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Distribution management system framework based on security region for future low carbon distribution systems

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Abstract In this paper, a new Distribution Management System (DMS) framework based on security region is proposed. First, the concept of Distribution System Security Region (DSSR) is introduced. DSSR is capable to describe the $N-1$ security boundary of the whole distribution network, including the secure output range of DGs. This new theoretic tool provides a chance for the implementation of real-time security analysis and active controls in DMS. Second, this paper proposes and describes five security states for distribution system. Third, an upgraded DMS enhanced with DSSR is proposed, which consists of advanced security functions such as preventive and predictive control of the trajectory of operating points. Finally, a practical case is presented to simulate the proposed DSSR-enhanced DMS, in which both the security region of network and the output range of DGs are calculated. Typical security functions are also demonstrated. In conclusion, the new DMS framework aims to help operate the system closed to its security boundary in order to improve the efficiency significantly within same security standard. This work is beneficial for future low carbon distribution systems with high penetration rate of DGs.

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1 Introduction

Climate change is recognized as one of the key challenges the world is facing in the 21st century. The measures of reduction of greenhouse gas emissions affect all economic sectors, but, due to its relevant emission levels, the electricity sector plays an important role in this strategy [1–3].

In the whole electricity power system, distribution system plays an important role in reduction of greenhouse gas emissions. On one hand, flexible network configuration and operation mode under distribution automation (DA) provide the great potential to improve operation efficiency and assets utilization resulting in less grid construction [4, 5]; on the other hand, smart grid introduces large amounts of renewable distributed generations (DG) into the distribution systems. These DGs produce far less CO_2 than traditional thermal power, and may reduce power losses [6–8].

However, DA and DGs also make the distribution network more complicated in operation. Efficiency and security is difficult to be balanced without proper management approach [4–7]. Although the problems aroused by DGs and electric vehicles have been studied in the research of Active Distribution Network (ADN) [8–11], on-line security assessment and control is rarely involved.

Distribution Management System (DMS) is an effective tool for operation. The traditional DMS has some defects in security control [12–14]:

1) Lack of preventive control approach. Traditional $N-1$ simulation cannot continuously offer the relative position of current operating points to security

boundary. Thus, dispatchers have not enough predictable information to make decisions [15].

2) Security analysis used only off-line. Traditional $N-1$ simulation needs repeatedly to perform power flow calculation on each component, which is time-consuming for on-line demand.
3) Low efficiency in asset utilization. With lower level of DA, load of faulted substation transformer can be only transferred in the same substation, which means that inter-connected medium-voltage network has not been fully utilized.
4) DG management. Output range of DGs is usually determined by voltages and frequency constraints. This decision method has not been analyzed under $N-1$ security guidelines from the whole system aspect.

A new proposed concept of Distribution System Security Region (DSSR) [16–18] may give new ideas for DMS to overcome the defects above. First, security boundary of a distribution system can be calculated off-line through DSSR theory, which describes the $N-1$ limit of a distribution system. Second, this boundary can be used as the criterion for fast security assessment, which provides a condition for on-line real-time security analysis. For instance, the information on security margins of each feeder can be obtained, thus, dispatchers can obtain the global information of the system by DSSR visualization technology to make effective preventive control decisions. Third, the security margin gives reference of DGs output range with consider of their contribution to system security. This paper applies DSSR to existing DMS to form a new framework focused on efficiency and security, which helps to operate the system closed to its security boundary.

At present, large-scale construction of distribution automation is undergoing in many urban areas in China, which will provide infrastructures for application of DSSR theory to DMS [4, 5]. A new DMS framework based on DSSR for future low carbon distribution networks is proposed in this paper. A practical case demonstrates the advanced security functions of future DMS.

2 DSSR theory for distribution network

The concept of DSSR originates from security region of transmission system [19]. The 'region' method can give systematic and global information about the feasible operation region, which has convinced advantages over the 'point-wise' method. It can provide operators with the relative location of a point in the region and other necessary operating information. Moreover, it can be calculated off-line and applied on-line to determine whether an operating point is secure [16], which can reduce computational burden of security assessment. The DSSR is defined as the set of all operating points that make the distribution system $N-1$ secure, which takes into account the capacity of substation transformers and feeders, network topology and operational constraints [16, 20]. According to [17], the DSSR model can be mathematically formulated as

$$\Omega_{DSSR} = \{\boldsymbol{W} | h(x) \le 0 \quad g(x) = 0\} \tag{1}$$

where $\boldsymbol{W} = (L_{F_1}, L_{F_2} \cdots L_{F_n})^{\mathrm{T}}$ is the operating point, and L_{F_i} represents the load of feeder i. The inequality and equality constrains is such that

$$t_{mn} + L_{F_n} \le r_n \ (\forall m, n) \tag{2}$$

$$T_{ij} = \sum_{m \in \Omega_1^{(i)}, n \in \Omega_1^{(j)}} t_{mn} \tag{3}$$

$$P_i = \sum_{m \in \Omega_1^{(i)}} L_{F_m} (\forall i) \tag{4}$$

$$T_{ij} + P_j \le R_j \ (\forall i, j) \tag{5}$$

where t_{mn} is the load that is transferred from feeder m to feeder n when an $N-1$ fault occurs at outlet of feeder m; r_n is the rated capacity of feeder n; T_{ij} is the load that is transferred from transformer i to transformer j when an $N-1$ fault occurs at transformer i; $\Omega_1^{(i)}$ is the set of feeders that derive from transformer i; P_i is all the load supplied by transformer i; $m \in \Omega_1^{(i)}$ means that feeder m derives from the corresponding bus of transformer i; R_i is the rated capacity of transformer i.

