Operational Risk Assessment for Integrated Transmission and Distribution Networks

Kunjie Tang, Shufeng Dong, Jian Huang, Xiang Ma

***Abstract*—To satisfy the requirements of accurate operational risk assessment of integrated transmission and distribution networks (I-T&D), an integrated operational risk assessment (I-ORA) algorithm is proposed. Specific cases demonstrate that I-ORA is necessary because it provides accurate handling of the coupling between transmission and distribution networks, accurate analysis of power supply mode (PSM) changes of important users and helps to improve security and stability of power grid operation. Two key technical requirements in the I-ORA algorithm are realized, integrated topology analysis and integrated power flow calculation. Under a certain contingency, integrated topology analysis is used to assess risks of substation power cut, network split and PSM changes of important users, while the integrated power flow calculation, based on the self-adaptive Levenburg-Marquard method and Newton method, can be implemented to assess risks of heavy load/overload and voltage deviation. Besides, graphics processing unit is used to parallelly process some computation-intensive steps. Numerical experiments show that the proposed I-ORA algorithm can realize accurate assessment for the entire I-T&D. In addition, the efficiency and convergence are satisfying, which indicates that the proposed I-ORA algorithm can significantly benefit real practice in the coordination operation of I-T&D in the future.**

***Index Terms*—global model, integrated transmission and distribution networks, operational risk assessment, power flow calculation, topology analysis.**

I. Introduction

Hierarchical dispatch and control have been adopted for power grids for a long time, where transmission network (TN) is managed by a transmission system operator (TSO) while distribution network (DN) is managed by a distribution system operator (DSO). Both TSO and DSO use detailed modeling of power grids within their service area but simplified models for the grids out of their service area. Accordingly, operational risk assessment (ORA) of power grids is processed by TSO and DSO independently [1]. The independence of modeling and analysis for TN and DN leads to the lack of computation synchronization, which further indicates that the calculation results and ORA results may have a potential deviation [2]. On the one hand, the boundary voltage and power mismatches exist due to the separate power flow calculation. On the other hand, the power flows produced by loops in DNs will not be accurately simulated [2]. Inaccurate power flow results will lead to inaccurate ORA results, finally.

ORA usually consists of several steps, such as contingency set (CS) generation, topology analysis, power flow calculation, etc. [3-5] Topology analysis and power flow calculation under hierarchical management system are usually based on an equivalent model, where a DN is equivalent to a load with known constant power for TSO and a TN is equivalent to a source with known constant voltage for DSO, as shown in TABLE I. Topology analysis and power flow calculation based on the equivalent model cannot realize collaborative analysis between TN and DN. For example, topology analysis for TSO cannot recognize the power supply mode (PSM) changes of important users while topology analysis for DSO cannot realize the operation mode self-adjustment of TN. In addition, independent power flow calculation may cause low accuracy when assessing voltage deviation and heavy load/overload risks.

Under such an environment, an integrated ORA (I-ORA) algorithm for integrated transmission and distribution networks (I-T&D) is necessary to realize ORA comprehensively and accurately for the entire networks. Reference [6] proposes a preliminary conception of ORA for I-T&D and analyzes the necessity of I-ORA, but there is no in-depth discussion on the specific steps and key technical requirements in the I-ORA process. Considering the effects of DN, [7] proposes a TN contingency analysis algorithm based on the master-slave-splitting model. Further, based on [7], [8] proposes two TN contingency screening methods considering the impacts of DN. This model allows heterogeneous modeling and solution to avoid numerical stability problems [2]. Also, its distributed manner usually alleviates computational burdens. However, this model is still layered and asynchronous, and the convergence of the master-slave-splitting method cannot be ensured [9], as shown in TABLE I. Also, the efficiency of this method is sensitive to communication conditions [10].

Recent reports show that the current cooperation level between TSO and DSO is low in most countries, but they have made specific plans for improving TSO-DSO cooperation in future operation [1, 11, 12]. For example, Belgium has proposed a project called 'ATRIAS' to enhance TSO-DSO cooperation. In France, a necessary and optimized way for the cooperation between TSO and DSO is in discussion [1]. Particularly, in China, State Grid Corporation is promoting the construction of dispatching and control cloud (d-Cloud) in recent years, based on advanced cloud computing and big data tech-

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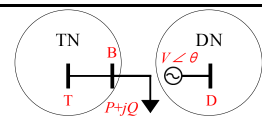
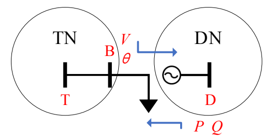
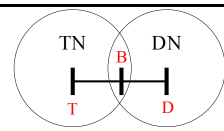
TABLE I
THREE COMMON MODELS FOR I-T&D ANALYSIS

Model	Application Situation	Basic Principles	Illustration	Pros and Cons
Equivalent model	Widely used in practical operation	DN is equivalent to a load with known constant power for TSO and a TN is equivalent to a source with known constant voltage for DSO.		Pros: simple and easy to implement; no divergence problem or numerical stability problem. Cons: not accurate enough to describe the coupling between TN and DN
Master-slave-splitting model	Discussed in previous research	TN is considered as the master system, while DN is considered as the slave system. Master and slave systems are connected to each other via boundary buses. During the analysis, alternative iterations are needed and these two systems exchange data at the boundary.		Pros: more accurate to describe the coupling between TN and DN; no numerical stability problem; heterogeneous modeling and solution Con: potential divergence problem; limited to real-time communication conditions
Global model	In the future based on the higher level of TSO-DSO coordination	TSO and DSO can share the models and data with each other. Thus, the models and data of TN and DN can be combined completely, accurately describing the coupling between TN and DN.		Pros: direct method; accurate enough to describe the coupling between TN and DN Cons: numerical stability problem; suffer from heavy computational burden; potential privacy issues

nologies [13-15]. This novel architecture will significantly enhance the capabilities of coordinated processing, information support, and global resource sharing among different levels of dispatching and control systems. At present, in some provinces of China, the d-Cloud has realized the model and data combination of networks, of which voltage level ranges from 10kV to 1000kV [13]. These new achievements demonstrate that it is still important, as well as possible in near future, to establish a global model for I-ORA. Admittedly, a global model will also arise some potential problems, as shown in TABLE I [2]. First, a global model is formed by combining TN and DN models, which means that TSO and DSO are willing to share all their information. This may lead to potential privacy issues. Also, due to the significant difference between the magnitude of data of TN and that of DN, such as branch power, network parameters, etc., a global model may cause numerical stability problems. Finally, due to the combination of TN and DN models, global-model-based algorithms usually suffer from a heavy computational burden.

