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Multidimensional Coordinated Optimal Dispatching Method for AC/DC Hybrid Distribution Network

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Abstract

With the largely accessing of distributed generations (DGs) and electric vehicles (EVs), the phenomenon of bilateral power flow and unbalanced load between feeders become more and more obvious. In order to realize the safe, reliable, economical and efficient operation of AC/DC hybrid distribution network, this paper proposed multidimensional coordinated optimal dispatching method, and designed the optimal dispatching strategy in three dimensions. In sequential dimension, multi-sequential scale coordinated optimal dispatching framework based on Model Predictive Control was designed and optimal models and algorithms were proposed; in spatial dimension, hierarchical optimal dispatching model based on bi-level optimization was designed; in status dimension, status transition model of AC/DC hybrid distribution network was designed and generation method of the adaptive goal was presented. The architecture improved the absorption rate of DGs, promoted the optimal operation level, and enforced the efficiency of energy utilization. Finally, the application scenarios of multidimensional coordinated optimal dispatch were designed.

Key words

AC/DC hybrid distribution network, optimal dispatch, model predictive control, bi-level optimization, status transition model

1. Introduction

Distribution network is positioned in the end of power system, and faces to the users directly, which undertakes the responsibilities of electricity distribution, power consumption supplying and customer service [1]. With the largely accessing of distributed generations (DGs) and electric vehicles (EVs), the phenomenon of bilateral power flow and unbalanced load between feeders become more and more obvious. Active distribution network [2] was put forward to solve the intermittent and fluctuations of DGs, and the rapid development of electric and electronic technology provided the solution for impact loads, such as EVs, so AC/DC hybrid distribution network became the main form of future distribution network. AC/DC hybrid distribution network could not only consume the clean energy, and also improve the capacity and reliability of power supply, and reduce losses. How to realize the optimal dispatch of AC/DC hybrid distribution network, which could improve the absorptive capacity of DGs, reduce the effects of impact loads and improve the quality of power supply, is an important research project [3].

Domestic and foreign experts studied the optimal dispatch for power distribution network from different ways. EPRI researched new energy resources modeling, parameter identification, and simulation tool, developed the distribution fast simulation modeling(DFSM) and proposed distributed autonomy real-time schema (DART)[4]; Sweden Royal Institute of technology in-depth researched AC/DC hybrid micro-grid containing AC grid, energy storage, and distributed generation, analyzed the several work mode and proposed controlling program of multi-mode conversion[5]; Denmark Aalborg University researched the controlling strategy of AC and DC energy exchange way in the AC/DC hybrid micro-grid[6]; literature [7] built AC/DC hybrid distribution network, and connected five different forms of energy router as flexible interconnected device in different position, and studied the various of operation modes; the author proposed architecture of multi-source coordinated optimal dispatch for active distribution network, and designed the optimal dispatching model taking into account the spatial and sequential scale characteristics[8].

Research status shows that abroad experts used fast simulation technology for cooperative control of DGs and flexible loads by real-time online monitoring and short-term load forecast [9]; domestic experts researched distributed power access, micro-grid system, EVs' charging facilities, and distribution automation independently, and designed the grading model, control schema, optimal target and coordination strategy. At present, there were some achievements in optimal dispatch of distribution networks in the research phase, but the research of optimal dispatch in the

AC/DC hybrid distribution network based on flexible DC facilities (energy router) was seldom involved.

Based on the existing research achievement, and considering various controllable resources, such as DGs, energy storage facility, flexible loads, flexible DC facilities, and their spatial and sequential characteristics, this paper designed optimal dispatching strategy in three dimensions of time, space and status, and put forward the dispatching model and optimal algorithm in every dimension, in order to improve the accommodation rate of DGs, and upgrade the optimal operation of distribution network.

2. Multidimensional coordinated optimal dispatching strategy for AC/DC hybrid distribution network

The optimal dispatching goal of AC/DC hybrid distribution network is to optimize the output of controllable resources, such as flexible DC facilities, DGs, flexible loads and energy storage facilities, and to improve the safety, reliability, high-quality, economy and friendliness, finally, confirm the efficient operation of AC/DC hybrid distribution network [10-12].

