Optimal Configuration of Hybrid AC/DC Urban Distribution Networks for High Penetration Renewable Energy

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Abstract: Existing AC medium voltage distribution networks are facing challenges on handling increasing loads and renewable energy integrations. However, it is very difficult to build new distribution lines in urban areas. This paper proposes a configuration method of hybrid AC/DC medium voltage distribution networks, in which some existing AC lines are converted to DC operation. Existing topologies and dispatching scenarios are considered during configuration because the overall power flow can be rescheduled in the hybrid AC/DC distribution network. Therefore, transfer capacities of the lines are fully utilized, and more renewable energies are accommodated. A bi-level programming model is established embedding chance constraint programming to consider the intermittent output of renewable energy. In the upper level, a multiple objective optimal model is proposed in order to balance investments, power losses, and the maximum load level and renewable energy capacity. In the lower level, daily operations of the newly installed VSCs are optimized by a chance constraint programming. The influences of energy storage systems on the configuration are also analysed. Simulations studies are performed to verify the proposed method.

1. Introduction

Loads in urban areas are concentrated and fast increased. However, existing AC distribution lines are virtually saturated because they are reaching critical values of ampacity and sag [1]. On the other hand, distribution networks are facing challenges on handling high penetration of distributed generations (DGs), whose power outputs are uncertain and may lead to overvoltage and load shedding to both the distribution system operator and consumers [2]. Therefore, traditional AC distribution networks need to be upgraded to satisfy the requirements of load increasing and integration of renewable energy. However, there are limited spaces to build new substations and distribution lines in urban areas.

DC technologies have been proposed and used in high voltage transmission networks due to the benefits for the maximum transfer capacity increment [3]. DC technologies are also adopted in low voltage microgrids or smart buildings for reducing losses by avoiding conversions from DC to AC [4]. Conversion of existing AC lines to DC operation through voltage source converters (VSCs) has been presented in CIGRE report [5], and analyzed in [6]. Moreover, powers can be flexibly shifted between the connected AC and DC lines through the VSCs in order to mitigate unexpected power fluctuations of DGs and loads. Thus, by converting AC links to DC ones, a hybrid AC/DC medium voltage distribution network might be formed. This "space-shifting" way helps an existing distribution network to accommodate increasing loads and DGs in urban areas. Thus, optimal planning of such conversions is of important value and deserves to be studied carefully.

Meanwhile, energy storage systems (ESSs) have been investigated to smooth out the intermittent renewable power generation, match demand and supply by smart charge/discharge. This "time-shifting" of energy supplies also benefits increasing transfer capacities and DG accommodation [8]. Therefore, functionalities of ESSs should be considered thoroughly during designing the hybrid AC/DC distribution network.

Focusing on high voltage transmission networks, reference [9] presented an analysis of different VSC-HVDC configuration for converting AC lines into DC lines, while reference [10] investigated the feasibility of converting a double circuit AC line to a composite ac-dc power high voltage transmission line to get the advantages of the parallel ac-dc transmission. Reference [11] assessed the technical and economic values of AC/DC distribution system configurations. Reference [12] introduced a project called "ANGLE DC", which would demonstrate the feasibility of converting existing AC assets to DC operation. Reference [13] proposed a stochastic planning model to generate the optimal AC-DC hybrid configuration of buses and lines. Reference [14] presented a planning model to determine topology features of a microgrid, where AC or DC links were chosen according to their economic costs and benefits. Reference [15] extended the work in [14] by including AC-DC hybrid topologies into the optimal configuration of a microgrid. However, in above works [13-15], only newly-built DC links were considered, while lacking models of DC-conversions of existing AC lines. In fact, existing AC lines should be carefully modelled for the optimal reconstruction of a distribution network. Then, the overall power flow of the system can be rescheduled regarding voltage and capacity constraints of all AC and DC links.

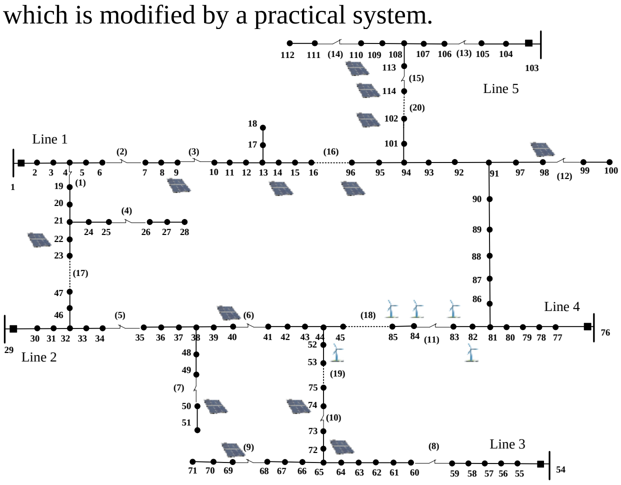
In this paper, in order to accommodate more loads and renewables, an optimal planning method is proposed for configuring hybrid AC/DC line conversions in an existing distribution network. Such an optimal configuration is formulated as a bi-level programming model. In the upper level, a multiple-objective optimal model is established to optimize the topology of the hybrid AC/DC distribution network comprehensively considering the balance of investments, power losses, and the increased network capability of accommodating loads and renewable energies. In the lower level, daily operations of the newly installed VSCs are optimized by a chance constraint programming, where uncertainties of renewable generations and load demands are both considered. To solve the proposed bi-level programming, A Pareto-based Non-dominated Sorting Genetic Algorithm-Ⅱ algorithm is adopted. The influences of ESSs allocation on the configuration of hybrid AC/DC distribution network are analyzed.