In summary, master-slave-splitting and global models both have their pros and cons. Previous research mainly focuses on the former and develops a series of distributed algorithms. These achievements are valuable because the privacies of TSO and DSO are well-preserved. However, previous achievements on the global model of I-T&D are limited. Since the global model may come true in some countries, such as China, this paper proposes a specific I-ORA algorithm for I-T&D based on the global model. The motivation of the paper is to explore a new possibility of the global model in I-T&D coordinated analysis, and try to deal with some drawbacks of this model: numerical stability problem and heavy computational burden. The main contribution of the paper is that it:

i) analyzes the necessity of I-ORA based on specific cases;

ii) proposes an I-ORA algorithm for I-T&D, realizing comprehensive and accurate assessment for different types of risks, substation power cut, network split, PSM changes of important users, heavy load/overload, voltage deviation, etc.;

iii) proposes the implementation for two key technical requirements in I-ORA: integrated topology analysis and integrated power flow calculation. Particularly, parallel computing techniques are used for acceleration and a self-adaptive Levenburg-Marquard method is applied to cope with potential numerical stability problems that exist in power flow calculation.

Numerical experiments show that the proposed I-ORA algorithm can realize a more comprehensive and accurate risk assessment compared with traditional hierarchical ORA. In addition, the proposed integrated topology analysis and power flow calculation algorithms have satisfying performance, which meets the requirements of real-time online analysis.

Noting that the work in this paper has some similarities to the N-1 contingency analysis because they both assess the security of a system under given contingencies. However, there are still some differences. First, the method in this paper focuses on the whole I-T&D system considering TN and DN contingencies as well as the coupling between TN and DN while conventional N-1 contingency analysis only focuses on one area, TN or DN. Although the effects of DNs are considered in N-1 contingency analysis of TN in some recent references [7, 8], the influences of DN contingencies on topology and power flow are not fully discussed. Second, N-1 security criterion assumes that only one component is removed in each contingency, while the risk assessment method may analyze more complex contingencies, in which more than one component are removed. Considering that hidden failures in the protection system can trigger additional outages based on the original fault, N-1 security criterion is not sufficient sometimes. Finally, the traditional N-1 security criterion provides a limited perspective on the security level of a system, while the goal of the proposed risk assessment method is to rate the risk for a given system with quantified risk-rating indices. These indices usually reflect the severity or expected costs to a system, which will not be fully calculated in N-1 security criterion. In short, N-1 contingency analysis is the basis of our work and our work is an extension of N-1 contingency analysis. The work in this paper mainly focuses on the risk severity assessment, and our further work will introduce actual probabilities and achieve a more comprehensive I-ORA.

The rest of the paper is organized as follows: Section II analyzes the necessity of I-ORA. Section III proposes a real-time I-ORA algorithm. Section IV proposes an integrated topology analysis algorithm and an integrated power flow calculation algorithm to meet the key technical requirements of I-ORA. Numerical experiments demonstrate the effectiveness of the proposed algorithms in Section V. Finally, conclusions are drawn in Section VI.

II. The Necessity of I-ORA for I-T&D

In this section, based on some specific cases, three aspects of the necessity of I-ORA for I-T&D are analyzed.

A. Accurate Handling of the Coupling between TN and DN

In recent years, the permeability of distribution generations, such as photovoltaics, wind turbines, and energy storages, is gradually increasing, and the activeness of DN is enhanced. The active and reactive power of TN and DN can be permeated with each other and achieve bi-directional flow, significantly enhancing the coupling between TN and DN [16, 17].

Traditional algorithms based on the equivalent model assume that TN is stable enough and will not be affected by the fluctuation of DN. However, with the increased coupling between TN and DN, this assumption is no longer established, and the effect cannot be neglected. To support this conclusion, CASE I and II are used to implement power flow calculation based on the equivalent model and the global model respectively. The detailed case information is shown in the appendix. TABLE II makes a comparison of voltage magnitude U_B/p.u., active power injection P_B/MW, and reactive power injection Q_B/MVar at the boundary node of TN and DN, obtained by power flow calculation under two different models.

TABLE II
POWER FLOW RESULTS UNDER DIFFERENT MODELS

Case	Equivalent Model			Global Model		
	U_B	P_B	Q_B	U_B	P_B	Q_B
CASE I	0.9293	3.8027	2.6946	0.9249	4.3177	2.9279
CASE II	0.9649	22.7273	17.1266	0.9635	24.5315	18.4951

As shown in TABLE II, the power flow results under the equivalent model have a non-ignorable deviation compared with those under the global model, which makes ORA based on power flow results will also have a significant deviation. Therefore, I-ORA based on the integrated power flow calculation under the global model is important for accurately describing the coupling between TN and DN.

B. Accurate Analysis of PSM Changes of Important Users

In the traditional TN ORA, the risk analysis of PSM changes of important users is relatively rough and asynchronous, because TSO only applies simplified models for the power grids out of their service area [6]. The risks led by DN contingencies will not be fully incorporated into the results of TN ORA.

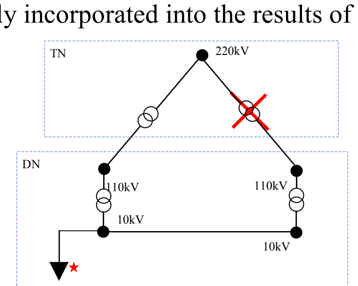


Fig. 1. A topology graph of I-T&D

Fig. 1 is the topology graph of an I-T&D system. The load marked the red star represents an important user, requiring duplicate-supply. Under normal operation mode, this requirement is satisfied. However, if the transformer labeled with a red 'X' is removed, although the important user will not lose the power, its PSM is transferred to single-supply. The power supply reliability of this important user is no longer satisfied. Thus, the network has an operational risk.

If TSO plans to remove this transformer for maintenance, a risk assessment will be made under this contingency. However, since the cooperation level of TSO and DSO is low, the potential risk of this PSM change will not be detected by the traditional TN ORA. This case indicates the necessity of I-ORA in recognizing the PSM of important users.

C. Improving Security and Stability of Power Grid Operation

Usually, in ORA for TN, DN is regarded as the injection load of TN nodes. This method can realize fast assessment for the entire network. However, with the rapid development of active DN and the increment of loop operation mode, the effectiveness of traditional ORA for TN is weakened. For example, one of the main reasons for the blackout in North America in 2011 is that the effect of the loop power flow in DN and its influence on TN are ignored in ORA for TN [18].

This shows that I-ORA, aiming at new problems and new situations in I-T&D operation, will further improve the security and stability of power grid operation.