The optimal dispatching need to consider the physical hierarchy and operating status, and spatial and sequential characteristics of flexible DC facilities, DGs, flexible loads and energy storage facilities, on this basis, designed the optimal dispatching goal from three dimensions in time, space and status, to form uniform multidimensional coordinated optimal dispatching strategy, and support the optimal dispatch of AC/DC hybrid distribution network. The optimal dispatching strategy was as Fig. 1.

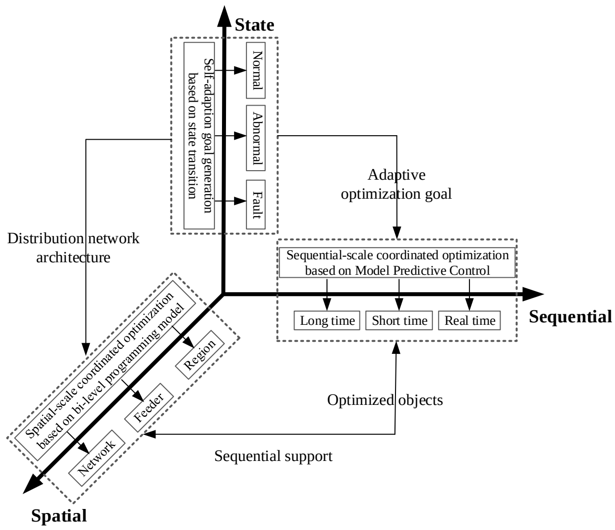

Fig.1. Multidimensional coordinated optimal dispatching strategy of AC/DC hybrid distribution network

In sequential dimension, according to the spatial and sequential characteristics of controllable resources, design the multi-sequential coordinated optimal dispatching architecture based on model predictive control (MPC), to realize the coordinated optimization of long-time scale, short-time scale and real-time scale; in spatial dimension, according to the physical gradation of distribution network, design the hierarchical optimal dispatching model, to realize the coordinated optimization of distribution network, feeder and region; in status dimension, according to the operation status of distribution network, design status transition model, to generate the adaptive goal.

The operation status provides the operation mode for optimization in spatial dimension, and provides the adaptive goal for optimization in sequential dimension; bi-level coordination provides the optimal objects for optimization in sequential dimension; multi-sequential coordination provides the sequence support for optimization in spatial dimension.

3. Multi-sequential coordinated optimal dispatch based on MPC

3.1 Model predictive control

Model predictive control (MPC) is also called receding horizon control. MPC could solve the problem with uncertain structure, parameters and environment, time-variable, and nonlinear in the industrial process control. MPC didn't require much in the model, but could achieve the optimal control, so it was popularized and applied in industrial control [13]. The core idea of MPC is: at time K, the current measuring status is sampled and the future status in limited periods is taken into account, by minimization of controlling constraint and the objective function, calculate current and future in limited periods optimal control variables. MPC could be realized in different algorithm, while they all contain three major components: prediction model, receding optimization and feedback correction.

(1) Prediction model: according to the historical information and future input, predicate the future response. Prediction model only paid attention to the function of model, not the form of model, so it could be divided into parametric model and nonparametric model [14].

(2) Receding optimization: MPC adopted receding horizon control strategy, that is, in every sampling moment, calculate the optimal control sequence of future limited periods according to the performance index from the moment. To prevent the control errors because of model mismatch and environment disturbance, just execute the current value, and the optimal control rate would be recalculated in the next sampling moment.

(3) Feedback correction: the prediction based on MPC would not stay the same with actual controlled process because of the uncertainty, time-variable, nonlinear in the industrial process control. So it needs to amend the prediction based on MPC with the actual measurement in every sampling moment, and then begin the next optimal period, to make the receding optimization not only use the model, but also use the feedback information, and form the closed-loop optimization.

3.2 Multi-sequential optimal dispatching architecture

To solve the contradiction of economy, safety and rapid response in the optimal dispatch of AC/DC hybrid distribution network, and the problem of unreasonable open-loop optimization in the case of imprecise prediction for wind turbine, PV and loads, this paper proposed multi-sequential optimal dispatch architecture based on MPC for AC/DC hybrid distribution network, which combined MPC with multi-sequence, showed as Fig. 2. The optimal dispatch in sequential dimension referred to long-time scale and short-time scale, and real-time scale only replied to emergency, not carried optimal dispatch.

