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Multi-Objective Approach to TCSC and DG Coordination under Contingency in an Integrated Transmission and Distribution Networks

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Abstract—Flexible AC Transmission System (FACTS) are deployed by Transmission System Operators (TSO) to manage congestion while meeting technical and multilateral supply commitments. Another issue is the de-carbonizing of the power supply framework by increasing penetration of Distributed Generation (DG) often at distribution network. However, separately planned FACTS and DG units by system operators (TSO and DSO) can worsen power systems performance in the presence of load growth. Therefore, this paper demonstrates the coordination of TCSC and DG through a multi-objective Particle Swarm Optimization (MOPSO) technique at the instance of $TSO-DSO$ coordination scheme, to improve transfer capability, power loss and voltage deviation in an integrated transmission and distribution network (iT & DN). Two models of DG were coordinated with TCSC under normal and contingency cases. Results indicate that while ATC improvement for various transactions was achieved with TCSC, additional power losses incurred were further reduced with DG deployment in coordination with TCSC. Furthermore, the Pareto front, which establishes the correlation between objectives shows a diving parabola that is partly nonlinear. Also, the $TCSC-DG_{PQ}$ provide superior ATC and power losses compared with $TCSC-DG_{PV}$. Again, under $(N-1)$ contingencies, the $TCSC-DG_{PQ}$ provides improved ATC compared with other contingency cases under TCSC only.

Index Terms—DG, Contingency, Coordination, Multi-Objective, Transfer Capability, TCSC.

I. INTRODUCTION

GLOBALLY, the dependence of human activities on electrical energy is rising steadily, which led to exponential growth in the demand for electricity under deregulation. However the load centres, often located far from the generation sources which necessitate bulk power transfers involving multilateral transactions remain a common feature of a deregulated electricity market. The competitive framework of deregulation involving multilateral bids with increased demand causes tie lines to operate closer to and sometimes above transfer limits - thermal, voltage and stability [1]–[3]. Operating tie lines at their limits have caused network congestion, huge losses, poor voltage profile, and instability [4], with cascading impacts on the low voltage Distribution Networks (DN) [5].

In order to manage network operational performance and stability, the Transmission System Operators (TSO) must relieve congestion while meeting technical and multilateral

supply commitments. Among the solutions adopted to enhance the static and dynamic performance of power systems, the Flexible AC Transmission System (FACTS) devices are favourable features of the Transmission Networks (TN) [6]–[8]. Different FACTS were deployed for Available Transfer Capability [9]–[11], voltage stability [12], power losses [13], [14], dynamic stability [15], and congestion management [4], [6], [8]. A cost effective series FACTS family which modifies the effective line reactance is the Thyristor Controlled Series Compensator (TCSC) [16]. In complementing FACTS' deployment, the recent drive to decarbonize the power supply framework witnessed increased deployment and utilization of Renewable Energy (RE) based Distributed Generation (DG), at the DN [17]. Although the increased penetration of DG reduces environmental impact, the grid-connected mode presents complexities if not properly planned [18]. Thus, increased penetration of DG raise concerns about stable and reliable operation due to intermittency in irradiance for power generation. Other issues of DG penetration, such as low fault ride-through, high fault current, and low power quality, may get worsen by FACTS' control operations [19], [20].

The Literature is replete with the benefits of FACTS and DG in power systems: enhanced voltage stability, minimising power loss, improving transfer capability, and power system's management close to operating points [21]. FACTS also provide economic benefits in cost savings from loss and fuel cost minimization [22]. However, the distinction between Transmission and Distribution Network (T & DN) planning, and by extension FACTS and DG, translate to the uncoordinated system operators, which worsen power systems performance in the presence of demand growth [9], is scarcely addressed. Therefore, discordance of DG planning ignoring active DN due to high DG penetration has been demonstrated to have adverse effects in [5], while the ability of TCSC to dampen oscillation is demonstrated in [23]. Accordingly, TSO and DSO coordination is critical to optimize the benefits of FACTS and DG planning. The basic concern in $TSO-DSO$ coordination is the ability of DSO to deploy its resources, to provide services to TSO [24]. Moreover, the $TSO-DSO$ coordination environment must depict the features of T & DN. Consequently, the model of an integrated Transmission and Distribution Network (iT & DN) is necessary, combining both the high and medium voltage sections [25]–[27]. Generally, services provided between TSO and DSO can be described in terms of cost functions of FACTS and DG [21].

II. LITERATURE REVIEW

Structural changes in modern power systems and manifestation of active DN are largely attributed to penetration of DG units. Consequently, separate planning of T & DN are no longer favourable. Economic dispatch, a major issue in planning and operation, requires coordinating resources available to the system operators. While TN planning concerns periodical location of new infrastructures such as FACTS; to meet the demand growth, DN planning targets the optimal location and sizes of the substations and DGs. Therefore, the modern framework enables DSO to provide services in coordination with TSOs for an inclusive benefit [28]. Thus, the need for coordination between TSO and DSO from operational and planning perspectives. Accordingly, [29] presented a hierarchical framework to optimise TSO and DSO coordination simultaneously.