III. I-ORA Algorithm for I-T&D

In this section, the classification of I-T&D operational risks will be presented in Subsection A. Then, the specific steps of the I-ORA algorithm will be introduced in Subsection B.

A. Classification of I-T&D Operational Risks

According to references [5, 6, 19], this paper mainly focuses on the assessment of five risks, including substation power cut, network split, PSM changes of important users, heavy load /overload, voltage deviation. The definitions and dependency parameters for risk severity ratings are shown as follows.

Substation power cut: This dimension indicates that there exist one or more substations suffer from an outage under a certain contingency. The severity of this risk is determined by the maximum voltage level among all power-cut substations.

$$\begin{aligned} Idx_{SPC}^{T} &= \begin{cases} \max\limits_{i \in S_{SPC}^{T}} \{VC_i^T\}, S_{SPC}^{T} \neq \varnothing \\ 0, S_{SPC}^{T} = \varnothing \end{cases} \\ Idx_{SPC}^{D} &= \begin{cases} \max\limits_{i \in S_{SPC}^{D}} \{VC_i^D\}, S_{SPC}^{D} \neq \varnothing \\ 0, S_{SPC}^{D} = \varnothing \end{cases} \end{aligned} \tag{1}$$

where S_{SPC} is the set of the substations that suffer from an outage under a certain contingency, and VC is the voltage level of substations. The superscripts T and D represent TN and DN, similarly hereinafter.

Network split: This dimension indicates that one or more subnets are split from the main network under a certain contingency. The severity of this risk is determined by the maximum voltage level among all nodes in the split subnet.

$$Idx_{NS}^{T}=\begin{cases}\max\limits_{i\in S_{NS}^{T}}\{VC_i^T\}, S_{NS}^{T}\neq\varnothing\\ 0, S_{NS}^{T}=\varnothing\end{cases}$$
$$Idx_{NS}^{D}=\begin{cases}\max\limits_{i\in S_{NS}^{T}}\{VC_i^T\}, S_{NS}^{T}\neq\varnothing\\ 0, S_{NS}^{T}=\varnothing\end{cases} \tag{2}$$

where S_{NS} is the set of the nodes in the split subnet.

PSM changes of important users: This dimension indicates that the PSM of one or more important users is changed (power cut or the minimum number of power supplies required for maintaining reliability is not satisfied) under a certain contingency. The severity of this risk is determined by the highest level of important users who suffers from a PSM change.

$$Idx_{PSM}=\begin{cases}\min\limits_{i\in S_{PSM}}\{R_i\}, S_{PSM}\neq\varnothing\\ 0, S_{PSM}=\varnothing\end{cases} \tag{3}$$

where S_{PSM} is the set of important users who suffer from a PSM change. R represents the level of important users. The smaller the R_i is, the more important the user i is. Here, it is assumed that R is valued as a positive integer, 1, 2, … In China, for instance, the levels of important users are regulated by local governments [19].

Heavy load /overload: This dimension indicates that one or more lines or transformers suffer from heavy load/overload under a certain contingency. The severity of this risk is determined by the maximum among the ratios of power of lines or transformers to their rated power.

$$Idx_{HL/OL}=\max_{i\in S_L}\{\frac{S_i}{Se_i}\} \tag{4}$$

where S_L is the set of lines and transformers. S is the actual apparent power under a given contingency while Se is the rated apparent power.

Voltage violation: This dimension indicates that one or more nodes suffer from voltage violations under a certain contingency. The severity of this risk is determined by the maximum among the relative deviation between nodal voltage magnitudes and nodal rated voltage magnitudes.

$$Idx_{VD}^{T}=\max_{i\in S_N^T}\{\frac{\left|V_i^T-\bar{V}_i^T\right|}{\bar{V}_i^T}\}, Idx_{VD}^{D}=\max_{i\in S_N^D}\{\frac{\left|V_i^D-\bar{V}_i^D\right|}{\bar{V}_i^D}\} \tag{5}$$

where $\bar{V}$ represents nodal rated voltage magnitude while V represents nodal actual voltage magnitude under a given contingency.

The risk-rating standard is designed based on these indices (1)-(5). However, designing a quantified risk-rating standard is subjective and it usually varies from country to country and region to region. Considering that this paper mainly focuses the I-ORA algorithm, a detailed and quantified risk-rating standard will not be discussed specifically.

B. Steps of the I-ORA Algorithm

The proposed process of I-ORA and rating system are shown in Fig. 2., including five essential parts, data acquisition, risk identification, risk assessment, risk rating, and risk early-warning.

• Step I: Data acquisition. In this step, the platform gathers various data, including weather data, operational data, and component data from both TN and DN, for risk identification and risk assessment.

• Step II: Risk identification. By analyzing the data gathered, various uncertain factors will be considered in this step. These factors will be quantified and a factor correlation model will be established. Based on this model, component outage models can be established, and real-time component outage possibilities can be obtained, accordingly. Considering that the goal of this paper is to handle the key technical requirements in the I-ORA algorithm for I-T&D, which are significantly different from those in the conventional ORA algorithm only for TN, the specific implementation of Step I and II will not be discussed.

• Step III: Risk assessment. This is the core part of the proposed I-ORA algorithm. First, the splicing of TN and DN models is used to establish a global model for the entire networks. Under the global model, models, and data of TN and DN can be completely combined without any approximation, accurately describing the coupling between TN and DN. Then, the generation of CS can be realized by Monte Carlo, state enumeration, event tree, and some other methods. Under a certain contingency, integrated topology analysis is used to assess risks of substation power cut, network split, and PSM changes of important users, while the integrated power flow calculation is used to assess risks of heavy load/overload and voltage deviation.

• Step IV: Risk rating. For each contingency, the comprehensive assessment will be implemented and the risk rating can be obtained based on the assessment result. This will be recorded for Step V to rate the risk for the whole I-T&D.

• Step V: Risk Early-warning. By analyzing the whole CS, the operational risk of the whole network can be rated. If there is any risk, a risk early-warning will be sent to operators.

