Flexible Topology for Mitigating the Congestion of Urban Power Grids with Dynamic Thermal Rating

Su,Yi
School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM)
https://orcid.org/0000-0002-9514-8555

Jiashen Teh (✉️ jiashenteh@usm.my)
School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM)
https://orcid.org/0000-0001-9741-6245

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Flexible Topology for Mitigating the Congestion of Urban Power Grids with Dynamic Thermal Rating

Yi Su, IEEE Student Member, Jiashen Teh, IEEE Senior Member, Qian Luo, Kang Miao Tan, Jia Ying Yong

Abstract—Urban power grid (UPG) combines transmission and distribution networks. Past studies on UPG congestion mitigation have focused on relieving local congestion while ignoring largescale energy transfer with safety margins load balancing. This situation is expected to worsen amid the proliferations of renewable energies and electric vehicles. In this paper, a two-layer congestion mitigation framework is proposed, which considers the congestions of UPG with flexible topologies. In the upper-layer, the PSO algorithm is employed to optimize the power supply distribution (PSD) of substation transformers, known as upper-layer PSD. The lower-layer model recalculates the new PSD, known as the lower-layer PSD, based on the topology candidates. A candidate topology is optimum when the Euclidean distance between the initial and optimum topologies is also smallest. This optimum topology is tested by the standard power mismatch between the upper- and lower-layer PSDs are the smallest. Past studies on UPG congestion mitigation have focused on relieving local congestion while ignoring large-scale energy transfer with safety margins load balancing. This proposed framework can determine the optimum transitioning sequence.

Index Terms—congestion mitigation; urban power grid; two-layer model; transitioning sequence; dynamic thermal rating.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Number of nodes in the UPG.</td>
</tr>
<tr>
<td>S</td>
<td>Number of steps of the transitioning sequence.</td>
</tr>
<tr>
<td>𝐴𝑖</td>
<td>𝑖𝑡ℎ unit group.</td>
</tr>
<tr>
<td>𝐿</td>
<td>𝑖𝑡ℎ substation transformer.</td>
</tr>
<tr>
<td>𝑃</td>
<td>An element (topology) of the set 𝑂′,</td>
</tr>
<tr>
<td>𝑆′</td>
<td>Optimum topology candidate.</td>
</tr>
<tr>
<td>B</td>
<td>Binary connectivity matrix between the load points and STs of a unit group based on the topology described by 𝑃′.</td>
</tr>
<tr>
<td>𝑥</td>
<td>Matrix of power supply level of 𝐴𝑖.</td>
</tr>
<tr>
<td>𝑥′</td>
<td>Normalized power supply of 𝐵, to 𝐴𝑖 in the upper layer between 0 and 1.</td>
</tr>
<tr>
<td>𝜀</td>
<td>Actual, optimal and average loading rate of the 𝑗𝑡ℎ ST.</td>
</tr>
<tr>
<td>𝐶</td>
<td>Rated capacity (MW) of the 𝑗𝑡ℎ ST.</td>
</tr>
<tr>
<td>𝐶(𝐴𝑖)</td>
<td>Power demand (MW) of 𝐴𝑖.</td>
</tr>
<tr>
<td>𝐶𝑙</td>
<td>Maximum power of the tie-line between the ST and distribution network. Normalized power supply of 𝐵, to 𝐴𝑖 in the lower layer between 0 and 1.</td>
</tr>
<tr>
<td>𝐶𝑙(𝑃′)</td>
<td>Real power demand (MW) of 𝐴𝑖, based on 𝑃′,</td>
</tr>
<tr>
<td>𝑑</td>
<td>Conductance and susceptance of the line between nodes 𝑎 and 𝑏.</td>
</tr>
<tr>
<td>𝑃, 𝑞</td>
<td>Active and reactive power of node 𝑎.</td>
</tr>
<tr>
<td>𝑢</td>
<td>Actual, minimum and maximum voltage of node 𝑎.</td>
</tr>
<tr>
<td>𝑢′</td>
<td>Power supply and maximum capacity of 𝑗𝑡ℎ ST.</td>
</tr>
<tr>
<td>𝑖, 𝑖′</td>
<td>Actual and maximum current rating of line 𝑖.</td>
</tr>
<tr>
<td>𝐵</td>
<td>Wind speed.</td>
</tr>
<tr>
<td>𝐵</td>
<td>Wind angle.</td>
</tr>
<tr>
<td>𝑇</td>
<td>Conductor temperature.</td>
</tr>
<tr>
<td>𝑇</td>
<td>Ambient temperature.</td>
</tr>
<tr>
<td>𝜃</td>
<td>The impact of the transitioning sequence.</td>
</tr>
<tr>
<td>𝑢</td>
<td>Voltage (p.u.) of node 𝑎 after 𝑅 transition.</td>
</tr>
<tr>
<td>𝑙</td>
<td>Actual current of line 𝑖 after 𝑅 transition.</td>
</tr>
</tbody>
</table>

I. INTRODUCTION

Urbanization has led to the formation of urban power grids (UPGs) which are hybrid of distribution and transmission networks [1] with the increasing penetration of renewable distributed generators (RDGs) and new loads [2], the congestion of urban power grid [3] has become more pronounced, sudden and unpredictable, which need to be solved urgently. Moreover, maintaining load balance and safety margin is crucial for UPG to accept the above uncertainties when relieving congestion, which was less considered in previous studies.

Several methods have been proposed to relief the congestions

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of UPGs. Generators have been re-dispatched to reduce certain line loadings and network congestions by minimizing the cost of energy rescheduling [4]. A day-ahead scheduling of generators and transmission switching have been employed to enable transmission system operators (TSOs) to optimize network deployments [5]. Although effective, both of these methods cannot be implemented in real-time. Hence, other methods with more real-time capability have been proposed. In [6], the real-time demand response (DR) program has been deployed by retail electricity providers based on game theory. In addition, the interactions between load aggregators and distribution system operators (DSOs) have been considered [7-8]. All the above rely on load-shedding to reduce congestions, which is undesirable because they also contribute to higher load losses.

