Reactive Power Support from Converter Connected Renewables in Active Distribution Network

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***Abstract*—Network operators have been increasingly concerned with procuring reactive power sources as the synchronous generators are decommissioned and number of distributed generation is on the rise. Reactive power is necessary in the evolving grid with distributed generation to support the additional power flow and avoid expensive grid reinforcements. Converter connected renewable generators can be a solution to provide the much needed reactive power support in distribution grids. An active distribution grid with significant converter connected generation is also capable of providing voltage regulation support to the transmission network via altering the reactive power feed-in. This research explores the reactive power capabilities of a mutli-voltage active distribution network. A semidefinite programming based optimal power flow is implemented to find the maximum reactive power support from converter connected generation for two different objectives, loss minimization in the distribution network and following a reactive power reference from the transmission network. Changes in voltage profiles in correlation to altering reactive power flow in the distribution network is also analyzed.**

***Index Terms*—reactive power, converter-connected generation, grid codes, loss minimization, transmission-distribution coordination, voltage regulation**

I. Introduction

REactive power regulation helps maintaining the voltage levels in transmission and distribution grids and it increases the capability of active power transfer on power lines. Reactive power has a supporting role in the power system although it is a local resource, i.e. it is cannot be transferred over long distances. Transferring more reactive power over a power line requires more current for the same amount of active power transfer which increases the active power losses. It might result in the power line being operated close to its thermal limits. However, an optimal amount of reactive power is necessary to maintain the voltage levels on power lines.

Centralized synchronous generators have normally been the main source of reactive power supply in the power system along with capacitor banks and VAR compensators at local substations [1]. The power system however is moving towards a decentralized generation structure with decomissioning of larger synchronous generators. Wind and solar energy account for a large share of the upcoming decentralized generation [2], [3]. This leads the system operators into two challenges, first is to find alternative sources of reactive power to replace the synchronous generators. The second challenge is in relation to the distribution generators being installed closer to the load centers or in distribution network. This increases the flow of active power in the distribution network increasing the need of local reactive power sources, and expensive grid reinforcements projects.

The distributed generators are connected to the grid with power electronic converters capable of providing reactive power support. Utilizing the reactive power capability of distributed generation sources not only reinforces the capability of the existing distribution grid for additional active power flow but also provides the transmission network with required ancillary services for voltage regulation. However, the research concerning formulating a market structure to enable reactive power services from distributed generation is in its nascent stage.

The challenge of procuring alternative reactive power sources via converter connected sources, and the required market mechanisms, to support the changing grid structure has been addressed by researchers as well as network operators [4]–[6]. The Danish energy agency has introduced reactive power ancillary services procured from wind power plants [7]. UK power grid has launched a project to demonstrate and study reactive power potential of converter connected generation to provide voltage control services to the transmission grid [8]. A parallel research studied the impact on active power losses in the distribution grid in the light of reactive power support to the transmission grid [9]. The German power grid's rooftop-PV experience highlights the potential of converter connected systems to provide voltage support in low-voltage distribution grid [10]. The aggressively expanding Indian power grid is also considering reactive power support from distributed generation [2]

It is thus timely and imperative to study in details the impact of reactive power on different operating parameters in a distribution network, especially the impact of changing reactive power flow in low voltage distribution grids. The main

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objective of this paper is to present an analysis of the benefits and effects of using converter connected generation as local reactive power sources, in a multi-voltage active distribution grid, considering the following,

1) Maximum reduction of active power loss in the distribution grid by using local converter-connected renewable energy sources (RES) as reactive power sources
2) Assessing the capability of an active distribution grid to provide voltage regulation services for the transmission grid
3) Analyze how the voltage profiles in an active distribution grid are affected by altering the reactive power flow.

The paper is structured as follows. Section II presents the grid code reactive power supply requirements for converter connected renewable generation in Europe. Section III describes the active distribution network model in brief and section IV presents the optimization methodology used in this research. Section V presents the results for the analysis and section VI presents some key conclusions and considerations.

II. Grid codes for reactive power from renewable generation

The European grid codes categorize power generation modules (PGM) into four types based on their installed capacities and termed as type A, B, C and D. A PGM is defined in the grid codes as a synchronous generator or a converter connected generation. For this research we assume that a PGM is a converter connected RES.