The work by [1] acknowledged that high penetration of DG causes reactive power demand, voltage instability, congestion, harmonics, power losses and other imbalances. Therefore, to avoid system-wide impacts, installing compensator such as TCSC, SVC, and STATCOM is necessary, to mitigate the impacts of DG. In [2], the optimal placement of TCSC and DG is presented to manage congestion from load growth and line outages. Based on OPF formulation, the impacts of DG on FACTS and vice-versa and lack of distinction between T & DN were ignored. Similarly, planning of multiple DG and TCSC for power loss reduction is presented by [14]. In addition to a single objective, it was limited to DN. Furthermore, the coordination of DG, Shunt Capacitors (SC) and Static Var Compensators (SVC) were presented in [9], [13]. While [13] compares *DG - SVC* with *DG - SC*, only power loss reduction is considered. In addition to power loss, [9] discussed the *SVC - DG* coordination to enhance Available Transfer Capability (ATC) in a multi-objective approach. However, both ignored the distinction between TSO and DSO. To mitigate the uncertainty caused by DG, [22] combined the reactive power, transmission expansion, and TCSC planning to minimize investment costs of transmission lines, reactive power sources, and TCSC devices.

In order to improve the technical and economic indices, a Multi-Objective Particle Swarm Optimization (MOPSO) is utilized to optimally place TCSC in [30]. While the work ignores DG, one of the Pareto-optimal solutions is selected using the fuzzy decision method as the best compromise. Also, a multi-objective approach to planning of FACTS and DG is presented in [21]. The objectives mainly constitute cost of FACTS and DG as well as loss discount. In addition to the none optimal solution due to the analytical approach, there is no distinction between TSO and DSO of the modern competitive framework. Similarly, a multi-objective biogeography-based optimization (MOBBO) algorithm is used in [31] to optimally plan Static Synchronous Series Compensator (SSSC) in the wind integrated network.

Therefore, from the survey, separate planning of TCSC and DG were targeted at the T & DN respectively, to improve various objectives. However, the planning of TCSC and DG often has ignored the imminent impacts of TCSC control

operations on DG and vice versa. Furthermore, power system operations involve monitoring multiple performance indices, hence multi-objective problem formulation. Consequently, this paper demonstrates the coordination of TCSC and DG to improve ATC, power loss and voltage deviation in an iT & DN using multi-objective approach.

III. TCSC - DG COORDINATION APPROACH

The consideration of DN to facilitate effective provision of services to the TN is an important factor in *TSO - DSO* planning [32]. The *TCSC - DG* planning scenario depicts the TSO managed model, a fully centralized dispatch model, accounting for T & DN constraints [26], [32]. In the *TCSC - DG* coordination model depicted in Fig.1 and operated by the TSO, resources available to both transmission and distribution levels are deployed and managed by the TSO in a coordinated manner for inclusive benefit.

IV. MULTI-OBJECTIVE PSO (MOPSO)

Planning studies often target multiple objectives, which sometimes are contradictory. Due to multi-objectives, the search space is not always well defined, hence the need for a Multi-Objective Optimization (MOO), which has no absolute global best, but set of non-dominated solutions. In MOO, the objectives may not have a direct correlation. A general minimization formulation is expressed in equation (1), subject to equality and inequality constraints of equations (2) and (3).

$$\text{minimize } \vec{f}(x, \lambda) = [f_1(x, \lambda), f_2(x, \lambda) \dots f_m(x, \lambda)] \quad (1)$$

$$f(x, \lambda) = 0 \quad (2)$$

$$X_i^{\min}(x, \lambda) \leq X_i(x, \lambda) \leq X_i^{\max}(x, \lambda) \quad (3)$$

In equations (1) to (3), x and λ are vector of state and control variables respectively. The Pareto optimal approach is applied to the problem of equation (1), described by dominance model. For a problem having m objectives, a solution (x_i, λ_i) dominates other solution (x_j, λ_j) , if (x_i, λ_i) is better than (x_j, λ_j) for at least one objective $\vec{f}_i(x, \lambda)$ and is not worse for any other $\vec{f}_j(x, \lambda)$ as described in equation (4). Where $j = 1, 2 \dots m$ and $j \neq i$. The symbol $\succ$ represents the domination concept. In a non-dominated pair, an improvement in objective $\vec{f}_i(x, \lambda)$ can cause the deterioration of other objectives [31].

$$\left. \begin{array}{l} \vec{f}_i(x_1, \lambda_1) < \vec{f}_i(x_2, \lambda_2) \\ \text{and} \\ \vec{f}_j(x_1, \lambda_1) \leq \vec{f}_j(x_2, \lambda_2) \end{array} \right\} \Rightarrow (x_1, \lambda_1) \succ (x_2, \lambda_2) \quad (4)$$

A. ATC-Objective using Continuation Power Flow (CPF)

MOO can exist in two fronts, involving both minimization and maximization, hence the need to transform to the same front. At the maximum power transfer limit imposed by thermal, voltage, and generator reactive power [10], the ATC evaluate to equation (5).

$$\text{Max.} \left\{ \sum_{i \in \sin k} P_L^i(\lambda = \lambda_{lim}) - \sum_{i \in \sin k} P_L^i(\lambda = 0) \right\} \quad (5)$$

Fig. 1. TCSC – DG Coordination Model.

