Rapid modelling for flexible DC distribution network considering droop control

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Abstract: With the growth of DC electricity load, the difficulty to improve the power quality, and the increasing penetration of renewable power, flexible DC distribution network, which contains complex renewable energy generation equipment and a large number of power electronic converters, become an important research direction. The modelling of the DC distribution network is an essential step for the research on the coordination control. However, the traditional modelling will be a burden for simulation software. This article models all electrical devices as equivalent power sources based on the proportional–integral control and the power–voltage curve, ignoring the complex internal control processes. Based on the simplified models of power, load, DC/DC converters, and AC/DC converters considering droop control, a simplified model of a multi-terminal flexible DC distribution network is derived. Taking the impact of droop control into account, the simulation of DC distribution power flow under the different distribution of generation and load is done. Results show that the simplified model of DC distribution network with droop control can accurately and rapidly simulate the transient process and steady states of the testing network.

1 Introduction

As the urban electricity load continuously grows, the power quality requirements of some loads become increasingly stringent, and the permeability of new energy and electric vehicles is gradually increasing, the flexible DC distribution network has become an important direction for the upgrading and rebuilding of the urban distribution network [1, 2]. Many countries and regions have focused on the research of the flexible DC distribution network in recent years, mainly the power sharing optimisation [3], the voltage stabilisation [4], the safety of DC network [5], and the application of new energy in DC network [6].

Currently, studies on DC distribution networks have a rapid growth. However, the existing research studies mainly focus on the optimisation and control of the operation, ignoring the study of the modelling method. Mohsenian-Rad and Davoudi [7] designed a demand response to optimise the internal parameters of power electronics loads to improve the operation of the DC distribution system. A new robust droop control strategy is proposed to mitigate the impact of terminal voltage drop and line impedance [8]. Hakala *et al.* [9] investigate the power transfer capacity of the low-voltage direct-current distribution network, which can be utilised in a large distribution network company. In [10], the stability of the DC distribution system is improved by a decentralised adaptive non-linear controller which employs neural networks after the disturbances have occurred.

The flexible DC distribution network contains numerous energy storage systems, distributed generations, active loads, e.g. smart micro-grids, and various types of power electronic converters. While the traditional physical modelling of the DC distribution network is precise, it can be time consuming and is often technically difficult to construct. Moreover, simulation software cannot even calculate when the terminals of the network increase sharply, which requires an efficient and simple modelling method. Based on the external power–voltage characteristic, this paper simplifies the models of electrical devices and constructs the model for DC distribution network, which underlies the study on the dynamic process during the power dispatch of the DC distribution network.

The main contributions of this paper are twofold: (i) the paper proposes a rapid and simple modelling method for the flexible DC distribution network based on the fundamental proportional–integral (PI) control principle, which accurately manifests the dynamic process during the power dispatch. (ii) With the simplified models, the simulation analysis of the large-scale multi-terminal flexible DC distribution network can be performed.

The structure of this paper is as follows: Section 2 introduces the droop control. The simplified models of power, load, DC/DC converter, and AC/DC converter are constructed in Section 3. Section 4 employs a testing DC distribution network to verify the accuracy of the model in Section 3. Conclusions are shown in Section 5.

2 Droop control of converters

Droop control, whose full name is power–voltage droop control, is a method to regulate the voltage of converter in droop characteristics with the power change of converters. When voltage increases, the power of the converter decreases under the droop control, which can relieve the uptrend of bus power. Similarly, the drop in voltage means the increase in power.

In order to overcome the shortcoming of deviating regulation, constant voltage control and constant power control are combined with the droop control to form a modified method, called droop control with the dead area, as shown in Fig. 1. The black line is normal droop control, the red dashed line represents droop control with voltage dead area, i.e. the horizontal part of the red dashed line, and the blue dashed line represents droop control with power dead area, i.e. the vertical part of the blue line. In the dead area, the droop control equals to constant voltage control or constant power control, which is a non-deviating regulation. The droop control with power dead area can be expressed as follows:

$$\begin{aligned} P &= P_e + k \times (V - V_1), & V < V_1 \\ P &= P_e, & V_1 < V < V_2 \\ P &= P_e + k \times (V - V_1), & V > V_2 \end{aligned} \quad (1)$$

where P is the power consumed by the load, P_e is the rated power of the load, k is the slope of droop control, V_1 and V_2 are the upper and lower limits of the voltage dead area, respectively.