It should be noted that the proposed configuration method of hybrid AC/DC distribution network in this paper is focused on medium voltage distribution network. Loads are still connected to AC grid because the converters connecting AC loads to the DC line are configured between DC medium voltage lines and low voltage substations.

The remainder of this paper is organized as follows. Section 2 describes the optimal configuration problem of hybrid AC/DC distribution networks. Section 3 introduces a bi-level multi-objective optimal configuration model. The algorithm for solving the proposed model is given in Section 4. Simulation results are illustrated in section 5. Conclusions are outlined in section 6.

2. Problem Description

Fig. 1(a) illustrates a 5-feeder medium voltage distribution network in urban areas with renewable energies, which is modified by a practical system.



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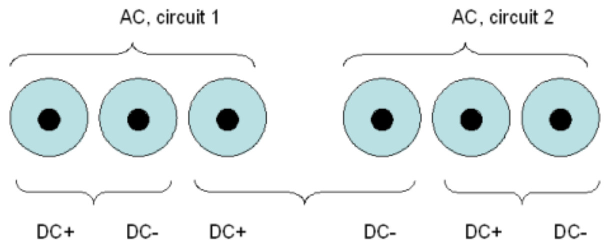

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Fig. 1. *Hybrid AC/DC distribution network configuration*
(a) 5-feeder medium voltage distribution network
(b) Configuration of converting AC lines to DC for double circuit lines

It is assumed that,

1) All feeders are double-circuit [17];

2) Load levels or renewable energy capacities are increased yearly while existing distribution networks are not able to meet further increase;

3) All existing lines are double-circuit [17] and are already pre-qualified for both AC and DC, in which the two AC circuits could be used for three DC circuits [18], as shown in Fig. 1(b).

4）Outputs of renewable energies and DC loads remain as AC output as they were connected to the AC system. DC/DC converters should be used if renewable generations and loads are moved to DC lines, but the DC/DC converters are not considered in this study.

5) Considering ageing factors, the DC operating voltage is chosen as the AC peak voltage [18], which has been used in a practical MVDC project [19].

This paper proposes to convert one or more existing AC lines to DC operation, and connect these lines with other AC lines through VSCs, in order to increase the maximum power capacities and achieve flexible power shifting between the interconnected AC and DC lines. A configuration optimization method is therefore needed to optimize the topology of the hybrid AC/DC distribution network, considering investments, power losses and the capabilities of loads and renewable energies.

Existing network structures and optimal dispatching results must be considered during the configuration optimization of hybrid AC/DC distribution networks, in order to maximize the benefits of rescheduling capability under unexpected fluctuations of renewable energies and loads. In addition, balances must be achieved between the investments of VSCs, power losses, and the network capabilities of accommodating load and renewable energy.

A bi-level optimization model is then proposed, in which a multiple-objective optimal model is established to optimize topologies in the upper level, and a chance constraint programming model is used in the lower level to optimize dispatching results. The results of the lower level, which are the power losses, the maximum load level and the most acceptable renewable energy capacity of the hybrid AC/DC distribution network, will be fed back to the upper level in order to produce a better topology of the hybrid AC/DC distribution network.

3. Bi-level optimization model

The topologies of hybrid AC/DC distribution networks are needed to be determined first, taking annual investments, power losses, and the capabilities of load and renewable energy as objectives. However, the power losses and the capabilities of load and renewable energy cannot be calculated accurately without a 24-hour dispatching optimization result. On the other hand, the 24-hour optimal dispatching cannot be conducted without the optimal result of VSC locations and capacities. Therefore, the two procedures must iterate to achieve optimal results as an upper level and a lower level, based on which a bi-level programming model is used in this paper. Chance constraint programming is embedded in the model due to uncertain outputs of renewable energies and loads.

3.1. Upper level

The minimum annual investments, maximum capability of load and renewable energy, and minimum power losses of the distribution network are considered in the objective of the upper level, as shown in equation (1).

The locations and capacities of the VSCs for connecting DC lines to the main power supply and AC lines are optimized as variables.

$$F_{upper} = \begin{cases} f_1 = \min C_{cost} \\ f_2 = \max P_{load} \\ f_3 = \max P_{DG} \\ f_4 = \min P_{loss} \end{cases} \tag{1}$$

where C_{invest} is the annual investment of configured VSC as shown in equation (2); P_{load} and P_{DG} are the maximum allowable capacity of load and renewable energy in the distribution network. P_{loss} is the power losses.

$$C_{invest} = \sum_{n=1}^{N} (C(r,l)) C_{vsc} S_{vsc}^{n} \tag{2}$$

where N is the total number of the VSCs for connecting DC lines to the main power supply and AC lines, and connecting AC loads to the DC line; $C(r,l)$ is uniform annual factor; r is discount rate; l is a lifetime of VSC; C_{vsc} is a unit investment of VSCs; S_{vsc}^{n} is the installed capacity of the n^{th} VSC.