Negating the ATC term of equation (5), transform the problem formulation to minimisation front.

B. Power loss-Objective

Equation (6) expresses the real power loss of an integrated power system comprising the T & DN losses. Where g_k is the conductance of transmission line. $V_i, V_j, \delta_i, \delta_j$ are the voltage magnitudes and angles at buses/nodes i and j respectively, nl is the number of lines in the network.

$$P_{loss}^{net} = P_{loss}^{TSO} + P_{loss}^{DSO} \quad (6a)$$

$$P_{loss}^{net} = \sum_{k=1}^{nl} g_k (V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)) \quad (6b)$$

C. Voltage Deviation-Objective

For each bus/node, the deviation of voltage magnitudes away from 1p.u measures the quality of voltage at such bus/node. Thus, the absolute sum of voltage deviation of all bus/nodes in the network is taken as a measure of the network's overall quality of voltage supply expressed by equation (7).

$$V_D^{net} = V_D^{TSO} + V_D^{DSO} = \sum_{i=1}^{nb} |1 - V_i| \quad (7)$$

Equation (8) describes the set of fitness vector ATC, P_{loss}^{net} and V_D^{net} , for the TCSC – DG coordination using MOPSO.

$$\vec{f}(x, \lambda) = \begin{cases} -ATC \\ P_{loss}^{net} = P_{loss}^{TSO} + P_{loss}^{DSO} \\ V_D^{net} = V_D^{TSO} + V_D^{DSO} \end{cases} \quad (8)$$

V. TCSC AND DG MODELLING

A. TCSC Power Injection Model (PIM)

The pie equivalent model of a transmission line with TCSC jx_c is given in Fig. 2. The equivalent line reactance with TCSC is given by the equation (9), while the active and reactive power flows with TCSC are expressed by the equations (10) - (15).

Fig. 2. Transmission line Model with TCSC.

$$X_{ij}^{equ} = X_{ij} + X_c \quad (9)$$

$$P_{ij} = V_i^2 G'_{ij} - V_i V_j (G'_{ij} \cos \delta_{ij} + B'_{ij} \sin \delta_{ij}) \quad (10)$$

$$Q_{ij} = -V_i^2 (B'_{ij} + B_{sh}) - V_i V_j (G'_{ij} \sin \delta_{ij} - B'_{ij} \cos \delta_{ij}) \quad (11)$$

$$P_{ji} = V_j^2 G'_{ij} - V_j V_i (G'_{ij} \cos \delta_{ij} - B'_{ij} \sin \delta_{ij}) \quad (12)$$

$$Q_{ji} = -V_j^2 (B'_{ij} + B_{sh}) + V_j V_i (G'_{ij} \sin \delta_{ij} + B'_{ij} \cos \delta_{ij}) \quad (13)$$

where,

$$G'_{ij} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2} \quad (14)$$

$$B'_{ij} = \frac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2} \quad (15)$$

Consequently, from Fig. 2, using the Power Injection Model (PIM), the effect of TCSC's series reactance on active power flow are represented by equivalent power injections at receiving and sending end of the line without TCSC [33], as shown in Fig. 3. Equations (16) and (17) give the real power injections at both ends of Fig. 3, while equations (18) and (19) give the change in conductance and susceptance, respectively.

$$P_{ic} = V_i^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} \cos \delta_{ij} + \Delta B_{ij} \sin \delta_{ij}) \quad (16)$$

$$P_{jc} = V_j^2 \Delta G_{ij} - V_j V_i (\Delta G_{ij} \cos \delta_{ij} - \Delta B_{ij} \sin \delta_{ij}) \quad (17)$$

Fig. 3. Power Injection Model of TCSC.

$$\Delta G_{ij} = \frac{x_c r_{ij} (x_c - 2r_{ij})}{(r_{ij}^2 + x_{ij}^2) (r_{ij}^2 + (x_{ij}^2 - x_c)^2)} \quad (18)$$

$$\Delta B_{ij} = \frac{-x_c (r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2) (r_{ij}^2 + (x_{ij}^2 - x_c)^2)} \quad (19)$$

B. DG Modelling

Based on DG's ability to inject real and reactive power [34], [35], two DG models are implemented [36]–[39].

- 1) **PV Model:** DG supplies only real power.
- 2) **PQ Model:** DG supplies real and reactive power.