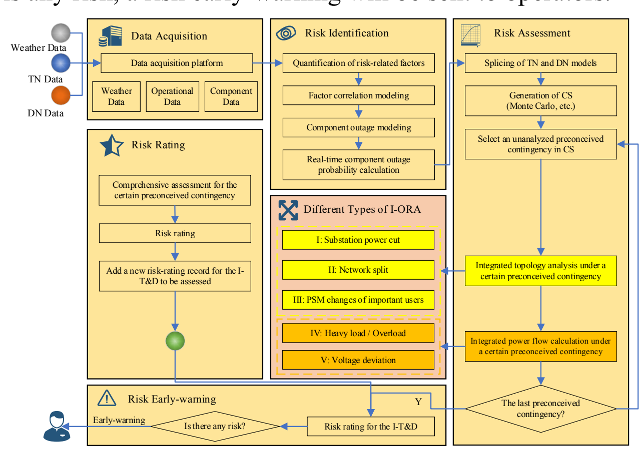


Fig. 2. Process of I-ORA and rating system

IV. Key Technical Requirements and Their Implementation in the I-ORA Algorithm

In the I-ORA, the specific implementation of some steps is significantly different from those in the traditional ORA. Particularly, the proposed I-ORA algorithm needs two key technical requirements to support, integrated topology analysis and integrated power flow calculation.

A. Challenges of I-ORA

Traditional topology analysis and power flow calculation algorithms cannot be simply transplanted to I-ORA, because these algorithms usually face some difficulties and challenges in the convergence, computational efficiency, and so on [16].

On the one hand, due to the significant difference between the magnitude of data of TN and that of DN, such as branch power, network parameters, etc., the Jacobian matrices in the Newton method are seriously ill-conditioned, whose condition numbers are large. As a result, inappropriate initial values will usually cause divergence, since the Newton method is sensitive to initial values. Thus, algorithms with better convergence are needed for integrated power flow calculation. Specifically, a self-adaptive Levenburg-Marquard method is proposed in this paper. By taking this method for determining initial values of the Newton method, better robustness will be achieved and the divergence which appears in the traditional Newton method is avoided. The detailed information of this method is shown in Section IV-C.

On the other hand, real-world I-T&D systems have a large scale, and traditional serial algorithms are difficult to satisfy the real-time requirements of I-ORA. Thus, algorithms with lower time and space complexity are needed, and some high-performance computation methods can be applied to further accelerate the algorithms. Specifically, the graphics processing unit (GPU) parallel computing is applied in this paper to accelerate certain computation-intensive steps. The detailed application is shown in Section IV-D.

B. Integrated Topology Analysis

The integrated topology analysis is used to realize integrated analysis for the topology information of the entire networks with different voltage levels based on the global model, in order to accomplish the assessment of substation power cut, network split, and PSM changes of important users.

1) Assessment of Substation Power Cut and Network Split

Based on a global model, integrated topology analysis can realize the assessment of substation power cut and network split by applying network connectivity test methods in graph theory. Traditional connectivity test methods are mainly based on search methods and adjacency matrix methods [20-22], but they usually suffer from high space and time complexity, which is not suitable for connectivity tests of large-scale I-T&D. This paper proposes a novel method based on union-find sets.

In the graph theory, a power grid model can be represented as a 'graph' G-an ordered tuple (V, E), where V is a vertex set and E is an edge set. Further, the elements in E can also be represented as tuples (x, y), where x, $y \in V$. When abstracting the power grid model, generators and loads are ignored because they are not related to the topology of the graph, while nodes are represented as vertices, and transmission lines and transformers are represented as edges.

The detailed steps of the proposed method are as follows, where the '***reach***' value of each vertex represents the maximum value of sequence numbers of other vertices that belong the same connected component with this vertex.

Algorithm 1 Assessment of Substation Power Cut and Network Split

for $i = 1 : n$ **do** // n is the number of vertices
  reach$(i) = i$;
end for
do
  flag = true;
  // If all values of ***reach*** are not updated, exit the loop.
  for $k = 1 : m$ **do** // m is the number of edges
    if ***reach***(***x***(k)) != ***reach***(***y***(k)) **then** *flag* = false;
    reach(***x***(k)) = **max**{***reach***(***x***(k)), ***reach***(***y***(k))};
    reach(***y***(k)) = ***reach***(***x***(k));
    // ***x***(k) and ***y***(k) are the sequence number of two connected vertices by Edge k.
  end for
loop until *flag* = true
if every value of ***reach*** is equal to n
  then the graph is connected
  else the graph is not connected
end if
if the graph is connected
  then there is no risk
  else calculate Idx_{SPC}^{T}, Idx_{SPC}^{D}, Idx_{NS}^{T}, and Idx_{NS}^{D}; there is a risk
end if

2) Assessment of PSM Changes of Important Users

The integrated topology analysis can also realize accurate assessment of PSM changes of important users based on a global model. Without loss of generality, it is assumed that the voltage level of the important user to be analyzed is M kV. In the proposed algorithm, the global model of I-T&D can be divided into two parts, as shown in Fig. 3. The nodes of M kV connecting with the nodes of higher voltage level via transformers belong to public areas of Area A and Area B, and they are considered as power supply nodes in Area B. These nodes and other nodes of higher than M kV belong to Area A, while all the nodes of equal to and lower than M kV belong to Area B.

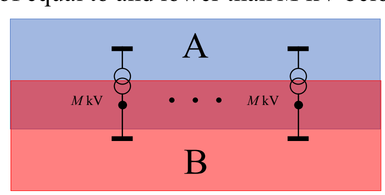


Fig. 3. Division of I-T&D for assessment of PSM changes of important users

First, under a certain contingency, Algorithm 1 is used to analyze the power grid model of Area A by neglecting the nodes of M kV which are not power supply nodes and the nodes of lower than M kV. Thus, it can be judged whether these power supply nodes lose power.

In the following analysis, those power supply nodes which lose the power will be no longer considered as power supply nodes but considered as common load nodes instead. Then, Algorithm 2, which has a slight difference with Algorithm 1, is used to analyze the power grid model of Area B.

Algorithm 2 Assessment of PSM Changes of Important Users

1-11 the same with **Algorithm 1**
12: **for** u **do where** u is an important user node
13: ***pscount***(u) = 0 // ***pscount***(u) is the number of power supplies of the important user node u
14: **for** $i = 1 : n$ **do** // n is number of vertices
15: **if** ***reach***(u) == ***reach***(i) and u is a power supply node
16: then ***pscount***(u) = ***pscount***(u) + 1
17: **end if**
18: **end for**
19: **end for**
19: let $S_{PSM} = \varnothing$
20: **for** u **do where** u is an important user node
21: **if** ***pscount***(u) < ***pscount0***(u) // ***pscount0***(u) is the number of power supplies required for the reliability of u
22: **then** $S_{PSM} = S_{PSM} \cup \{u\}$
23: **end if**
24: **end for**
25: **if** $S_{PSM} = \varnothing$
26: **then** there is no risk
27: **else** calculate Idx_{PSM} ; there is a risk
28: **end if**

C. Integrated Power Flow Calculation Algorithm

DC power flow and sensitivity analysis are widely used in ORA because of their high efficiency [23, 24], but their accuracy is low. To ensure the accuracy of integrated power flow calculation, AC power flow method is still the basis.