Equality constraints include power flow equation.

$$\begin{cases} P_i = U_i \sum_{j=1}^{n} U_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij}) \\ Q_i = U_i \sum_{j=1}^{n} U_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) \end{cases} \tag{3}$$

where P_i and Q_i are active and reactive power injection of bus i; U_i and U_j are voltages of i and j; n is node number; G_{ij} and B_{ij} are real part and imaginary part of admittance matrix, δ_{ij} is the difference of phase angle i and j, respectively.

Inequality constraints are voltage deviation range

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{4}$$

where V_i, $V_i^{\min}$, $V_i^{\max}$ are voltage value, allowable minimum voltage value, and allowable maximum voltage value of node i, respectively.

$$S_k \le S_k^{\max} \tag{5}$$

where S_k and $S_k^{\max}$ are power flow in branch k and allowable maximum power flow of branch k respectively.

3.2. Lower level

Outputs of the VSCs between AC and DC lines, and ESSs for 24-hour in day-ahead scheduling are optimized in this level, in order to calculate power losses, and the maximum loadabilities of loads and renewable energies.

The overall power flow can be rescheduled and optimized through the optimization of VSC2 outputs (P_{VSC}^{DC} and Q_{VSC}^{AC}, P_{VSC}^{AC} is not included because it is determined by P_{VSC}^{DC} and VSC loss).

The minimum power losses are considered in the objective of the lower level, as shown in equation (6). The outputs of the VSCs between AC and DC lines are decision variables.

$$P_{loss} = \sum_{n=1}^{N} P_{loss}^{VSCn} + P_{loss}^{system} \tag{6}$$

where P_{loss}^{VSCn} is the power losses of the n^{th} VSC, which are set as 2% of VSC output capacities [20]. P_{loss}^{system} is network losses, which is the objective of the lower level.

In order to analyze the influences of ESSs on the configuration optimization of hybrid AC/DC distribution network, ESSs are assumed to be allocated in the network. The real and reactive power regulations of ESSs are limited by the maximum available capacity according to State of Charges (SOCs), shown as S_e in equation (2).

$$P_e^2 + Q_e^2 = S_e^2 \tag{7}$$

where S_e is the maximum available capacity during optimization according to SOCs.

Chance constrained programming [21]-[22] is used in the lower level optimization due to the uncertainty of renewable energies and loads. A multi-state system theory method is used to describe the uncertainty of random variables, and system states are used to describe operation scenarios [23].

The objective at time t is formulated as follows:

$$prob\{ f_{lower}(x,j) \le F \} \ge \beta \tag{8}$$

$$f_{lower}(x,j) = P_{loss}^{system}(j) \tag{9}$$

where x denotes decision variables, including P_{VSC}^{DC} and Q_{VSC}^{AC}; j means the jth state; $P_{loss}(j)$ represents network losses under system state j; β is confidence level; F is the maximum value when the confidence level is not lower than β; $prob$ means the probability.

Besides the equality constraint (3), an inequality constraint of (10) and two probabilistic constraints (11)-(12) are considered in the lower level optimization.

$$0 \le S_{vsc,t}^{n} \le S_{vsc}^{n} \tag{10}$$

$$prob\left\{ V_i^{\min} \le V_i \le V_i^{\max} \right\} \ge \beta \tag{11}$$

$$prob\left\{ S_k \le S_k^{\max} \right\} \ge \beta \tag{12}$$

where $S_{vsc,t}^{n}$ is output capacity of the n^{th} VSC at time t.

The maximum loadability of loads and renewable energies are mainly influenced by line transfer limits and node voltage limits, which are described by constraints (11) and (12) in the lower level. In order to obtain the maximum load that can be served by the hybrid AC/DC distribution network, lower level optimization will increase the load power at all nodes at the same rate until the outputs of VSCs hit their limits defined by equation (10)-(12). The maximum renewable energy penetration is obtained in the same way. Details will be introduced in section 4.

The concept of overall optimization procedure is shown in Fig 2.

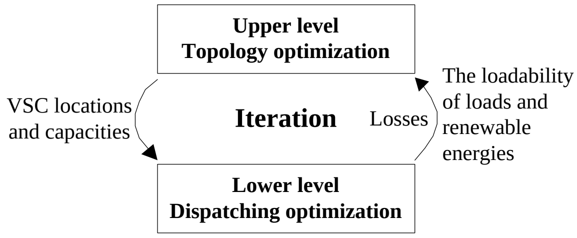


Fig. 2 The concept of overall optimization procedure

The results of the lower level optimization are power losses, the maximum loadabilities of loads and renewable energies, and outputs of the VSC connecting DC lines and AC lines for 24 hours separately.

4. Solution algorithm of the proposed model

A Pareto-based Non-dominated Sorting Genetic Algorithm-Ⅱ (NSGA-Ⅱ) algorithm [24] is used to solve the proposed multiple-objective problem in the upper level, and the set pair analysis (SPA) theory is used for decision-making [25]. Genetic algorithm (GA) with elitist strategy [26] is used for solving the proposed lower level optimization, in which the real and reactive power outputs of VSC2s for day-ahead scheduling are optimized.

The encoding of upper-level optimization is shown in Fig. 3(a), in which two chromosome regions are used, namely, S_k and T_k.