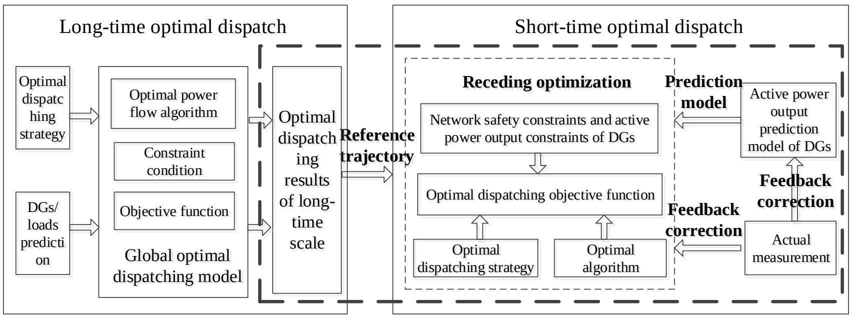

Fig.2. Multi-sequential optimal dispatching architecture based on MPC

In long-time scale: firstly, in the basis of power topology structure, divide the DGs which were intensive distribution and small capacity, into a autonomy region, and make the region equivalent to a DG to calculate its supply and storage capacity in the condition of power quality and security constraints; secondly, in the basis of region supply and storage capacity, considering the constraint condition of active power upper and lower bounds, network safety and other constraints, build global optimal dispatching objective function with the optimal goal of economy and safety, and calculate the optimal power flow with prime-dual interior point method; thirdly, calculate the long-time scale optimal dispatching results by optimal power flow, store and issue for the reference values of short-time scale optimal dispatch.

In short-time scale: amend the long-time scale optimal dispatching results using closed-loop receding optimal algorithm based on MPC. At first, according to the characteristics of DGs, build DGs' active power output prediction model, and predict the active power output tends in the limited periods; then referring to the optimal dispatching results issued by long-time scale, build secondary optimal performance index with the optimal goal of smallest amending offset; finally, build the feedback correction model according to actual measurement, and amend optimal results in every receding periods, to reduce the offset caused by environmental disturbance.

3.3 Multi-sequential optimal dispatch model based on MPC

In long-time scale, optimal dispatching model adopts minimum dispatching cost of active power for AC/DC hybrid distribution network, as follows:

$$\min F = \min \sum_{t=1}^{T_l} \{ c_{grid}(t) P_{grid}(t) + \sum_{i=1}^{m} C_{loadi}(t) + \sum_{j=1}^{NS} C_{storj}(t) + \sum_{k=1}^{NG} C_{DG}(t) \} \tag{1}$$

where T_l is dispatching period of long-time scale; m, NS, NG are the number of flexible load, energy storage facility, controllable DGs respectively; $c_{grid}(t)$ is time-of–use price; $P_{grid}(t)$ is the active power with the main link; $C_{loadi}(t)$ is the dispatching cost of flexible load; $C_{storj}(t)$ is the dispatching cost of energy storage facility; $C_{DG}(t)$ is the dispatching cost of controllable DGs.

Optimal dispatch based on MPC selects receding predictive values of intermittent DGs as input variables, actual measurement of controllable DGs as initial value $P_o(k)$, DGs' active power increment of future limited periods as control variables, to achieve receding optimization in future limited periods.

Optimal goal of short-time scale is to track the optimal results of long-time scale, and make the amending offset smallest, so the optimal performance index of short-time scale is as follows:

$$\min J(k) = \sum_{i=1}^{N} \| P(k+i|k) - \tilde{P}(k+i) \|_Q^2 = \sum_{i=1}^{N} \| P_o(k) + \sum_{t=1}^{i} \Delta u(k+t|k) - \tilde{P}(k+i) \|_Q^2 \tag{2}$$

where $\tilde{P}(k+i)$ is the reference of active power at time $k+i$, $P(k+i|k)$ is the predictive active power output of controllable DGs in future $k+i$ at time k, $\Delta u(k+i|k)$ is the predictive active power output variation of controllable DGs in future $k+i$ at time k.

