Distributed Flexibility to Maintain Security Margin through Decentralised TSO-DSO Coordination

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Abstract

The increasing role of distribution networks as an active entity in the whole power and energy system, development of a unified power flow method to provide an integrated analysis of transmission and distribution networks becomes essential. Traditional methods have not addressed the challenge of voltage security in the coordination, while disconnecting the whole distribution network is considered as a solution for preventing major issues. This paper proposes a decentralised scheme for the coordination of transmission and distribution networks while maintaining the voltage security of the whole integrated system. At the transmission level, the transmission network operator (TSO) solves a centralised optimisation problem to minimise the system load curtailment while maintaining the system security margin. The TSO communicates the required set-points in the interface with distribution grids to the distribution system operators (DSOs.) At the distribution level, the DSOs utilise their available distributed flexibilities, such as conservation voltage reduction and feeder reconfiguration, to provide the required set-points and preserve the whole system security margin, with minimum load curtailment. This decentralised optimisation scheme preserves the system security with minimum information exchange between operators, as well as minimum physical load curtailment. The distributed flexibilities of all DSOs are utilised to meet the required security margin of the whole system. The proposed TSO-DSO coordination model is applied to the IEEE 118-bus transmission network, and the 83-bus practical distribution network of Taiwan Power Company and IEEE 33-bus feeder are considered as the connected distribution networks. The results show that the distributed flexibilities are capable of reducing the system demand to preserve the desired security margin, without any need for imposing direct load curtailment.

Keywords: TSO-DSO coordination, distributed flexibilities, security margin, feeder reconfiguration, voltage regulator.

Sets and Indices

$\mathcal{B}_b$	Set of distribution network buses.
$\mathcal{B}_S$	Set of distribution network substations.
Ω_b	Set of transmission system buses.
ψ	Index for voltage-dependent load model. $\psi \in \{$*residential, commercial, industrial*$\}$ load model.
b, j	Index of transmission or distribution system buses.
d	Index of parallel distribution feeders connected to a specific transmission bus.
N_b	Total number of parallel distribution feeders connected to the *b*-th transmission bus.

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Parameters

$(\alpha/\beta)_{b,d}^{\psi}$	The active/reactive exponent of load type ψ at Bus b of the d-th parallel distribution bus b.
$(\widehat{P/Q})_b^D$	Active/reactive power demand in b-th bus of transmission system at SLP.
$(\overline{p/q})_{b,d}^D$	Initial active/reactive power demand of b-th bus in the d-th parallel distribution feeder.
$(g/b)_{bj,d}$	Conductance/susceptance of the line connecting buses b and j in the d-th parallel distribution feeder.
$(kp/kq)_{b,d}^{\psi}$	Active/reactive power share of load type ψ at Bus b of the d-th parallel distribution bus.
$(P/Q)_b^D$	Active/reactive power demand in b-th bus of transmission system at COP.
$(P/Q)_b^{G_{\max\,/\,\min}}$	Maximum/minimum limits of $(P/Q)_b^G$.
$(p/q)_{b,d}^{S_{\max\,/\,\min}}$	Maximum/minimum value of $(p/q)_{b,d}^S$.
$(p/q)_b^{LC,max}$	Maximum limit of $(p/q)_b^{LC}$.
$(Y/\phi)_{bj}$	Magnitude/angle of bj-th element of the transmission system's admittance matrix.
Λ_b^D	Increment rate of the transmission system load.
Λ_b^G	Increment rate of active power output of generation units.
λ_{des}	Desired loading margin.
$\overline{v}_{b,d}$	Initial voltage magnitude of b-th bus in the d-th parallel distribution feeder.
$\pi_{b,d}^{dg}$	Available DG output.
$\pi_{b,d}^{(p/q)}$	Active/reactive power share of d-th parallel feeder connected to the transmission Bus b.
$i_{bj,d}^{\max}$	Maximum limit of $i_{bj,d}$.
$S_{bj}^{\max}$	Maximum limit of S_{bj}.
$V_b^{\max\,/\,\min}$	Maximum/minimum limits of V_b.
$v_{b,d}^{\max\,/\,\min}$	Maximum/minimum limits of $v_{b,d}$.

Variables

$(\widehat{P/Q})_b^G$	Active/reactive power output of generation unit of Bus b at the SLP.
$(\widehat{V/\theta})_b$	Voltage magnitude/angle of b-th bus of transmission system at the SLP.
$(P/Q)_b^G$	Active/reactive power output of generation unit of Bus b at the COP.
$(P/Q)_b^{LC}$	Active/reactive load curtailment at b-th transmission bus.
$(p/q)_{b,d}^S$	Active/reactive power injection at b-th bus of the d-th parallel distribution feeder.
$(p/q)_{b,d}^{dg}$	Active/reactive DG output.
$(p/q)_{bj,d}$	Active/reactive power flowing through the line connecting buses b and j in the d-th parallel distribution feeder.
$(p/q)_b^{LC}$	Active/reactive load curtailment in the b-th bus in the d-th parallel distribution feeder.
$(V/\theta)_b$	Voltage magnitude/angle of b-th bus of transmission system at the COP.
$(v/\theta)_{b,d}$	Voltage magnitude/angle of b-th bus in the d-th parallel distribution feeder.
$\chi_{bj,d}^l$	Binary variable indicating the on/off status of line l connecting buses b and j in the d-th parallel distribution feeder.
λ	Loading margin of the transmission network.
$\tau_{bj,d}$	Tap level of the voltage regulator on the line between buses b and j in the d-th parallel distribution feeder.
$i_{bj,d}$	Current flowing through the line connecting buses b and j in the d-th parallel distribution feeder.
$S_{bj}/\hat{S}_{bj}$	Power flow between transmission buses b and j at COP/SLP.

1. Introduction

Restructuring within the electricity power industry has created opportunities for small businesses, enabling more competition and possibly ending electricity market monopolies. It has also enabled the engagement of distribution system operators (DSOs) in the energy markets. Despite substantial opportunities created by this new paradigm, the lack of sufficient coordination between transmission system operator (TSO) and DSOs can create critical challenges, especially during an emergency condition (e.g. sudden changes in the system load or generation failure) in the network. The UK power outage in 2019 can be an example of lack of TSO-DSO coordination, where millions of customers at the distribution level were disconnected from the main grid by under-frequency load shedding [1].

This event highlights the necessity of cooperation between TSO and DSOs. The cooperation between operators can enable a coordinated control architecture in the whole network [2]. Although a coordinated scheme allows the DSOs to have a direct role in the market, in practice, TSOs are still responsible for the secure operation of the whole system [3]. Consequently, under emergency conditions, TSOs can disconnect the distribution feeders and all of their connected loads to preserve system security. This, however, can bring about significant techno-economic losses to the system managers. Therefore, system security is a challenge that questions the effectiveness of available TSO-DSO coordination models [4]. A practical coordinated framework should enable flexibility in the DSOs to preserve system security. This raises an important question (recently considered in the Global Power System Transformation Consortium's Research Agenda Group) [5]: *"How can grid topology be flexibly adapted to various operating conditions?"*

In the literature, network flexibility is mainly achieved through optimal management of different types of distributed energy resources (DERs) at the distribution system level. In [6], a reserve provision capability method is utilised for estimating the reserve requirement of TSOs and the capability of DSOs in complying with the upper-level needs. This proposed model is solved for a planning stage, however, it has not considered the sudden changes in the operation of the coordinated system. The capability of distribution networks in providing reactive power support for the transmission system is studied in [7], where intermittency of renewable distributed generation units is considered, with the authors proposing a capability chart for investigating the effect of uncertainty on the service provision. In [8], the influence of local markets on the TSO-DSO coordination is investigated with a bi-level optimisation problem considering the conflicting objectives. The results show that both TSOs and DSOs should consider a budget to be robust in face of renewable power generation uncertainty. Reference [9] proposed a real-time energy management strategy for distribution systems, analysing various flexibility services that could be provided for the transmission level in the interface of these networks.

The cooperation between transmission and distribution systems is subjected to several technical and operational challenges, which have been summarised in [3]. These aspects can also affect the policies of cooperation. Each entity has its own objectives. For example, TSOs might aim to minimise their costs. DSOs focus on addressing the reliability of load supply. These different objectives create a substantial challenge in terms of information exchange privacy [10]. A decentralised control approach could address this coordination challenge. A decentralised coordination scheme for distributed generation units is proposed in [11] to meet the reactive power set-points of the TSO-DSO interface, with the aim of minimising the power losses while satisfying the distribution grid constraints. The authors also proposed a control scheme for on-load tap changer so as to unlock higher level of reactive power flexibility. A market clearing framework is proposed in [12] for trading the flexibility provided by the distributed generation in the distribution level. The results show that the flexibility in the distribution level can affect the locational marginal prices in the transmission level. A decentralised control model is introduced in [13], where the DSO and TSO solve their own optimisation and balance the reactive

Table 1
Taxonomy of control models in TSO-DSO coordination literature.

	Flexibility measure				Control method		Power flow constraints		
Ref. No	DER	Reconfiguration	CVR	load	Centralised	Decentralised	Transmission network	Distribution network	Voltage stability
[6, 7, 9, 22]	✓	x	x	x	✓	x	x	✓	x
[8, 13, 15, 17]	✓	x	x	x	x	✓	✓	✓	x
[11, 14]	✓	x	x	x	x	✓	x	✓	x
[12]	✓	x	x	✓	x	✓	✓	✓	x
[21]	✓	x	x	x	x	✓	✓	✓	x
[23]	✓	x	x	x	✓	x	✓	✓	x
[24, 25]	✓	x	x	✓	✓	x	x	✓	x
This study	✓	✓	✓	x	x	✓	✓	✓	✓

power in their interface. This iterative approach in coordination is also utilised in [14]. Yuan *et al.* [15] proposed a hierarchical coordination approach based on the economic dispatch, where DSOs solve their optimisation at an upper level and report the solution to the TSOs. The final solution is achieved in an iterated manner. Considering the high rate of (R/X) in the distribution systems, however, a simple economic dispatch or a DC-OPF cannot reflect the operational and dynamic characteristics of the network [16]. In [17], a diagonal quadratic approximation method is utilised for coordinating the OPF problems of the TSOs and DSOs. The security of the coordination with the least information exchange remains a challenge in available methodologies.

Preserving the integrated system security is a challenging issue of the coordination [18]. An important indicator for evaluating system security is the voltage stability margin [19, 20]. Therefore, voltage stability assessment has been followed by researchers to evaluate the security of TSO-DSO coordination. A joint static voltage stability analysis is introduced in [21] for evaluating the security of integrated distribution and transmission systems. In [22], voltage stability requirement is translated into the need for reactive power and a methodology is proposed to defer investment in reactive power compensation equipment while satisfying the required margin through optimal control of synchronous and non-synchronous generation units. The impact of DER technologies installed in the distribution level is shown by the authors. Tang *et al.* [23] compared the accuracy of data-driven methods with the OPF-based models in the coordination of TSO and DSOs. The positive role of flexibility services, provided by the distribution networks, on the heavily loaded buses of the transmission network is shown in [24]. The dynamics of the distribution system are neglected and the evaluation of transmission contingency analysis is performed based on the forecasted load and generation. In [25], the role of distribution network in providing the voltage support for the transmission level is studied in a real-time centralised optimisation method. A model-free framework is introduced in [26] for exploiting the flexibility provided by the low-voltage level DERs in order to provided voltage support both in normal and emergence condition for the transmission network. Reference [27] proposed a security constrained unit commitment for TSO-DSO coordination with the aim of reducing the computational time. In an emergency condition, however, the objective functions of system operators would focus on secure operation of the system rather than a cost-optimal unit commitment. The main challenge that remains, however, is how to introduce security measures as critical components of TSO-DSO coordination.