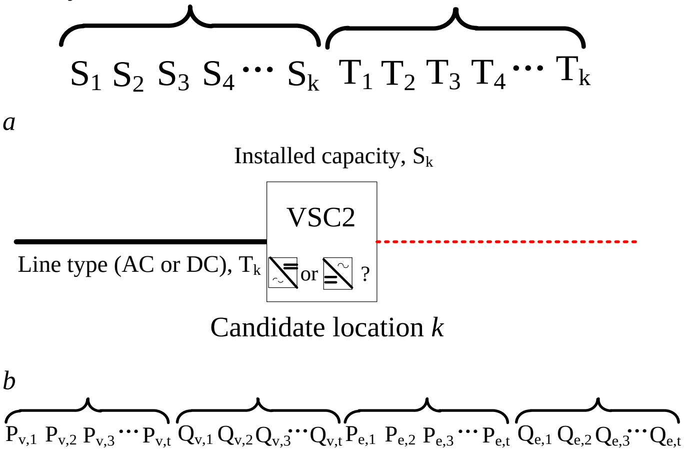


Fig. 3. *Solution algorithm of the propose model*

(a) Encoding of upper-level control variables

(b) Representation of upper-level encoding

(c) Encoding of lower-level control variables

k is the number of candidate locations of the VSC2s for connecting DC and AC lines; S_k is the installed capacity at location *k*; there will be no VSC installed if S is zero; T_k determines the type, i.e., AC or DC, of the two lines connecting the VSC at location *k*, as shown in Fig. 3(b). Then, VSC1 for connecting the DC line to the main power supply is configured at the start of the line which is determined to be DC operation. Therefore, the topology of the hybrid AC/DC distribution network is formed.

The capacity of VSC1 is determined by the maximum transfer capacity of the DC line, and the capacity of the converter for connecting an AC load to the DC line is determined by the load level.

The encoding of lower level optimization is shown in Fig. 3(c), in which four chromosome regions are used, namely, $P_{v,t}$, $Q_{v,t}$, $P_{e,t}$ and $Q_{e,t}$, *t* is the *t* th hour.

In order to consider the uncertainty of renewable energy and load, a system state is divided into *n* states based on a multi-state system theory. The objective values, power losses, which are calculated for each state, are arranged from the best to the worst. The probabilities are cumulated until the confidence level is achieved, then the last objective value is used as the final result [26].

In order to guarantee the new chromosomes, which are produced in crossover and mutation procedures, satisfy their constraint requirements respectively, segmented chromosome management is applied in crossover and mutation procedures of lower level optimization.

A flowchart of the proposed bi-level optimization problem is shown in Fig. 4.

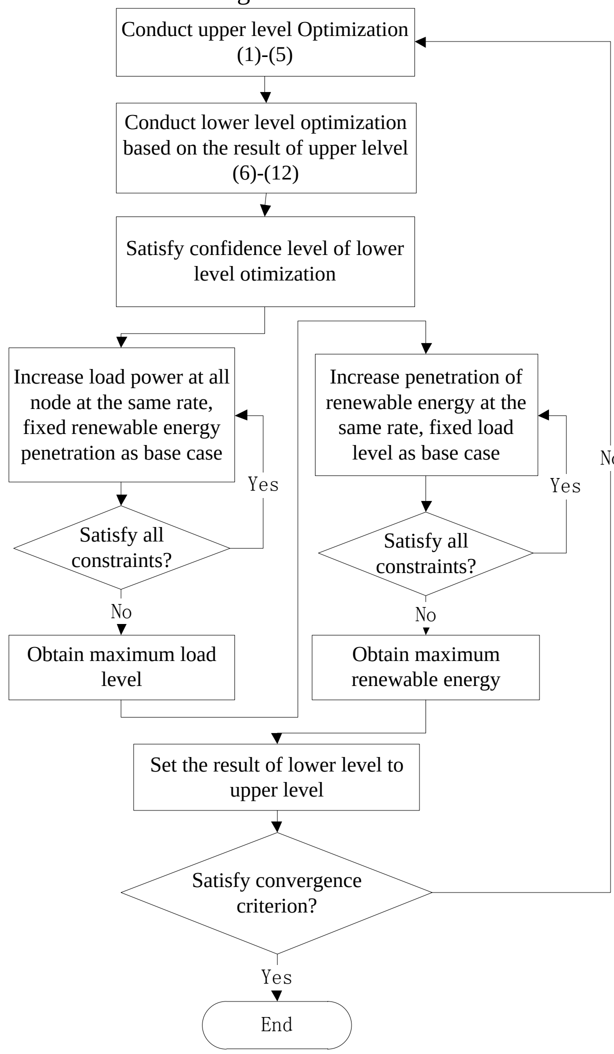


Fig. 4 The flowchart of the proposed bi-level optimization problem

5. Case study

5.1. Simulation background

A 5-feeder 114-node medium voltage distribution network with high penetration of renewable energies, as shown in Fig .1, was used to test the proposed method. The load level of the base case is 20 MW, and the rated capacity of renewable energy is 1 MW.

The investment of VSC is \$160/kVA [27], roughly equivalent to ¥1000/kVA. The price of energy loss is ¥0.49/kWh considering practical electricity purchase price. The cost of the converters connecting AC loads to DC lines was considered in investments, whose cost was roughly estimated by the maximum load in each node.