Another set of literature coordinates the TSO and DSO to achieve a holistic dispatching of network resources. A decentralized, secure and economical generator dispatch plan of TSO and DSO on an hourly basis has been proposed [9]. This work is extended by considering also the flexibility region construction and cooperation of TSO and DSO in optimal power flow dispatch [10]. Retailers have been considered for hedging against network usage tariffs based on peak-load pricing of TSO and DSO [11]. A bi-level optimization model across the transmission and distribution networks for coordinating the safety dispatch of large-scale distributed energy resources has been proposed [12]. The above methods can control the behavior of electricity consumption but load shedding during peak hours is still unavoidable due to the lack of safety margin. And they all ignore the potential of a flexible network in redirecting power flow to relieve congestions [13].

In response, flexible network topologies have been optimized by the reinforcement learning algorithm [14] and particle swarm optimization algorithms (PSOA) [15-16] to improve the adequacy of power supply. Because these methods consider all circuit breakers (CBs) as switches when optimizing network topology, a large number of variables are involved in the optimization process and this prolongs simulation time. Several methods such as the Kruskal algorithm [17], a fast one-step method based on a set of binary descriptor matrices [18] and a heuristic based on a set of simplified load flow equations considering voltage and thermal limits [19] have been proposed before to speed up simulations. However, the proposed methods have only been applied in the radial distribution network (DN), which is different from the more complicated UPG structure. As a result, the simplification of objective functions and optimization constraints in a single framework shown by methods in [17-19] is not suitable for UPGs. Nonetheless, it is still clear that a flexible topology is beneficial for managing the congestions.

In general, the literature review shows the following shortcomings: (1) The congestion mitigation is mainly based on flexible load-shedding, which does not meet the reliability of power supply; (2) The UPG is the mixed of TSO+DSO, whose structure is complex, which means difficult to apply the flexible network reconfiguration directly as in the radial DN; (3) The dynamic operation process from the congestion state to the optimal state is not considered. Thus, this paper solves the problem described above by proposing a two-layer congestion management framework for UPGs. The layering feature is due to the separation of the power supply distribution (PSD) of high-voltage substation transformers (STs) in the upper-layer from the flexible topology model in the lower-layer. The two-layer framework undergoes an optimization process whereby both models improve the solution of each other. This ensures that: (1) no new congestions are formed when existing congestions are cleared with the safety threshold and load-shedding can be avoided, (2) the computation of transmission and distribution network decoupling is suitable for large-scale UPG (3) the optimum transitioning sequence between the initial and optimal states to minimize power system impacts based on dynamic thermal rating (DTR) has been considered. The contributions of this paper are summarized as follows:

1) A two-layer congestion mitigation framework is proposed for the UPGs.

In the upper-layer model, the PSOA is employed to optimize the PSD of STs, known as the upper-layer PSD, which represents the power supply from the transmission into the distribution networks. Searching the solution space at this level is fast because network topology is ignored and there is no need to perform power flow. The fittest upper-layer PSD is selected and pass down to the lower-layer model. In the lower-layer model, the optimal topology of the DN is determined. To speed up the searching process, all the load points are clustered into different unit groups and all the groups are considered in parallel. Each unit group has a set of optimum topology candidates and a PSD level is associated with every candidate, known as the lower-layer PSD. The candidate topology with the minimum distance between its associated lower-layer PSD and the upper-layer PSD is considered as the optimum topology of the unit group. The feasibility of the pair of optimum topology and lower-layer PSD is ascertained by the standard ACOPF. This approach is more efficient and faster as opposed to considering the entire DN without forming unit groups.

2) The proposed framework has balanced the power supply among STs in the upper-layer model to have the safety margin, so that it can tolerate more fluctuations of RDGs and EVs.

3) The proposed framework determines the optimum line switching sequence when optimizing the network topology based on DTR. Compared with the static thermal rating (STR) system, the DTR system systematically unlocks actual line capacity and the UPG can achieve rating gains when line switching.

The remaining of this paper is presented as follows. In section II, the UPG model and the methods of forming unit groups and finding the optimum topology candidates are described. In section III, the proposed two-layer congestion management framework is presented. In section IV, the optimum transitioning sequence model is presented. Results and discussions are given in section V. Finally, the paper is concluded in section VI.

II. URBAN POWER GRID MODEL

A. Modelling of UPG components

Fig. 1 shows the typical structure of the UPG and its characteristics are summarized in Table I. Note that the distribution transformers cannot supply power in reverse. Thus, the power demand of one DN could be seen as the equivalent
load, which is the power demand after power supply of RDG and discharge/charge of ESS, as shown by $P_2$ in Fig.1.

Fig. 1. A typical structure of an urban power grid.

**TABLE I**

<table>
<thead>
<tr>
<th>Network</th>
<th>Structural</th>
<th>MVA</th>
<th>Control object</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPG</td>
<td>Meshed network of a city</td>
<td>100-1000</td>
<td>Load &amp; topology</td>
</tr>
<tr>
<td>Distribution</td>
<td>Radial network of towns</td>
<td>1-100</td>
<td>Load &amp; topology</td>
</tr>
<tr>
<td>Transmission</td>
<td>Meshed network of multiple</td>
<td>&gt;1000</td>
<td>Generator</td>
</tr>
</tbody>
</table>

Fig. 1 shows that UPG1 has 45 CBs. They are found on both endings of each line and in between transformers. If all the CBs are considered as control variables during switching and that each CB can toggle between two states (open/close), then there are $2^{45}$ candidate solutions to consider. This huge number of variables is reduced by directly considering the lines themselves as the control variables instead. This makes sense because the purpose of topological control is to manipulate the switching of lines, which requires the CBs at both endings to open/close simultaneously. Hence, modelling the status of line switching directly and ignore the CBs can also simulate the intended changes in the network topology, but with a lesser number of controlling variables. Following the above and considering that the STs are the power sources, the simplified topology of UPG1 is obtained in Fig. 2. The figure shows that this method needs to consider only the switching of 24 lines ($2^{24}$ candidate solutions). These lines are the distribution lines and the tie-lines between the STs and DN. Note that the switching of tie-lines between the STs themselves are not considered.