DSSR and its boundary have three characters [17]: 1) the security boundary is linear and composed of some hyperplanes, which can be fast calculated. 2) DSSR is dense inside. Thus, if the operating point is inside the DSSR, it is secure. Otherwise, it is insecure. Moreover, the location of an operating point in DSSR can be expressed as the distance from the operating point to all the security boundaries, abbreviated as SD (security distance). If SD is positive, the operating point is secure. Otherwise, it's insecure. The greater the positive SD is, the securer the operating point is. Also the greater the negative distance is, the more insecure the operating point is. 3) The dimension of the DSSR can be reduced to 2 or 3 by DSSR visualization technology, which makes the location of the operating points visualized. So operators can supervise the security state of the grid and the security margin of each direction conveniently [18].

Based on the model and characters above, real-time security monitoring can be performed. The location of the operating point in the DSSR can be adjusted to make it $N-1$ secure by adjusting the load distribution among substation transformers and feeders. The DSSR theory provides new tool for real-time security monitoring, assessment and control.

3 Division of security states

The security control of distribution system should establish a system similar to Dy Liacco security framework for transmission system, which can perform real-time monitoring, alarming, control and optimization. Thus, the distribution system can be decomposed into following operating states, as is shown in Fig. 1.

1) Secure state. The distribution system matches all operating constraints and passes all $N-1$ tests, which means that any single fault in primary feeders or substation transformers will lead to a service interruption in the faulted section only, and all the other affected loads will be restored immediately without violating any operating constraints. As for DSSR, the operating point is inside the boundary of DSSR.
2) Insecure state. The distribution system matches all operating constraints but cannot pass all the $N-1$ tests. As for DSSR, the operating point is outside the boundary of DSSR.
3) Secure and efficient state. Based on the secure state, the load distribution uniforms with the network structure and equipment capacity further and the security margin of each feeders and substation transformers is maximum and well-balanced.
   The three states above are normal, on which conditions the distribution system matches all operating constraints. While the following states are abnormal, on which conditions the distribution system doesn't match all operating constraints.
4) Emergency state. In this state, there exists fault, critical overload or overload duration exceeding the limit time.

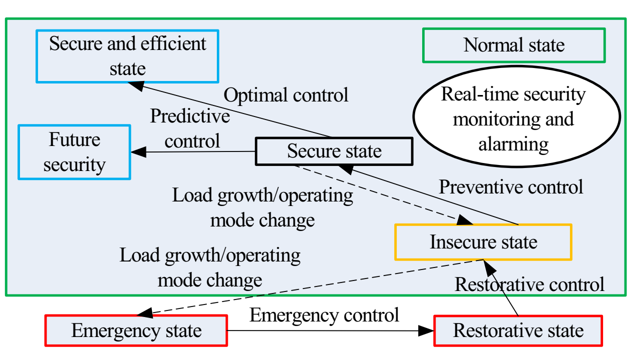

Fig. 1 Security states of distribution systems

5) Restorative state. The system situation is a transition to normal state after a series of power service restoration measures. Usually this is the aftermath of an emergency.

In Fig. 1, five security control approaches are also presented to describe the conversion of five states. The five control approaches are all proposed based on DSSR theory, and, the detailed function is discussed in section 4.

4 Framework with advanced security control

The paper expands new functions for DMS in advanced security control, of which framework is shown in Fig. 2.

4.1 Basic functions

The basic functions of the management system consists of real-time data acquisition, basic data reduction, topology analysis, network connection modes identification, state estimation, power flow calculation, short circuit calculation, short-term load forecasting, load management, reliability analysis, $N-1$ simulation and other traditional basic function. Moreover, we strengthen the basic functions with some new security analysis functions such as real-time security distance calculation, security boundary visualization and calculation of output range of DGs. The new security analysis approaches are explained in detail as follows.

1) Real-time security distance calculation. The minimum distance from the operating point to all the security boundaries and overall weighted distance are calculated based on real-time load data [16]. DSSR boundary can be calculated in advance based on the topology and without considering load information. Once the boundary is determined, simple SD calculation without power flow will be enough for security assessment.
2) Security boundary visualization. Operators cannot directly observe the locations of operating points in DSSR, because the entire security boundary is a hyperplane, of which dimensions is commonly high. To visualize the location of the operating point, dimension-reduction security boundary figures will be drawn. We first find out components failing in $N-1$ test and its relative components as variables so that the dimension of DSSR can be reduced to 2 or 3. With the dimension-reduction security boundary figures, operators can obtain security margins in each direction intuitively to perform security controls [17].
3) Security boundary of output range of DGs. The security distance of feeder loads can be used as