Outputs of wind turbines (WT), photovoltaic (PV) and loads are assumed to obey a fixed Gaussian distribution in day-ahead [28], and are divided into five, three, three states in an hour, respectively, based on which the system state n is set as 45 [26]. Confidence level, β, is set as 0.9. Renewable energies are modeled as PQ nodes in the hybrid AC/DC power flow, in which the injected real power depends on available resources, and reactive power is decided by a constant power factor 0.9 in AC system. The multiple-terminal hybrid AC/DC distribution network is considered in this paper, which will be further researched in the future. The lifetime of VSC is set as 40 year [29], and the discount rate is set as 10% [30].

DGs, including PVs and WTs, are simplified as uncertain variables aiming at evaluating the accommodation capability of renewable energies considering uncertainties in urban distribution networks [31].

Power electronic devices, including Solid State Transformers or Power Electronics Transformers [32] [33], and Soft Open Point [34] are not considered in this paper because the DC side of these power electronic devices is not utilized for load supply or DG integration.

Renewable energy outputs and loads for 24 hours are shown in Fig. 5.

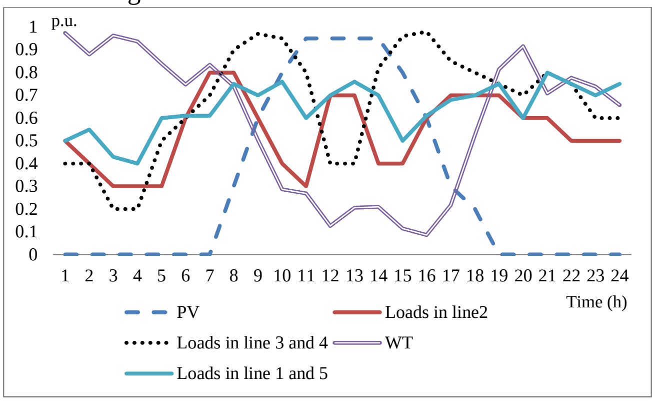
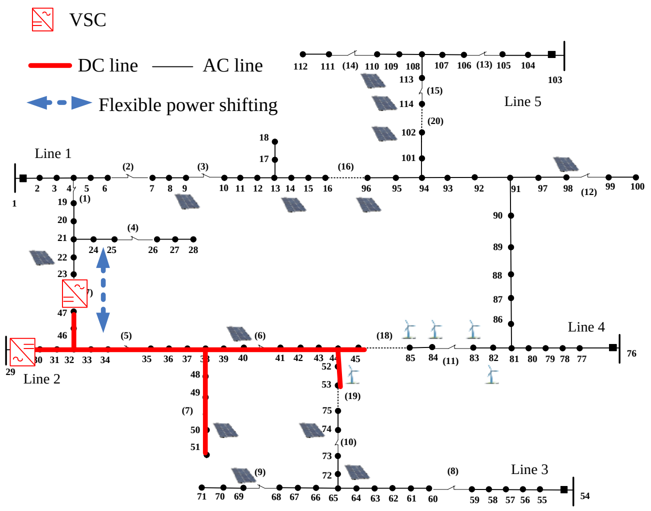


Fig. 5 Renewable energy outputs and loads for 24 hours

5.2. Superiority of the proposed method considering existing network structures and optimal dispatching results

Case 1 is the configuration considering existing topologies and dispatching results of the hybrid AC/DC distribution network, while case 2 only choose to convert the line, which has the lowest loadability of loads and renewable energies, to DC operation.



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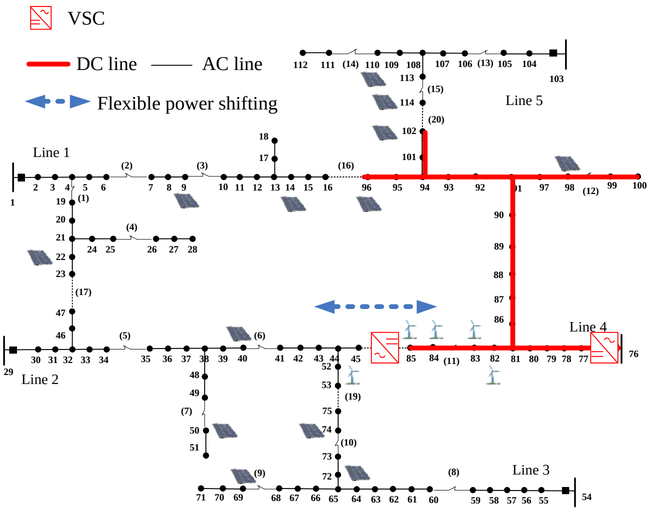

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Fig. 6. *Configuration result comparison*

(a) Configuration result without considering existing topologies and optimal dispatching results
(b) Configuration result considering existing topologies and optimal dispatching results

Tab. 1 Capability of AC system

	Line 1	Line 2	Line 3	Line 4	Line 5
Maximum load level (MW)	9.5	7.2	10.3	9.6	10.6
Maximum renewable energy penetration (%)	220	175	190	145	315

Tab. 2 Comparison of load and renewable energy capabilities

Solution method	Maximum load level of hybrid AC/DC distribution network (MW)	Maximum renewable energy penetration of hybrid AC/DC distribution network (%)
Case 1	61.6	190%
Case 2	56	145%