4. Hierarchical optimal dispatch based on bi-level optimization

4.1 Bi-level optimization theory

Bi-level optimization theory is optimal method based on game theory. By dividing the optimal problem into higher level and lower level, it could reflect the profit of both levels, and the model of higher level and lower level obeys master-slave relation [15]. The general type of bi-level optimization is as follows:

$$\min_{x} F(x,y) \tag{3}$$

$$s.t. \quad Q(x,y) \le 0 \quad H(x,y) = 0 \tag{4}$$

$$\min_{y} f(x,y) \tag{5}$$

$$s.t. \quad q(x,y) \le 0 \quad h(x,y) = 0 \tag{6}$$

where F , H , Q , x are the objective function, equality constraint, inequality constraint, decision variable of higher level respectively; f , h , q , y are the objective function, equality constraint, inequality constraint, decision variable of lower level respectively.

In the bi-level optimization, higher level controls and affects lower level by decision variable x , while lower level makes decision according to x delivering by higher level, and forms the optimal response y to higher level, who could obtain the feedback, and then confirm the optimal results. For bi-level optimal model, optimal results of higher level depend on the optimal variables and the optimal solution from lower level, and optimal results of lower level are limited to optimal variables from higher level, that is, by associated variables, higher level and lower level need to keep the iteration until the optimal results of both levels are calculated.

4.2 Hierarchical optimal dispatching architecture

According to the operating characteristics of distribution network, considering that a huge number of DGs, energy storage facilities, flexible loads and flexible DC facilities are accessing to distribution network, optimal dispatch of AC/DC hybrid distribution network is divided into distribution network, feeder and region in spatial dimension. Region is divided automatically aiming at autonomy, and feeder is combination of several regions, and interconnection of feeders by flexible DC facilities forms distribution network, controlled objects are set optimal goal and dispatching strategies respectively in every level. Optimal dispatch in spatial dimension is to realize the coordination of distribution network, feeder and region by uploading information in the basis of dispatching capacity and given information in the basis of optimal results, and hierarchical optimal dispatching architecture was showed as Fig. 3.

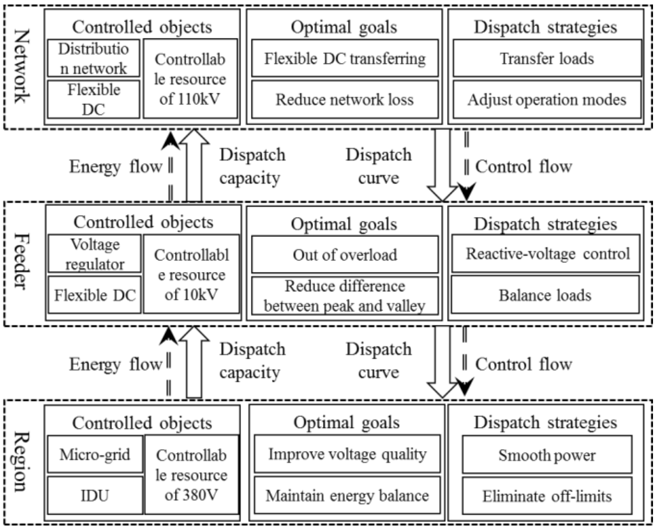

Fig. 3. Hierarchical optimal dispatching architecture of AC/DC hybrid distribution network

4.3 Bi-level optimal dispatching model

Hierarchical optimal dispatch of AC/DC hybrid distribution network is typical multi-level optimal problem, in the following, bi-level optimal dispatching model will be built for coordinated optimization of feeder and region.

Optimization of feeder considers dispatching cost of controllable resource, and builds the objective function of minimum active power loss for optimal period, the model is as follows:

$$\min F_1 = \sum_{t=1}^{T} P_{\text{loss}}(\text{t}) + \alpha' \sum_{\eta=1}^{\eta_n} C_{s\eta}(\text{t}) \tag{7}$$

Where the whole optimal period is divided into T_l section; $P_{\text{loss}}(t)$ is the active power loss of AC/DC hybrid distribution network; $C_{si}(t)$ is the dispatching cost of region i; η_n is the number of regions; α' is the penalty coefficient. Optimization of feeder considers the dispatching cost of regions to obtain the region exchanging power of both economy and power constraints, not to dispatch for regions.