**B. Unit groups formation rules**

The load points of UPG is clustered into different unit groups to further speed up simulation. The rule of thumb when forming a particular unit group is any two load points should be connected, either directly or indirectly, without passing through any STs. This method simplifies the topology optimization process because the network of each unit group is smaller and, can be handled more efficiently as compared to optimizing the topology of the entire bigger DN without grouping. It also makes the UPG work as the radial topology to avoid the high-voltage hoop network. The step-by-step process of forming a unit group is as follows:

1) Randomly select a load as the initial member of the first unit group, $A_1$. Then, identify all the other loads that are connected to the selected load without passing through any STs as the new members of $A_1$. For example, based on the UPG1 in Fig. 1, the load $P_2$ is selected at random and initialized as the first member of $A_1$. Then, because $P_2$ is connected to $P_1^2$, $P_1^1$, and $P_1^0$ without passing through any ST, these additional load points are also included into the group $A_1$. Hence, the final membership of $A_1$ is $\{P_2^1, P_1^2, P_1^1, P_1^0\}$.

2) The load points that have been identified with a group are excluded from all the subsequent considerations. The above process is repeated with a new load point until all the remaining load points have been assigned with a group. Using the same example, the final grouping outcome of UPG1 is shown in Fig. 2. The figure shows that 5 unit groups are formed in total and the numbers of switchable lines of each unit group are 6, 3, 9, 3, and 9, respectively. Considering that each line can only open or close, the numbers of switching combination in each unit group are $2^6, 2^3, 2^9, 2^3$ and $2^3$ for $A_1$ to $A_5$, respectively. Although the total number of switchable lines before and after grouping remain the same at 24, the unit group method is markedly more efficient than handling the entire DN without grouping, which has to consider $2^{24}$ switching combinations all at the same time. The unit group method breaks down the solution space into smaller searching area that can be optimized in parallel and, hence, faster.

**C. Optimum topology candidates**

The line switching of each unit group produces a set of $c$ number of possible topologies, $\Omega_{A_i}$. All possible topologies of the set can be listed exhaustively because the number of lines in each unit group is small. An element of $\Omega_{A_i}$ is represented by the binary string variable $\psi_{c}^{A_i}$, i.e., $\psi_{c}^{A_i} \in \Omega_{A_i}$; each binary number represents a line status (close/open) of the unit group.

For example, the unit group $A_1$ in Fig. 2 has the following 6 line switching candidates: $S_1, P_1^1, P_1^2, P_1^3, P_1^{10}, P_1^{10}, P_1^{10}$, $P_2^0$, $S_2$ and $P_1^{10}$, $S_3$. These lines form 64 combinations of line...
statuses \((c = 2^6 = 64)\), and each combination, \(\psi_c^{A_1}(c \in [1,64])\), is a possible topology that \(A_1\) could adopt. For example, the combination \([000000]\) represents that all the 6 lines are opened, and vice versa for the combination \([111111]\). Each binary number represents the line status of \(A_1\) in the order mentioned previously.

Only the topologies that can form the radial DN are considered as the optimum topology candidates, notated by the variable \(\psi_c^{A_1}\), i.e., \(\psi_c^{A_1} \in \Omega_{A_1}\). The radial network is advantageous because it avoids a closed loop current that is 1.34 times larger than the normal current \([20]\), hence, also avoids overloading and cascading failures. This approach is adopted by the China National Grid Company \([21]\).

The optimum topology candidates are determined by examining the \(B_{LS}(\psi_c^{A_1})\) binary matrix; it shows the direct and indirect connections between the load points and STs of a unit group in one of the topology candidates. If there is a connection, the value of one is assigned and vice versa. The binary values can indicate whether each load point is receiving power from only a single ST in a particular candidate topology - the cornerstone of a radial network. A topology is radial when the summation of each row in the binary matrix is equal to one.

For example, the topology \([101011]\) of the unit group \(A_1\) in Fig. 2 has the following \(B_{LS}(\psi_c^{A_1})\) binary matrix:

\[B_{LS}(101011) = \begin{bmatrix} p_1^3 & 1 & 0 & 0 \\ p_2^3 & 0 & 0 & 1 \\ p_1^{10} & 0 & 0 & 1 \\ p_2^{10} & 0 & 1 & 0 \end{bmatrix} \] (1)

### III. TWO-LAYER CONGESTION MANAGEMENT FRAMEWORK

#### A. Overview of the proposed framework

Considering the entire UPG when mitigation congestion creates a high-dimensionality problem that is difficult to solve. Partitioning the UPG and solve each partition separately may create new congestions in other parts of the network. This dilemma is addressed by the novel congestion management framework proposed here, as shown and summarized in Fig. 3. The proposed framework is carried out in two layers, namely the upper and lower layers, based on the idea that the power supplies of STs and the topology of unit group influence the state of one another.

The proposed framework begins with the PSOA initializes the first generation of solution population. Each solution is a set of normalized values which represent the power supply distribution (PSD) of STs. This first generation of solutions is applied onto the upper-layer model, where their fitness values are calculated. The fittest solution is selected and pass down to the lower-layer model. The factors considered in the calculation are the optimal and average loading rates of STs and the tie-line capacity between the STs and DN. These factors ensure a balanced PSD and avoid the overloading of tie-line. The topology of the DN is not considered in the upper layer.

