wire distribution system utilizing unified power quality conditioner (UPQC)," *IEEE Trans. Ind. Appl.*, vol. 45, no. 5, pp. 1897–1902, Sep./Oct. 2009.

[7] A. K. Jindal, A. Ghosh, and A. Joshi, "Interline unified power quality conditioner," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 364–372, Jan. 2007.

[8] M. Brenna, R. Faranda, and E. Tironi, "A new proposal for power quality and custom power improvement: OPEN UPQC," *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 2107–2116, Oct. 2009.

[9] V. Khadkikar and A. Chandra, "A new control philosophy for a unified power quality conditioner (UPQC) to coordinate load-reactive power demand between shunt and series inverters," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2522–2534, Oct. 2008.

[10] A. Ghosh and G. Ledwich, "A unified power quality conditioner (UPQC) for simultaneous voltage and current compensation," *Elect. Power Syst. Res.*, vol. 59, pp. 55–63, 2001.

[11] S. B. Karanki, M. K. Mishra, and B. K. Kumar, "Particle swarm optimization-based feedback controller for unified power-quality conditioner," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2814–2824, Oct. 2010.

[12] H. Heydari and A. H. Moghadasi, "Optimization scheme in combinatorial UPQC and SFCL using normalized simulated annealing," *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1489–1498, Jul. 2011.

[13] B. Han, B. Bae, H. Kim, and S. Baek, "Combined operation of unified power-quality conditioner with distributed generation," *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 330–338, Jan. 2006.

[14] N. G. Jayanti, M. Basu, M. F. Conlon, and K. Gaughan, "Rating requirements of the unified power quality conditioner to integrate the fixed speed induction generator-type wind generation to the grid," *IET Renew. Power Gen.*, vol. 3, no. 2, pp. 133–143, 2009.

[15] M. Hosseini, H. Shayanfar, and M. Fotuhi-Firuzabad, "Modeling of unified power quality conditioner (UPQC) in distribution systems load flow," *Energy Convers. Manage.*, vol. 50, pp. 1578–1585, 2009.

[16] V. Khadkikar, A. Chandra, A. O. Barry, and T. D. Nguyen, "Analysis of power flow in UPQC during voltage sag and swell conditions for selection of device ratings," in *Proc. IEEE Can. Conf. Elect. Comput. Eng.*, Ottawa, ON, Canada, 2006, pp. 867–872.

[17] S. Ghosh and D. Das, "Method for load-flow solution of radial distribution networks," *Proc. Inst. Elect. Eng., Gen. Transm. Distrib.*, vol. 146, no. 6, pp. 641–648, 1999.

[18] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Trans. Power Del.*, vol. 4, no. 2, pp. 1401–1407, Apr. 1989.

[19] J. S. Savier and D. Das, "Impact of network reconfiguration on loss allocation of radial distribution systems," *IEEE Trans. Power Del.*, vol. 22, no. 4, pp. 2473–2480, Oct. 2007.

[20] R. S. Al Abri, E. F. El-Saadany, and Y. M. Atwa, "Optimal placement and sizing method to improve the voltage stability margin in a distribution system using distributed generation," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 326–334, Feb. 2013.

[21] S. Jazebi, S. H. Hosseinian, and B. Vahidi, "DSTATCOM allocation in distribution networks considering reconfiguration using differential evolution algorithm," *Energy Convers. Manage.*, vol. 52, pp. 2777–2783, 2011.

[22] D. Das, "Reactive power compensation for radial distribution networks using genetic algorithm," *Int. J. Elect. Power Energy Syst.*, vol. 24, pp. 573–581, 2002.

Sanjib Ganguly (M'12) was born in 1981 in India. He received the B.E. degree in electrical engineering from IIEST Shibpur, Howrah, India, in 2003 and the M.E. degree in electrical engineering from Jadavpur University, Kolkata, India, in 2006, and the Ph.D. degree in electrical power systems from IIT Kharagpur, India in 2011.

His research interests include power system operation and planning, evolutionary algorithms, and DFACTS technologies.