The constraint conditions of feeder optimization contain: power balance constraints, voltage upper and lower limits constraints of AC nodes, voltage and current upper and lower limits constraints of flexible DC facilities, and so on.

Optimization of region is to make the dispatching cost lowest, containing controllable DGs, flexible loads, energy storage facilities, and its model is as follows:

$$\min F_2 = \sum_{t=1}^{T}\sum_{i=1}^{N_R} C_{DGi}(t) \tag{8}$$

$$C_{DGi} = c(\mathrm{t})\,\mathrm{P}_{DGi}(\mathrm{t})^2 \tag{9}$$

where N_R is the number of controllable resources in the region; C_{DGi} is the dispatching cost of flexible load i; $c(\mathrm{t})$ is the coefficient of dispatching price, which is different for various controllable resources; P_{DGi} is the active power output of controllable resources in the region.

The constraint conditions of region optimization contain: power balance constraints, voltage upper and lower limits constraints of AC nodes, exchanging power constraints of region connecting line, minimum and maximum output constraints of controllable DGs, and so on.

5. Adaptive optimal dispatch based on status transition mode

5.1 Status transition mode of AC/DC distribution network

According to the operating characteristics and optimal dispatching requirements of distribution network, its operating status were defined for 4 types: failure status, abnormal status, normal status and optimal status, the typical feature of various status were:

Failure status: distribution network is failure, and begins isolated island operation or power outage;

Abnormal status: voltage is out of limit, power is overload, power quality is below standard, and exists risk of load shedding;

Normal status: all loads are normal operation, not exist voltage out-of-limit and power overload, but utilization of DGs and difference between peak and valley could be improved;

Optimal status: distribution network is normal operation, and exists a large safety margin, at the same time, DGs are absorptive fully, and power supply is satisfied absolutely.

Optimal dispatching goal of AC/DC hybrid distribution network is to prompt the operation to optimal status, and make the distribution network safety, stabilization, efficiency and economy. Status transition mode of all status are showed as Fig. 4.

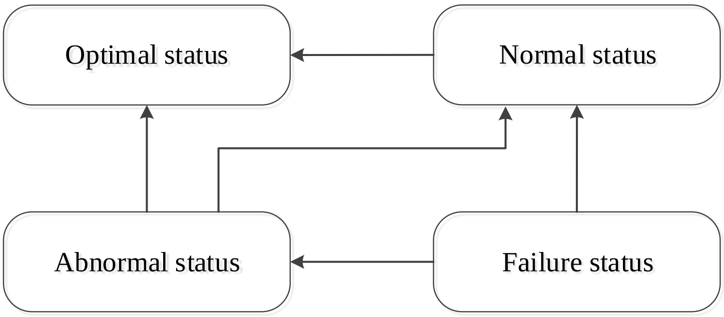

Fig. 4. Status transition mode of AC/DC distribution network operation

5.2 Adaptive optimal goal generation

According to the status transition mode of AC/DC hybrid distribution network, in order to prompt operation status of distribution network to optimal status, optimal dispatching strategy library is designed for different operating status, sequential scale and spatial scale, to support the adaptive optimal goal generation. Optimal dispatching strategy of normal, abnormal and failure status are showed as Tab. 1-Tab. 3.

Tab. 1. Optimal dispatch strategy of normal status

	Long-time scale	**Short-time scale**
Network	① Reconstruct network and optimize network operation; ② Generate optimal dispatching plan in distribution network level.	① Update optimal dispatching plan of long-time scale; ② Generate dispatching plan considering temporary electricity interruption.
Feeder	① Improve voltage quality by switching reactive power compensation device and capacitor; ② Eliminate out-of-limit power, and balance the feeder energy.	① Smooth active power fluctuation of feeder; ② Make sure voltage stabilization of feeder.
Region	① Maximize the elimination of DGs; ② Realize coordinated optimization of power sources and loads in the region.	① Make sure energy balance of region; ② Improve voltage quality of region.