The lower-layer model determines its own set of PSD for each optimum topology candidate. The candidate topology that corresponds to the smallest Euclidean distance mismatch between the upper- and lower-layer PSD is selected as the optimum topology. Therefore, the upper-layer PSD also

...
where the variable $x_{S_j}^{A_i,up}$ is a value between 0 and 1 which represents the upper-layer PSD and is a ratio of the total power capacity of the ST.

For example, in Fig. 2, the variable $X_k$ is shown as (4), which is only a 13-dimension variable, as compared to a 24-dimension variable (24 lines) if the topology of the DN was to be optimized without using the proposed two-layer approach.

$$X_k = \begin{bmatrix} x_{S_1}^{A_1,up}, x_{S_2}^{A_1,up}, x_{S_3}^{A_1,up}, x_{S_4}^{A_1,up}, x_{S_1}^{A_2,up}, x_{S_2}^{A_2,up}, x_{S_3}^{A_2,up}, x_{S_4}^{A_2,up} \end{bmatrix}$$  \hspace{3cm} (4)

Noted: the random initialization of PSO might influence the final performance, but it can be solved by improvement of PSOA, which is not the key in this paper. And Other PSOA parameters are employed from the reference [16].

C. Upper-layer model

The upper layer model minimizes the following fitness function that is comprised of three objective functions:

$$F_{up} = \min (\mu_1 F_1 + \mu_2 F_2 + \mu_3 F_3). \hspace{3cm} (5)$$

The variable $F_1$ is the first objective function that shows the deviation between the upper-layer PSDs given by the PSOA and the optimal loading rate of ST. Notice that the PSO and loading rate of STs are the same because the power supply is delivered to the DN through the STs. Loading the ST at the optimal rate, $\xi_{jref}$, minimizes transformer loss while meeting power demand [22]. Therefore, this is considered in $F_1$ to ensure that the PSDs of the STs are optimum. The variable $F_1$ is determined as follow:

$$F_1 = \left( \sum_{j=1}^{M} |\xi_j - \xi_{jref}| \right) / M, \hspace{3cm} (6)$$

$$\xi_j = \left( \sum_{i=1}^{N} x_{S_j}^{A_i,up} \times C(A_i) \right) / C_j. \hspace{3cm} (7)$$

The variable $F_2$ is the second objective function and it is similar to $F_1$, but it shows the deviation with the average loading rate of the ST instead. This additional factor is considered because it is not possible to always load STs optimally. Therefore, the variable $F_2$ is determined to ensure a margin of safety:

$$F_2 = \left( \sum_{j=1}^{M} |\bar{\xi}_j - \bar{\xi}| \right) / M, \hspace{3cm} (8)$$

$$\bar{\xi}_j = \left( \sum_{j=1}^{M} \xi_j \right) / M. \hspace{3cm} (9)$$

The variable $F_3$ is the third objective function that indicates whether the ratings of all the tie-lines, $L_2$, can support the upper-layer PSD to avoid overloading. This is performed by comparing the tie-line ratings with the PSD of the STs, which shows the amount of power that is to be injected into the DN, as follow:

$$F_3 = \sum_{l=1}^{N} L_2 = \sum_{j=1}^{m_l} \sum_{j=1}^{m_l} f_{1,2,up}, \hspace{3cm} (10)$$

$$f_{1,2,up} = \begin{cases} 1, x_{S_j}^{A_i,up} \times C(A_i) \geq C_{l_2}^{max}, & \forall l_2 \in L_2, \\ 0, x_{S_j}^{A_i,up} \times C(A_i) < C_{l_2}^{max} \end{cases} \hspace{3cm} (11)$$

Finally, the variable $\mu_1$, $\mu_2$ and $\mu_3$ are the weightages that indicate the emphasis level of the objective functions, which are set based on user’s requirement. In this paper, they are set to 1, 10, and 100, respectively.

D. Lower-layer model

The lower-layer model determines the optimum topology by minimizing the following function:

$$F_{low} = \min (\mu_4 F_4^{A_1} + \mu_5 F_5^{A_1}). \hspace{3cm} (12)$$

The variable $F_4^{A_1}$ is the first objective function that ensures the chosen topology of $A_1$ is optimum for minimizing the Euclidean distance mismatch between the upper- and lower-layer PSD:

$$F_4^{A_1} = \sum_{j=1}^{m_l} \left[ x_{S_j}^{A_i,up} - x_{S_j}^{A_i,low} (\psi_j^{A_1}) \right]^2, \hspace{3cm} (13)$$

such that,

$$\sum_{j=1}^{m_l} x_{S_j}^{A_i,low} = 1, \hspace{3cm} (14)$$

$$x_{S_j}^{A_i,low} (\psi_j^{A_1}) = C_j^{A_1} (\psi_j^{A_1}) / C(A_i). \hspace{3cm} (15)$$

The variable $x_{S_j}^{A_i,low}$ is the lower-layer PSD that is determined based on the optimum topology candidate, $\psi_j^{A_1}$. Based on the same example in Fig. 2 and the unit group $A_1$, the variable $F_4^{A_1}$ is further elucidated. For the purpose of this example, it is assumed that the upper-layer PSDs of $A_1$ are $x_{S_1}^{A_i,up} = 0.2$, $x_{S_2}^{A_i,up} = 0.3$ and $x_{S_3}^{A_i,up} = 0.5$ and all load points in $A_1$ are equal. Table II shows the resultant $F_4^{A_1}$ values of all the optimum topology candidates. The table shows that the topology {101011} has the minimum $F_4^{A_1}$ value of 0.07 and, it is therefore chosen as the optimum topology.