Although the coordination between TSOs and DSOs has been studied before, the amount of data exchange, distribution system flexibility, and system security are three important considerations that need more investigation.

1. With increasing the numbers of distribution systems connected to a transmission network, it is important to reduce the volume of data exchange. This can help in optimising TSO problems with short computational time. Therefore, an efficient method that solves the optimisation on

both sides with the least information exchange and while preserving the system security needs to be developed.

2. The study of distribution system flexibility focuses mainly on the potential of distributed generation to provide services for the upper network in a normal situation. Nevertheless, there are other practical methods that should be studied for evaluating the distribution level flexibility under different circumstances including an emergency condition (e.g. conservation voltage reduction and network reconfiguration).

3. Although voltage stability analysis has been studied to evaluate the security of TSO-DSO coordination, it is not considered a critical constraint in designing decentralised optimisation models. This security measure should be added to the OPF model of decentralised optimisations of TSO and DSO. Such a scheme should highlight the importance of DSOs in preserving the security of TSO-DSO coordination.

This study aims at addressing these challenges by introducing a decentralised security-constrained TSO-DSO coordination framework. The proposed method investigates the practical flexibility options at the distribution level for preventing load curtailment in an emergency condition. A decentralised control architecture is proposed for optimising the critical components of the power flow model (i.e. active/reactive power, and voltage magnitude) in the interface between transmission and distribution networks. Rather than consider models of frise coordination, this method is designed to achieve optimal values in the boundary points connecting the transmission and distribution networks. To ensure secure coordination, the proposed model considers the loading margin as the security measure. This measure should be satisfied under different circumstances. The TSO optimises the system operation while preserving the system security. The desired values of power exchange and voltage level in the interface are sent to the DSOs. To respond to the required set-point given by the TSO, the distributed DSO optimisers try to benefit from available network flexibility options while respecting the integrity of their internal constraints. The first promising flexibility option is the use of voltage regulators in the distribution level, as the demands are voltage-dependent. This scheme is widely known as conservation voltage reduction (CVR) [28]. The next network flexibility option is the reconfiguration of the distribution network, which has been used to improve different techno-economic characteristics of distribution grid separately [29]. The solutions of DSO optimisers are sent to the interface and compared with the requirement of TSO. This process is repeated by optimisers until a degree of convergence is achieved. If the DSOs fail in satisfying the required boundary points, they would apply the load curtailment to preserve the security of the whole system. This paradigm highlights the role of DSOs in providing flexibility measures for preserving the TSO-DSO coordination. This framework can converge with a small number of iterations and with a short computational time (only seconds), which enables it as a suitable practical TSO-DSO coordination scheme for research and industry. The main contributions of this paper are:

- A decentralised control framework is introduced for TSO-DSO coordination with the least information exchange between them. In this method, DSOs use their available flexibility measures or/and load curtailment to comply with the requirements of the TSO. This proposed method benefits from short computational time spans and achieves the required convergence degree with a small number of iterations.

- Distributed optimal conservation voltage reduction and network reconfiguration are adopted as the flexibility measures preserving the security of TSO-DSO coordination with minimum physical load curtailment. In the upper level, the TSO ensures the minimum loading margin for the transmission network considering the critical components of the power flow model. In the lower-level distributed optimisation models, DSOs aim at minimising the actual load curtailment, using the available flexibility options. Each DSO provides a different level of flexibility in the proposed distributed framework. However, the total flexibility provided comply with the requirements of the TSO.

- The transmission network's loadability constraint is considered as the main security margin influencing the TSO-DSO coordination. This index can be utilised as a measure for evaluating the degree of security of TSO-DSO coordination.

The remainder of this paper is organised as follows: Section 2 explains the framework of the proposed TSO-DSO coordination. Mathematical formulation is introduced in Section 3. Section 4 explains the solving process of the decentralised optimisation approach. The simulation results are given in Section 5. Finally Section 6 concludes the paper.

2. Framework Description

A visualisation of the proposed TSO-DSO coordination framework is presented in Fig. 1. This framework is suggested for a known number of parallel distribution feeders that are connected to a transmission network in the interface of these networks. Based on this architecture, an optimisation problem is first solved by the TSO. Since voltage stability is an important security criterion in the cooperation between TSO and DSO [21], it can be considered as the main influence on the coordination between networks. Accordingly, the optimisation in the transmission level always considers a degree of loading margin (i.e. security margin) as an important constraint of the model. This is shown in the upper left-hand side of Fig. 1. In this regard, a sudden change in the system load (e.g. increasing above the generation capacity) can create security issues for the TSO if the aim is to keep the loading margin in the preferred range.

In a conventional TSO-DSO coordination scheme, the TSO optimiser is more likely to apply load curtailment to some heavily loaded buses which are connected to the lower-level distribution grids. However, TSOs can benefit from the flexibility measures in the distribution networks. The methodology designed in this paper highlight the role of the flexibility measures in the distribution networks for preserving the system security. Therefore, the outcomes of the TSO optimiser in the point of connection with the distribution grids are sent to the distributed DSO optimisers. These values are shown with $U_{1...n}^{TSO}$ in Fig. 1. Each DSO compiles its distributed optimisation based on the received data. To prevent load curtailment, DSOs try to utilise the available flexibility options in the distribution level to comply with the requirements of the TSO. To do so, they utilise the CVR to adjust voltage within the permissible range which can result in load reduction. Simultaneously with this strategy, the DSOs adopt the network reconfiguration to decrease the power loss and improve the voltage profile. After applying these strategies to the distribution network via an optimisation model, the DSOs compare the preferred values (i.e. $U_{1...n}^{DSO}$) with those received from the TSO. If the values are lower than that of the TSO, they are sent to the TSO optimiser for another round of optimisation. This process is repeated until the DSO values are equal or bigger than those of the TSO. The DSOs would apply load curtailment if they cannot decrease their load level to preserve the security of coordination. The proposed method converges in a small number of iterations and respects data privacy by considering only critical components of the power flow model in the interface of the networks.

It is worth mentioning that this framework investigates the role of distributed flexibilities in TSO-DSO coordination while complying with the security margin. Therefore, it does not address the sizing of distribution networks. The number of distribution networks is assumed as a known parameter. In the

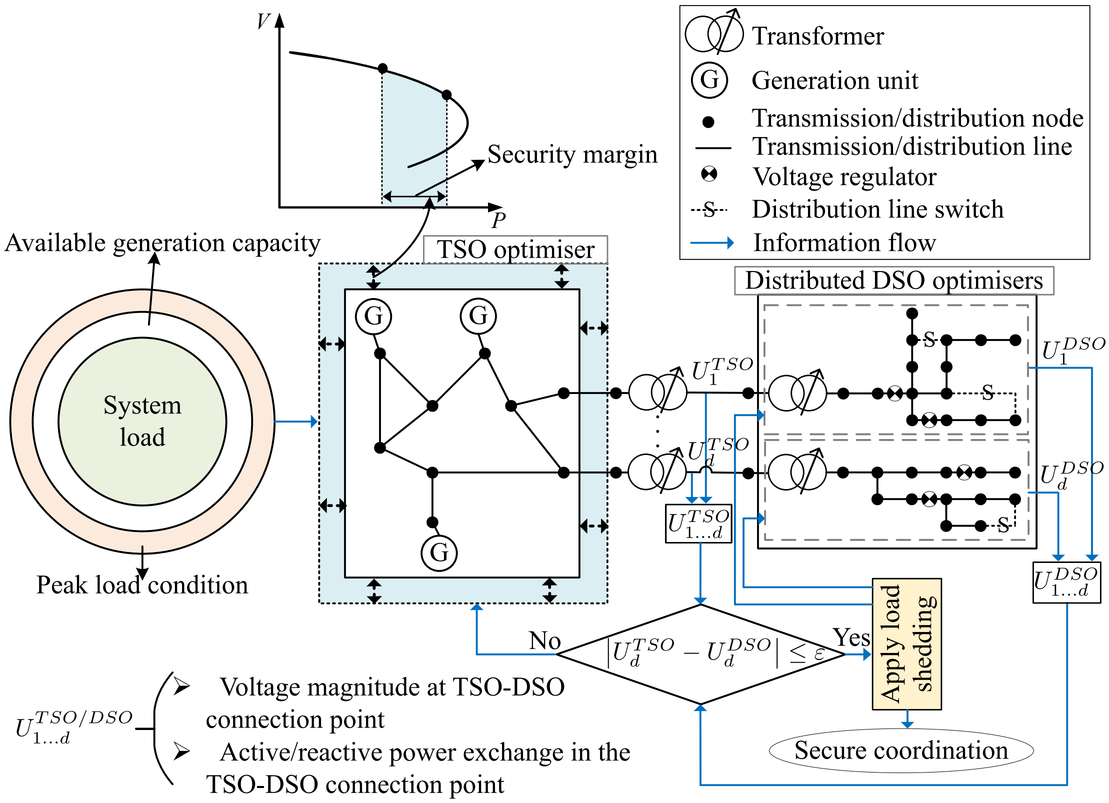

Figure 1: Conceptual illustration of the proposed architecture.

meantime, sensitivity analysis has been performed to show the variation of the results over the changes in the number of distribution networks.

3. Formulation of the Proposed TSO-DSO Coordination Framework

The proposed formulation for the decentralised control method is illustrated in Fig. 1. At the transmission level, the optimisation is solved with the aim of minimising the load curtailment under a peak loading condition while satisfying the required loading margin (i.e. security margin). The desired solutions of the optimisation in the connection point with the distribution networks are reported to the DSOs. The distributed DSO optimisers then utilise their available flexibility options to minimise the value of load curtailment and the difference between their required decision variables in the point of connection with the upper network. The following subsections express the mathematical model of the optimisation at each level.

3.1. TSO Centralised Optimiser

At the transmission network level, the TSO optimiser aims at minimising load curtailment and the difference between set-points in the interface with the distribution networks under a peak loading condition (i.e. emergency condition) while satisfying the operational and security constraints.

3.1.1. Objective function

The objective function of the TSO is given below:

$$OF^{TSO} = \min\left\{w_1 \times of_{lc}^{tso} + (1 - w_1) \times of_{dif}^{tso}\right\} \tag{1}$$

$$of_{lc}^{tso} = \sum_{b\in\Omega_b} P_b^{LC} \tag{2}$$

$$of_{dif}^{tso} = \sum_{b\in\Omega_b} \begin{pmatrix} \left|(P_b^D - P_b^{LC}) - p_b^{I_{dso}}\right| \\ + \left|(Q_b^D - Q_b^{LC}) - q_b^{I_{dso}}\right| + \left|V_b - v_b^{I_{dso}}\right| \end{pmatrix} \tag{3}$$

Equation (2) represents the load curtailment in the transmission system, while Eq. (3) is the difference between the set-points in the interface with the distribution networks.