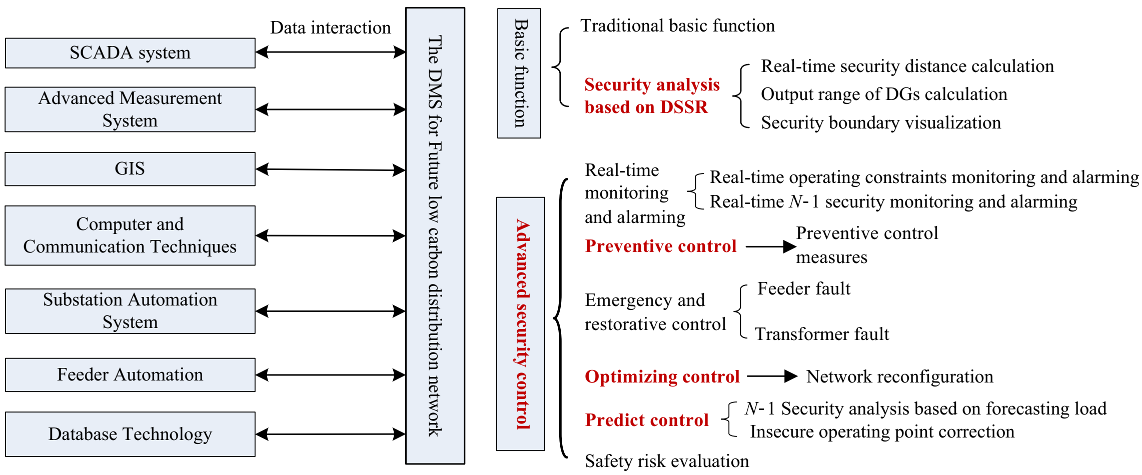

Fig. 2 The expansion of DMS framework with security functions

reference to determine the minimum output of DGs. Besides, the security region of DGs can be obtained, which is used to dispatch DGs' output limit.

New security analysis method based on DSSR is superior in calculation speed and it also can give operators more information about security operation, which is very suitable to be applied on line. Though the traditional $N-1$ simulation is time-consuming, it can discover the detailed data of $N-1$ contingency and form fault treatment measures. Meanwhile, the traditional $N-1$ simulation can verify the new security analysis approaches. These two methods are mutually complementary.

4.2 Advanced security control

1) Real-time monitoring and alarming. The problems and hidden threats would be monitored and alarmed based on real-time data in this function. Detailed procedures are conducted as follows.
   a) Real-time operating constraints monitoring and alarming. If any operating parameter is out of limits, operators should receive warnings and take measures immediately. It should be pointed out that $N-1$ criteria are not considered in this procedure.
   b) Real-time $N-1$ security monitoring and alarming. The previous procedure can't monitor hidden threats, which may lead to load shedding after a rational contingency. While this procedure can predetermine the DSSR boundary and calculate security distance online, by which operators can judge the system $N-1$ security. If the system is not secure, an alert message would be given. Meanwhile the $N-1$ simulation will be activated to find out the components not passing $N-1$ test and to obtain detailed fault data.
2) Preventive control. Once the system becomes insecure, the feeders or transformers, of which the security distance is negative, would be found out immediately through real-time monitoring and alarming. Then, $N-1$ simulation for these components will be activated. If necessary, dimension-reduction security boundary figures of these feeders or transformers will be drawn. Preventive controls will be taken according to the two results above. After the preventive control, the system becomes stronger when faced with any rational contingency.
3) Predictive control. Predictive control can help operators master the security development trend of the system and guide the system away from the dangerous operating region. First, the trajectory of operating points is tracked and forecasted in different time scales. Then, based on the load development trend and security distance calculation, security development trend is obtained. Finally, if the operating point is predicted to overflow the DSSR in the future, predict control will be implemented to correct its development trend. In other word, predict control ensures the system always operating inside the DSSR.
4) Optimizing control. Even if the operating point is secure, it could still be optimized further. When local network is heavy-load-carrying, hidden dangers for security operating such as little security margin, load disequilibrium and operating parameters that almost meet their limits would appear. Since these problems, optimizing control should be made, which resets open point of loop structure. By this way, load can be re-distributed well while maintaining enough security margins. Different from traditional model to optimize

nodal voltages and network losses mainly, the objective functions of the new optimizing control model also include security distance and load equilibrium.

5) Emergency and restorative control. When fault occurs at substation transformer, processing in the new management system would be different from traditional way. The traditional way is designed for current distribution automation. In tradition, auto-switch-on device would act immediately, so load of faulted transformer is firstly transferred to backup transformers in the same substation through bus connection switch. Here, overloading rate of the backup transformer less than 1.3 within limit time is permitted. And load should be transferred to other substations through linked feeders in 2 hours until the backup transformer is no longer overloaded. But if overloading rate is greater than 1.3, all load of faulted transformer would be cut off. Because overloading rate greater than 1.3 is usually considered too high and auto-switch-on device will lock itself automatically [18]. With large-scale distribution automation initiatives, transferring load among substations becomes much faster so that transformer overloading duration could decrease to minute level. Thus transformer can run with a higher loading level under the $N-1$ criteria. As for this management system, a maximum load capacity and security operation boundary considering the $N-1$ criteria can be calculated based on DSSR respectively, which can greatly improve system operation efficiency.