Calculating Table II is fast because the list of all the optimum topology candidates can be determined exhaustively. It is apparent from this example that the choice of the optimum topology depends on the upper-layer PSD that is determined by the PSOA.

<table>
<thead>
<tr>
<th>$\psi_j^{A_1}$</th>
<th>$x_{S_1}^{A_1,low}$</th>
<th>$x_{S_2}^{A_1,low}$</th>
<th>$x_{S_3}^{A_1,low}$</th>
<th>$F_4^{A_1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>011001</td>
<td>C(P_1^2)</td>
<td>0.25</td>
<td>0.75</td>
<td>0.32</td>
</tr>
<tr>
<td>011110</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.88</td>
</tr>
<tr>
<td>001101</td>
<td>0.5</td>
<td>0.25</td>
<td>0.75</td>
<td>0.62</td>
</tr>
<tr>
<td>101101</td>
<td>0.25</td>
<td>0.75</td>
<td>0.5</td>
<td>0.67</td>
</tr>
<tr>
<td>110101</td>
<td>0.25</td>
<td>0.25</td>
<td>0.75</td>
<td>0.39</td>
</tr>
<tr>
<td>110101</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>0.62</td>
</tr>
<tr>
<td>110011</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
<td>0.39</td>
</tr>
<tr>
<td>110101</td>
<td>0.3</td>
<td>0.5</td>
<td>0</td>
<td>0.42</td>
</tr>
<tr>
<td>111001</td>
<td>0.75</td>
<td>0.25</td>
<td>0</td>
<td>0.74</td>
</tr>
<tr>
<td>111100</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.99</td>
</tr>
</tbody>
</table>

To distinguish $F_4^{A_1}$ with similar values, the variable $F_5^{A_1}$ is determined. It indicates whether the tie-line ratings between the STs and DN can support the lower-layer PSD:

$$F_5^{A_1} = \sum_{j=1}^{m_l} f_{1,2,low}, \hspace{3cm} (16)$$

such that.
Finally, the variable $\mu_4$ and $\mu_5$ are the weightages that indicate the emphasis level of the objective functions, which are set based on user’s requirement. In this paper, they are set to 10 and 1, respectively. It is important to mention again that the lower-layer model is applied on every unit group in parallel. Therefore, (12) - (17) are performed at the same time on all the unit groups. At this point, a pair of variables are associated with each unit group: (1) lower-layer PSD and (2) the optimum topology. However, it has not been determined whether employing the pair can satisfy all the conventional AC power flow (ACPF) constraints and is, therefore, feasible. The lower-layer PSD is used as the fixed, instead of the dispatchable, power supply of the ACPF to ensure that the power output is the same as the lower-layer PSD levels. The ACPF is as follows:

$$
p_a = u_a \sum_{b=1}^{n} u_b(G_{ab} \cos \phi_{ab} + B_{ab} \sin \phi_{ab}),$$  \hspace{1cm} (18)

$$q_a = u_a \sum_{b=1}^{n} u_b(G_{ab} \sin \phi_{ab} - B_{ab} \cos \phi_{ab}),$$  \hspace{1cm} (19)

$$u_a^{\min} \leq u_a \leq u_a^{\max}, \forall a \in a,$$ \hspace{1cm} (20)

$$p_{S_j} \leq p_{S_j}^{\max}, \forall j \in S,$$ \hspace{1cm} (21)

$$l_l \leq l_{max,l}, \forall l \in L.$$ \hspace{1cm} (22)

The variable $l_{max,l}$ is the maximum line rating, which can either be the static thermal rating (STR) or the dynamic thermal rating (DTR). The STR is calculated based on a fixed set of conservative weather assumptions and the DTR is calculated based on real-time weather conditions, as follow:

$$l_{DTR} = \frac{Q_c(T_{a}, T_c, V_{w}, \theta_{w}) + Q_v(T_{a}, T_c)}{R(T_c)}.$$ \hspace{1cm} (23)

Equation (23) is the steady state DTR calculation described in the reference [23]. The equation shows current capacity of lines is greatly affected by micro meteorological conditions.

If the power flow is not feasible, which is when the ACPF constraints cannot be satisfied and convergence cannot be achieved, the upper-layer PSD associated with the pair of variables is discarded and, a new upper-layer PSD is generated by the PSOA. On the contrary, if the power flow is feasible, then the lower-layer PSD will replace the upper-layer PSD in the candidate solution pool and the fitness value in (5) is recalculated. This process is repeated on all the solution population.

IV. STATE TRANSITIONING SEQUENCE MODEL

In Section III, both the optimum PSD and the optimum topology of the DN is obtained. Although the optimized state of the UPG can be found, the sequence of transitioning between the initial to the final state is unknown and has never been considered. This is an important factor that this section intends to address because the transitioning sequence determines whether certain power system conditions can be met during the transitioning and, before the optimized state is reached. The conditions that are considered here are: (1) line overloading and (2) overvoltage of nodes.

For example, consider that the initial and final states of $A_1$ are \{011110\} and \{101011\}, respectively. From the initial to the final state, four lines have been switched; the second ($P_1^3 - P_2^3$) and fourth ($P_1^{10} - P_2^{10}$) lines are switched off, while the first ($S_1 - S_2^3$) and sixth ($P_1^{10} - S_4$) line are switched on. However, the sequence of line switching and the effect of a particular switching towards the power system conditions is unknown. The state transitioning sequence model is presented now.