On the other hand, as mentioned in Section I, the equivalent model and master-slave-splitting model are two common methods for I-T&D modeling, but they suffer from inaccuracy and divergence. In these two models. Also, they usually have some limitations when applied to DN with loops and distributed generations, multiple DNs, etc. Therefore, this paper proposes an integrated power flow calculation algorithm based on the global model and an improved Newton method, which can accurately analyze the coupling between TN and DN, and are applicable to various situations.

1) Initial Values Selection of Newton Method Based on Self-adaptive Levenburg-Marquard Method

The convergence of the Newton method is closely related to initial values. Particularly, large-scale I-T&D systems are usually seriously ill-conditioned, and inappropriate initial values will lead to divergence. Traditional initial values selection methods, such as Gauss-Seidel, suffer from low computational efficiency for large-scale I-T&D analysis. Thus, it is necessary to select appropriate initial values with as low as possible time complexity.

The self-adaptive Levenburg-Marquard method deals with the challenge of the ill-conditioned systems through solving the nonlinear least-square problems [25, 26]. Its essence is an optimization problem. Some researchers have applied this method to solve the ill-conditioned power flow. It shows powerful robustness but it has a larger amount of computation and slower convergence rate compared with the Newton method if it is used for a complete power flow calculation. By analyzing the convergence curve of this method, it has a steep curve at the first iterations, which indicates that the accuracy improves fast in these iterations. Making use of this feature, the method can be used for selecting initial values for the Newton method. The detailed steps of the self-adaptive Levenburg-Marquard method are shown in Appendix A.

Numerical experiments demonstrate that combining the self-adaptive Levenburg-Marquard method with traditional Newton method can achieve satisfying efficiency.

2) Assessment of Heavy Load/Overload and Voltage Deviation

According to the power flow results, heavy load/overload and voltage deviation risks can be assessed as follows.

Algorithm 3 Assessment of Heavy Load/Overload and Voltage Deviation

1: Power flow calculation
2: calculate $Idx_{HL/OL}$
3: **if** $Idx_{HL/OL} < H_{HL/OL}$ // $H_{HL/OL}$ is a security threshold
4: **then** there is no heavy load/overload risk
5: **else** there is a heavy load/overload risk
6: **end if**
7: calculate Idx_{VD}^{T} and Idx_{VD}^{D}
8: **if** $Idx_{VD}^{T} < H_{VD}^{T}$ and $Idx_{VD}^{D} < H_{VD}^{D}$ // H_{VD}^{T} and H_{VD}^{D} are security thresholds
9: **then** there is no voltage deviation risk
10: **else** there is a voltage deviation risk
11: **end if**

D. Graphics Processing Unit Acceleration

As mentioned before, I-ORA usually suffers from low computational efficiency, because the scale of ITD is very large. GPU acceleration measurements are proposed here to accelerate the proposed I-ORA algorithm.

1) The Parallelization of Integrated Topology Analysis under Different Contingencies

In I-ORA, connectivity test (Line 1-11 of Algorithm 1 and Algorithm 2) needs to be implemented under each contingency in the CS. The topology analysis under different contingencies is independent, which has natural parallelism. Thus, these problems can be parallelly processed with GPU.

Reference [27] gives an example to process a batch of topology analysis problems. It sets the number of enabled thread-blocks equal to the number of N-1 contingencies, and enable one thread in each block to process topology analysis for each N-1 contingency [27]. Like [27], Line 1-11 of Algorithm 1/Algorithm 2 is designed as a GPU kernel function in this paper, and the number of enabled thread-blocks is set to the number of the contingencies in the CS.

2) *The Parallelization of the Newton Method Based on the Self-adaptive Levenburg-Marquard method*

Many matrices are needed to form during integrated power flow calculation. When the system is large, calculating the elements one by one in a serial manner is time-consuming. Therefore, parallel acceleration is necessary.

The formation of Jacobian matrices has natural parallelism. It is usually a sparse matrix, which can be stored as a CSR form. The row deviation array, column number array, and value array all can be generated by GPU in parallel [28]. This paper also applies the CSR form for matrix storage. Since the Jacobian matrix will not be concatenated like [28], the numbers of enabled thread-blocks and threads in each thread-block are both set as the order of the Jacobian matrix. Thus, one element in the Jacobian matrix will be achieved with one thread.

Besides, matrix operations also have natural parallelism. When the data scale is large, GPU can realize acceleration for the matrix operations with intensive computation, including the matrix-vector multiplications in (A-5) and (A-9).

E. *Discussions and Extensions*

This paper proposes a combined method for integrated power flow calculation, where the self-adaptive Levenburg-Marquard method is adopted to determine initial values of the Newton method. Also, GPU is used to accelerate the method. To further enhance the efficiency of the method, especially in extremely large-scale systems, the parallelization of trial steps could be considered. In a sequential implementation of the method, as shown in Appendix A (A-6)-(A-7), during each step of this iterative process, if the trial step is unsuccessful, $\tau_k \leq p_0$, $\boldsymbol{X}$ is unchanged and a point closer to $\boldsymbol{x}_k$ will be examined. In practice, there are often some unsuccessful trial steps that slow down the convergence. Therefore, the trial steps could be parallelized by CPU multi-threading [29]. Each thread performs one search determined by α. In the k-th iteration, the first thread uses the value of α_k, the second thread uses the value of $s\alpha_k$, the third thread uses the value of $s^2\alpha_k$, and so forth. If at least one trial step is successful, accept one of these successful trial steps.

Besides, matrix preprocessing techniques can also be adopted to alleviate the numerical stability problems. As mentioned before, the Jacobian matrices in the integrated power flow calculation are usually seriously ill-conditioned. Choosing a proper preconditioner to preprocess these matrices may improve the spectral properties of them. Correspondingly, the convergence rate of iterative methods will be enhanced.

These above directions will be fully considered in our future work, to further improve the performance of IORA.

V. Numerical Experiments

This paper uses or constructs the cases CASE A-F for numerical experiments, as shown in the appendix. The programs are written in MATLAB R2015a and run on the Windows 10 of 64 bits. The CPU is Intel Core i7-7700K, with 4.20GHz master frequency and 32GB memory. The used GPU is NVIDIA GeForce GTX1080, supporting CUDA8.0. The maximum iteration times of the Newton method and the tolerance are set to 50 and 1e-4 p.u. respectively.