6) Safety risk evaluation. Probabilities of any single fault and security influences of faults are different. So precise safety risk evaluation takes fault probabilities, risk acceptances of users and operators into consideration. Based on the bearing degree of risks, the DSSR boundary would be expanded to exploit power supply potentiality of the distribution system. Moreover, the security level of the whole power network and key component can be evaluated and obtained by identifying different kinds of insecure factors and fault probabilities. Thus through selective equipment maintenance, fault probability and influence would be reduced. In other words, the risk would be managed. Meanwhile, safety risk evaluation also provides detailed information for reforming and programming the distribution network.

5 Case study

In this section, the proposed DSSR-based DMS is demonstrated on a real medium-voltage distribution system of one city in South China.

This system consists of 12 substations, 26 substation transformers and 114 feeders, as is shown in Fig. 3. Total capacity of substation transformers is 1094.5 MVA. All main feeders form single loop structure with a normally open switch; the whole medium-voltage network is completely upgraded with distribution automated (DA). The substation transformers and feeders are numbered in Fig. 3. T_i represents substation transformer i and F_i represents feeder i.

5.1 Calculation of DSSR boundary

The dimension of the operating point and the number of sub-formulas of DSSR boundary are both 114, because the feeder scale of the test case is 114. The expression for DSSR boundary [17] is calculated and shown in the Appendix.

5.2 Preventive control

Take the operating point W_A as an example. Security distances are calculated according to the method in literature [17], which is listed in Table B1 in the Appendix.

In the SD (security distance) calculation result, the number of negative SD is 4, and its corresponding feeders are F_8, F_{16}, F_{28} and F_{40}. Thus, W_A is insecure. The 4 feeders above and corresponding substation transformers (T_2, T_4, T_6, T_8) all fail to pass the $N-1$ test. Based on the topology, we obtain that the feeders with negative SD form link structure with the feeders of T_7 respectively, which means T_7 is the back-feed source for these feeders in the post-fault network. Therefore, overloading of T_7 could lead to the $N-1$ test fail. We visualize the 2D DSSR boundaries which describe the relationship of F_{36} (from T_7) and relative feeders, including F_8, F_{16}, F_{26}, F_{40} and F_{56}, as is shown in Fig. 4.

It is shown in Fig. 4 that W_A is out of the security boundaries B1-B4. For this problem, it is found that F_8, F_{16}, F_{28} and F_{40} can go back into the security region after reducing the load of F_{36}, which will cause outage of some loads. Then, we can reduce the F_{36} and increase F_{56}. F_{36} and F_{56} form a loop structure, among which load can be re-distributed via various selection of open-loop point, as is shown in Fig. 5.

As is shown Fig. 5, the load of F_{56} and F_{36} can be relocated by disconnecting switch K_6 and closing K_5. Then, load of F_{36} reduces to 5.500 MVA by 2.000 MVA, meanwhile, load of F_{56} increases to 4.000 MVA by 2.000 MVA. After these preventive controls, the operating point W_A outside the security boundary is adjusted to W_B, which is inside the security region. The data for W_B is shown in Table B3 in the Appendix and the operating point W_B passes the $N-1$ test.