Consider that the transition from the initial to the final optimal state requires $S$ number of switching, the multi-objective of the state transitioning sequence model is as follow:

$$\Theta = \min \sum_{S=1}^{S} \left[ \frac{\tau_1}{H} \left( \sum_{a=1}^{n} f_{1}^{R}(a) \right) + \frac{\tau_2}{L} \left( \sum_{l=1}^{L} f_{1}^{R}(l) \right) \right].$$ \hspace{1cm} (24)

The first objective function, $f_{1}^{R}(a)$, is the index of nodal voltage deviation from the ideal rated voltage (1 p.u.):

$$f_{1}^{R}(a) = \begin{cases} \frac{|u_a^{R} - 1|}{0.07}, & 0.93 \leq u_a^{R} \leq 1.07, \\ 1, & \text{others} \end{cases}$$ \hspace{1cm} (25)

The second objective function, $f_{1}^{R}(l)$, is the index of line loading deviation from the maximum ratings of the line:

$$f_{1}^{R}(l) = \begin{cases} l_{l}, & l_{l} \leq l_{max,l}, \\ 1, & l_{l} \geq l_{max,l} \end{cases}$$ \hspace{1cm} (26)

where the variable $l_{max,l}$ is the maximum line rating, which can either be the STR or DTR.

Finally, the variable $\tau_1$ and $\tau_2$ are the weightages that indicate the emphasis level of the objective functions, which are set based on the priority of the user. Their values can be set as equal if both conditions are equally important.

Based on the same $A_1$ example mentioned earlier, there are 24 (4 x 3 x 2 x 1) different transitioning sequences between the initial and final states because 4 lines are switched. In each of the sequence, the states of the 4 lines are changed one at a time. Based on (24), the sequence with the biggest $\Theta$ value is the most undesirable because it has the total worst impact towards the power system conditions. On the contrary, the sequence with the smallest $\Theta$ value is the most desirable and it is the optimum transitioning sequence between the initial and final states.

The number of possible transitioning sequence is reduced based on the following rules: (1) the switching operation gives priority to closing over opening lines to ensure adequate power supply and (2) the closing and opening of lines should be executed in pair to ensure a radial network, which avoids closed loop flow. With these two rules, the number of transitioning sequence of $A_1$ is reduced from 24 to 4.

V. RESULTS AND DISCUSSIONS

The test system used in this study is a 56-node UPG, as shown in Fig. 4. The test system is formed by combining one IEEE 14-node transmission network [25] and three IEEE 14-node distribution networks [26], which the latter is used to describe the topology of the load points. The unit groups $A_1$, $A_2$ and $A_3$ in the figure are formed based on section II. C. The total
load demand of the UPG is 258.3 MVA and this is obtained by increasing the original load level of each unit group by three times so that the total supply and demand levels are balanced. The rated capacity and optimal loading rate ($\xi_{\text{ref}}$) of all the STs in the test system are 75 kVA and 0.5, respectively. All the tie-lines between the STs and load points are considered to be the 110kV 110-LGJ-95 lines from China with 60 MVA capacity. The per unit resistance and reactance of the line are 0.035 and 0.13, respectively. The entire test system is considered to be in the same weather area to simplify DTR calculations in one of the case studies (case 4). All standard PSOA parameters [17] are used in the simulation of this study, which is performed on the PC with AMD 5-3500U 2.10 GHz CPU and 8.00 GB of RAM. Note that the topology shown in Fig. 4 is the considered initial state of the network. Four case studies are simulated and they are all described next.

**Case 1: Load point multiplication**

Case 1 simulates the scenario of high load growth in several load points, which are spread across the entire UPG. The STR is implemented. The load points 104, 109, 203, 207 and 303 from different unit groups are selected at random and their load level is doubled to create network congestions, which is mitigated by the proposed two-layer framework. The changes in the loading percentage of the tie-lines (between STs and unit groups) before and after congestion mitigation is shown in Fig. 5. The modifications of the network topology to enable the congestion mitigation are shown in Fig. 6.

Fig. 5 shows that the loading percentages among $l_2$, $l_3$, and $l_4$ that are connected with $A_1$, are more balanced after the congestion is relieved. The loading on $l_4$ is reduced by 25.5% and is transferred to $l_2$, $l_3$, which cause their loadings to increase by 9.9% and 16.9%, respectively. These changes are due to two sets of load transfer as shown in Fig. 6: (1) Load points 108 and 110 are transferred from $l_2$, $l_3$, and (2) load points 104 and 112 are transferred from $l_2, l_3$. Next, Fig. 5 also shows that the overloading in $l_{12}$ that is connected with $A_2$ has been relieved after employing the proposed framework. The loading of the tie-line has been reduced by 55.4% due to the transfer of its load points 201, 203 and 211 to $l_{12}$, which is initially disconnected from $A_2$, as demonstrated in Fig. 6. Another overloaded tie-line $l_{10}$ that is connected with $A_3$ has also been relieved. Its loading is reduced by 47.1% by transferring its load points 303 and 311 to $l_{10}$, which is initially disconnected from $A_3$. Additionally, the load point 301 that is initially served by $l_{14}$ has also been transferred to $l_{10}$. This preempts the overloading of $l_{14}$ that already has an initial loading of 80%. The loading percentages of the remaining tie-lines ($l_5, l_6$, and $l_{11}$) are mostly unchanged.

The effect of load increment on nodal voltages is also investigated and the results are shown in Fig. 7. The figure
shows the voltage level of every node before and after employing the proposed network congestion mitigation framework. Initially, the voltages of the nodes that are highlighted in the figure dip below the minimum acceptable level of 0.93 p.u. due to the drastic increment of load demand. However, the transfer of load performed by the proposed framework as shown in Fig. 6 helps to improve those voltage levels back to within the acceptable range (0.93 p.u.-1.07 p.u.).

Fig. 7. Changes of nodal voltage for mitigating congestions (Case 1)

Ultimately, all the results presented above show that the proposed framework can mitigate network congestions. The end results are that line overloading is avoided and all nodal voltages are maintained within the acceptable range.