DGs are modelled as negative load [36] when the dynamics and fast transients associated with converter-based DG are neglected. Accordingly, if P_{li} and Q_{li} represent the real and reactive load at the i^{th} node of a DN, equations (20) and (21) describe the new loads (P_{nli} , Q_{nli}) after DG integration; where γ_{dg}^p and γ_{dg}^q are real and reactive power injections from DG units.

$$P_{nli} = P_{li} - \gamma_{dg}^p \quad (20)$$

$$Q_{nli} = Q_{li} - \gamma_{dg}^q \quad (21)$$

Equations (20) and (21) imply that DG units replace a certain amount of load demand at the said DN's node and is subject to the power balance equations (22) and (23).

$$P_G^i - P_L^i - P_{inj}^i = 0 \quad (22)$$

$$Q_G^i - Q_L^i - Q_{inj}^i = 0 \quad (23)$$

The power injections P_{inj}^i and Q_{inj}^i is described by equations (24) and (25) respectively; where P_G^i , Q_G^i , P_L^i , Q_L^i are real and reactive generation and load at the i^{th} node.

$$P_{inj}^i = \sum_{j=1}^n V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \quad (24)$$

$$Q_{inj}^i = \sum_{j=1}^n V_i V_j Y_{ij} \sin(\delta_i - \delta_j + \theta_{ij}) \quad (25)$$

DG penetration level stipulates the limit of real or reactive power supply from DG, and the equation (26) defines penetration level [34].

$$\sum_{i=1}^{ndg} PQ_{dg}^i \leq \mu \sum_{j \in PQ_{load}} PQ_{load}^j \quad (26)$$

In the equation (26), the total real or reactive power injected by DG is a percentage of the DN real or reactive power demand; hence, the penetration level is μ . The inequality

constraint described by equations (3), limits the maximum real and reactive from DG to 75% of PQ_{load} load in DN [40]–[42] as described by equation (27) and (28).

$$0 \leq \gamma_{dg}^p \leq 0.75 P_{load}^{dn} \quad (27)$$

$$-0.75 Q_{load}^{dn} \leq \gamma_{dg}^q \leq 0.75 Q_{load}^{dn} \quad (28)$$

VI. REDUCED SEARCH SPACE

Since power flows and overloads are major constraints to ATC [43], the sensitivity of real power flow to TCSC's reactance is used to obtain the list of candidate lines for TCSC location [44].

A. Real Power Flow Sensitivity

The sensitivity of real power flow in a line where TCSC is located can be expressed in terms of partial derivatives of the power injection in terms of equations (16) and (17), as expressed by equations (29) and (30), respectively [33].

$$\left. \frac{\partial P_i}{\partial X_k} \right|_{x_k=0} = \left. \frac{\partial P_{ic}}{\partial X_k} \right|_{x_k=0} = \quad (29a)$$

$$(V_i^2 - V_i V_j \cos \delta_{ij}) \left. \frac{\partial \Delta G_{ij}}{\partial X_k} \right|_{x_k=0} - (V_i V_j \sin \delta_{ij}) \left. \frac{\partial \Delta B_{ij}}{\partial X_k} \right|_{x_k=0} \quad (29b)$$

$$\left. \frac{\partial P_j}{\partial X_k} \right|_{x_k=0} = \left. \frac{\partial P_{jc}}{\partial X_k} \right|_{x_k=0} = \quad (30a)$$

$$(V_j^2 - V_i V_j \cos \delta_{ij}) \left. \frac{\partial \Delta G_{ij}}{\partial X_k} \right|_{x_k=0} + (V_i V_j \sin \delta_{ij}) \left. \frac{\partial \Delta B_{ij}}{\partial X_k} \right|_{x_k=0} \quad (30b)$$

$$\text{where } \left. \frac{\partial \Delta G_{ij}}{\partial X_k} \right|_{x_k=0} = 2G_{ij} B_{ij} \text{ and } \left. \frac{\partial \Delta B_{ij}}{\partial X_k} \right|_{x_k=0} = B_{ij}^2 - G_{ij}^2$$

B. Hybrid Real Power Flow Sensitivity and PSO (PI-PSO)

Consequently, with the reduced search space constituting the candidate locations obtained by real power flow sensitivity, PSO is deploy to locate and size TCSC for ATC enhancement. The complete documentation of the hybrid real power flow sensitivity and PSO is given in [10].

VII. SYNTHETIC TEST NETWORK (iT & DN)

The power system test network is carefully selected to model an integrated Transmission and Distribution Network (iT & DN). The high voltage transmission section is the Western System Coordinating Council network (WSCC) at a nominal of 230 kV, while the IEEE 16 nodes form the distribution section at a nominal of 23 kV. Fig. 4 depicts the topology of the iT & DN [5]. Fig. 4a shows the one-line diagram of iT & DN illustrating the point of common coupling between transmission and distribution sections, while Fig. 4b gives the entire topology of the modified test network with part of the loads at buses 5, 6 and 8 of the transmission section replaced by IEEE 16 nodes distribution network.

Fig. 4. Topology of the iT & DN. (a) One-line diagram of iT & DN. (b) Case Entire topology of iT & DN.