Type A PGM is connected below 110 kV voltage level with total installed capacity of 0.8 kW or more. Type B and type C PGMs are also connected below 110 kV voltage level and their categorization based on installed capacities is decided by relevant transmission system operators (TSOs). For example, the maximum capacity threshold for a PGM to be categorised as Type C is 50 MW in continental Europe and 10 MW in the Baltic region [11]. Danish grid connection codes define the limit for type B PGMs as between 125 kW and 3 MW and for type C between 3 MW and 25 MW [12]. Whereas, the Spanish grid connection codes define the limti for type B between 100 kW and 5 MW and for type C between 5 MW and 50 MW [13].

The minimum required services from PGM depend on their category. Type D PGM is expected to provide a wide range of services in relation to voltage stability, fault ride through capability, frequency services etc. owing to their installed capacity and advanced converter capabilities. Type A and B PGMs are required to be registered with the local network operators and may not have the control capabilities to provide any grid services.

The most relevant grid code requirement for this research is reactive power control. The EU commission regulation hands the responsibility for specifying reactive power requirements on the relevant system operators. In accordance, Danish grid operators have specified reactive power requirements for Type B, C, and D PGMs. Fig. 1 (a) shows the reactive power that a PGM must be capable of supplying at different voltage levels at maximum power production. While for production levels below the maximum, the PGM must be capable of providing reactive power within the specified region in Fig. 1 (b). The reactive power support requirements for type A PGMs are relaxed due to their small size, and they may or may not participate in the reactive power control.

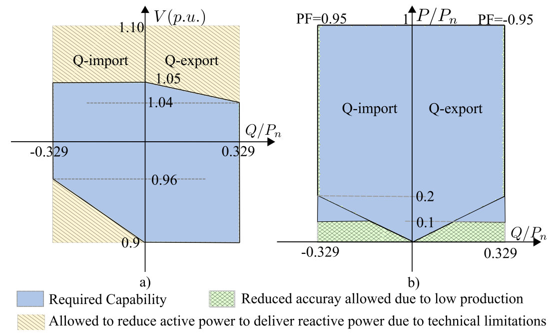

Fig. 1. Minimum required reactive power supply requirements [12]

It has to be noted that the bandwidth of reactive power support specified in Fig. 1 is the lower bound for the must have reactive power. PGM owners and operators can provide reactive power support to the grid beyond the specified minimum. However, due to lack of adequate compensation measures, the PGM operators are discouraged from providing more reactive power support. The converters for renewable generators could be oversized for more reactive power support, but the current reactive power compensation structures are inadequate to justify the cost for oversized converters. However, the inherent reactive power capabilities of the converters is already greater than the minimum grid codes shown in Fig.1

III. Distribution Network Model

This section describes the multi-voltage distribution network model used in this research. An open-source multi-voltage level distribution network model, called the DTU-7k Bus Active Distribution Network, is used in this study [14]. The distribution network model, based on a real Danish medium voltage (i.e. 60 kV) distribution network, and is described in the following in [15], [16] research works. Fig. 2 illustrates the layout of this network, which is connected to the high voltage (HV) transmission network through a step-up 60 /150 kV transformer, and to the low voltage (LV) 10 kV buses through several step-down 60 /10 kV transformers. A 10-0.4 kV network is connected to the 60 kV network making it a three voltage level distribution network. The 10-0.4kV is a large but sparse network with more industrial and commercial load profiles in comparison to household or agricultural loads.

The multi-voltage network has a high share of distributed RES. Three controllable wind power plants (WPPs) are connected to the 60 kV in the distribution network, rated 12 MW, 15 MW, and 15 MW each. The 10 kV network hosts further 9.6 MW of WPPs and the 0.4 kV network hosts 1.6 MW of solar generation. The RES at 60 kV is categorized as Type D

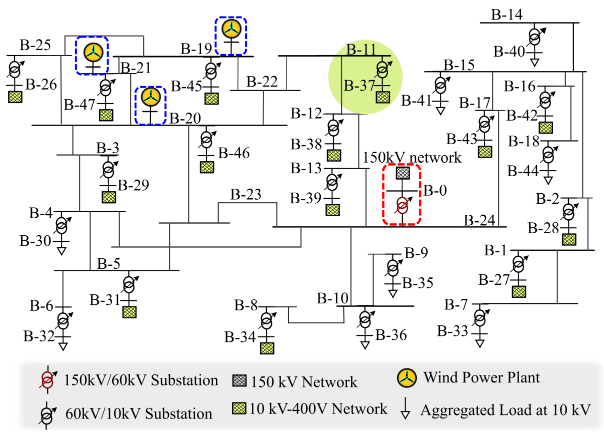

Fig. 2. Topology of the 60 kV distribution network. The 10 kV-400 V network is connected at the highlighted Bus-37

RES, at 10 kV is categorized as Type C RES and the at 0.4 kV is categorized as Type B or A.