Case 2: Regional load growth

Case 2 simulates large-scale demand growth by increasing the entire load demand of the unit groups $A_2$ and $A_3$ by 30% and 20%, respectively. The STR is implemented. The resultant congestions of the network are mitigated by employing the proposed framework which determines the optimum PSD and topology. All the corresponding line switching decisions of the optimum topology is shown in Table III. As large demand growth may cause overloading of STs, the loading condition of STs is investigated and shown in Fig. 8. The figure shows that the optimal network topology enables all STs to be operated within their acceptable loading range [22] (40%-60%). The loading rates of $S_2$ and $S_3$ are initially below 40% and they are improved to 42.5% and 41.4%, respectively, after the congestions of the network is cleared. This is possible because the tie-lines that are connected to these two STs have more available capacity now to serve more load points. At the same time, the initially overloaded $S_{10}$, $S_{13}$ and $S_{14}$ have been relieved by 49.6%, 52.4% and 48.3%, respectively, and they are all operating within the acceptable range after topology optimization. The reason is more power supply can be drawn from other STs that are previously underutilized after the congestion is cleared. Subsequently, reducing the power supply dependency of these three STs. As a result, the less overloaded STs are better prepared for supporting other STs during unexpected outages and, hence, have a better margin of operation risk. The voltage profile of the STs before and after optimizing the network topology is shown in Fig. 9. The figure shows that the voltage of $S_{14}$ has been improved from 0.927 p.u. to 0.97 p.u. after congestion mitigation, which is within the acceptable operating voltage range of STs (0.95 p.u.-1.05 p.u.).

<table>
<thead>
<tr>
<th>Unit group</th>
<th>From node</th>
<th>To node</th>
<th>Initial</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>$S_3$</td>
<td>114</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$A_2$</td>
<td>$S_6$</td>
<td>212</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$A_3$</td>
<td>$S_9$</td>
<td>301</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

1 indicates connect; 0 indicates disconnect

Fig. 8. Changes of loading percentages of STs (Case 2).

Fig. 9. Changes of nodal voltages of the STs (Case 2).

Case 3: Line outage

Case 3 simulates N-1 line outages and the STR is implemented. It is considered that the tie-line $l_2$ 2 of the test system has an outage. This outage cuts off power supply to load points 101, 103, 104, 111 and 112 and the subsequent priority is to restore all their power supplies. This can be achieved by closing one of the following three distribution lines: 103-108, 101-102 and 104-113. Each of this option might cause new congestions in other parts of the network and this would have to be determined. If there were new congestions, they can be mitigated by the proposed framework.

For example, consider that the distribution line 103-108 is closed. The effect of this decision towards the loading of all the tie-lines between the STs and DN is shown in Fig. 10. It can be observed from the figure that although the decision restores the power supplies of the affected load points, the tie-line $l_2$ 4 has
been loaded to 95.9% of its maximum capacity. Essentially, it is no longer safe to further deploy the tie-line because the low margin of the remaining line capacity is very risky to overloading. In other words, the tie-line $l_2$ has been congested and this inhibits load growth of the unit group $A_1$. To overcome the congestion, the proposed framework is deployed. Fig. 10 shows that the proposed framework is able to reduce the loading of $l_2$ by 14.3% from 95.9% to 81.6%. The most heavily loaded tie-line has now been shifted to $l_2$ 11, which has 82.3% loading. Overall, the loading has become more uniformly distributed among all the tie-lines, as compared to before the optimum topology is employed.

**Case 4: Transitioning sequence effects**

The above cases are based on the STR and only the optimal topology is proposed. The transitioning sequence between the initial and optimal states and, the effects of line rating (STR vs DTR) toward the transitioning sequence are never investigated. These two factors are studied in this section. Case 2 is selected as the case study of this section. The best transitioning sequence to achieve its optimum topology, as shown in Table III, with the least impacts toward the UPG is investigated. Other cases can also be used and they would only affect the numerical values.

The DTR values considered here are based on the weather conditions at Haiyang, China at two different times: (1) hour 0000-0100 on 1/1/2019 (winter) and, (2) hour 1100-1200 on 1/6/2019 (summer). The weather data of these two times, along with the calculated DTR values of the tie-lines $L_2$ (110-LGJ-95), are shown in Table IV. The STR of the conductor is 310A, based on $V_w = 0.5$ m/s, $\theta_w = 0^\circ$, $T_a = 40^\circ$C and $T_c = 100^\circ$C. For simplification, the capacity of tie-lines between STs are not considered. It is also considered that the distribution lines are underground cables which have very different thermal behavior than the overhead line. As the IEEE 738 standard is used to describe the DTR system and it is only suitable for the overhead lines, the DTR system is not applied onto the DNs (unit groups). As a result, the DTR system is only considered in the tie-lines between the STs and DN, $L_2$. The STR and DTR are implemented by replacing $I_{\text{max}}$ in (22) for all the lines $L_2$. Depending on the chosen line rating value, different optimum transitioning sequences are obtained and their impacts are shown in Table V. The first and second sequences are the optimum transitioning sequences based on the STR (310A) and DTR (342A), respectively. The third and fourth sequences are the optimum and worst transitioning sequence based on the DTR1 (507A).