3.1.2. Power flow and network constraints

Concerning the security of the system, it is necessary to consider the current operation power flow constraints in the transmission level simultaneously with those of the security limit point (SLP). This level also contains physical and operational constraints of the transmission grid (e.g., voltage magnitude/angle). The power flow and network constraints at the current operation point (COP) of the network are presented as below ($\forall b, j \in \Omega_b$):

$$P_b^G + P_b^{LC} - P_b^D = V_b \sum_{j\in\Omega_b} V_j Y_{bj} \cos(\theta_b - \theta_j - \phi_{bj}) \tag{4}$$

$$Q_b^G + Q_b^{LC} - Q_b^D = V_b \sum_{j\in\Omega_b} V_j Y_{bj} \sin(\theta_b - \theta_j - \phi_{bj}) \tag{5}$$

$$P_b^{G_{min}} \leq P_b^G \leq P_b^{G_{max}} \tag{6}$$

$$Q_b^{G_{min}} \leq Q_b^G \leq Q_b^{G_{max}} \tag{7}$$

$$0 \leq P_b^{LC} \leq P_b^{LC,max} \tag{8}$$

$$0 \leq Q_b^{LC} \leq Q_b^{LC,max} \tag{9}$$

$$V_b^{\min} \leq V_b \leq V_b^{\max} \tag{10}$$

$$-S_{bj}^{\max} \leq S_{bj} \leq +S_{bj}^{\max} \tag{11}$$

Constraints (4) and (5) are active and reactive power flow at the COP respectively; constraints (6) and (7) limit the upper and lower capacity of generation units respectively; constraints (8)-(9) show the limits on the load curtailments. Constraint (10) represents the limits on the voltage magnitude of system buses; constraint (11) shows the the transmission line capacity.

3.1.3. Security constraints

Due to the importance of security measures in the TSO-DSO coordination, they are considered as the critical component of the OPF model in the TSO optimisation. To do so, as shown in the top left corner of Fig. 1, the loading margin is considered as the security measure of TSO-DSO coordination. This security margin is defined by generation capacity requirements to supply rises in the system demand prior to the violation of SLP [30]. In the P-V curve shown in Fig. 1, the distance from point A (i.e. COP) to point B (i.e. SLP) is the loading margin (i.e. security margin). This margin is defined by the system load. For example, increasing the system demand from P_{D_0} (i.e. point A) to P (i.e. point

B) leads to a violation of the operational constraints of the network. Consequently, the system loading margin should be more than/equa to the preset level to keep the entire network in a secure operational state. In order to address this concept, the power flow equations in COP (i.e. (4)-(9)) should be simultaneously considered along with those of SLP, which are represented as below ($\forall b, j \in \Omega_b$):

$$\hat{P}_b^G - \hat{P}_b^D = \hat{V}_b \sum_{j \in \Omega_b} \hat{V}_j Y_{bj} \cos(\hat{\theta}_b - \hat{\theta}_j - \phi_{bj}) \tag{12}$$

$$\hat{Q}_b^G - \hat{Q}_b^D = \hat{V}_b \sum_{j \in \Omega_b} \hat{V}_j Y_{bj} \sin(\hat{\theta}_b - \hat{\theta}_j - \phi_{bj}) \tag{13}$$

$$P_b^{G_{\min}} \leq \hat{P}_b^G \leq P_b^{G_{\max}} \tag{14}$$

$$Q_b^{G_{\min}} \leq \hat{Q}_b^G \leq Q_b^{G_{\max}} \tag{15}$$

$$V_b^{\min} \leq \hat{V}_b \leq V_b^{\max} \tag{16}$$

$$- S_{bj}^{\max} \leq \hat{S_{bj}} \leq +S_{bj}^{\max} \tag{17}$$

$$\hat{P}_b^D = (1 + \Lambda_b^D \times \lambda) \left(P_b^D - P_b^{LC}\right) \tag{18}$$

$$\hat{Q}_b^D = (1 + \Lambda_b^D \times \lambda) \left(Q_b^D - Q_b^{LC}\right) \tag{19}$$

$$\hat{P}_b^G = \min\left(P_b^{G_{\max}}, (1 + \Lambda_g^G \times \lambda) P_g^G\right) \tag{20}$$

$$\hat{V}_b = V_b + v_b^l - v_b^u \tag{21}$$

$$(Q_b^{G_{\max}} - \hat{Q}_b^G) \times v_b^u \leq 0 \tag{22}$$

$$(\hat{Q}_b^G - Q_b^{G_{\max}}) \times v_b^l \leq 0 \tag{23}$$

$$v_b^l, v_b^u \geq 0 \tag{24}$$

$$\lambda \geq \lambda_{des} > 0 \tag{25}$$

where constraints (12) and (13) represent the active and reactive power flow at SLP respectively; limit on active and reactive power, voltage magnitude, and transmission line capacity at SLP are shown by constraints (14)-(17) respectively. The amount of increase in the active and reactive system demand from COP to the SLP is shown by (18) and (19) respectively. This increase in the system demand should be supplied by generation units, as represented by Equation (20). Constraints (21)-(24) describe the dynamics of load increase from COP to the SLP and the way it would affect the voltage at the system buses. Finally, the desired loading margin of the system can be defined by Constraint (25).

The net load seen in the interface of TSO and DSO is a key parameter that determines the security margin in the transmission network. This load is characterised by its active and reactive power components. The DSO is responsible to govern this demand, and in the proposed TSO-DSO coordination approach, the DSO tries to manage the demand profile in the interface of TSO and DSO, by the available options such as VRs, network reconfiguration, and DERs.

The defined security margin in Eq. (25), is a unique parameter for the entire system, as in reality, when the system is pushed toward its loadability limit, the demand in almost all buses tends to increase. The load increment pattern in different buses may not be the same, and one can consider different load increment patterns in Eqs. (18) and (19), by considering different values for Λ_b^D. But, as from the security perspective, the worst load increment pattern is increasing both active and reactive powers simultaneously, in this paper a constant power factor increment pattern is considered for all buses.

By solving the above optimisation model for the TSO, the required load curtailment and voltage level at the interface of TSO-DSO are obtained. The following parameters will be determined:

$$\begin{bmatrix} P_b^{I_{tso}} \\ Q_b^{I_{tso}} \\ V_b^{I_{tso}} \end{bmatrix} = \begin{bmatrix} P_b^D - P_b^{LC} \\ Q_b^D - Q_b^{LC} \\ V_b \end{bmatrix} \tag{26}$$

The active and reactive power shares (i.e., $\pi_{b,d}^p$ and $\pi_{b,d}^q$) of d-th downstream feeder in the DSO's overall demand at the boundary point with the TSO (i.e. at bus b) is a known parameter for the DSO, which can be expressed as follows:

$$p_{b,d}^{I_{dso}} = \pi_{b,d}^p \times P_b^{I_{tso}} \tag{27}$$

$$\sum_d^{N_b} \pi_{b,d}^p = 1 \tag{28}$$

$$q_{b,d}^{I_{dso}} = \pi_{b,d}^q \times Q_b^{I_{tso}} \tag{29}$$

$$\sum_d^{N_b} \pi_{b,d}^q = 1 \tag{30}$$

3.2. Distributed DSO optimisers

After receiving the set-points required by the TSO at the TSO-DSO interface, a set of distributed optimisation models are solved in the distribution level to comply with the TSO's set-points, with minimum actual load curtailment, as the demands are mainly connected to the distribution level. In the distribution level optimisation model, the DSOs aim at minimising the physical load curtailment required by the TSO, via optimal coordination of distribution-level flexibilities. In this paper, network reconfiguration and CVR are considered as the DSO flexibility options. By optimising the distribution network topology via feeder reconfiguration, power losses and voltage profile of the network can be modified to achieve the DSO goals. Moreover, since the demand connected to the distribution feeder is mainly voltage-dependent, CVR can be considered as an effective flexibility option for DSOs. To implement CVR, coordinated operation of voltage regulators (i.e. boosting transformers) along the feeders can be utilised. The system demand can be modified through the coordinated operation of voltage regulator transformers. In the following, the distributed optimisation model for DSOs is presented, taking into account the network reconfiguration and voltage regulators' flexibilities.

3.2.1. Objective function

In the distribution level, each grid's optimiser tries to minimise the load curtailment and the difference between its set-points in the TSO-DSO connection point with those obtained by the TSO's centralised optimiser, as below:

$$OF^{DSO} = \min\left\{w_2 \times of_{lc}^{dso} + (1 - w_2) \times of_{dif}^{dso}\right\} \tag{31}$$

$$of_{lc}^{dso} = \sum_{b \in B_b} p_{b,d}^{lc} \tag{32}$$

$$of_{dif}^{dso} = \sum_{b \in \mathcal{B}_s} \left(\left| p_{b,d}^S - p_{b,d}^{I_{dso}} \right| + \left| q_{b,d}^S - q_{b,d}^{I_{dso}} \right| + \left| v_{b,d} - V_b^{I_{tso}} \right| \right) \tag{33}$$

where w_2 is a weight coefficient defining the importance of each objective in the distribution level optimisers.

3.2.2. Power Flow and Network Constraints

In this study, the power flow constraints in the distribution level are adopted by adding two important flexibility measures: network reconfiguration and CVR. The former adds a binary variable to the branch flow model and the voltage-dependent loads are considered for the latter. The power flow constraints in the distribution level are represented as below ($\forall b, j \in \mathcal{B}_b$):

$$p_{b,d}^{S} + p_{b,d}^{LC} - p_{b,d}^{D} = \sum_{j \in \mathcal{B}_b} \chi_{bj,d}^{l} \times p_{bj,d} \tag{34}$$

$$q_{b,d}^{S} + q_{b,d}^{LC} - q_{b,d}^{D} = \sum_{j \in \mathcal{B}_b} \chi_{bj,d}^{l} \times q_{bj,d} \tag{35}$$

$$\begin{aligned} p_{bj,d} = &+ g_{bj,d}\tau_{bj,d}^{2} v_{b,d}^{2} \\ &- \tau_{bj,d} v_{b,d} v_{j,d} \left(g_{bj,d} cos(\theta_{bj,d}) + b_{bj,d} sin(\theta_{bj,d}) \right) \end{aligned} \tag{36}$$

$$\begin{aligned} q_{bj,d} = &- b_{bj,d}\tau_{bj,d}^{2} v_{b,d}^{2} \\ &- \tau_{bj,d} v_{b,d} v_{j,d} (g_{bj,d} sin(\theta_{bj,d}) - b_{bj,d} cos(\theta_{bj,d})) \end{aligned} \tag{37}$$

$$p_{b,d}^{D} = \hat{p}_{b,d}^{D} \sum_{\psi} kp_{b,d}^{\psi} \left(\frac{v_{b,d}}{\hat{v}_{b,d}} \right)^{\alpha_{b,d}^{\psi}} \tag{38}$$

$$q_{b,d}^{D} = \hat{q}_{b,d}^{D} \sum_{\psi} kq_{b,d}^{\psi} \left(\frac{v_{b,d}}{\hat{v}_{b,d}} \right)^{\beta_{b,d}^{\psi}} \tag{39}$$

$$p_{b,d}^{S_{\min}} \leq p_{b,d}^{S} \leq p_{b,d}^{S_{\max}}, \quad \forall b \in \mathcal{B}_S \tag{40}$$

$$q_{b,d}^{S_{\min}} \leq q_{b,d}^{S} \leq q_{b,d}^{S_{\max}}, \quad \forall b \in \mathcal{B}_S \tag{41}$$

$$0 \leq p_{b,d}^{LC} \leq p_{b,d}^{LC,max} \tag{42}$$

$$0 \leq q_{b,d}^{LC} \leq q_{b,d}^{LC,max} \tag{43}$$

$$v_{b,d}^{\min} \leq v_{b,d} \leq v_{b,d}^{\max} \tag{44}$$

$$(v_{b,d} \times i_{bj,d})^2 = p_{bj,d}^2 + q_{bj,d}^2 \tag{45}$$

$$0 \leq i_{bj,d} \leq \chi_{bj,d}^{l} \times i_{bj,d}^{\max} \tag{46}$$

where constraints (34) and (35) represent the active and reactive power balance in the distribution network respectively. Constraints (36) and (37) show the active and reactive power flow in the distribution network respectively. Binary variable $\chi_{bj,d}^{l}$ indicates the status of line connecting the distribution buses b and j. Due to the fact that the majority of loads in the distribution level are voltage-dependent, the exponential load model for active and reactive loads are considered in equations (38) and (39) respectively. In these equations, it is assumed that the load in each distribution bus b, comprises of residential, commercial and industrial components. Constraints (40) and (41) respectively limit the active and reactive power imported from the transmission network to the distribution network from the substation bus. Constraints (42) and (43) limit the active and reactive load curtailment in the distribution network respectively. The voltage magnitude of system buses is limited by Constraint (44). Finally, the power flow through the distribution system lines is represented by (45) and limited by constraint (47).