Tab. 2. Optimal dispatch strategy of abnormal status

	Long-time scale	**Short-time scale**
Network	① Calculate spinning reserve rate, and warn the abnormal status.	① Warn the abnormal status of out-of-limit frequency and exchanging power oversize of connecting line.
Feeder	① Calculate voltage stability margin with predicted data, and warn the abnormal status.	① Warn the abnormal status of out-of-limit voltage and voltage fluctuation oversize of feeder; ② Transfer loads using flexible DC facilities.
Region		① Handle the abnormal facilities in the region.

Tab. 3. Optimal dispatch strategy of failure status

	Long-time scale	**Short-time scale**

Network		① Locate the position of failure and separate it rapidly; ② Control in sequence with section switch, execute network reconstruction and power restoration.
Feeder		① Transfer loads using flexible DC facilities.
Region		① Locate the position of failure, separate it and execute island operation.

6. Application scenarios designing

6.1 Scenario 1: Reduce valley-to-peak and shift peak load

Power supply and demand are imbalance in when the power is peak of in summer, and main goal of dispatching will is reduce reducing loads by connecting line. In order to respond to the main dispatch goal, distribution network needs to reduce peak loads according to their own circumstances. Dispatch of distribution network will send down the peak clipping to every feeder considering the distribution of DGs and flexible loads, and feeders break the demand down to every region. The process of peak clipping is shown as Figure 5. The inverse process is executed when electricity demand is low.

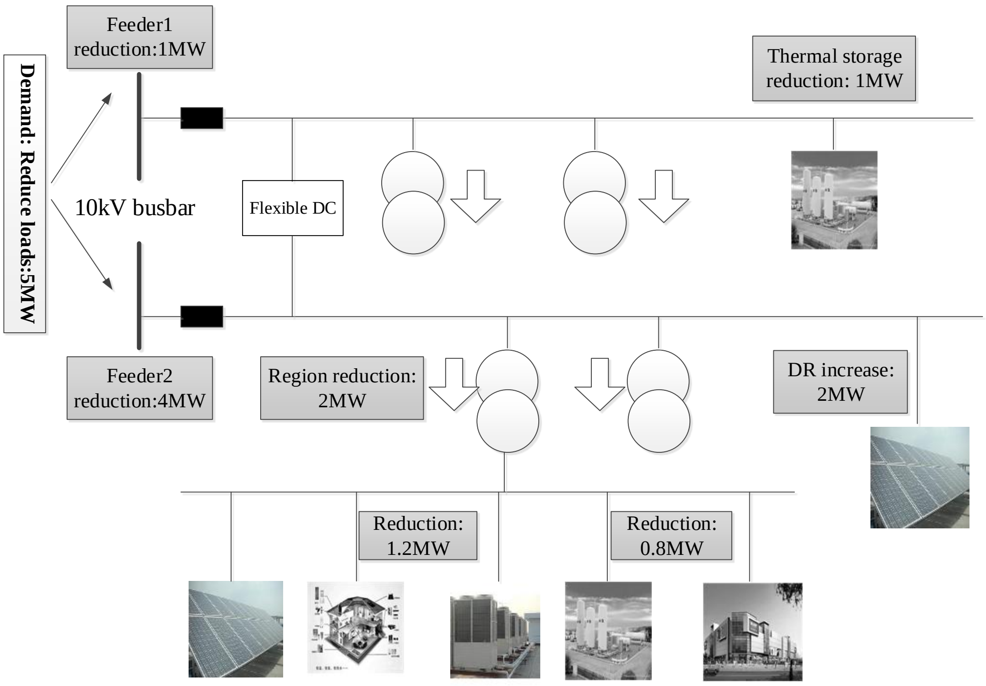

Fig. 5. Cut the peak load by increasing energy and decreasing load

6.2 Scenario 2: Reduce device overload and network loss

According to the operation characteristic of distribution network, part of lines will overload on-peak demand, it needs to take steps to regain the normal status from abnormal status. Figure 6 showed a feeder of 10kV, whose overloading rate was 95%, it need to reduce 2MW loads by transferring loads with flexible DC facilities, increasing outputs of energy storage facilities, and reducing power loads on demand side.