Tab. 3 Comparison of overall power losses

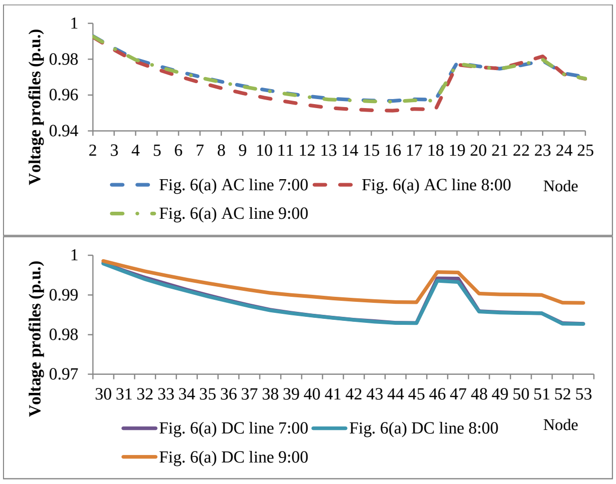
Solution method	Overall power losses of AC system under	Overall power losses of hybrid AC/DC

	56 MW (¥)	distribution network under 56 MW (¥)
Case 1	1646	1345
Case 2	1646	1372

Line 2 is converted from AC to DC operation and interconnected with line 1 in case 2, as shown in Fig. 6 (a). That is because the line with lowest transfer capacity is chosen to be converted in order to increase line transfer capacity without considering existing topologies and dispatching results, as shown in Tab. 1.

Line 4 is converted from AC to DC operation and interconnected with line 2 in case 1, as shown in Fig. 6 (b). That is because the benefits of the hybrid AC/DC distribution network can be fully utilized considering existing topologies. Moreover, the power coordination between the two lines which is depends on the differences between load curve and renewable energy outputs, is fully achieved through considering dispatching results during configuration. In particular, the maximum load level of hybrid AC/DC distribution network is increased to 61.6 MW, and the maximum renewable energy penetration is increased to 190% in case 1. Although the maximum transfer capacity in case 2 is increased due to DC operation of line 2, the maximum renewable energy penetration is not increased, because the DC line, line 2, was interconnected with line 1, whose maximum transfer capacity is lower than the other three.

Therefore flexible power shifting must be fully achieved in order to maximize the benefit of a hybrid AC/DC distribution network.



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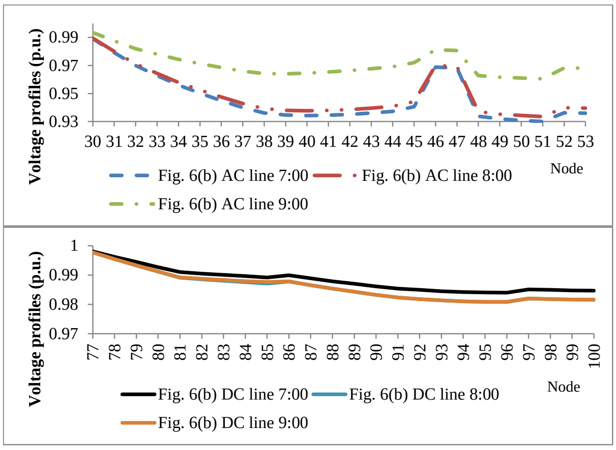

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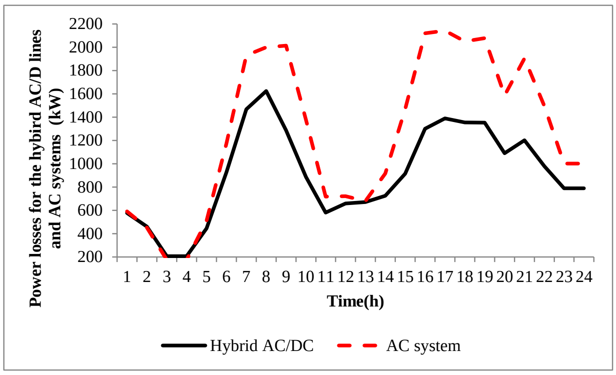


c

Fig. 7. *Voltage profiles and power losses*

(a) Voltage profiles during 7-9 am for case 2
(b) Voltage profiles during 7-9 am for case 1
(c) Power losses for line 2 and line 4 in hybrid AC/DC distribution networks and AC systems

Node voltages of the AC line in case 2 are increased from 7am to 8am, and then decreased from 8am to 9am as shown as the dashed lines in Fig 7(a), that is because loads in line 1 fluctuated during 7am to 9am. Node voltages of the DC line in case 2 nearly kept the same from 7 am to 8 am, and then increased from 8 am to 9am, that is because loads in line 2 are decreased in a sudden from 8am to 9am, as shown in Fig. 5. Nodes voltages of the DC line in case 1 are decreasing from 7 am to 9 am with the continuous increasing of loads in line 4, as shown in Fig 7(b).

Fig. 7c illustrates the power losses for line 2 and line 4 in hybrid AC/DC distribution networks and AC systems. During the peak period of loads, such as 7-10am, and 3-22pm, power losses are higher than other periods. However, the power losses in hybrid AC/DC distribution networks are much lower than those in AC systems during peak period. That is because losses in DC lines are lower than AC lines under the same load level, and powers between AC and DC lines can be optimal rescheduled through VSC.