3.2.3. DER flexibility

Distribution-level DERs can play a vital role in providing flexibility for the transmission network [11]. In order to unlock higher levels of flexibility, the network reconfiguration and CVR can be used along with DER. To do so, active and reactive power output of DERs are added to the power balance equations in constraints (34) and (35), as below:

$$p^S_{b,d} + p^{dg}_{b,d} + p^{LC}_{b,d} - p^D_{b,d} = \sum_{j \in \mathcal{B}_b} \chi^l_{bj,d} \times p_{bj,d} \tag{47}$$

$$q^S_{b,d} + q^{dg}_{b,d} + q^{LC}_{b,d} - q^D_{b,d} = \sum_{j \in \mathcal{B}_b} \chi^l_{bj,d} \times q_{bj,d} \tag{48}$$

$$0 \leq p^{dg}_{b,d} \leq \pi^{dg}_{b,d} \tag{49}$$

$$-tg(\varphi_{lead}) \times P^{dg}_{b,d} \leq Q^{dg}_{b,d} \leq tg(\varphi_{lag}) \times P^{dg}_{b,d} \tag{50}$$

where constraints (47) and (48) represent the active and reactive power balance equations with consideration for active and reactive power output of DG units respectively. Constraint (49) represents the active power output of DG units based on their available capacity. Finally, Constraint (50) limits the reactive power output of DGs.

3.2.4. Distribution network's radiality constraints

Network reconfiguration is considered as one of the more efficient methods in improving system characteristics [31]. This method has been utilized to improve different aspects of the network including voltage profile. Therefore, it can be adopted to improve the distribution system voltage profile when the substation voltage level is reduced to save energy. In this study, the network reconfiguration is modeled based on the graph theory. Accordingly, to have a radial configuration, the number of distribution lines should be equal to the number of nodes minus one. This concept can be mathematically modelled as below [32] ($\forall b, j \in \mathcal{B}_b$):

$$s_{b,d} - d_{b,d} = \sum_{(bj) \in \Omega_l} f_{bj,d} - \sum_{(jb) \in \Omega_l} f_{jb,d} \tag{51}$$

$$f_{bj,d} + f_{jb,d} = 0 \tag{52}$$

$$|f_{bj,d}| \leq \chi^l_{bj,d} f^{max}_{bj,d} \tag{53}$$

$$0 \leq s_{b,d} \leq s^{max}_{b,d}, \ \ \forall b \in \mathcal{B}_S \tag{54}$$

$$\sum_{(bj) \in \mathcal{B}_b} \chi^l_{bj,d} = 2 \times (card(\mathcal{B}_b) - 1) \tag{55}$$

$$\chi^l_{bj,d} = \chi^l_{jb,d} \tag{56}$$

where $\chi^l_{bj,d}$ is a binary variable indicating the status of lines. It is equal to one if the circuit is closed and 0, otherwise. Combining (51) and (55) ensures that there is a path to every node and the graph connectivity is ensured. Therefore, in the proposed model for the distribution system, in addition to constraints (55) and (56), there is a need to have a path from the substation to all system loads, which has been reflected in equations (34) and (35).

By solving this, the model will determine the distributed DSO optimizers, the realized load absorbed by the downstream distribution networks, as well as the optimal voltage at the interface point of TSO-DSO. Usually, several distribution feeders are supplied on the downstream side of a given interface point of the TSO-DSO. Therefore, the DSO aggregates the obtained load of all parallel feeders as follows:

$$\begin{bmatrix} p_b^{I_{dso}} \\ q_b^{I_{dso}} \\ v_b^{I_{dso}} \end{bmatrix} = \begin{bmatrix} \sum_{d=1}^{N_b} p_{b,d}^S \\ \sum_{d=1}^{N_b} q_{b,d}^S \\ \frac{1}{N_b} \sum_{d=1}^{N_b} v_{b,d} \end{bmatrix} \tag{57}$$

4. TSO-DSO Coordination Procedure

At the connection bus between transmission and the downstream distribution networks, the boundary variables including voltage magnitude, active and reactive power are obtained via the above optimization models. The vector of these boundary variables should converge to the same values for both the TSO and DSO optimizations. Hence, the convergence condition is as follows:

$$\begin{bmatrix} \epsilon_p \\ \epsilon_q \\ \epsilon_v \end{bmatrix} = \begin{bmatrix} |P_b^{I_{tso}} - p_b^{I_{dso}}| \\ |Q_b^{I_{tso}} - q_b^{I_{dso}}| \\ |V_b^{I_{tso}} - v_b^{I_{dso}}| \end{bmatrix} \leq \begin{bmatrix} \epsilon_p^{des} \\ \epsilon_q^{des} \\ \epsilon_v^{des} \end{bmatrix} \tag{58}$$

The process of solving the proposed coordination scheme is shown in Fig. 2. Based on this flowchart, the process starts with initializing the model parameters and defining the preferable degree of security (i.e. λ_{des}). Then, the TSO performs the following optimisation:

$$\min \left\{ OF^{TSO}(X_{tso}^{DV}) \right\} \tag{59}$$

$$Subject\ to:$$

$$H^{tso}(X_{tso}^{DV}) \leq 0 \tag{60}$$

$$G^{tso}(X_{tso}^{DV}) = 0 \tag{61}$$

where (59) is the TSO optimizer's objective function (i.e. (1)), and the constraints (60) and (61) represent all equality and inequality constraints of the transmission network (i.e. the constraints (4)-(25)). X_{tso}^{DV} represents the decision variables of the transmission network optimizer including those of the boundary points. The optimal solution of the boundary variables is reported to the DSO's distributed optimizers via (27)-(30). For any given transmission bus, the corresponding downstream distribution feeders are optimized based on (62)-(64) in a distributed manner.

$$\min \left\{ OF^{DSO}(X_{dso}^{DV}) \right\} \tag{62}$$

$$Subject\ to:$$

$$H^{dso}(X_{dso}^{DV}) \leq 0 \tag{63}$$

$$G^{dso}(X_{dso}^{DV}) = 0 \tag{64}$$

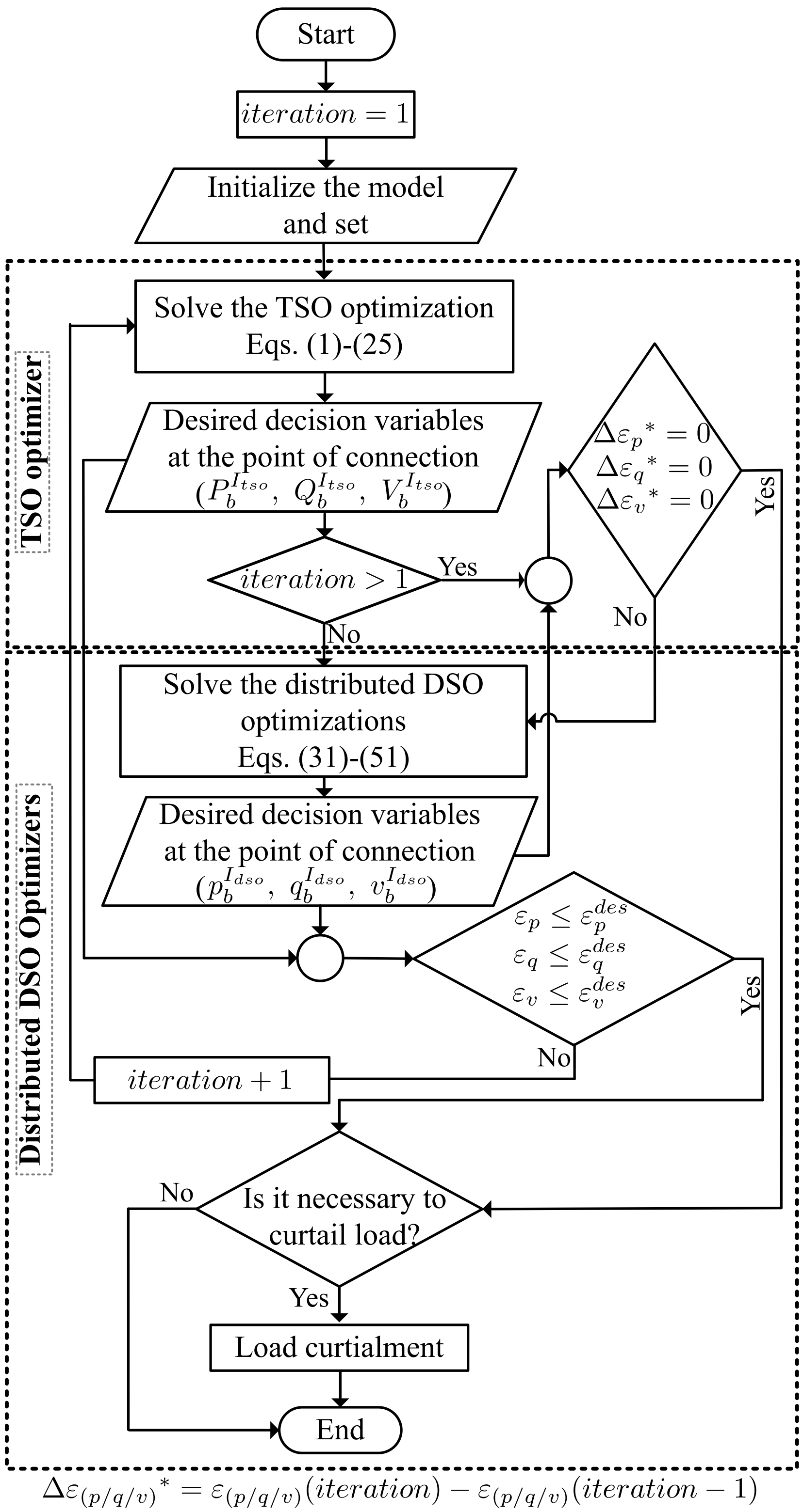

Figure 2: Flowchart of the proposed framework for TSO-DSO coordination.

where (62) is the objective function of the distribution network d and equations (63) and (64) are the equality and inequality constraints of each distribution network (i.e. constraints (34)-(56)). X_{dso}^{DV} is the set of decision variables for each distribution network. At the distribution level, each DSO applies