The salient features of this network are tabulated as follows:

TABLE I
KEY FEATURES OF THE 60-10-0.4 KV DISTRIBUTION NETWORK

Network Element	#	Voltage Level
Buses	25	60 kV
	59	10 kV
	516	0.4 kV
Type D RES	3	60 kV
Type C RES	4	10 kV

IV. OPTIMIZATION METHODOLOGY

The focus of the exercise is to determine the potential of RES connected in the distribution grid to optimize the distribution network operation in terms of active power losses, voltage profiles, and reactive power at the transmission-distribution interface. To this end, the Type D and Type C RES connected at 60 kV and 10 kV voltage level in the distribution network are assumed controllable.

The optimization is formulated in the form of an optimal power flow problem with minimizing the losses in the 60 kV and 10 kV networks as the principal objective. It is assumed that the state of the system at 60 kV and 10 kV voltage levels is known with 100% certainty via voltage and current measurement devices. In other words, the 60 kV and 10 kV network is assumed to be completely observable.

The following notations are used to describe the optimal power flow.

- $\mathcal{N}_b = \{1, 2..., n_b\}$: set of all network buses
- $\mathcal{L}_{lm}$: set of distribution lines connecting nodes $l \in \mathcal{N}_b$ and $m \in \mathcal{N}_b$
- $\mathcal{N}_g \subset \mathcal{N}_b$: set of network buses with controllable generation
- $P_{D_k} + j\, Q_{D_k}$: apparent power demand at node $k \in \mathcal{N}_b$
- P_{G_k}: power generation at node $k \in \mathcal{N}_g$
- $S_{lm} = P_{lm} + j\, Q_{lm}$: apparent power flow in the distribution line connecting $(l, m) \in \mathcal{L}_{lm}$
- S_{lm}^{max}: thermal limit of apparent power flow through the distribution line
- $\overline{V}_k = V_k \angle \theta_k$: complex voltage vector at bus $k \in \mathcal{N}_b$, where V_k is the magnitude and θ_k is the voltage angle with respect to the reference bus
- V_k^{max}, V_k^{min}: maximum and minimum voltage magnitude limit at bus $k \in \mathcal{N}_b$ according to the grid codes.

A. Objective function

The objective of this optimization is to reduce the total active power losses P_L in the network, given by,

$$P_L = \sum_{(i,j) \in \mathcal{E}_{\mathcal{B}}} G_{ij} \left(V_i^2 + V_j^2 - 2 V_i V_j \cos\left(\theta_{ij}\right) \right) \qquad (1)$$

where $(i, j) \in \mathcal{L}_{lm}$, G_{ij} is the series conductance of the line connecting nodes (i, j), and θ_{ij} is the phase difference between voltages at buses i and j.

B. Control variables

The control variable in this optimization is the reactive power from RES at 60 kV and 10 kV level. The RES at 60 kV level are Type D WPPs, and are deployed according to the inverter capabilities. The RES at 10 kV level are Type C WPPs, and provide the minimum required reactive power support according to the grid codes (see Fig. 1).

C. Constraints

1) Equality constraints: The equality constraints of the optimization problem are the active and reactive power balance equations for each bus k, accounted directly inside the load-flow algorithm:

$$P_{D_k} - P_{G_k} + P_{I_k} = 0 \quad \forall k \in \mathcal{N}_{\mathcal{B}} \qquad (2)$$

$$Q_{D_k} - Q_{G_k} + Q_{I_k} = 0 \quad \forall k \in \mathcal{N}_{\mathcal{B}} \qquad (3)$$

where P_{I_k} and P_{I_k} denote the active and reactive power injections into the k^{th} bus.