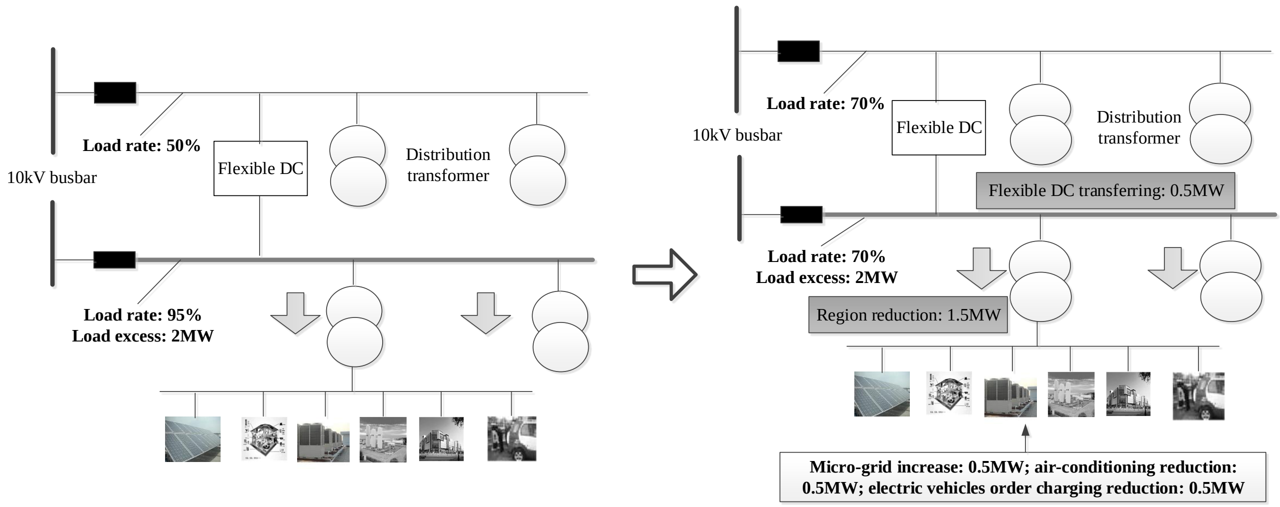

Fig. 6. Reduce the rate of equipment overload and line loss by AC/DC device and controllable resource

7. Discussion

As the wind turbine, PV, energy storage facilities, flexible DC accessing, distribution network becomes active, and the power flow becomes bidirectional. The dispatching of distribution network faces with the following challenge: various distribution resources have different time response characteristics, and the control strategy is different to them; distribution networks have complex structure and a huge number of controllable elements, at the same time, it's hierarchical with the voltage classes; distribution network has different operating status and it needs to adopt different dispatching strategy for various status. In order to satisfy the challenges, this paper proposed the optimal dispatching method to solve the dispatching problems of distribution network from sequential, spatial and status dimensions.

The proposed optimal dispatching method is suitable for distribution network with all kinds of distributed resources. As fundamental and perspective research area, the paper designed the potential application scenarios for the theory to describe the application of the optimal dispatching theory. The designing principle of application scenarios include: add several kinds of distributed resources and flexible DC facilities to the traditional distribution network; capacity of one feeder is over the loads and it needs to transfer loads by flexible DC facilities; peak loads are far more than the average loads, even reach the capacity of facilities.

The application scenarios showed that it could stabilize the volatility of distributed resources to improve the power quality, transfer loads of heavy lines to reduce device overload and network loss, cut peak loads and fill valley loads to reduce the investment of distribution network.

8. Conclusion

To face with the dispatch problems in AC/DC hybrid distribution network, this paper put forward the optimal dispatch method for AC/DC hybrid distribution network, designed optimal dispatch strategy in three dimensions of time, space and status, researched multi-sequential coordinated optimal dispatching method based on MPC, hierarchical optimal dispatching model based on bi-level optimization and generation method of the adaptive goal based on status transition model, finally, designed application scenarios to discuss the application of multi-source coordinated optimal dispatch. While authors just proposed the solution of optimal dispatch of AC/DC hybrid distribution network, in the following research, the optimal dispatching details of time, space and status dimensions, and the coordination of every dimension will be the important directions.

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