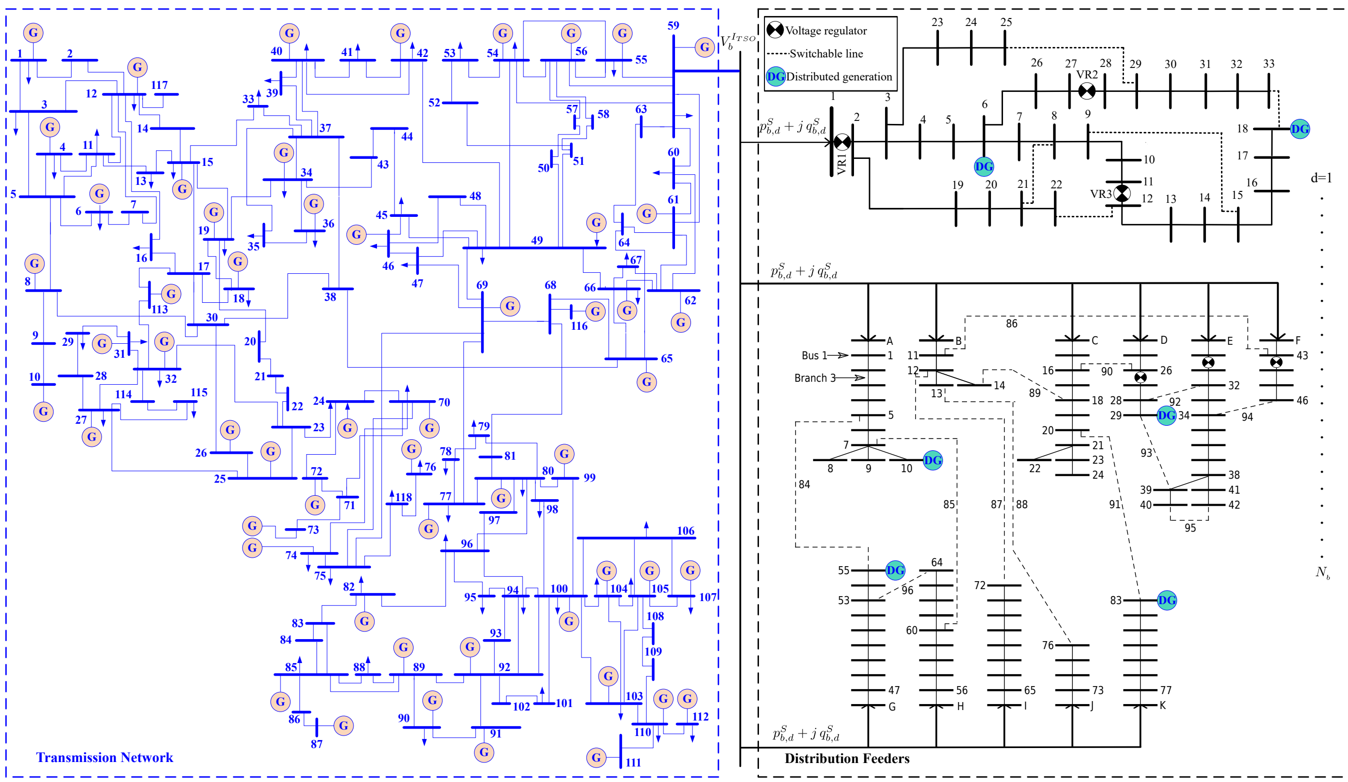

Figure 3: One-line diagram of the studied transmission and distribution networks.

its available flexibility measures in all feeders in a distributed manner to comply with the requirements of the TSO. While each DSO can provide a different degree of flexibility based on their capabilities, secure coordination is achieved if the convergence condition (i.e. (58)) is met.

If the convergence criterion is not met in the current iteration, the boundary set-points obtained by the DSO's distributed optimisers, are aggregated via (26) and sent back to the centralised TSO optimiser to set up the next iteration. The TSO then solves the optimisation in equations (59)-(61). From the second iteration, the TSO has the autonomy to check the desired values of set points in the point of connection. If the values of the boundary set-points obtained from the TSO are equal to those received from the previous iteration of the DSOs, it is not possible to apply further changes using the flexibility measures at the distribution level. At this point, the TSO sends the order to the DSOs to check for the load curtailment. The necessary load curtailment is then applied by the DSOs. In the first iteration and for the TSO's centralised optimiser, it is worth noting that , the DSOs' distributed optimisation models have not been solved yet, Eq. (3).

Conversely, if there is a difference between the set-points, the TSO allows the DSOs to perform their own distributed optimisations and utilise their flexibility measures to decrease load curtailment. This process is repeated by the TSO and distributed DSO optimisers until the convergence criterion is met or it is not possible to apply more adjustment to the set-points indicated by TSO.

5. Case study

The optimisation models in the TSO and DSO levels are non-linear programming and mixed-integer non-linear programming, respectively. Both models are implemented in general algebraic modelling system (GAMS) software [33]. In order to solve the MINLP problem, the DICOPT solver considers two important solutions: (i) "best estimate"; (ii) "best integer". The optimal bound of integer solution is provided by "best estimate", while the best solutions of the problem which complies with the integer requirements is provided by "best integer". In the solver algorithm, the quality of the optimal solution can be measured using a criterion which defines the distance between "best estimate" and the "best integer", called "relative gap". In the GAMS environment, this criterion is defined as "optcr". The "optcr" defines the quality of the optimality of MIP master problems. The value of "optcr" is obtained as below [34]:

$$optcr = \frac{|best\, estimate - \; best\, \mathrm{integer}|}{\max\{|best\, estimate| \; - |best\, \mathrm{integer}|\}} \tag{65}$$

For example, if "best integer" =200 and the "best estimate" =250, the "optcr"=0.20. For a large problem, the MIP solver can be stopped earlier by defining the value of "optcr". For instance if "optcr"=0.20, the MIP solver is forced to stop as soon as the relative gap is less than 0.20. The value of "optcr" is defined as zero in this paper so as to define an optimal solution which guarantees the quality of convergence degree. In this case, the solver does not stop until the distance between the best possible integer solution and the best found integer solution is zero.

The IEEE 118-bus system, here, is considered the test transmission network. The data of this system is available in [35]. The 83-bus practical distribution network of Taiwan Power Company [36] and the IEEE 33-bus distribution feeder [37] are considered as the sample downstream distribution networks. It is assumed that 8 parallel IEEE 33-bus distribution feeders and 5 parallel 83-bus Taiwan Power Company distribution networks are connected to Bus 59 of the IEEE 118-bus transmission system. This bus has the largest amount of load in the transmission network and is more likely to experience load shedding in case of an emergency condition (e.g. sudden load increase). The rest of the load in this bus, and other buses of the transmission network, are assumed as aggregated load in transmission level. The one-line diagram of IEEE 118-bus transmission network and connected distribution networks including the location of voltage regulators and potentially switchable lines in each feeder is shown in Fig. 3.The location of distributed generation (DG) units in distribution level is shown in this figure. The data of DGs is taken from [12].

The active and reactive power share of each distribution network (i.e., $\pi^p_{b,d}$ and $\pi^q_{b,d}$ in (27) and (29)) is defined based on their total load. Therefore, the values of $\pi^p_{b,d}$ and $\pi^q_{b,d}$ are 0.178 and 0.156 for IEEE 33-bus distribution feeders respectively, and they are respectively 0.822 and 0.844 for 83-bus Taiwan Power Company distribution networks. Moreover, $\epsilon_(p/q/v)^{des}$ are assumed to be $0.004\ p.u$ in (58). Furthermore, w_1 and w_2 are both assumed to be 0.5 in (1) and (31), respectively. The share of various demand models, including the residential (R), commercial (C) and industrial (I) loads in exponential (EXP) load model is summarised in Table 2.

To analyse the effectiveness of the proposed TSO-DSO coordination scheme under an emergency condition, it is assumed that the transmission system's load is increased by 10% (evenly in all buses). The desired security margin of the TSO-DSO coordination (i.e. λ_{des}) is taken to be 10%.

5.1. Flexibility with Network reconfiguration and CVR

The computational data of the proposed model is summarised in Table 3. The simulations are performed on an Intel(R) Core(TM) i5-6600 CPU 3.30GHz with 16 GB of RAM. Table 3 demonstrates that the proposed method achieved a considerable short computational time, in order of seconds. The distributed DSO optimisation models can be solved in a distributed manner via parallel computing. The convergence characteristics of the proposed TSO-DSO coordination model are shown in Fig. 4 for 8 parallel IEEE 33-bus distribution feeders and 5 parallel 83-bus Taiwan Power Company distribution

Table 2
Various demands share in EXP load model.

Load model	ψ	$\alpha_{b,d}^{\psi}$	$\beta_{b,d}^{\psi}$	$kp_{\psi,b}$	$kq_{\psi,b}$
EXP	R	1.20	2.90	0.33	0.33
	C	0.99	3.50	0.33	0.33
	I	0.18	6.00	0.34	0.34

R: Residential, C: Commercial, I: Industrial and EXP: Exponential load model

Table 3
Computational size of the proposed TSO-DSO coordination model.

Parameter	TSO	DSO (33-bus)	DSO (83-bus)
# of model variables	8,398	808	2,022
# of model constraints	6,256	708	2,048
Total execution time [s]	36.19	1.28	2.25

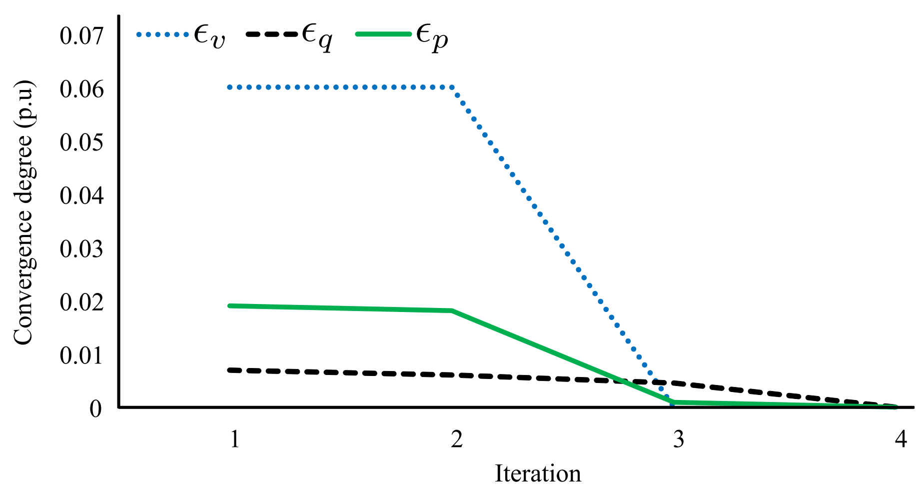

Figure 4: The convergence characteristics of the TSO-DSO coordination model for $N_b = 13$ and $\lambda_{des} = 10\%$.

networks connected to Bus 59 and the security margin of 10%. It can be seen that the proposed decentralised TSO-DSO coordination model converges in a few iteration (e.g. four iterations for $\lambda_{des} = 10\%$). Moreover, voltage at the interface point is converged even faster, such that $\epsilon_v \leq \epsilon_v^{des}$ after three iterations. Having the voltage regulators in distribution feeders enables more flexibility in both active and reactive power demands to enhance the convergence degree of the proposed framework.