A. Single Line $(N - 1)$ Outage Contingency

A composite severity index for transmission line outage, which is a function of apparent power flow and voltage limit violations, is adopted to measure the impacts of a given single line $(N - 1)$ outage contingency. Equation (31) describes the performance index of the composite m^{th} line outage contingency $PI_{S-V}^m(N - 1)$.

$$PI_{S-V}^m(N - 1) = f(f_p(x), f_v(x)) \quad (31)$$

In equation (31) x is a vector of the state variable (voltage magnitude and angle). $f_p(x)$ is the apparent power flow performance index defined by equation (32), where ω_m is a real non-negative weight coefficient that reflects the importance of the line, P_{lm} is active power flow, P_{lm}^{rated} is maximum allowable active power flow through the line, n is integer exponent.

$$f_p(x) = \sum_{m=1}^{Nl} \frac{\omega_m}{2n} \left(\frac{P_{lm}}{P_{lm}^{rated}} \right)^{2n} \quad (32)$$

Equations (33) and (34) give two variants of the voltage index measures of line outage performance index $f_v(x)$.

$$f_v(x)_1 = \sum_{i=1}^{nb} \frac{\omega_i}{2} \frac{\Delta V_i}{\Delta V_i^{lim}} \quad (33)$$

$$f_v(x)_2 = \sum_{i \in V_{vio}} \frac{|V_i - V_i^{lim}|}{V_i^{lim}} \quad (34)$$

From equations (33) and (34), nb and ω_i are the number of buses and weight coefficient respectively, while equations (35) and (36) define the terms ΔV_i , ΔV_i^{lim} and V_i^{lim} of equations (33) and (34).

$$\left. \begin{aligned} \Delta V_i &= V_i - V_i^{sp} \\ \Delta V_i^{lim} &= 0.5 \times (V_i^{max} - V_i^{min}) \end{aligned} \right\} \quad (35)$$

$$V_i^{lim} = \begin{cases} V_i^{max} & \text{if } V_i > V_i^{max} \\ V_i^{min} & \text{if } V_i < V_i^{min} \end{cases} \quad (36)$$

where V_i and V_i^{sp} are the post and pre contingency voltage magnitude at the i^{th} bus, V_i^{min} and V_i^{max} are upper and

lower voltage limits. Also, in equation (34) V_{vio} defines the set of all buses with post contingency voltage violation. The equation (37) gives the simplified form of equation (31) with the two voltage variant, respectively. In Fig. 4a, the outage of a transformer branch that causes a generator outage are excluded.

$$PI_{S-V}^m(N-1) = \begin{cases} \sum_{m=1}^{Nl} \frac{\omega_m}{2n} \left(\frac{S_{lm}}{S_{lm}^{rated}} \right)^{2n} + \sum_{i=1}^{nb} \frac{\omega_i}{2} \frac{\Delta V_i}{\Delta V_i^{lim}} \\ \text{OR} \\ \sum_{m=1}^{Nl} \frac{\omega_m}{2n} \left(\frac{S_{lm}}{S_{lm}^{rated}} \right)^{2n} + \sum_{i \in V_{vio}} \frac{|V_i - V_i^{lim}|}{V_i^{lim}} \end{cases} \quad (37)$$

B. Implementation

The proposed $TCSC - DG$ coordination approach is implemented within MATLAB/MATPOWER environment [10]. Data exchange is between MATPOWER, which evaluate load flow and CPF, and MATLAB implementation of MOPSO. Table I gives PSO and MOPSO parameters.

TABLE I
PSO AND MOPSO PARAMETERS

Parameters	PSO	MOPSO
ω_o	0.9	0.5
ω_{damp}	—	0.99
ω_{it}	$= 0.1 * \frac{it-1}{Max_it-1}$	$= \omega_o * 0.99$
C_1	1.5	1.0
C_2	$4 - C_1$	2
Max_{It}	150	150
$Swarm_{size}$	9	200
Repositorty	—	100
Grids per Dim.	—	7
Inf. rate (α)	—	0.1
Lead. Sel.Pre. (β)	—	2
Del. Sel. Pre. (γ)	—	2
Mutation Rate (mu)	—	0.1

VIII. RESULT AND DISCUSSION

The various power transfer directions [10], are described in Table II. The transfer direction comprises both bilateral and

multilateral transactions. The 2nd and 3rd column of Table II outline the source and sink buses corresponding to each transaction. Additionally, the base case multiple objectives comprising the ATC, power losses and voltage deviation of the test network (iT & DN) are also shown in Table II. From Table II, the binding limitation to each transaction is specific to transfer direction, which is either branch apparent power flows for T1 to T10 or bus voltage constraints in the case of T11 to T13.

Using $PI - PSO$, the active power loss and voltage deviation corresponding to the enhanced ATC values with TCSC for transactions T1 to T10 are given in Table III. The results in Table III are obtained such that the percentage compensation for TCSC is bounded within $-0.2 \leq X_{TCSC} \leq 0.8$.

A comparison of the results of these objectives in Table II and Table III is depicted in Fig. 5. Observed that while ATC enhancement with TCSC was recorded, there are corresponding active power losses resulting from additional power flows due to bilateral and multilateral transactions. Also, the voltage profile resulting from the transactions shows further deviation from the base case conditions. Hence, the need for coordinated approach between TSO and DSO, thereby ensuring better performance (measured by the objectives) of the iT & DN.

Fig. 5. Comparison of Objectives.