A. *Assessment of Substation Power Cut and Network Split*

This section compares the assessment results of traditional ORA for TN based on the equivalent model and I-ORA for I-T&D based on the global model. The CS consists of N-1 completed contingencies.

TABLE III
Assessment Test of Substation Power Cut and Network Split

Case	Method	Number of Substation Power Cut Risks		Number of Network Split Risks	
		135kV	23kV	135kV	23kV
CASE A	ORA for TN	3	0	1	0
	I-ORA	3	16	1	17
CASE B	ORA for TN	1	0	1	0
	I-ORA	1	1	1	1

As shown in TABLE III, there are some differences between the results. In ORA for TN, the DN is equivalent to constant loads, which indicates that substation power cut and network split of lower voltage level in the DN will not be discovered, and that is why the number of risks of 23kV in ORA for TN is 0. However, I-ORA can completely reflect the risks both in TN and DN. Besides, comparing CASE A and B, the conditions of interconnection switches will make difference for the topology of DN parts, so the numbers of risks of 23kV of CASE A and CASE B are different. According to TABLE IV, only I-ORA can accurately reflect the difference.

B. *Assessment of PSM Changes of Important Users*

This section uses CASE A to compare the assessment results. Without losing generality, all load nodes of the DN in CASE A are considered as 'important users', requiring duplicate supply. CS consists of N-1 completed contingencies. TABLE II shows the results under the situations of different interconnection switches closed. Node numbers in TABLE IV are all the numbers of DN nodes.

TABLE IV
Assessment Test of PSM Changes of Important Users

Closed Interconnection Switches	Number of Risks under ORA for TN	Number of Risks under IORA	Contingencies with CPSMIU Risks
5-11, 10-14	0	12	4-5, 4-6, 6-7, 8-9, 8-10, 9-11, 9-12, 13-14, 13-15, 15-16, 5-11, 10-14
5-11, 7-16	0	12	4-5, 4-6, 6-7, 8-9, 8-10, 9-11, 9-12, 13-14, 13-15, 15-16, 5-11, 7-16
7-16, 10-14	0	12	4-5, 4-6, 6-7, 8-9, 8-10, 9-11, 9-12, 13-14, 13-15, 15-16, 10-14, 7-16
5-11, 7-16, 10-14	0	1	9-12

As shown in TABLE IV, traditional ORA for TN cannot discover the PSM changes of important users in the DN, especially when considering the contingencies in the DN or the boundaries of TN and DN. On the contrary, I-ORA can accurately and completely find all the situations with risks of PSM changes of important users.

C. *Assessment of Heavy Load/Overload and Voltage Deviation*

Take CASE A and B for instance. TABLE V compares the assessment results under different N-1 contingencies. 'T' and 'D' before the node numbers are used to distinguish TN nodes and DN nodes. It is assumed that the voltage deviation limit of

TN nodes H_{VD}^{T} is 10%, and that of DN nodes H_{VD}^{D} is 15%. Meanwhile, it is assumed that the apparent power limit of branches in the TN is determined by the column named 'rateA' in the branch matrix of CASE 30 in MATPOWER, and that of branches in DN is set as 16MVA.

TABLE V
ASSESSMENT OF HEAVY LOAD/OVERLOAD AND VOLTAGE DEVIATION

Case & Contingencies	Branches of which apparent power is over the apparent power limit		Nodes of which voltage is over voltage deviation limit	
	ORA for TN	IORA	ORA for TN	IORA
CASE A Transformer T6-T9	T6-T8, T27-T29, T27-T30	T6-T8, T25-T26, T27-T29, T27-T30, D2-D8	T29, T30	T26, T29, T30, D9, D11, D12
CASE A Generation T27	T6-T8, T21-T22, T22-T24, T23-T24, T24-T25, T27-T29, T27-T30	T6-T8, T21-T22, T22-T24, T23-T24, T24-T25, T27-T29, T25-T26, T27-T30, T6-T28, D2-D8	T25~T27, T29, T30	T25~T27, T29, T30, D1~D16
CASE A Generation T2	T6-T8, T21-T22, T27-T29, T27-T30	T6-T8, T21-T22, T25-T26, T27-T29, T27-T30, D2-D8	T29, T30	T26, T29, T30, D9, D11, D12
CASE B Transformer T6-T9	T6-T8, T27-T29, T27-T30	T6-T8, T25-T26, T27-T29, T27-T30, D2-D8	T29, T30	T26, T30, D1~D16
CASE B Generation T27	T6-T8, T21-T22, T22-T24, T23-T24, T24-T25, T27-T29, T27-T30	T6-T8, T21-T22, T22-T24, T23-T24, T24-T25, T27-T29, T25-T26, T27-T30, T6-T28, D1-D4	T25~T27, T29, T30	T25~T27, T29, T30, D1~D16
CASE B Generation T2	T6-T8, T21-T22, T27-T29, T27-T30	T6-T8, T21-T22, T25-T26, T27-T29, T27-T30, D2-D8	T29, T30	T26, T30, D12

Three conclusions can be obtained from TABLE V: first, I-ORA can accurately analyze these two risks in DN parts but ORA for TN cannot; second, even for TN parts, there is a significant difference between assessment results from ORA for TN and I-ORA, because ORA for TN is based on the equivalent model and the equivalence leads to deviation; third, assessment results for CASE A and B are different in I-ORA while they are the same in ORA for TN, because ORA usually neglects loops in DN, which leads to inaccurate results.

D. Integrated Power Flow Calculation Algorithm Test

Three ill-conditioned I-T&D systems CASE D-F are used to test the performance of the proposed integrated power flow calculation algorithm. The Newton method (NM) with flat start, the Newton method based on the Gauss-Seidel (GS) method for initial values selection, and self-adaptive Levenburg-Marquard method (SALM) are taken as benchmarks. TABLE VI shows that the proposed algorithm has the best convergence performance and efficiency for all these three ill-conditioned systems.

Then, TABLE VII compared the proposed algorithm with the traditional power flow algorithms based on the equivalent model and the master-slave-splitting model with CASE G-I. Also, a comparison of voltage magnitude U_B, active power injection P_B, and reactive power injection Q_B at the boundaries are also shown in TABLE VII. To make it fair, three algorithms are processed in CPU in serial without GPU acceleration. But in the master-slave-splitting method, it is assumed that all DSOs work in a distributed manner, i.e. the time cost of DSOs is equal to that of the most time-consuming DSO in each iteration. Also, communication delays between TSO and DSOs are neglected.