Figure 5 shows the changes in the optimal value of load curtailment for different number of distribution networks connected to the Bus 59, and different levels of the security margin. The main observations based on this figure are:

1. Number of parallel distribution networks (i.e. N_b): it can be seen from Figs. 5-(a)-(c) that increasing the number of connected distribution networks can reduce the number of iterations. Increasing the number of distribution networks raises the degree of flexibility and contribution in the load reduction. The optimisation achieved the desired convergence degree in two iteration for $N_b = 13$. Also, this factor can influence the load curtailment. For example, in Fig. 5-(b), the total amount of load curtailment for the distributed DSO optimisers is zero for $N_b^{33bus} = 15$ and $N_b^{33bus} = 13$, while it is $0.14\ MW$ for $N_b^{33bus} = 7$. The value of actual load curtailment is

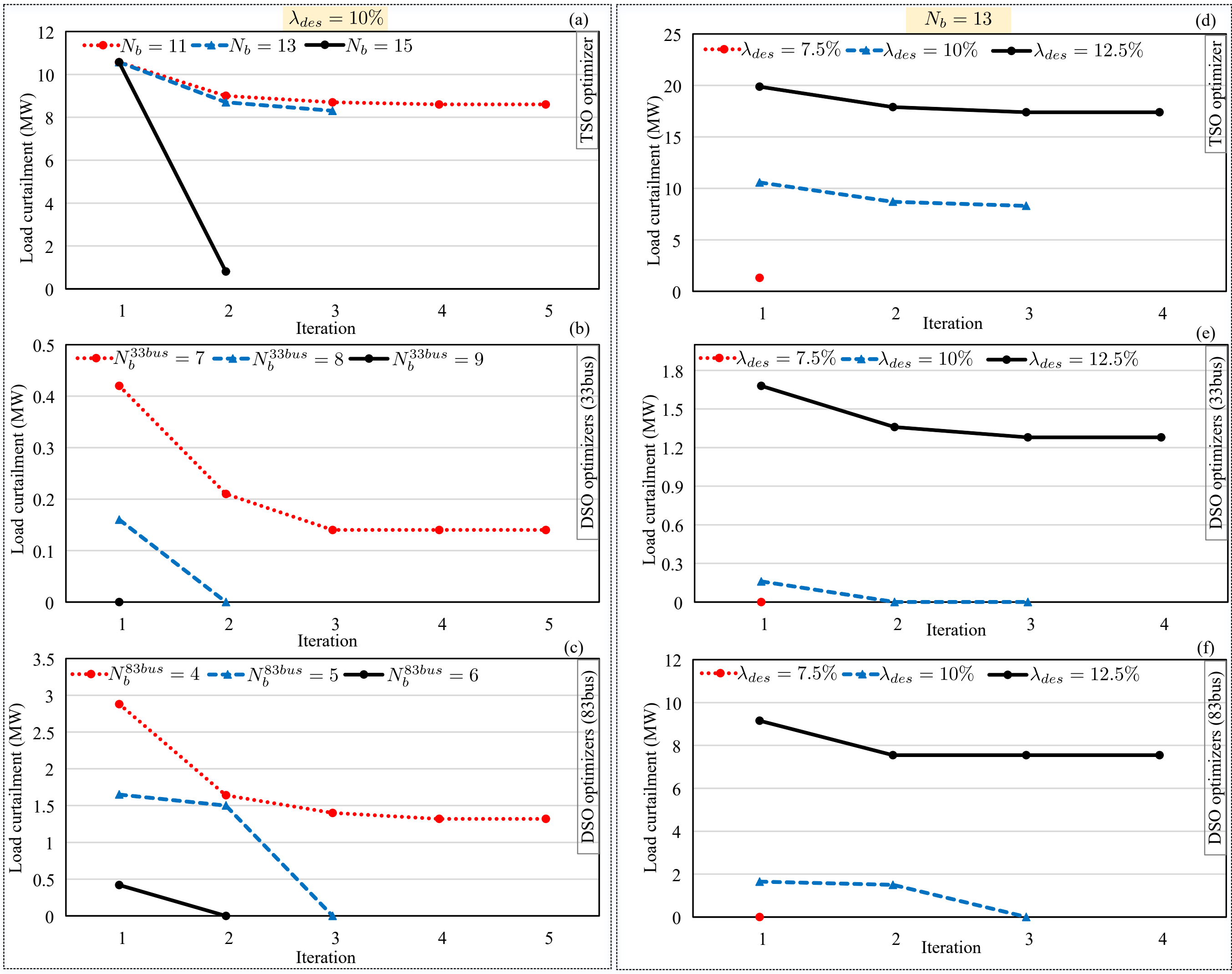

Figure 5: Load curtailment for different values of N_b and λ_{des}: (a)-(c) TSO and DSO optimisers' results for $\lambda_{des} = 10\%$ and different values of N_b, (d)-(f) TSO and DSO optimisers' results for $N_b = 13$ and different security margins.

$1.32\ MW$ in 83-bus distribution network for $N_b^{83bus} = 4$. This means that the actual value of load curtailment increases for the larger distribution networks.

2. The role of distributed flexibility measures: these techniques play a crucial role in decreasing the load curtailment in the distribution networks. For instance, for $N_b = 11$ in Fig 5-(a), although the TSO requested $8.6\ MW$ load curtailment in the TSO-DSO interface, the distribution network optimisers only curtailed $0.14\ MW$ and $1.32\ MW$ in Figs. 5-(b) and 5-(c) respectively. This means that $8.6 - (1.32 + 0.14) = 7.0\ MW$ (i.e. 81%) of the requested load curtailment by the TSO is handled via the available flexibility measures, namely feeder reconfiguration and conservation voltage reduction. It is worth mentioning that no physical load curtailment is realized by the DSO optimisers for $N_b = 13$ and $N_b = 15$.

3. Security margin (i.e. λ_{des}): this transmission-level parameter has a significant impact on the load curtailment. Increasing the security margin from 10% to 12.5% in Fig. 5-(d) doubles the amount of required load curtailment by the TSO optimiser in the boundary point (i.e. Bus 59).

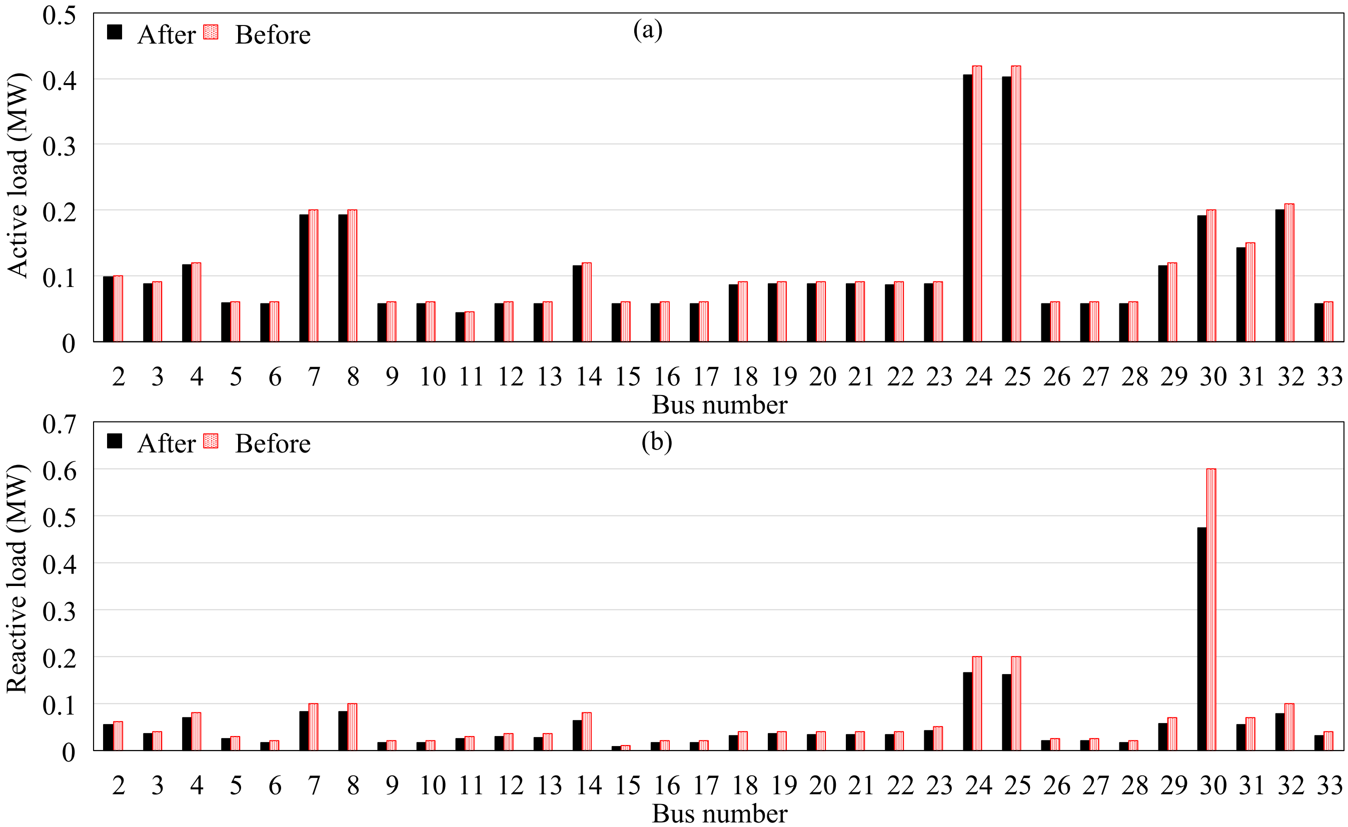

Figure 6: Nodal demand values in IEEE 33-bus distribution feeder before and after applying the flexibility measures (for $N_b = 13$ and $\lambda_{des} = 10\%$): (a) active power, (b) reactive power.

Additionally, one can observe from Figs. 5-(e) and 5-(f) the higher the λ_{des} the more the actual load curtailment by DSO. Moreover, this measure also influences the number of iterations for achieving desired convergence degree.

4. Secure coordination: in Figs. 5-(e) and 5-(f), since the TSO optimiser has not observed any changes in the interface set-points from iteration 3 to 4 for $\lambda_{des} = 12.5\%$, the DSO optimisers observed load curtailment in iteration 3 for maintaining the desired security margin over the whole system.

Active and reactive power of an IEEE 33-bus distribution network connected to Bus 59 before and after applying the flexibility measures is shown in Fig. 6. It is observed that the flexibility measures reduce the active and reactive loads, especially for high demanded buses. The total active and reactive power of each distribution feeder before applying the flexibility measures are $3.72\ MW$ and $2.30\ MVAr$ respectively, while after applying the CVR and feeder reconfiguration the net active and reactive demands of each feeder decrease to $3.57\ MW$ and $1.86\ MVAr$, respectively. This means that each distribution network is capable of reducing its active and reactive demands by $0.14\ MW$ (i.e. 3.8% of total active power demand) and $0.43\ MVAr$ (i.e. 19% of total reactive power demand), respectively, without any need for actual load curtailment (as also shown in Fig. 5-(b) for $N_b^{33bus} = 8$ and $\lambda_{des} = 10\%$). For the 83-bus Taiwan Power Company distribution network, 2.6% and 14.2% of active and reactive power is compensated by the distribution flexibilities without the need for physical load curtailment (as also shown in Fig. 5-(c) for $N_b^{83bus} = 5$ and $\lambda_{des} = 10\%$).