Accordingly, the $TCSC - DG$ coordination model described in Fig. 1 is implemented. Thus, for different transactions of Table II, Fig. 6 shows the three dimensions (3D), non-dominated Pareto front of $TCSC - DG$ coordination, for the optimisation of ATC, active power loss, and voltage deviation with both PV and PQ models of DG. As indicated in Table I, the Pareto front plots constitute the 100 members of the repository, which are the non-dominated solutions providing unique solutions among the competing objectives. It is observed that the 3D Pareto front in Figs. 6a to 6d indicates a diving parabolic like shape, which is partly nonlinear.

Furthermore, to gain a clearer insight into the relationships among the competing objectives, the slices of the 3D Pareto front plot illustrating the correlation between any two of the competing objectives will establish a unique understanding of the relationship between: ATC versus Ploss, ATC versus V_D and Ploss versus V_D respectively.

The slices of the Pareto front are obtained from the 3D plots of Figs. 6a to 6d, thereby illustrating the correlation between

Fig. 6. Pareto front Plot of T1 with $TCSC - DG$. (a) T1 under $TCSC - DG_{PV}$ (b) T1 under $TCSC - DG_{PQ}$ (c) T2 under $TCSC - DG_{PV}$ (d) T2 under $TCSC - DG_{PQ}$.

any two objectives. For transactions T1 and T3, the Pareto plot slices of ATC against real power loss (Ploss) and ATC against voltage deviation (V_D) are given in Fig. 7 and Fig. 8 respectively. It is worthy to state here that the Pareto plot slices between Ploss and V_D depicts disorderliness and hence were not discussed further.

Fig. 7. Slices of Pareto plot for transaction T1 under $TCSC - DG$. (a) ATC versus P_{loss} ($TCSC - DG_{PV}$) (b) ATC versus V_D ($TCSC - DG_{PV}$) (c) ATC versus P_{loss} ($TCSC - DG_{PQ}$) (d) ATC versus V_D ($TCSC - DG_{PQ}$)

For the power transfer transaction illustrated in Fig. 7 and Fig. 8, the sub-figures such as Figs. 7a and 7b depict the Pareto front slices with $TCSC - DG_{PV}$ while Figs. 7c and 7d depicts $TCSC - DG_{PQ}$ coordination. Similarly, sub-figures Figs. 7a and 7c give the Pareto front slices for the correlation between ATC versus Ploss, whereas Figs. 7b and 7d gives the correlation between Pareto front of ATC versus

TABLE II
BASE CASE ATC FOR VARIOUS TRANSACTIONS OF IT & DN TEST NETWORK

Trans ID	Source	Sink	Loading Factor λ_{max}	ATC		P_{loss} [MW]	V_D [p.u.]	Limiting Element
				[p.u.]	[MW]			
T1	1,3	5	1.5761	1.41817	141.8172	6.2044	3.6935	3(5 to 7)
T2	1,2	5,8	0.6620	1.25676	125.6763	3.9991	2.6895	5(7 to 8)
T3	1,2,3	5,6	0.5520	1.18561	118.5608	3.7575	3.4024	3(5 to 7)
T4	1,2,3	6,8	0.6770	1.52260	152.2604	4.3310	3.7203	5(7 to 8)
T5	2,3	5	0.4860	0.43772	43.7716	2.5070	2.0115	3(5 to 7)
T6	1	8	1.2410	1.24089	124.0892	4.4390	2.2023	5(7 to 8)
T7	1,2,3	5,8	0.7380	1.40208	140.2082	4.4523	3.2861	3(5 to 7)
T8	2,3	6	0.6010	0.75099	75.0992	2.9377	3.0173	3(5 to 7)
T9	1,2	8	0.5950	0.59529	59.5292	2.6632	1.7187	5(7 to 8)
T10	1,2	5,6	0.7450	1.60236	160.2364	4.8511	4.2759	3(5 to 7)
Voltage Constrained Transactions								
T11	1	6	0.9700	1.21272	121.2717	4.0264	3.0622	bus-6
T12	1,3	6	0.9320	1.16474	116.4743	3.9116	3.1138	bus-6
T13	1,2,3	5,6,8	0.7140	2.24809	224.8094	5.9844	4.8829	bus-6

TABLE III
ENHANCED ATC VALUES WITH TCSC USING $PI - PSO$ FOR IT & DN

Trans ID	ATC [MW]	P_{loss} [MW]	V_D [p.u.]	TCSC Solution	
				Line No.	% Comp
T1	154.5033	6.7954	3.4577	8(9 to 6)	80
T2	153.4515	4.7291	3.044	3(5 to 7)	49.2712
T3	172.1144	5.0027	3.9008	8(9 to 6)	75.5499
T4	178.2661	5.0092	4.2383	3(5 to 7)	44.6538
T5	64.4571	3.052	2.3949	8(9 to 6)	80
T6	153.3719	5.5736	2.3356	9(6 to 4)	80
T7	151.2495	4.7096	3.2706	5(7 to 8)	53.965
T8	101.3858	3.5028	3.3194	8(9 to 6)	56.4783
T9	79.304	3.1254	2.1354	3(5 to 7)	68.1384
T10	171.4634	5.0718	4.1904	8(9 to 6)	34.4068