Overall losses of both case 1 and case 2 are reduced in hybrid AC/DC distribution network, in which losses in case 1 is a little lower than those in case 2. That is because the fully utilization of VSC increases losses, although power losses of the distribution network are reduced.

5.3. Analysis of the configured hybrid AC/DC distribution network

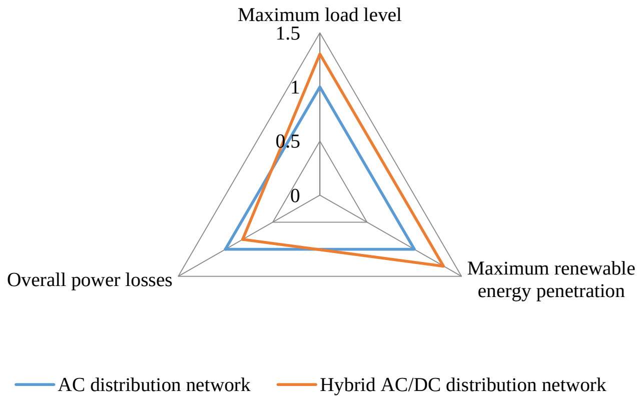


Fig. 8 Benefits of hybrid AC/DC distribution networks

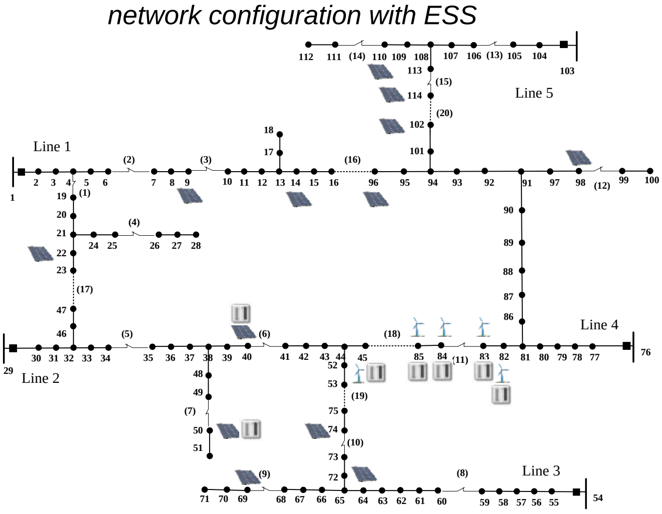
A comprehensive benefit comparison of hybrid AC/DC distribution network is shown in Fig. 8. The maximum load level and renewable energy penetration are increased to 1.29 and times, 1.31 times of the AC system respectively, while overall power losses are reduced to 81.7%. That is because flexible power shifting is achieved to optimize power flow of the distribution network. Investments of ￥6.3 M are needed as a uniform annual cost in order to achieve above benefits.

Tab. 4 Analysis of the maximum renewable energy penetration

Case	The maximum renewable energy penetration	Reason of bottleneck	Time
AC system	145%	Node voltage violation (node 40)	11 am
Hybrid AC/DC distribution network	190%	Line transfer capacity violation (line 83-84)	14 pm

A node voltage violation happens at 11 am in original AC system when the penetration of renewable energy reaches 145%, while a transfer capacity violation in DC line happen at 14 pm in the hybrid AC/DC distribution network, as shown in Tab. 4. That is because PV outputs are high and load requirements are reduced at 11 am and 14 pm. A node voltage violation happens in the AC system because of reverse flowing of active power produced by PV, which is shifted to the DC line through VSC by power flow rescheduling. However, the maximum transfer capacity limit is reached at 14 pm with 190% renewable energy penetration. That is because powers, not only from the PV in the AC line, but also from the WT in the DC line, are flowing through the line (83-84).

5.4. Discussion of hybrid AC/DC distribution network configuration with ESS



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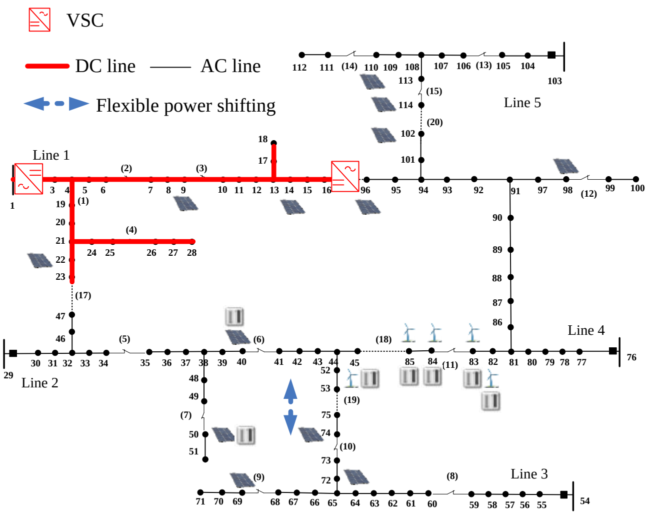

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Fig. 9 *5-feeder medium voltage distribution network with ESS*