3 Rapid modelling of equivalent power source

The core concept of the equivalent power source model is to control the output power of the model by constantly adjusting the
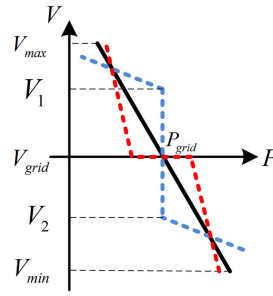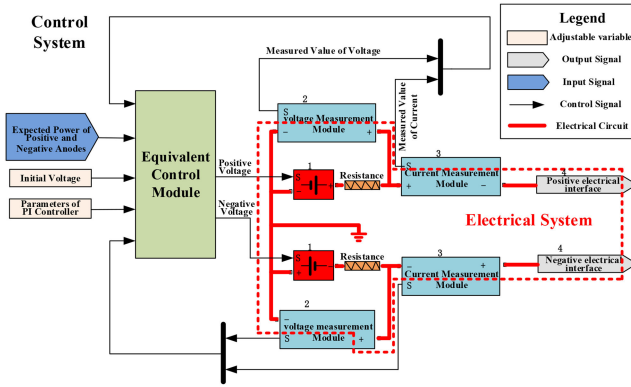
Fig. 1 *Characteristic of droop control*

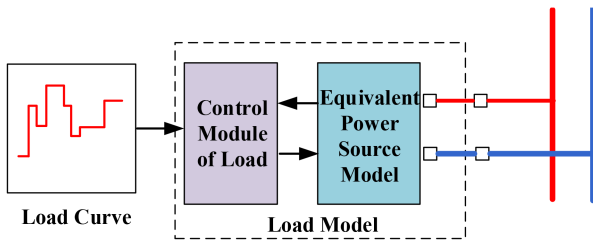**Fig. 2** *Structural diagram of the model*

Fig. 3 *Schematic diagram of the load model*

port voltage so as to achieve the goal that the actual output power is consistent with the expected power of the model. The structural diagram of the equivalent power source model is shown in Fig. 2. It is clear that the model is divided into two parts which are the control system and the electrical system. The basic control algorithm of the control system is PI control.

Based on the equivalent power source model, this paper establishes the bipolar power supply model, load model, and converter model according to external electrical characteristics of the corresponding parts of the network.

3.1 Load model

The load model is a comprehensive model including the load and its converter. The main function of this model is to simulate the voltage and power characteristics of the load in the DC distribution network. This model does not contain any specific power electronic switching elements so that the actual electrical characteristics of the load are reflected by the control module. The principal diagram of the load model is shown in Fig. 3.

Assuming that the DC distribution network has a stable bus voltage, the power absorbed by the load from the distribution network is shown in

$$P = \frac{V_{\text{DC\_line}} \times V_{\text{DC\_load}} - V_{\text{DC\_load}}^2}{R_{\text{DC\_line}}} \tag{2}$$

where P represents the power absorbed by the load, $V_{\text{DC\_line}}$ is the bus voltage, $V_{\text{DC\_load}}$ is the voltage of the load, and $R_{\text{DC\_line}}$ represents the line resistance from the load to network.

At first, the output power is calculated by the measured output voltage and current of the controllable voltage source. The positive current direction is the direction of flow into the controllable voltage source

$$P_0(k) = I(k) \times V(k) \tag{3}$$

Then the error ε between the expected power P_{expect} and the actual power P_0 is calculated in

$$\varepsilon(k) = P_{\text{expect}}(k) - P_0(k) \tag{4}$$

When the power required for the load changes, the converter will adjust the output voltage V by controlling the on–off time of the switch tubes. This paper employs PI control to simplify the control process. The time-domain expression of PI control is shown in

$$V(t) = k_{\text{p}}\varepsilon(t) + k_{\text{i}}\int \varepsilon(t)\mathrm{d}t \tag{5}$$

where k_{p} and k_{i} are the proportional coefficient and integral coefficient.

Considering T_{sam} is step size, the upper equation is discretised into the difference equation, and the output voltage of the kth step is as follows:

$$V(k) = k_{\text{p}}\varepsilon(k) + k_{\text{i}}T_{\text{sam}}\sum_{i=1}^{k}\varepsilon(i) = k_{\text{p}}\varepsilon(k) + V_i(k)$$
$$= k_{\text{p}}\varepsilon(k) + k_{\text{i}}T_{\text{sam}}\varepsilon(k) + V_i(k-1) \tag{6}$$

Thus, the increment of the output voltage can be calculated as

$$\Delta V(k) = V_i(k) - V_{i-1}(k) = k_{\text{p}}[\varepsilon(k) - \varepsilon(k-1)] + k_{\text{i}}T_{\text{sam}}\varepsilon(k) \tag{7}$$

Then, the output voltage $V_{\text{out}}(k)$ of the kth adjustment can be calculated as

$$V_{\text{out}}(k) = V(k) + \Delta V(k) \tag{8}$$

Finally, when the output power is the same as the expected power, i.e. $P_0 = P_{\text{expect}}$, the output voltage of the controllable voltage source reaches a stable value, i.e. $\Delta V = 0$.

It should be noted that control modes of the converter that are connected to the load affect the modelling. Specifically, if the load is under constant power control, P_{expect} is constant. Also if the load is under droop control, $P_{\text{expect}}(k)$ is calculated by the output voltage at the previous step $V_{\text{out}}(k-1)$ according to the droop characteristic introduced in (1). The control flow of the load model is shown in Fig. 4.