Fig. 8. Slices of Pareto plot for transaction T3 under $TCSC - DG$. (a) ATC versus P_{loss} ($TCSC - DG_{PV}$) (b) ATC versus V_D ($TCSC - DG_{PV}$) (c) ATC versus P_{loss} ($TCSC - DG_{PQ}$) (d) ATC versus V_D ($TCSC - DG_{PQ}$)

V_D , respectively. In the case of $TCSC - DG_{PV}$, from Figs. 7a and 7c, it was observed that the Pareto front peaks with ATC, P_{loss} and V_D values around 168 MW, 6.2 MW and 3.8 p.u. as against 154.5 MW, 6.7 MW and 3.5 p.u. respectively. These improvements are attributable to DSO's resources, such as DG in coordination with the TSO's TCSC.

For comparison and deeper insight into the non-dominated solutions, a two-level criterion is adopted to select one non-dominated solution as the optimum compromise of the three objectives. In the first level, the ATC enhancement is given priority, such that all solutions with higher ATC compared to TCSC only constitute the optimum solution. The second level criterion is based on the concept of dominance, and a member of the non-dominated solution with at least two superior objectives compared to TCSC only equally constitute the optimum solution. Finally, from the list of the optimum solutions, a non-dominated solution is selected as the optimal solution by applying the first level criteria again. Subsequently, for transactions T1 to T10, Tables IV and V gives the objective terms and the corresponding solutions for $TCSC - DG_{PV}$ and $TCSC - DG_{PQ}$ coordination, respectively.

For Transaction T1, from Table V, Figs. 7c and 7d, it is seen that the PQ model of DG, in coordination with TCSC (as in $TCSC - DG_{PQ}$), provide superior ATC values compared with the PV model of DG, which is depicted by Table IV and Figs. 7a and 7b. Also, for the ATC versus P_{loss} , such as illustrated in Figs. 8c and 8d, the Pareto slices indicate that at some maximum ATC, the slope of the Pareto front approaches zero, implying that additional power losses are incurred without a corresponding enhancement in ATC.

An important event considered in power systems planning and operations is the outage of the TSO's equipment, such as the transmission line. Therefore, in the TSO managed model, a single line outage ($N - 1$) contingency can illustrate the impacts of TSO's contingency on the integrated Transmission and Distribution Networks. Consequently, Table VI gives the result of ($N - 1$) contingency based on equation (37). From the topology of Fig. 4, at the transmission section, the transformer branch outages are termed Invalid in Table VI, since it also results in the outage of a generator; while the unfeasible term refers to line outages that cause singularity and hence non-convergence of the load flow at the base case. In Table VI, PI_S , PI_{V1} and PI_{V2} are the apparent power version of the performance index, and the two voltage variant measurements of line outage performance index described by equation (37). The ranks of the outage lines based on the composite severity indices PI_{S-V1} , PI_{S-V2} and PI_S are shown in **boldface**.

TABLE IV
 $TCSC - DGPV$ COORDINATION SOLUTION FOR T1 TO T10

Trans ID	ATC [MW]		$TCSC - DG_{PV}$ Solution					
	TCSC	$TCSC - DG_{PV}$	$P_{loss}[MW]$	$V_D[p.u.]$	Line No.	% Comp.	Node No.	P_{size} [MW]
T1	154.503	168.8304	6.206	3.8241	8(9 to 6)	80	21	3.9664
T2	153.452	153.5067	4.7252	3.0241	3(5 to 7)	48.9181	10	8.7171
T3	172.114	172.2701	4.8214	3.8249	8(9 to 6)	80	49	10.2293
T4	178.266	178.8987	4.999	4.1679	3(5 to 7)	25.6021	28	21.5
T5	64.4571	63.5931	2.9089	2.3187	8(9 to 6)	80	31	6.3847
T6	153.372	168.3154	4.7358	2.3954	9(6 to 4)	80	50	21.5
T7	151.25	151.6302	4.6989	3.2171	5(7 to 8)	80	42	11.9087
T8	101.386	101.5266	3.5288	3.11	8(9 to 6)	69.1184	48	21.5
T9	79.304	79.6278	2.9211	1.9826	3(5 to 7)	62.1141	36	14.7665
T10	171.463	169.5974	5.0629	4.1745	5(7 to 8)	68.3549	26	14.2134