(a) 5-feeder medium voltage distribution network with ESS

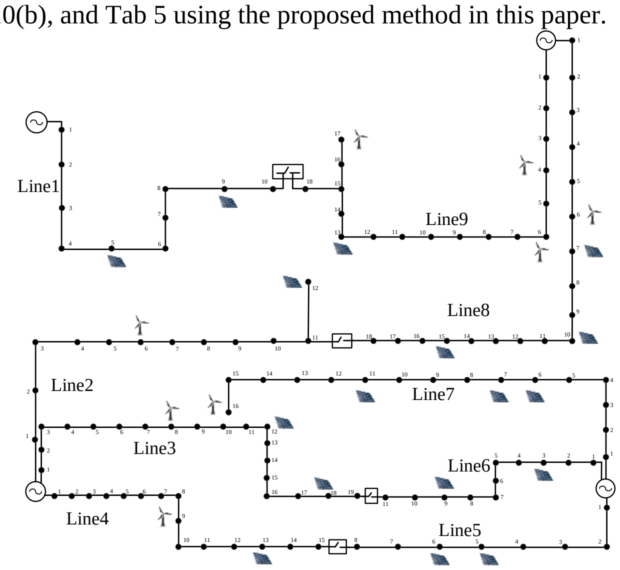
(b) Configuration result with ESS in line 1 and line 4

ESSs are added at node 40, 45, 50, 82, 83, 84, and 85 where wind turbines are allocated [35], in order to analyze the influence of ESS on the configuration of hybrid AC/DC distribution network. The capacity of each ESS is 1MVA. Configuration optimization results are shown in Fig. 9 (a).

Line 1 is converted from AC to DC operation and interconnected with line 4, as shown in Fig. 9 (b). That is because the capability of transfer capacity and DG accommodation of line 2 and line 4 were increased due to the integration of ESSs. ESSs can balance powers during periods within capacity constraints, however, load shedding and DG curtailments will happen when DGs or loads kept their powers for periods. Therefore, hybrid AC/DC distribution network is needed to achieve power balance between line 1 and line 4, in which DG outputs and load curves are different.

5.5. Case study of a real grid

Fig 10(a) is modified by a real grid in Hebei province, China. The optimization results are shown in Fig. 10(b), and Tab 5 using the proposed method in this paper.



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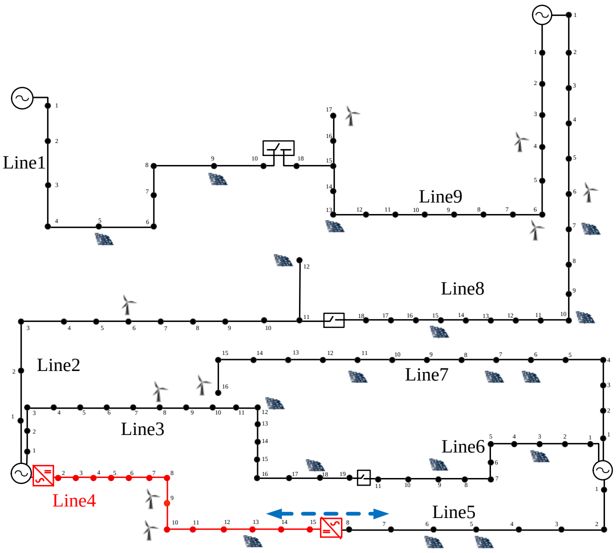

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Fig. 10 *Hybrid AC/DC distribution network configuration of a real grid*

(a) A modified real grid topology

(b) Configuration result

Tab.5 Configuration results

Optimization results	
The DC line converted by AC	Line 4
The AC line connected with the DC line	Line 5
Total cost/million yuan	27
Increased maximum loadability	27.73%
Increased maximum DG penetration	8.85%

Line 4 was converted to DC operation and connected with line 5 through the configuration method proposed in this paper, as shown in Tab.5. The maximum loadability is increased by 27.73% compared with traditional AC systems because flexible power shifting is achieved between line 4 and line 5, whose capability of power transfer needs to be improved, and the differences of load curves can be fully utilized, as shown in Fig.5. The maximum DG penetration is increased by 8.85% because powers are balanced between the two lines considering the differences of WT and PV outputs.

6. Conclusions

This paper proposed a configuration method for hybrid AC/DC distribution networks. Existing topologies of AC systems and optimal dispatching results are considered through a bi-level programing model. Investments, power losses, and the maximum load level and renewable energy capacity of the hybrid AC/DC distribution network are balanced through a multiple objective optimization. Uncertain outputs of renewable energies and loads are considered through an embedded chance constraint programming. The influences of ESS integration on the configuration of hybrid AC/DC distribution network are analysed.

Flexible power shifting can be fully considered during configuration through the proposed method, based on which the maximum load level is increased from 56 MW to 61.6 MW, and the maximum renewable energy penetration is increased from 145% to 190% in the a 5-feeder 114-node case study.

Overall power losses are reduced by converting AC lines to DC and forming a hybrid AC/DC distribution network because line power losses are reduced through an optimal rescheduling, even VSC losses are increased.

The integration of ESS changes the configuration result of hybrid AC/DC distribution network. Transfer capacities and DG accommodation can be increased by power rescheduling through both space-shifting and time-shifting.

Considering existing AC infrastructures, hybrid AC/DC distribution network is a necessary stage from AC system to DC system. The benefits of DC distribution may be more and more outstanding in future with the increasing of DC loads.

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8. References

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