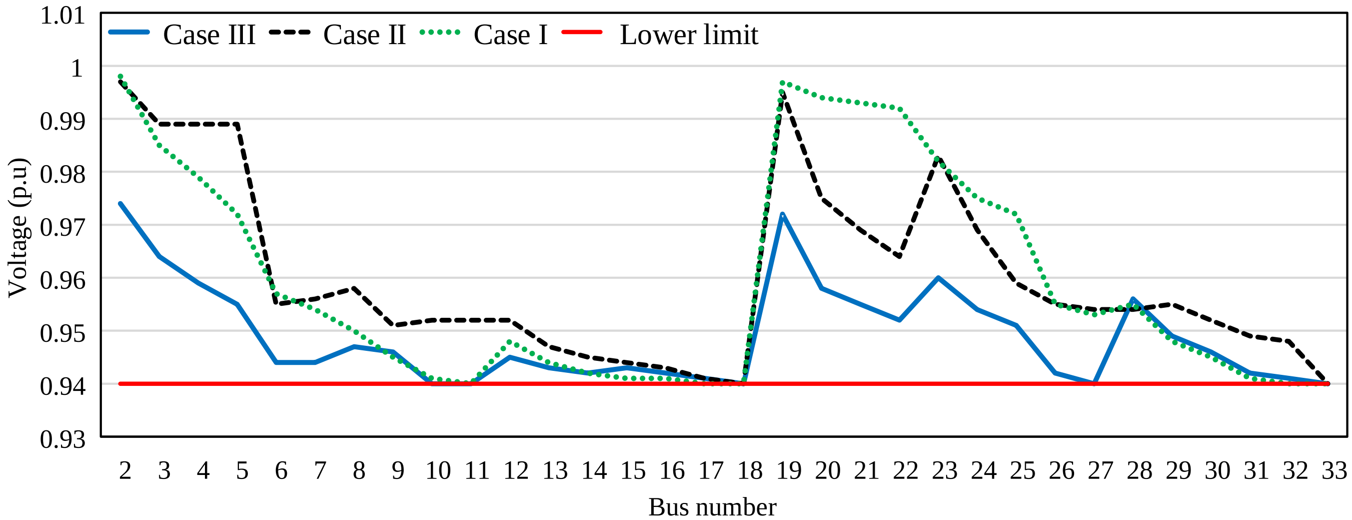

Figure 7: Optimal value of voltage magnitude in the IEEE 33-bus distribution network for different case studies (for $N_b = 13$ and $\lambda_{des} = 10\%$).

Figure 7 investigates the voltage profile obtained by the distributed DSO optimisers for a specific feeder connected to bus 59 in the following three cases:

- ***Case I:*** With CVR and without feeder reconfiguration;
- ***Case II:*** Without CVR and with feeder reconfiguration;
- ***Case III:*** With both CVR and feeder reconfiguration.

This figure shows that solely using CVR (i.e. *Case I*) decreases the voltage level in the end buses to the corresponding lower limit. In *Case II*, however, just feeder reconfiguration has resulted in better values of voltage level across the feeder.In *Case III*, where both CVR and feeder reconfiguration are considered as the flexibility measures, the voltage level is reduced in a coordinated manner to satisfy the demand reduction forced by the TSO. The active and reactive demands, in this case, have already been shown in Fig. 6.

Moreover, for $N_b = 13$ and $\lambda_{des} = 10\%$, the overall active power curtailment in all distribution networks in cases *I*, *II* and *II* is $3.6\ MW$, $2.4\ MW$, and $0.0\ MW$, respectively. Although each of the CVR and feeder reconfiguration flexibilities can individually decrease the actual load curtailment, their coordinated utilisation is a better practice for reducing the load curtailment in the TSO-DSO coordination process.

Finally, the effect of security margin on the voltage regulators' settings as well as the optimal configuration of each sample distribution feeder are shown in Figs. 8 and 9, respectively. Figure 8 demonstrates that how the tap setting is changed for voltage regulators to cope with the TSO's requirements in terms of the desired security margin. For example, the voltage regulator installed on the line between buses 1 and 2 (i.e., VR1) changes its tap by 5% in order to cope with a 2.5% rise in the security margin. These results can also be seen in Fig. 9, where the distribution feeder's configuration is changed for different values of λ_{des}. Note that the radial configuration is preserved for all security margins.

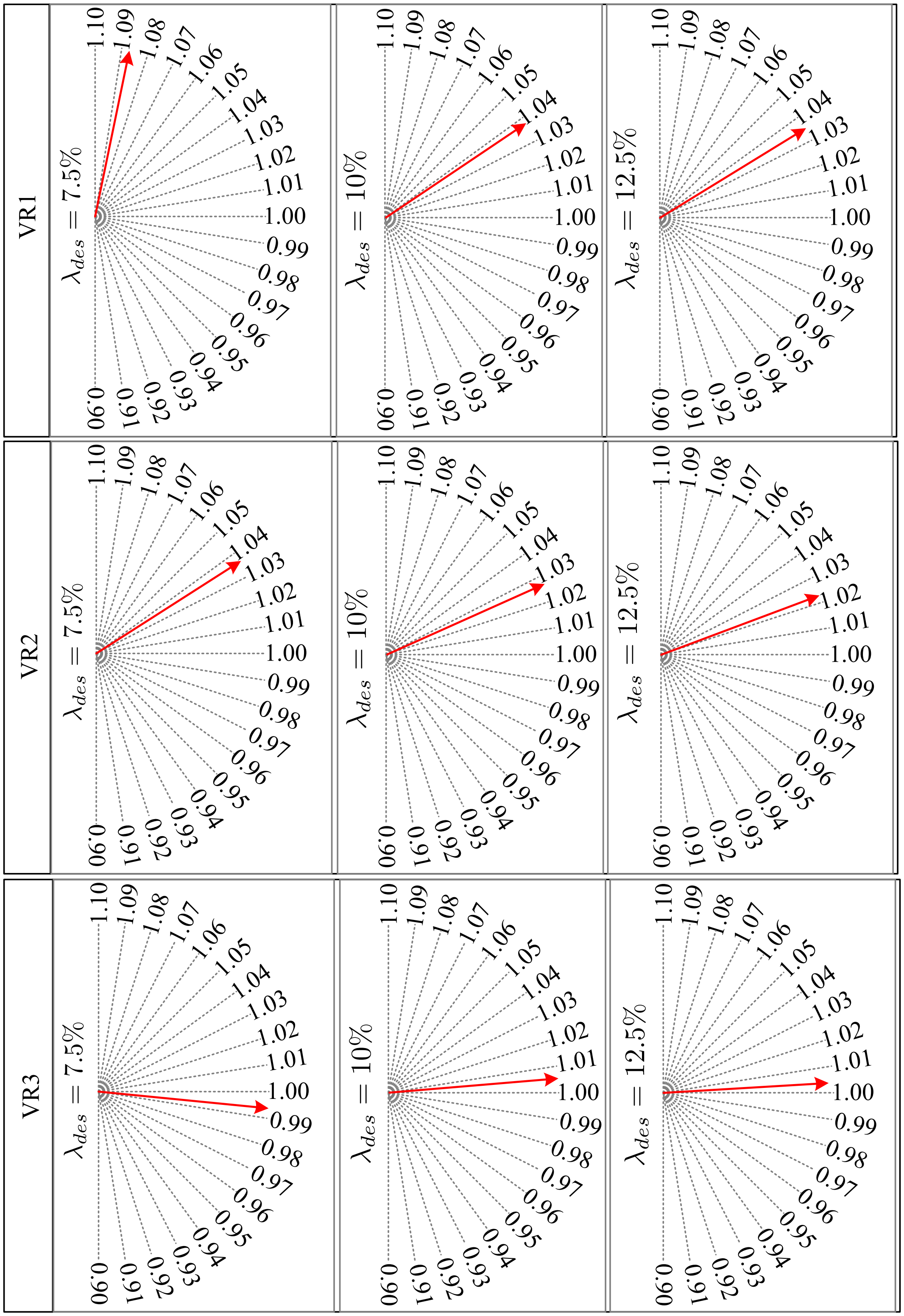

Figure 8: The optimal setting of voltage regulators installed in the IEEE 33-bus distribution network for different values of security margin and $N_b = 13$.

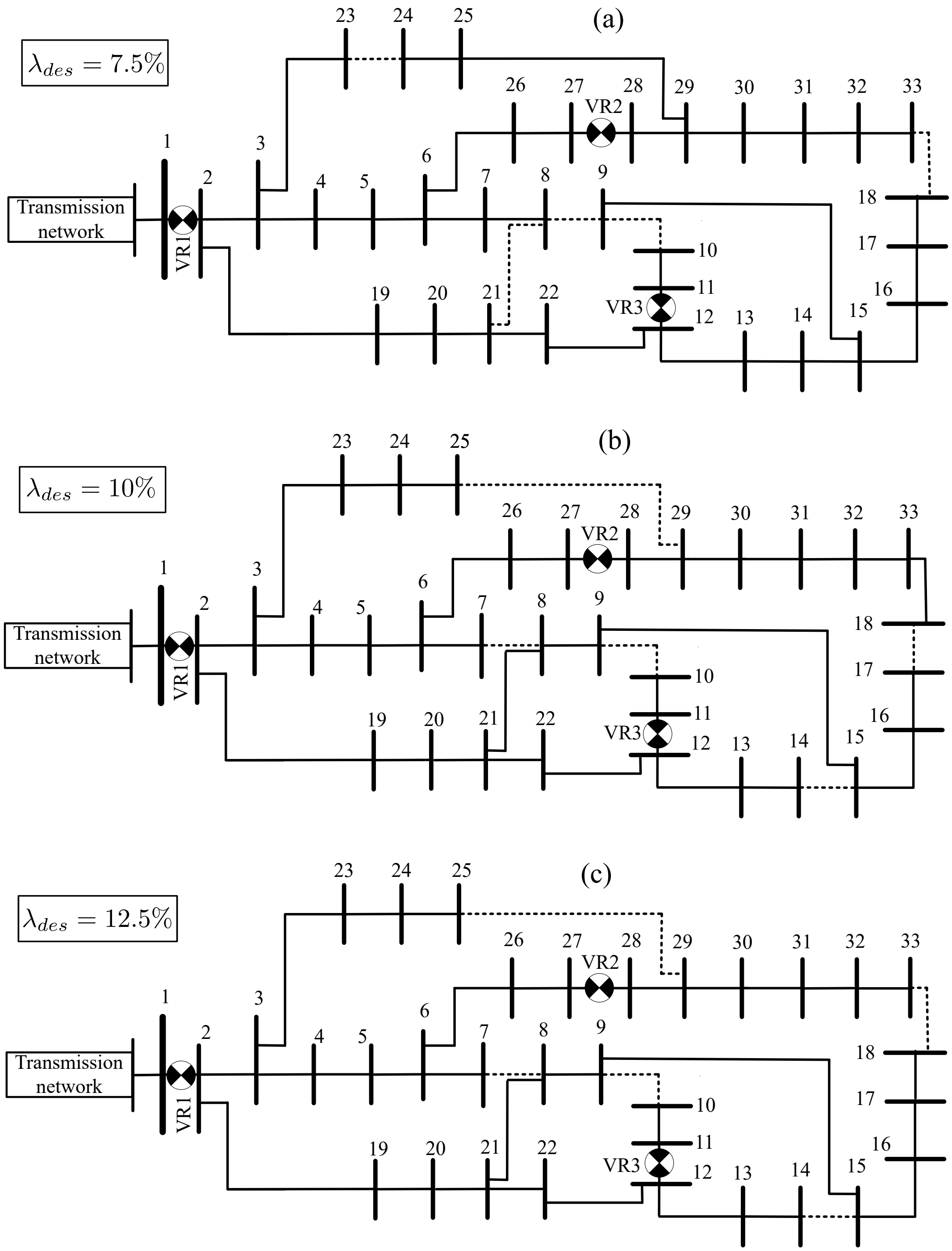

Figure 9: Variation of the IEEE 33-bus distribution network configuration for different values of security margin and $N_b = 13$.