2) Inequality Constraints: Four type of inequality constraints are considered in this optimal power flow.
Security constraints - these are inequality constraints, which define the lower and upper voltage limits for all the buses, and the thermal loading capacity for each bus.

$$V_k^{min} \leq V_k \leq V_k^{max} \quad \forall k \in \mathcal{N}_{\mathcal{B}} \qquad (4)$$

$$S_{ij} \leq S_{ij}^{max} \quad \forall (i, j) \in \mathcal{L}_{lm} \qquad (5)$$

In addition to the above voltage magnitude limits, the voltage reference at Bus-37, the lower voltage bus of the 60/10 kV transformer is fixed at 1.04 p.u. according to the distribution network operator guidelines.
MVAr transfer constraint - this is the constraint which is imposed on the reactive power flow between distribution and transmission networks. The reactive power transfer range between the distribution and the transmission network is limited to 48 % of the maximum apparent power of the 150 kV/60 kV

transformer [17].

Transformer constraints - these are minimum and maximum constraints on the transformer tap-setting, τ, as follows,

$$\tau^{min} \leq \tau \leq \tau^{max} \tag{6}$$

It should be mentioned that, in this investigation, the transformer tap-setting is considered as a continuous variable and rounded to the closest integer settings after the load flow converges.

WPP generation constraints - these are inequality constraints on the voltage at point of connection for WPPs, and their reactive power capability.

$$Q_{G_k}^{min} \leq Q_{G_j} \leq Q_{G_k}^{max} \quad \forall k \in \mathcal{N}_g \tag{7}$$

where $Q_{WPP_j}^{l}$ and $Q_{WPP_j}^{u}$ are the minimum and maximum reactive power limits from the RES. For Type C RES, the maximum and minimum reactive power from RES is given by the grid codes, as shown in Fig. 1, whereas, for Type D RES, the maximum and minimum reactive power limit depends on the grid side converter capability as shown in Fig. 3. The equations for the reactive power capability curves shown in Fig. 3 are described in greater details in [18].

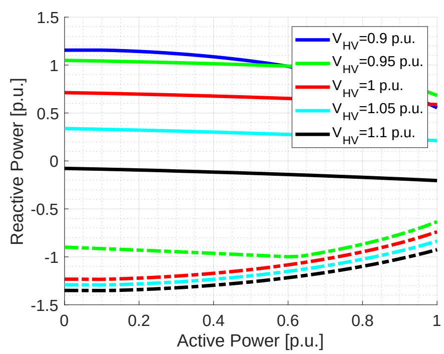

Fig. 3. Reactive power capability curve of a typical Type IV WT for different voltages levels on the HV side [18]

The optimization problem described above is solved using the semi-definite programming framework for optimal power flow to ensure a global minimum solution [19]. A virtual bus transformer model is used to change the on-load tap changer settings of the 60/10 kV transformer [**?**]. On-load tap changers are employed to maintain a constant 1.04 p.u. voltage reference at the lower voltage side of the 60/10 kV transformer or at Bus-37.

V. Results

In this section, results are presented to analyze the reactive power potential of converter connected RES in the distribution network described in section II. The first part of this section analyzes the effect of reactive power on the active power losses in the multi-voltage level distribution network. The second part presents the ability of an active distribution network to provide reactive power flexibility for the transmission network. The results also outline effect of the mentioned objectives on distribution network voltage profiles.

A. Active power loss minimization

Four different time-stamps are chosen from the dataset to demonstrate the potential of local reactive power support from converter connected RES to minimize active power loss in a multi-voltage level distribution network. The four time-stamps represent combinations of high or low generation with high or low load demand in the network as tabulated in Table II

TABLE II
Time-stamps for loss minimization- Description

Index	Generation [MW]		Load [MW]	Category	
	60 kV	10 kV	10 kV	Gen	Load
T1	0.67	0	1.9	Low	Low
T2	38.2	15.6	1.8	High	Low
T3	6.5	6.9	3.6	Low	High
T4	35	15.7	4.1	High	High

The active power loss in the distribution network is positively correlated with the local generation in network [**?**], [20]. The combination of high generation with low load demand in the network however has the most active power losses in the network, as there is no local sink for the active power generated in the network which creates a high reverse power flow. The RES connected to the distribution network can function as local sources or sinks of reactive power, supporting the voltage level in the network. Higher voltages in turn reduce the current required for the same amount of active power flow, which reduces the active power losses in the distribution lines.