![Fig. 10. Change of loading percentages of tie-lines (Case 3)](image)

<table>
<thead>
<tr>
<th>No</th>
<th>$V_w$ (m/s)</th>
<th>$\theta_w$ ($^\circ$)</th>
<th>$T_a$ ($^\circ$C)</th>
<th>$T_c$ ($^\circ$C)</th>
<th>DTR (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.06</td>
<td>31.01</td>
<td>-5.1</td>
<td>100</td>
<td>507</td>
</tr>
<tr>
<td>2</td>
<td>1.86</td>
<td>30.34</td>
<td>15.9</td>
<td>100</td>
<td>342</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No</th>
<th>$I_{\text{max}}$ (A)</th>
<th>Transitioning sequence</th>
<th>$\sum f_b^R$</th>
<th>$\sum f_i^R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>310</td>
<td>$l_2$ 9; 301-302; 301-303; 303-308; $l_2$ 12; 201-202; 201-204; $l_2$ 6; 104-113; $l_2$ 3;</td>
<td>4.67</td>
<td>5.37</td>
</tr>
<tr>
<td>2</td>
<td>342</td>
<td>$l_2$ 12; 201-202; $l_2$ 9; 301-302; 301-303; 303-308; 201-204; 201-202; $l_2$ 12; $l_2$ 6; 104-113; $l_2$ 3;</td>
<td>4.86</td>
<td>4.90</td>
</tr>
<tr>
<td>3</td>
<td>507</td>
<td>$l_2$ 9; 301-302; 301-303; 303-308; 201-204; 201-202; $l_2$ 12; $l_2$ 6; 104-113; $l_2$ 3;</td>
<td>4.67</td>
<td>3.30</td>
</tr>
<tr>
<td>4</td>
<td>301-303; 303-308; 104-113; $l_2$ 3; 201-204; $l_2$ 6; 12; 201-204; 201-202; $l_2$ 9; 301-302;</td>
<td>8.82</td>
<td>3.44</td>
<td></td>
</tr>
</tbody>
</table>

The impact of the first transitioning sequence based on the STR is worse than the second and third sequences. This is expected because the STR limits power flows and this creates more congestions than if the DTR was employed. For example, the line $l_2$ 13 remains congested until the line $l_2$ 12 is closed, which enable some of its loading to be shared by $l_2$ 12. Interestingly, the third transitioning sequence based on the highest DTR value, i.e., DTR1 (507A), is about the same as the first sequence. The only difference is the switching sequence of the two lines: $l_2$ 12 and 201-204, are opposite of one another. However, it is noticed that the impact of line overloading is significantly lower in the third sequence than the first sequence by 39%. Switching the line 201-204 before the line $l_2$ 12 causes the tie-line $l_2$ 6 to be overloaded in the first sequence, but the same problem is avoided in the third sequence.

The second sequence employs a lower DTR value than the third sequence. In the second sequence, the lines in unit group $A_2$ have to be switched first in order to keep the loading of all lines under the DTR2 (342A). In doing so, the voltage levels in $A_3$ are compromised. Consequently, the total impacts of the voltage deviation of the second sequence is slightly higher than the third sequence by 4.1%. The higher DTR1 used in the third sequence causes less overloading when transitioning through the line switching sequence, resulting in 32.6% lesser total line overloading impact than the second sequence.

The third (optimum) and fourth (worst) sequences are based on the same DTR1 (507A) and they are used to demonstrate the effects of different transitioning sequences under the same DTR level. Both the impact indicators of the fourth sequence are worse than the third sequence. The reason is switching the lines 301-303 and 303-308 first in the fourth sequence increases the loading of the tie-line $l_2$ 14 to 102.37% of DTR1 (507A). At the same time, all the nodal voltages from 301 to 307 and from 311 to 314 dip to around 0.82 p.u., which is below the allowable range (0.93 p.u. - 1.07 p.u.). This adverse situation lasted almost until the end of the sequence and is cleared only after the 9th line is switched, i.e., closing line $l_2$ 9. In the third sequence, the highest line loading is only 349A in $l_2$ 13, which is lower than its DTR1 maximum capacity. Therefore, all the tie-lines are
operating within the allowable limit. In addition, all nodal voltages of the third sequence are also within the allowable range during the entire transitioning sequence. Due to this, the third sequence outperforms the fourth sequence in both of the impact indicators.

**Case 5: Performance benchmarking**

In this case, we compare the ability of the ACOPF [3], PSOA (0-1 coding), and SOCP [3] with our proposed method in mitigating congestion. The ACOPF is solved by MIP, the PSOA (0-1 coding) method is solved by MATLAB, and the SOCP is solved by CPLEX. The computing times, load shedding and safety margins of these methods are shown in Table VI. The definition of safety margin is shown below:

\[ f_s = \max \{ |I|/I_{\text{max}} \}, \forall l \in L_2 \]  

(27)

where the margin is the maximum capacity after mitigating congestion. Smaller margin values indicate a more safety operation. The maximum capacity in this paper here is the STR.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Time (s)</th>
<th>Load shedding</th>
<th>Safety margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACOPF [3]</td>
<td>0.37</td>
<td>0.105 p.u.</td>
<td>0.79</td>
</tr>
<tr>
<td>PSOA (0-1 coding)</td>
<td>1.75</td>
<td>0.216 p.u.</td>
<td>0.63</td>
</tr>
<tr>
<td>SOCP [3]</td>
<td>1.75</td>
<td>0 p.u.</td>
<td>0.82</td>
</tr>
<tr>
<td>Proposed method</td>
<td>1.73</td>
<td>0 p.u.</td>
<td>0.56</td>
</tr>
</tbody>
</table>

In term of computation time, our proposed method is significantly faster than the PSOA because the TSO and DSO are decoupled by the two-layer model. Although the proposed method is slower than the ACOPF, load shedding is avoided in the proposed method but not in the ACOPF. The SOCP performs equally well as the proposed method in terms of time and load shedding, but the proposed method has a smaller safety margin between them. In fact, the safety margin of the proposed method is the lowest among all the methods shown in Table VI.

**VI. CONCLUSION**

This paper proposes a two-layer congestion mitigation framework of UPG. And the transitioning sequence between the initial and optimal state of the UPG is also considered. The results in this paper show that the proposed framework is able to mitigate UPG congestion with sporadic load growth (case 1), large scale load growth (case 2) and N-1 line outages (case 3). The effects of STR and DTR on the transitioning sequence have also been demonstrated and compared. The layering approach in the proposed framework enables a faster computation and produces topologies with sufficient safety margin. Hence, the framework can easily be applied on other larger UPGs.

**REFERENCES**