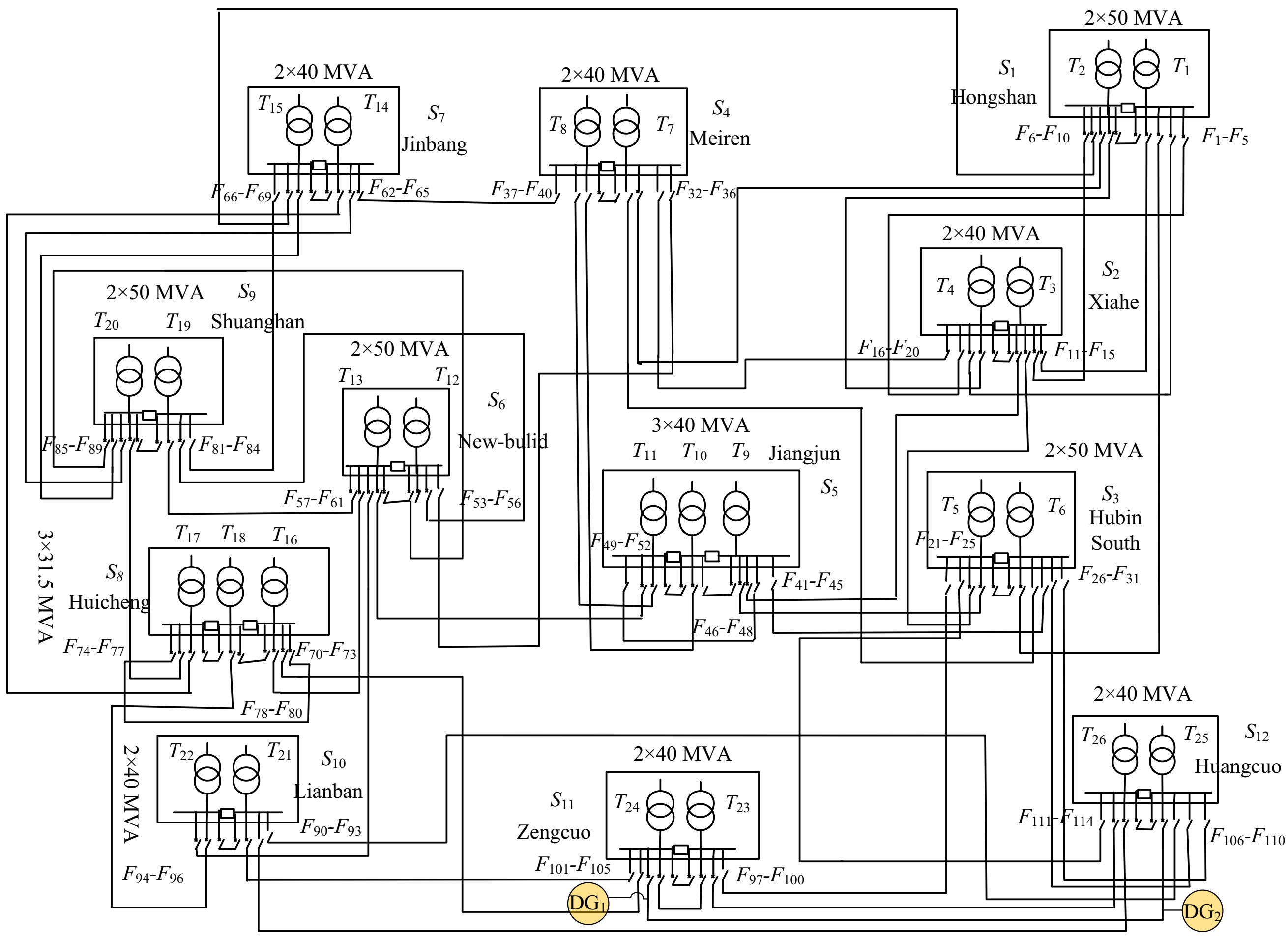

Fig. 3 Network configuration of a real system in a South China city

From Fig. 4 and Fig. 5, it can be seen that insecure operating point can be adjusted back into security region by re-distributing load in preventive control process.

5.3 Predictive control

Assume a practical event in summer workday peak load hours to illustrate the predictive control. W_C is the operating point of test case at 8:00 a.m. W_D is the operating point that W_C will operate to in the peak load at 14:00 p.m. W_D is 1.5 times of W_C in the quantity of each feeder load. By security assessment, W_D is an insecure point. To avoid the operating point outside the security region, dispatchers should adjust the W_C to $W_C{}'$ at 8:00 a.m., by which the insecure W_D will be adjusted to secure $W_D{}'$ at 14:00 p.m. The control above is based on such method: current operating point has effects on the future one, so measures for current operating point should be taken to induce the future one to the state with larger security margin.

A 3D DSSR section is shown in Fig. 6 to illustrate the control process above. Load profile, distance calculation

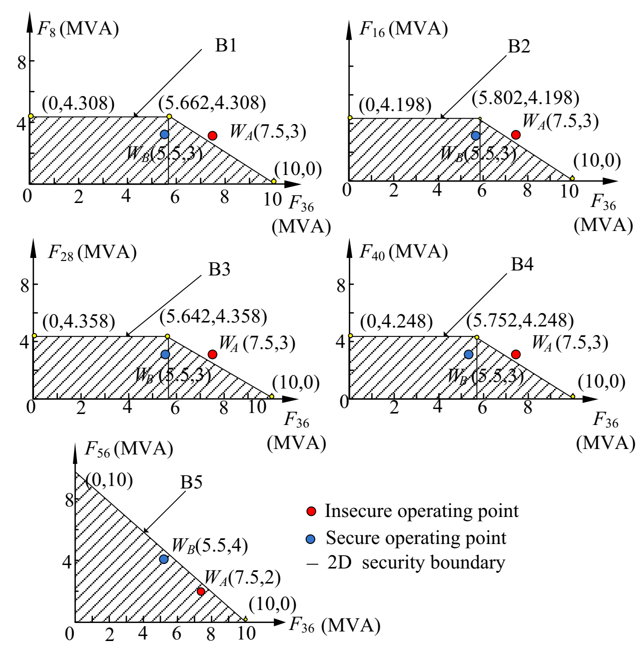

Fig. 4 The dimension reduction figure of security boundary

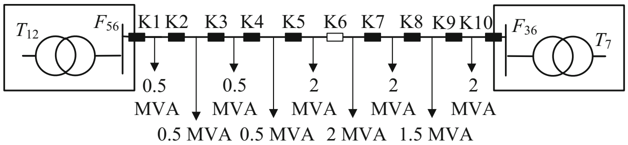

Fig. 5 Load re-distribution by network reconfiguration

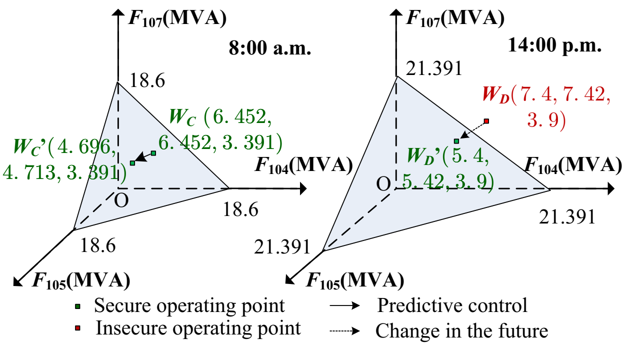

Fig. 6 Illustration of predictive control

and $N-1$ test result of operating points W_C, W_D, W_C', W_D' are shown in Table C1, Table C2 and Table C3 in the Appendix, the operating points W_C, W_C' and W_D' all pass the $N-1$ test, so $N-1$ security verification result tables are omitted.