TABLE V
 $TCSC - DGPQ$ COORDINATION SOLUTION FOR T1 TO T10

Trans ID	ATC [MW]		$TCSC - DG_{PQ}$ Solution						Q_{Size} [MVAR]
	TCSC	$TCSC - DG_{PV}$	P_{loss} [MW]	V_D [p.u.]	Line No.	% Comp.	Node No.	P_{Size} [MW]	
T1	154.503	196.4656	4.4158	3.1387	8	80	18	11.2398	13
T2	153.452	155.3124	4.6795	2.4445	3	46.5784	56	0	13
T3	172.114	174.1671	4.5908	3.3141	8	68.634	18	0	12.9518
T4	178.266	183.2228	4.8576	3.7687	3	41.3541	45	0	12.9919
T5	64.4571	66.5036	3.0491	2.1733	8	80	11	19.7611	12.7953
T6	153.372	181.9170	3.6233	1.5008	9	80	50	21.5	13
T7	151.25	153.7433	4.685	2.7673	5	52.0642	56	0.2591	12.9781
T8	101.386	101.9827	3.0216	2.6511	8	54.8568	34	0	13
T9	79.304	80.9899	3.1235	1.9333	3	46.5589	44	15.6893	13
T10	171.463	173.9668	4.8871	3.8261	5	44.2909	14	0	10.9326

From each severity indices shown in Table VI, a list of severe and credible contingencies considered are obtained.

The ATC enhancement with TCSC was obtained under the credible $(N - 1)$ outage contingencies for all power transfer transactions in Table II. Fig. 9 depicts the impacts of various $(N - 1)$ contingencies on the power transfer transactions outlined in Table II. From Figs. 9a to 9i observed that the line 9(6 to 4) outage results in zero ATC, which is also consistent with the contingency status of Table VI caused by the singularity of the base case load flow solution. However, with the optimal deployment of TCSC, for all the transactions, Fig. 9 also depicts enhancement of the ATC above zero under line 9(6 to 4) outage.

Furthermore, among the credible contingencies, line 6(8 to 9) outage results in the least ATC value with and without

TCSC. Generally, TCSC enhances ATC above base case under all contingencies considered.

Additionally, while the impacts of TSO's contingencies have been illustrated in Fig. 9, DSO resources such as DG reduces the severity of the $(N-1)$ contingency, which is a vital feature of the TSO managed model. Consequently, Figs. 10 to Fig. 12 depicts the Pareto front slices of ATC versus Ploss and ATC versus V_D with $TCSC - DG$ coordination under the credible contingencies.

From Figs. 10 to 12, compared with TCSC only under contingencies, the ATC, Ploss and V_D were further improved with $TCSC - DG$ coordination. Similar to the cases without contingencies, comparing Figs. 10a and 10c, Figs. 10b and 10d, the $TCSC - DG_{PQ}$ under $(N - 1)$ obtained superior ATC values than $TCSC - DG_{PV}$. Similar deduction is made

TABLE VI
 $TCSC - DGPQ$ COORDINATION SOLUTION FOR T1 TO T10

[illegible]

Fig. 9. Impacts of $(N - 1)$ Contingencies on power transfers: (a)T1 under $(N - 1)$ Contingencies (b)T2 under $(N - 1)$ Contingencies (c)T3 under $(N - 1)$ Contingencies (d)T4 under $(N - 1)$ Contingencies (e)T5 under $(N - 1)$ Contingencies (f)T6 under $(N - 1)$ Contingencies (g)T7 under $(N - 1)$ Contingencies (h)T8 under $(N - 1)$ Contingencies (i)T9 under $(N - 1)$ Contingencies (j).

Fig. 10. Slices of Pareto plot for T1 under line 6(8 to 9) outage: (a)ATC Versus Ploss ($TCSC - DGP_{PV}$) (b)ATC Versus VD ($TCSC - DGP_{PV}$) (c)ATC Versus Ploss ($TCSC - DGP_{PQ}$) (d)ATC Versus VD ($TCSC - DGP_{PQ}$)

with Figs. 12. The Pareto front shapes are similar and specific to transfer directions.

IX. CONCLUSION

This paper demonstrates the $TSO - DSO$ coordination through a TSO managed model. The developed approach which allows for multiple objectives, account for both the TSO and DSO performance indices. While the various contingencies considered reduces the ATC values, improvements in the ATC, Ploss and V_D were obtained by the deployment

Fig. 11. Slices of Pareto plot for T2 under line 2(4 to 5) outage: (a)ATC Versus Ploss ($TCSC - DGP_{PV}$) (b)ATC Versus VD ($TCSC - DGP_{PV}$) (c)ATC Versus Ploss ($TCSC - DGP_{PQ}$) (d)ATC Versus VD ($TCSC - DGP_{PQ}$)

Fig. 12. Slices of Pareto plot for T4 under line 8(9 to 6) outage: (a)ATC Versus Ploss ($TCSC - DGP_{PV}$) (b)ATC Versus VD ($TCSC - DGP_{PV}$) (c)ATC Versus Ploss ($TCSC - DGP_{PQ}$) (d)ATC Versus VD ($TCSC - DGP_{PQ}$)

of DG as a DSOs resource in coordination with the TCSC under single line $(N - 1)$ outage contingencies. The Pareto front plots provide deeper insight into the correlation between ATC against Ploss and ATC against V_D . Compared to the PV model of DG, the PQ model aside the improvement in ATC, also reduces the power losses. This improvement is attributable to the reactive power supply by the PQ model of DG. The parabolic like shape of the Pareto front indicate that after some maximum ATC values, additional power losses are incurred without a corresponding improvement in the ATC, hence power transfer are not implemented beyond such point.

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