TABLE III
Active power losses - optimization results
C0: Base Case ; C1: Loss minimization

Index	Case	Active power loss					
		Total		60 kV		10-0.4 kV	
		[MWh]	Δ%	[MWh]	Δ%	[MWh]	Δ%
T1	C0	0.3		0.24		0.06	
	C1	0.27	-11	0.22	-7	0.04	-25
T2	C0	9.04		6.6		2.46	
	C1	7.38	-18	5.9	-10	1.48	-40
T3	C0	0.25		0.15		0.1	
	C1	0.247	-2	0.145	-3	0.1	0
T4	C0	5.2		4.25		0.94	
	C1	4.8	-7	3.93	-8	0.91	-4

Table III lists the active power loss reduction due to reactive power contribution from RES for the four time-stamps (T1-T4). The greatest amount of loss reduction in the 60-10-0.4 kV distribution network is 18% at T2 (High gen X Low load) and the lowest is 2% at T3 (Low gen X High Load). The highest loss reduction in the 10 kV-0.4 kV network is 40% at T2 and 25% at T1 and the lowest 0% at T3.

Total loss reduction at any time-stamp due to local reactive power from RES depends upon multiple factors, including the load demand, generation and the location of the demand and generation relative to each other. The amount of generation from the RES directly has an impact on their reactive power contribution due to physical constraints of the grid side converters. One of the constraints is the total apparent power rating of the grid side converter which limits the reactive power at very high generation levels. The other constraint is the loss within the converter system if it acts as a reactive power source at very low generation levels. Table III, thus, presents a snapshot of the interplay of these different factors and hints at the potential of using reactive power from RES for loss reduction in a distribution grid.

B. Reactive power at the transmission-distribution interface

This section demonstrates the potential of an active distribution network to provide reactive power services to the transmission network. The optimal power flow is deployed to provide a reference value of reactive power at the transmission-distribution interface. To make the optimal power flow reference following, the MVAr transfer constraints are fixed to a single value representing the reactive power demand by the transmission network.

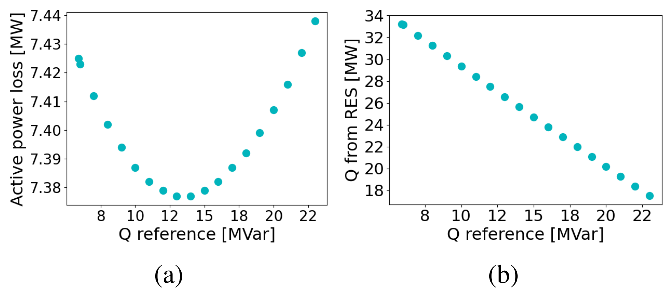

Fig. 4. Timestamp T5: High generation — (a) Active power loss Vs. Reactive power at transmission-distribution interface; (b) Reactive power from RES Vs. Reactive power at transmission-distribution interface

Two different timestamps are chosen for this purpose, T5 and T6, with high and low generation from the RES respectively. When the power generation from the RES is high, the distribution network requires reactive power to sustain the high voltage levels due to high local active power injection. In this case, an active distribution network is more likely to function as a sink of reactive power. This is demonstrated with a timestamp with has a high renewable generation. The distribution network for T5 has a potential to absorb reactive power in the range from 5.9 MVar to 23 MVar. The quadratic relation between reactive power at the transmission-distribution interface and active power losses is shown in Fig. 4 (a). The optimization sets the RES to inject reactive power in the distribution network to maintain voltage levels during high generation. However, as the power flow from the transmission to distribution network is increased, the reactive power injection from the RES is reduced. This balancing of the reactive power is plotted in Fig. 4 (b).

At the other end of the spectrum, the distribution network has the potential to supply reactive power to the transmission network. This is demonstrated using time-stamp T6 with low generation as an example. The distribution network can provide 5.9 MAr upto 30 MVar of reactive power to the transmission network. The negative values in Fig 5 (a) represent

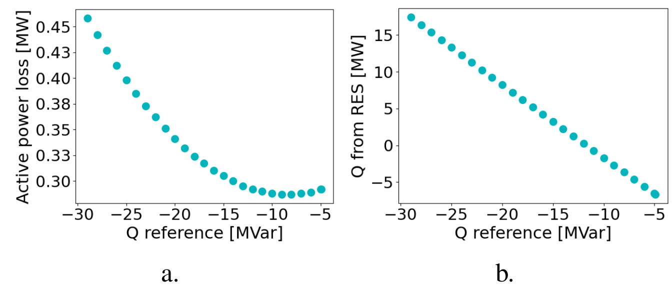

Fig. 5. Timestamp T6: Low generation — a. Active power loss Vs. Reactive power at transmission-distribution interface; b. Reactive power from RES Vs. Reactive power at transmission-distribution interface

a reverse reactive power flow, i.e. from distribution to the transmission network. The quadratic relationship between the active power losses and the reactive power at transmission-distribution interface is also depicted in Fig 5 (a). In addition, Fig 5 (b) portrays the balancing of reactive power from the RES as the reactive power reference at transmission-distribution interface changes.