5.4 Optimal control

In this section, we take the operating point W_E as an example, of which load distribution is unbalanced. Loading rate of T_2, T_7 and T_{24} is over-high and respectively reaches at 70%, 83.75%, 83.75%. Additionally, the load profile and distance calculation of operating point W_E are shown in Table D1 in the Appendix. Thus, some load should be transferred form high-ratio transformers to others. By this means, the load of system can fit with the network structure better, which optimizes the operation within security

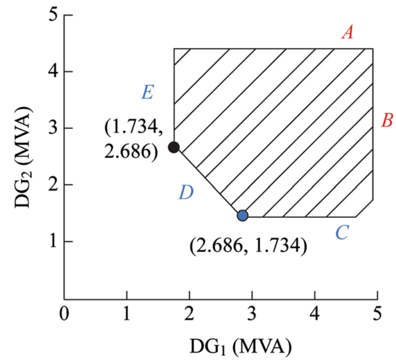

Fig. 7 Secure output range of DG_1 and DG_2

constrains. Here, W_E is adjusted to W_F by network reconfiguration. The complete load profile and distance calculation of W_F are shown in Table D2 in the Appendix. Table 1 shows the comparison before and after optimal control.

From the Table 1, we can see that the minimum distance security is increased and the load equilibrium of substation transformers and feeders is also improved to maintain enough security margins by optimizing control.

5.5 Secure output range of DGs

Take operating point W_F as an example, the complete load profile, SD calculation and $N-1$ test result of operating point W_F are shown in Table E1 and Table E2 in the Appendix. The system is insecure without enough DGs output under current operating point, 4 feeders and 3 substation transformers fail in $N-1$ test. To ensure the system security, output of DGs should be kept in a range, as is shown in Fig. 7.

In Fig. 7, boundary A and B represent the upper limit of DG_1 and DG_2. Boundary C, E represents the $N-1$ constrains. Boundary D represents the power flow constrain between two DGs.

Table 1 Comparison before and after the optimal control

Operating point	Equilibrium degree of feeder	Equilibrium degree of transformer	Sum of SD (MVA)	No. of negative SD
W_E	14.314	31.486	124.906	0
W_F	9.724	17.475	126.708	0

Operating point	Total load (MVA)	Minimum value of SD (MVA)	Number of failed feeder $N-1$ test	No. of failed transformer $N-1$ test
W_E	451.000	0.330	0	0
W_F	451.000	0.466	0	0

6 Features of new DMS based-on DSSR

Compared with traditional distribution automation, the new DMS has following features.

1) Regular distribution automation is passive and focused on the post-fault state. When faced with peak load, load shedding and power consumption limitation may often occur In contrast, solution in this paper is active and capable to monitor the hidden threats in advance and then to take necessary preventive or predictive controls to guarantee that loads can be transferred without violating any constraints in case of any $N-1$ contingency. In other words, these controls ensure that operating points are always inside the security region. Thus, the system security and reliability can be improved significantly.
2) The operation mode based on distribution automation is focused on local feeder automation and do not make full use of the connection between substations. So the secure loading level for substation transformers is conservative. The new operation mode based on the proposed management system makes full use of connection between substations. The new idea is to combine the network transfer capability and substation supply capability, which results in a higher loading rate and better assets utilization within the $N-1$ criteria.
3) As for security assessment, the existing approaches are based on $N-1$ simulation. This case by case simulation approach is inferior in calculation speed to be applied on-line in large-scale grid. The new operation mode based on security region can precisely predetermine the security boundary and assess security much faster, which makes real-time security monitoring possible.

The proposed extended DMS framework is conceptually similar to Dy Liacco security framework for transmission system. However, they are different in control strategies and methods. Compared to transmission system, distribution system has lower security requirements and cares about only static security instead of transient security. Meanwhile, Distribution system is constructed in closed loop but operates radially, while the transmission network operates in closed loop. These contribute to more complex security region in transmission system. Also, [18] shows that distribution security boundary is approximately linear. Thus, it is easier to calculate the secure distance, which results in more convenient to realize security monitor and control in distribution systems.

7 Conclusion

This paper proposes a new DMS framework based on security region for future active distribution systems under low carbon background. This new approach aims to upgrade existing DMS, featuring with following characteristics:

1) Preventive and predictive security controls are easy to implement and provide active operational capability for distribution systems.
2) On-line security analysis is available based on $N-1$ security region.
3) The output range of DGs in the system security boundary can be calculated.
4) Good economic benefit is gained through higher loading rate within same security standard.