The algorithms under the global model and the master-slave-splitting model can achieve accurate solutions, but the algorithm under the equivalent model cannot because the equivalent model neglects the network losses and the effect of distributed generation in the DNs. Besides, as shown in TABLE VII, the algorithm proposed in this paper has better convergence and efficiency than the algorithm based on the master-slave-splitting model. To be more specific, the latter will diverge in CASE H while the former still converge. Although these two algorithms can achieve the same accuracy in CASE G and CASE I, the latter requires many iterations and converges slowly. In the large-scale CASE I, even if DN power flow is calculated parallelly and communication delays between TSO and DSOs are neglected, the time consumption of the algorithm based on the master-slave-splitting-model is still around 8 times of that of the algorithm proposed in this paper.

TABLE VII
COMPARISON OF TIME CONSUMPTION AND ITERATION NUMBERS

Model	Results	Case G	Case H	Case I
This paper	Time /ms	3.8	4.2	7.9
	U_B /p.u.	1.0253	1.0190	0.9769, 0.9850, 0.9808, 0.9895, 1.0122, 1.0155, 1.0037, 1.0450
	P_B /MW	2.7328	3.2087	3.2314, 3.0583, 3.1912, 2.9420, 2.6768, 2.6778, 2.7176, 3.0535
	Q_B /MVar	3.3923	6.0261	-6.8510, -5.5863, -6.5788, -4.5520, 0.5308, 1.2640, -1.3394, 7.5793
Equivalent Model	Time /ms	3.0	3.6	3.7
	U_B /p.u.	1.0258	1.0258	0.9736, 0.9809, 0.9768, 0.9860, 1.0104, 1.0140, 0.9914, 1.0448
	P_B /MW	3.8022	3.8022	3.8022, 3.8022, 3.8022, 3.8022, 3.8022, 3.8022, 3.8022, 3.8022
	Q_B /MVar	2.6946	2.6946	2.6946, 2.6946, 2.6946, 2.6946, 2.6946, 2.6946, 2.6946, 2.6946
Master-slave-splitting Model [4]	Time /ms	62.6	-	62.3
	Iterations	16	Diverge	17
	U_B /p.u.	1.0253	-	0.9769, 0.9850, 0.9808, 0.9895, 1.0122, 1.0155, 1.0037, 1.0450
	P_B /MW	2.7328	-	3.2314, 3.0583, 3.1912, 2.9420, 2.6768, 2.6778, 2.7176, 3.0535
	Q_B /MVar	3.3923	-	-6.8510, -5.5863, -6.5788, -4.5520, 0.5308, 1.2640, -1.3394, 7.5793

E. Acceleration Effect Test

Fig. 5 compares the time cost of parallel and serial integrated

TABLE VI
INTEGRATED POWER FLOW CALCULATION ALGORITHM TEST

Case	NM with Flat Start		NM based on GS			SALM		The proposed algorithm		
	Iteration Times	Time Cost /ms	Iteration Times		Time Cost /ms	Iteration Times	Time Cost /ms	Iteration Times		Time Cost /ms
			GS	NM				LM	NM	
CASE D	Diverge	-	2	4	383.25	9	230.72	2	4	140.58
CASE E	Diverge	-	Diverge		-	13	690.88	5	6	510.75
CASE F	Diverge	-	Diverge		-	11	1413.14	1	6	705.17

topology analysis algorithms for CASE A-F. CS is assumed as N-1 complete contingencies. As shown in Fig. 5, GPU accelerates the computational efficiency of integrated topology analysis effectively. Generally, the larger scale of the system is, the larger the speedup ratio is. In specific, for the largest case-CASE C, the speed-up ratio is over 30 times.

Similarly, Fig. 6 analyzes the GPU acceleration effect of the parallelization of the proposed method, including the parallelization of formation of Jacobian matrix (JM) and the parallelization of matrix-vector multiplications in (A-5) and (A-9).

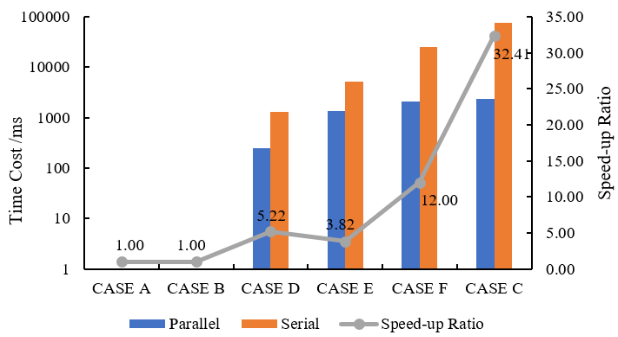


Fig. 5. The time cost of parallel and serial integrated topology analysis

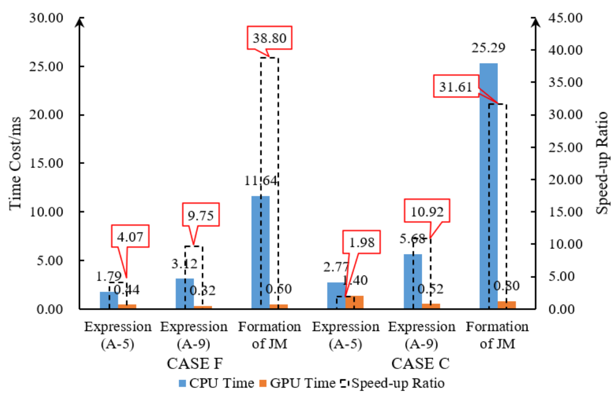


Fig. 6. GPU acceleration effect of the Newton method based on the self-adaptive Levenburg-Marquard method

Here, some readers may have concerns and believe that the master-slave-splitting method should be compared with the proposed method under the same GPU acceleration environment. Unfortunately, GPU parallel computing techniques will not bring a significant improvement in the efficiency of the master-slave-splitting method. This method is processed with alternating iterations between TSO subproblem and DSO subproblem [2]. Power flow is calculated once in each subproblem. So, the master-slave-splitting method is a logical and sequential algorithm. However, GPU is only suitable for cases that computation is intensive but with simple logic [28]. The logical and sequential steps can only be processed with CPU. Thus, enforcing the GPU to process the master-slave-splitting method will lead to a large quantity of data transfer between GPU and CPU, which is very time-consuming. Therefore, to make it fair, the master-slave-splitting algorithm is compared with the proposed algorithm processed serially in CPU, as presented in Subsection D.