5.2. *Value of DER flexibility*

This section evaluates the effectiveness of DERs in providing flexibility services for the TSO-DSO coordination. As shown in Fig. 3, a number of DGs are installed in the distribution network and their effect on decreasing the needs for load curtailment in the emergency condition is analysed.

The simulation result shows that the coordination with the IEEE 33-bus distribution network converges in one iteration and the value of load shedding is zero with the DGs in the system; the 83-bus

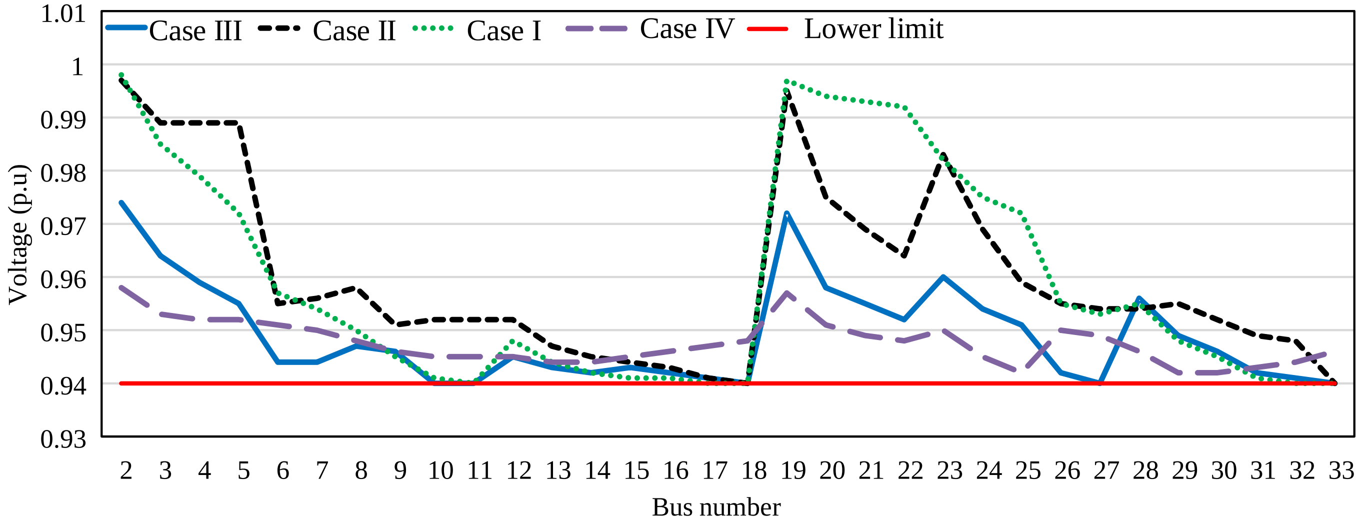

Figure 10: Optimal value of voltage magnitude in the IEEE 33-bus distribution network for different case studies with consideration for the DER effect (for $N_b = 13$ and $\lambda_{des} = 10\%$).

Taiwan Power Company distribution networks converges after two iteration, also with zero load shedding. This results show the importance of DERs in decreasing the needs for extra communication between DSO and TSO, while achieving zero load shedding. Therefore, optimal coordination of DERs is an efficient method in achieving the secure TSO-DSO coordination.

In order to evaluate the effect of DERs on voltage profile, the case studies described in Fig. 7 are compared against a case study with DERs, network reconfiguration and CVR (called Case IV). The result of this comparison is given in Fig. 10. It can be seen from this figure that the combination of distributed flexibility methods with DERs provides better threshold for the voltage profile, without the need for load curtailment.

Also, the optimal setting of voltage regulators in Case III and Case IV are compared in Fig. 11. This figure shows that adding the DERs decreased the need for higher level of tap changing in the voltage regulators. This means the local generation decreases the need for higher contribution from the loads in complying with the security measures of the TSO-DSO coordination.

Finally, to evaluate the effect of linking multiple transmission network buses, IEEE 33-bus distribution networks are connected to Bus 59 while 83-bus Taiwan Power Company distribution networks are connected to Bus 116 of transmission network. Fig. 12. It can be seen from this figure that the DER flexibility can provide the required flexibility without the need for the load curtailment. Although network reconfiguration and CVR provided considerable value of flexibility, some load curtailment sill happened in this case.

6. Conclusion

The transformation of power systems towards integrated networks of different entities in which distribution and transmission system operators cooperate together towards a coordinated TSO-DSO scheme is a promising development. This scheme enables traditionally passive distribution networks to be active entities of such coordination. However, the challenge of voltage security and distributed flexibilities provided by DSOs for keeping the whole system in the desired loading margin needs further investigations. This paper highlights the distributed flexibility measures for preserving the voltage

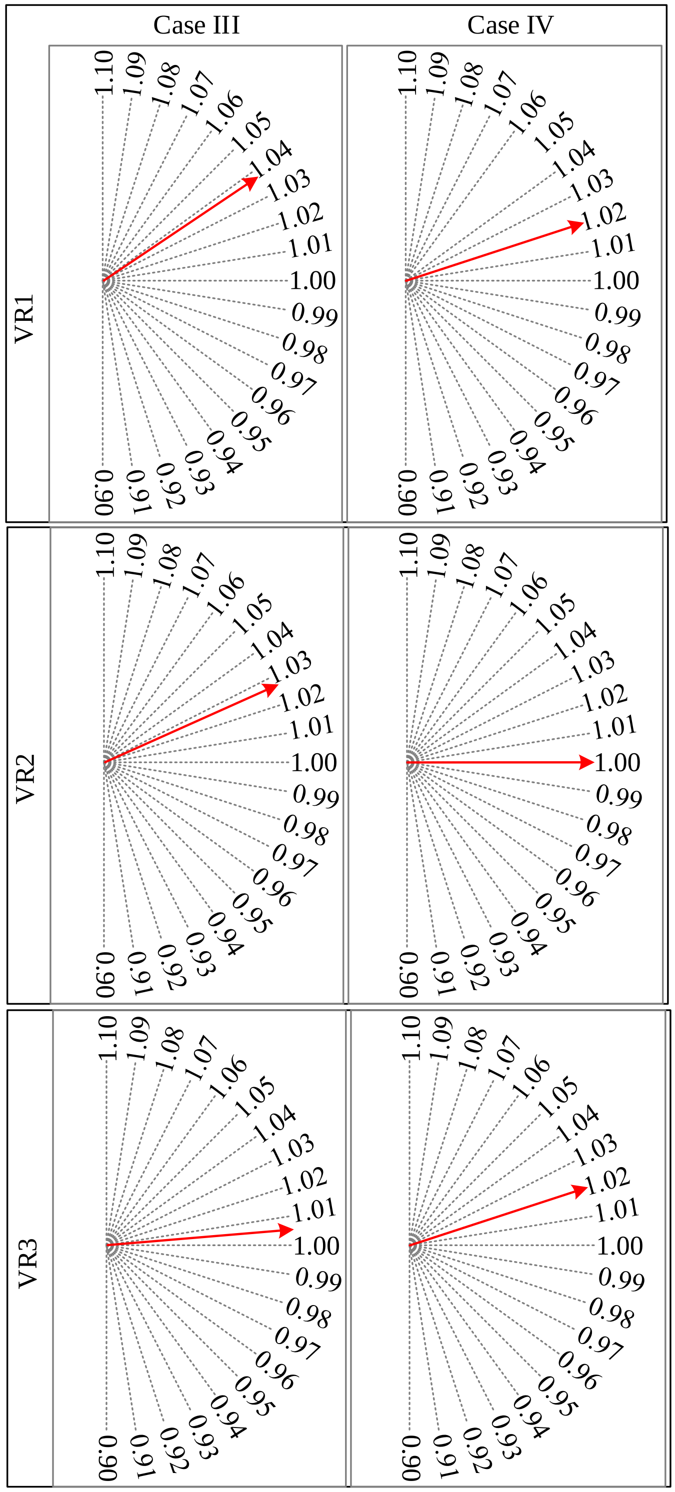

Figure 11: The optimal setting of voltage regulators installed in the IEEE 33-bus distribution network for cases III and IV (for $N_b = 13$ and $\lambda_{des} = 10\%$).

security margin of the TSO-DSO coordination approach via a decentralised optimisation framework. At the transmission level, the centralised TSO optimizer aims at minimising the load curtailment in the heavily loaded transmission network buses to preserve the required security margin under a contingency condition (i.e. sudden increase in the system load). The optimal set-points of transmission

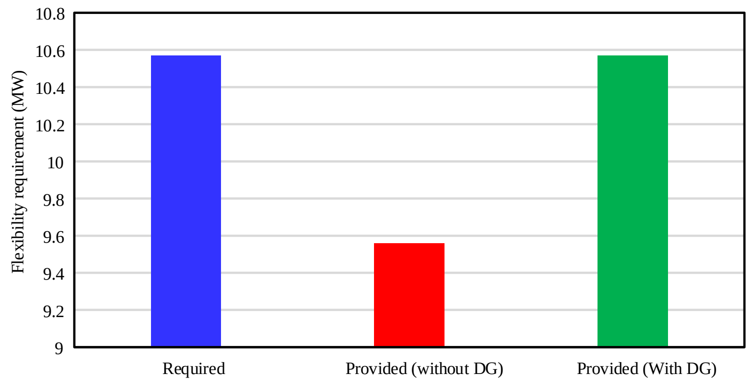

Figure 12: Optimal value of flexibility provided when IEEE 33-bus distribution networks are connected to Bus 59 while 83-bus Taiwan Power Company distribution networks are connected to Bus 116.

buses in terms of active/reactive power and voltage level, are determined by this optimisation model and sent to the downstream distribution networks at the point of connection between these grids. At the distribution level, the distributed optimisers of DSOs aim at minimising the difference between their set-points and the corresponding values sent by the TSO in the TSO-DSO boundary points as well as physical load curtailment, simultaneously. To achieve these goals with minimum unavoidable load curtailment, DSOs utilise their distributed flexibilities such as conservation voltage reduction and feeder reconfiguration. The efficiency of these flexibility methods is evident in the results. These distributed flexibility measures compensated 81% of load curtailment requested by the TSO. This result shows the importance of benefiting from flexibility measures in the distribution networks, highlighting their role as an active player in the TSO-DSO coordination. The results show that the number of distribution feeders available in the DSO distributed optimisers can reduce both the actual load curtailment and the number of iterations for the TSO-DSO coordination. This means that the proposed framework can achieve short computational time, in order of seconds, when the number of distribution networks is increased. According to the results, it can be concluded that:

- The coordinated utilization of CVR and feeder reconfiguration is a promising option for the reduction of physical load curtailment in the TSO-DSO coordination process. Joint utilisation of CVR and feeder reconfiguration reduced the need for curtailing the active and reactive load in each individual distribution network by 3.8% and 19% respectively. These methods can be utilised along with DER flexibility options in the future studies to guarantee system security.

- Increasing the security margin raises the required load curtailment by the TSO and consequently the actual load curtailment by DSOs. Increasing the security margin by 2.5% resulted in a twofold increase in the required load curtailment by the TSO. This criteria is important in the coordination schemes that require a higher level of security. Under such paradigm, the system operators need to curtail load to preserve higher security margins.

- A 2.5% increase in the security margin requires 5% change in the tap settings of voltage regulators installed in the distribution networks. This shows the effect of security margin in the transmission level on the flexibility measures taken by DSOs. It also highlights the active role of distributed flexibilities in preserving the whole system security.

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