A practical case is presented to illustrate the proposed DSSR-based DMS. The security region of both networks and DGs are calculated and the real-time security controls are demonstrated. It is shown that the new DMS framework can improve the efficiency and ensure the security of distribution systems.

This paper shows good prospects for the application of DSSR theory in future DMS. However, there are many works need to do, such as upgraded models and methods considering demand response and electric vehicles.

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Appendix

Please note that only the important data are listed because of the limited space. If you need more data, please contact with the authors.

Partial expression of security region boundary

$$B_{DSSR}=\begin{cases} L_{F_1}\leq \min[11.778-L_{F_{10}},50- \\ \quad (L_{F_6}+L_{F_7}+L_{F_8}+L_{F_9}+L_{F_{10}})] \\ L_{F_2}\leq \min[11.778-L_{F_{15}},40- \\ \quad (L_{F_{11}}+L_{F_{12}}+L_{F_{13}}+L_{F_{14}}+L_{F_{15}})] \\ L_{F_3}\leq \min[11.778-L_{F_{27}},50- \\ \quad (L_{F_{26}}+L_{F_{27}}+L_{F_{28}}+L_{F_{29}}+L_{F_{30}}+L_{F_{31}})] \\ L_{F_4}\leq \min[11.778-L_{F_{18}},40- \\ \quad (L_{F_{16}}+L_{F_{17}}+L_{F_{18}}+L_{F_{19}}+L_{F_{20}})-L_{F_5}] \\ L_{F_5}\leq \min[11.778-L_{F_{17}},40- \\ \quad (L_{F_{16}}+L_{F_{17}}+L_{F_{18}}+L_{F_{19}}+L_{F_{20}})-L_{F_4}] \\ L_{F_6}\leq \min[11.778-L_{F_{14}},40- \\ \quad (L_{F_{11}}+L_{F_{12}}+L_{F_{13}}+L_{F_{14}}+L_{F_{15}})] \\ L_{F_7}\leq \min[11.778-L_{F_{67}},40- \\ \quad (L_{F_{66}}+L_{F_{67}}+L_{F_{68}}+L_{F_{69}})] \\ \cdots\cdots \\ L_{F_{108}}\leq \min[10.566-L_{F_{93}},40- \\ \quad (L_{F_{90}}+L_{F_{91}}+L_{F_{92}}+L_{F_{93}})] \\ L_{F_{109}}\leq \min[11.778-L_{F_{30}},50- \\ \quad (L_{F_{26}}+L_{F_{27}}+L_{F_{28}}+L_{F_{29}}+L_{F_{30}}+L_{F_{31}})-L_{F_{110}}] \\ L_{F_{110}}\leq \min[11.778-L_{F_{31}},50- \\ \quad (L_{F_{26}}+L_{F_{27}}+L_{F_{28}}+L_{F_{29}}+L_{F_{30}}+L_{F_{31}})-L_{F_{109}}] \\ L_{F_{111}}\leq \min[11.778-L_{F_{22}},50- \\ \quad (L_{F_{21}}+L_{F_{22}}+L_{F_{23}}+L_{F_{24}}+L_{F_{25}})] \\ L_{F_{112}}\leq \min[10.566-L_{F_{99}},40- \\ \quad (L_{F_{97}}+L_{F_{98}}+L_{F_{99}}+L_{F_{100}})] \\ L_{F_{113}}\leq \min[10.566-L_{F_{92}},40- \\ \quad (L_{F_{90}}+L_{F_{91}}+L_{F_{92}}+L_{F_{93}})] \\ L_{F_{114}}\leq \min[10.566-L_{F_{106}},40- \\ \quad (L_{F_{106}}+L_{F_{107}}+L_{F_{108}}+L_{F_{109}}+L_{F_{110}})] \end{cases} \tag{6}$$

Table A1 Capacity of transformer links

Number of connected transformers	Number of feeder connections	Feeder capacity (MVA)
1–2	1	11.778
1–3	1	11.778
1–4	2	11.778
1–6	1	11.778
2–3	1	11.778
2–4	1	11.778
2–7	1	11.778
2–15	1	11.778
3–4	1	11.778
3–5	1	11.778
3–9	1	11.778
4–7	1	11.778
5–6	1	11.778
5–9	1	11.778
5–23	1	11.778
5–26	1	11.778
6–7	1	11.778
6–9	1	11.778
6–25	2	11.778
7–8	1	11.778
7–12	1	10.566
8–10	1	10.566
8–11	1	10.566
8–14	1	10.566
9–10	1	10.566
9–11	1	10.566
10–11	1	10.566
11–13	1	10.566
12–13	1	10.566
12–19	1	10.566
12–20	1	10.566
13–16	1	10.566
13–19	1	10.566
13–22	1	10.566
14–15	1	10.566
14–17	1	10.566
14–20	1	10.566
15–19	1	10.566
15–20	1	10.566
16–17	1	10.566
16–18	1	10.566
16–24	1	10.566
17–18	1	10.566
17–20	1	10.566
18–22	1	10.566
19–20	1	10.566
21–22	1	10.566
21–24	1	10.566
21–25	1	10.566
21–26	1	10.566
23–24	2	10.566
23–26	1	10.566
24–25	1	10.566
25–26	1	10.566