VI. CONCLUSIONS

Based on the analysis of the necessity of I-ORA, this paper proposes an integrated topology analysis algorithm and an integrated power flow calculation algorithm to assess five types of risks. Through extensive demonstration in many cases, the following observations can be obtained:

- The proposed integrated topology analysis algorithm can accurately assess different types of risks, substation power cut, network split, and PSM changes of important users, particularly for the risks in DN parts in I-T&D. GPU acceleration effect is significant, and it can even reach 30 times speed-up ratio for some large systems.
- The proposed integrated power flow calculation algorithm can accurately assess risks of heavy load/overload and voltage deviation, particularly for the risks in DN parts in I-T&D. The core of the algorithm, an improved Newton method, has much better convergence than the Newton method with a flat start, especially for some seriously ill-conditioned systems.

Future work will extend the proposed methods to solve other problems in ORA of I-T&D, such as flexibility area estimation and risk handling according to the results of ORA.

APPENDIX A

SELF-ADAPTIVE LEVENBURG-MARQUARD METHOD

Taking polar coordinates as an example, the power flow equations can be expressed as nonlinear equations:

$$\boldsymbol{F}(\boldsymbol{X}) = \boldsymbol{0} \tag{A-1}$$

$$\boldsymbol{X} = [\boldsymbol{V} \quad \boldsymbol{\theta}]^{\mathrm{T}} \tag{A-2}$$

where $\boldsymbol{X}$ represents state variables of PF equations, $\boldsymbol{V}$ represents node voltage amplitude and $\boldsymbol{\theta}$ represents node phase. The detailed steps are as follows:

a) Set initial values of the state variables of PF $\boldsymbol{X}_1$(flat start), lower limit threshold of selection index p_0, upper and lower limit threshold of damping factor correction p_H, p_L, lower limit threshold of self-adaptive factor m, adjustment coefficient of self-adaptive factor s, the initial value of adjustment coefficient α_1 and convergence accuracy requirement of residual vector r. Set the number of iterations k = 1.

b) Calculate the damping factor in the k-th iteration λ_k:

$$\lambda_k = \alpha_k \left\| \boldsymbol{F}(\boldsymbol{X}_k) \right\| \tag{A-3}$$

c) Calculate correction $\Delta\boldsymbol{X}_k$ in the k-th iteration, where $\boldsymbol{J}(\boldsymbol{X}_k)$ represents JM in the k-th iteration.

$$\Delta\boldsymbol{X}_k = -[\boldsymbol{J}(\boldsymbol{X}_k)^{\mathrm{T}}\boldsymbol{J}(\boldsymbol{X}_k) + \lambda_k \boldsymbol{I}]^{-1}\boldsymbol{J}(\boldsymbol{X}_k)^{\mathrm{T}}\boldsymbol{F}(\boldsymbol{X}_k) \tag{A-4}$$

d) Calculate selection index τ_k:

$$\tau_k = \frac{\left\|\boldsymbol{F}(\boldsymbol{X}_k)\right\|^2 - \left\|\boldsymbol{F}(\boldsymbol{X}_k + \Delta\boldsymbol{X}_k)\right\|^2}{\left\|\boldsymbol{F}(\boldsymbol{X}_k)\right\|^2 - \left\|\boldsymbol{F}(\boldsymbol{X}_k) + \boldsymbol{J}(\boldsymbol{X}_k)\Delta\boldsymbol{X}_k\right\|^2} \tag{A-5}$$

e) Compare τ_k with p_0 to decide whether to accept the current iteration:

$$\boldsymbol{X}_{k+1} = \begin{cases} \boldsymbol{X}_k + \Delta\boldsymbol{X}_k & \tau_k > p_0 \\ \boldsymbol{X}_k & \tau_k \le p_0 \end{cases} \tag{A-6}$$

f) Adjust the self-adaptive factor:

$$\alpha_{k+1} = \begin{cases} s\alpha_k & \tau_k < p_L \\ \alpha_k & p_L < \tau_k < p_H \\ \max\{\dfrac{\alpha_k}{s}, m\} & \tau_k > p_H \end{cases} \tag{A-7}$$

g) If $\|\boldsymbol{F}(\boldsymbol{X}_k)\|_\infty < r$, go to Step h), otherwise $k = k + 1$ and go back to Step b).

h) Select $\boldsymbol{X}_k$ as initial values.

The parameters involved in the above algorithm is related to the convergence performance and computational efficiency, which should be determined by numerical experiments.

In the above algorithm, (4) is the closed-form solution of the following linear equations:

$$\begin{bmatrix} \sqrt{\lambda_k}\boldsymbol{I} & \boldsymbol{J}(\boldsymbol{X}_k)^{\mathrm{T}} \\ \boldsymbol{J}(\boldsymbol{X}_k) & -\sqrt{\lambda_k}\boldsymbol{I} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{X}_k \\ \dfrac{\boldsymbol{J}(\boldsymbol{X}_k)\Delta\boldsymbol{X}_k}{\sqrt{\lambda_k}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{F}_1(\boldsymbol{X}_k) \\ \boldsymbol{0} \end{bmatrix} \tag{A-8}$$

where

$$\boldsymbol{F}_1(\boldsymbol{X}_k) = -\frac{\boldsymbol{J}(\boldsymbol{X}_k)^{\mathrm{T}}\boldsymbol{F}(\boldsymbol{X}_k)}{\sqrt{\lambda_k}} \tag{A-9}$$

APPENDIX B

TABLE VIII
CASE INFORMATION

Case	Case Source / Construction Method
CASE I	Bus 30 of IEEE CASE 30 connects two CASE69 [30] DNs at Bus 1.
CASE II	Bus 3 of IEEE CASE 30 connects CASE118 DN at Bus 1. Boundary bus is named as A.
CASE A	The three feeders of the CASE 16 DN [31] connects Bus 26, 29 and 30 of CASE 30, respectively.
CASE B	Close all the interconnection switches in the DN in CASE A.
CASE C	Connecting IEEE CASE 118 TN with as many CASE69 DNs as possible. Here, 'as many as possible' means that as many DNs as possible are connected to TN at each node, but the total loads should not exceed the original loads of each node. In addition, loads of each node in TN should deduct the total loads of the connected DNs at this node, and all the interconnection switches are open.
CASE D	MATPOWER case – case3375wp
CASE E	MATPOWER case – case6515rte
CASE F	MATPOWER case – case13659pegase
CASE G	Bus 14 of IEEE CASE 14 connects one modified CASE 69 DN (three PV-typed distributed generations are accessed into Node 8, 15, 20 with active power 0.5MW)
CASE H	Bus 14 of IEEE CASE 14 connects one modified CASE 69 DN (two PV-typed distributed generations are accessed into Node 45, 61 with active power 0.5MW)
CASE I	Bus 5, 10, 13, 15, 16, 17, 18, 51 of IEEE CASE 57 respectively connect one modified CASE 69 DN (the same with the modified CASE 69 DN in CASE G)

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