C. Voltage profiles in relation to reactive power

Altering the reactive power flow in the distribution network has a direct effect on the voltage profiles. Voltage profiles in the distribution network directly affect the quality of power supply for the consumers. Thus, the objectives presented earlier, namely loss minimization or following a reactive power reference at the transmission-distribution interface, are do not give a complete picture of optimal operating conditions without investigating the voltage profiles.

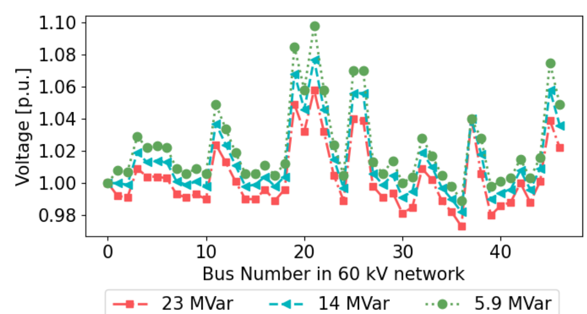

Fig. 6. Timestamp T5: High generation — Voltage profiles at different values of reactive power reference at the transmission-distribution interface

Fig. 6 and 7 plot the voltage profiles in the 60 kV distribution network shown in Fig. 2 for three different values of reactive power reference at the transmission-distribution interface each. It is observed that the voltages at all buses are higher with high local reactive power generation. With a higher local active power generation the voltages are closer to the upper voltage limit of 1.1 p.u., especially at the buses with RES (bus 19, 20 and 21 in Fig. 6). Voltage profiles close the upper limit is not an optimal operating condition for a distribution network. This challenge can be remedied by reducing the local reactive power from RES. Conversely, at lower local generation, local reactive power from RES has the potential to increase the voltage profiles to optimal operating levels, as observed in Fig. 7.

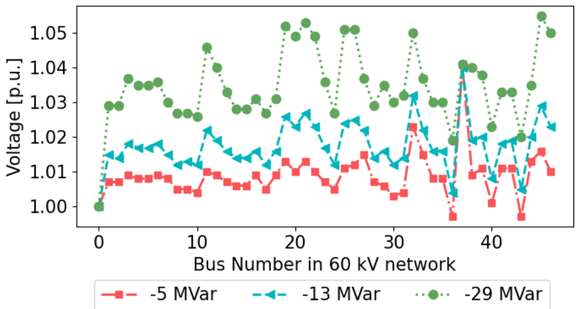

Fig. 7. Timestamp T6: Low generation — Voltage profiles at different values of reactive power reference at the transmission-distribution interface

VI. Conclusion

The brief evaluation conducted in this research it is observed that converter connected sources are capable of reducing active power losses upto a maximum of 18% in the multi-voltage network and 40% in 10 kV-0.4 kV level network for high generation low load scenario. The reduction in active power losses depends upon the load demand, generation and multiple factors in the network. The optimal power flow was also formulated to allow the distribution network to act as a source or sink of reactive power for the transmission network. The voltage profiles in the network are observed to be positively correlated with the amount of local reactive power support in the network. However, the voltage levels can exceedingly grow close to the higher voltage limit of 1.1 p.u. if not actively controlled.

The 10 kV-0.4 kV voltage profiles for this study remain constant as the voltage at 10 kV substation bus is fixed at 0.4 p.u.. This also limits potential reactive power advantages from the converter connected RES in the 10 kV-0.4 kV network. A natural extension of this work is to remove the fixed voltage at 10 kV bus and allow the RES in 10-0.4 kV network to contribute to the reactive power at transmission-distribution interface. The results presented in this paper can be used for future studies to design an optimization methodology including weather dependent variability in the distribution network, and to greater possibilities of transmission-distribution coordination.

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