Table B1 Load and security distance of feeders before the prevent control

Number	Load (MVA)	SD (MVA)
F8	3.33	−0.830
F16	3.62	−1.120
F28	3.23	−0.730
F32	7.53	0.448
F33	7.42	1.128
F34	7.47	0.978
F35	7.58	0.578
F36	7.50	1.066
F40	3.80	−1.300
F56	2.00	0.500
…	…	…

Table B2 $N-1$ security verification of feeders and transformers before the prevent control

Number	$N-1$ result	Number	$N-1$ result
F8	0	F28	0
T2	0	T6	0
F16	0	F40	0
T5	0	T8	0

Note: Failed $N-1$ test of feeders and transformers are listed, but successful $N-1$ test for feeders and transformers are omitted

Table B3 Load and safety distance of feeders after the prevent control

Number	Load (MVA)	SD (MVA)
F8	3.33	0.978
F16	3.62	0.588
F28	3.23	1.128
F32	7.53	0.448
F33	7.42	1.128
F34	7.47	0.978
F35	7.58	0.578
F36	5.50	1.066
F40	3.80	0.448
F56	4.00	0.500
…	…	…

Table C1 Load and safety distance of feeders of working point W_C and W_D

Number	Load of W_C (MVA)	SD of W_C (MVA)	SD of W_D (MVA)
F101	6.435	2.288	1.046
F102	6.435	1.957	0.666
F105	6.435	2.653	1.466
F103	5.739	1.436	0.066
F104	6.452	2.723	1.546
F107	3.391	1.436	−0.120

Note: The load capacity of operating point W_D is 1.15 times of that of operating point W_C. Detailed load information of W_D is omitted

Table C2 $N-1$ security verification of feeders and transformers of operating point W_D

Number	$N-1$ result
F107	0
–	–

Table C3 Load and safety distance of feeders of operating point W_C' and W_D'

Number	Load of W_C' (MVA)	SD of W_C' (MVA)	SD of W_D' (MVA)
F101	6.435	2.288	1.046
F102	6.435	1.957	0.666
F105	4.696	2.653	1.466
F103	5.739	1.436	0.066
F104	4.713	2.723	1.546
F107	3.391	1.436	0.066

Note: The load capacity of operating point W_D' is 1.15 times of that of operating point W_C'. Detailed load information of W_D' is omitted

Table D1 Load and safety distance of feeders before the optimal control

Number	Load (MVA)	SD (MVA)
F1	3.12	0.658
F6	8.00	0.888
F7	8.03	0.628
F9	7.84	1.048
F10	8.00	0.658
F14	2.89	0.888
F16	3.12	1.368
F19	2.89	1.048
F28	3.03	1.748
F32	7.40	0.578
F33	7.00	1.748

Table D1 continued

Number	Load (MVA)	SD (MVA)
F35	7.30	1.358
F36	6.80	0.766
F40	3.80	0.578
F46	4.80	1.936
F47	5.20	1.566
F48	5.00	2.446
F56	3.00	0.766
F67	3.12	0.628
F72	3.00	0.566
F91	3.12	0.446
F97	3.04	0.330
F98	3.13	0.330
F101	7.00	0.446
F102	7.00	0.566
F103	7.00	0.536
F104	6.50	0.936
F105	6.00	1.526
F107	3.03	0.536
…	…	…

Table D2 Load and safety distance of feeders after the optimal control

Number	Load (MVA)	SD (MVA)
F1	5.12	0.658
F6	6.00	0.888
F7	6.03	0.628
F9	5.84	1.048
F10	6.00	0.658
F14	4.89	0.888
F16	5.12	1.368
F19	4.89	1.048
F28	5.03	1.748
F32	5.40	0.578
F33	5.00	1.748
F35	5.30	1.358
F36	4.80	0.766
F40	5.80	0.578
F46	5.00	1.736
F47	4.80	1.966
F48	5.20	2.246
F56	5.00	0.766
F67	5.12	0.628
F72	5.00	0.566
F91	5.12	0.446
F97	5.04	1.526
F98	5.13	0.936

Table D2 continued

Number	Load (MVA)	SD (MVA)
F101	5.00	0.446
F102	5.00	0.566
F103	5.00	0.536
F104	4.50	0.936
F105	4.00	1.526
F107	5.03	0.536
…	…	…

Table E1 Load and safety distance of feeders of W_F

Number	Load (MVA)	SD (MVA)
F97	2.05	−1.730
F98	1.76	−1.730
F99	3.89	2.476
F100	3.94	4.838
F101	7.34	2.206
F102	6.90	1.776
F103	7.56	−1.734
F104	8.8	0.006
F105	7.32	1.196
F106	3.12	4.516
F107	4.74	−2.66
F108	2.96	3.776
F109	2.29	6.638
F110	3	5.738
…	…	…

Table E2 $N-1$ security verification of feeders and transformers of W_F

Number	$N-1$ result
F97	0
T23	0
F98	0
T24	0
F103	0
T25	0
F107	0

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