3.2 Power supply model

According to the control of the converter that connects the power supply to the network, this paper designs two types of power supply models which are constant voltage controlled power supply model and droop controlled power supply model. The construction of the power supply model is similar to the load model, except that

the power flow direction and the control modes of the converter. The load model and the power supply model are hereinafter collectively referred to as DC source model for convenience.

3.3 DC/DC converter model

DC/DC converter is mainly used to connect DC network with different voltage levels, playing the role of transformer and power transmission. The core part is two DC source models which have opposite power flow directions and the power are always the same. The model adopts constant voltage control on the low-voltage side to maintain the bus voltage within a certain range, which ensures the output of renewable energy sources such as wind power and photovoltaic power. The high-voltage side adopts constant power control to transmit the output of distributed generations in the low-voltage side to the DC distribution network. The design principle of the DC/DC converter model is shown in Fig. 5.
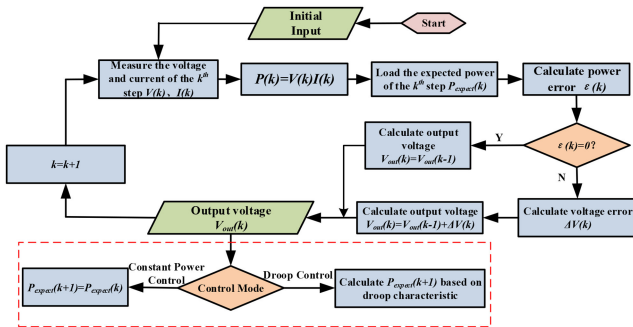

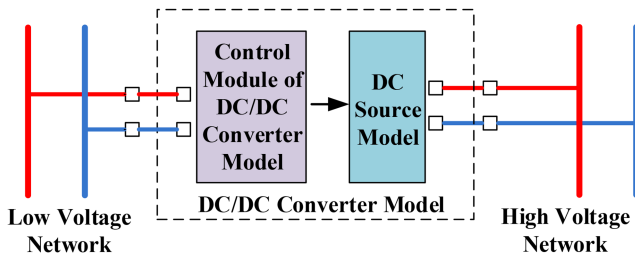**Fig. 4** *Control flow of the load model*

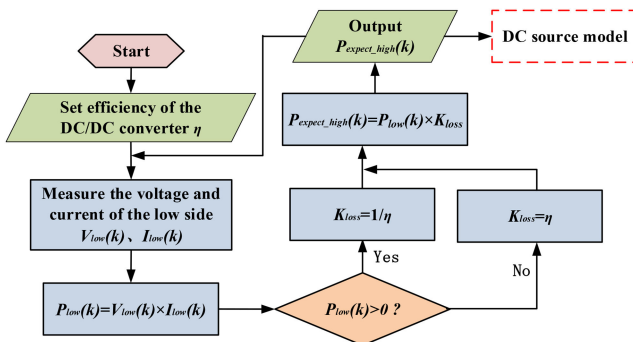**Fig. 5** *Schematic diagram of the DC/DC converter model*

Fig. 6 *Control flow of the DC/DC converter model*

The control flow of the DC/DC converter model is shown in Fig. 6. At first, the loop algorithm of the control calculates the input/output power $P_{low}(k)$ of the low-voltage side of the model according to the voltage $V_{low}(k)$ and the current $I_{low}(k)$ of the low-voltage side of the model. Then the direction of power flow of the model is determined by judging whether $P_{low}(k)$ is greater than zero, and the expected power $P_{expect\_high}(k)$ of the high-voltage side is calculated. Finally, $P_{expect\_high}(k)$ is input to a DC source model, through which the input/output of the power is realised.

3.4 AC/DC converter model

AC/DC converter model can be divided into constant power control model and the constant DC voltage control model in accordance with the control mode. The design idea of the AC/DC converter model is basically consistent with the DC/DC converter model.

The control algorithm of the constant power control AC/DC converter model is that the AC side adjusts the power angle of the controllable AC voltage source with a power control target given by the external, the control target of the AC reactive power is zero, and the DC power takes the measured actual power as the control target. Whereas the control method of the constant DC voltage model is similar to the DC/DC converter model.

4 Cases demonstration

This paper refers to a looped DC distribution network as the testing network, and the detailed information of the testing network is shown in Fig. 7 and Table 1. The based voltage of the main bus is ±10 kV. The control type '1' in Table 1 reflects constant voltage control of converter and '2' represents droop control with voltage dead area, which is ±1.5% of based voltage. Besides, the allowable fluctuation range of bus voltage is ±3% of ±10 kV. Based on the models presented in Section 3, this paper establishes the simulation model of the testing network on the SIMULINK platform.

When the output power of distributed generations and the loads change at 1.5 s, the model of distribution network simulates the dynamic process between two steady states in accordance with the network parameters and control modes of converters. Table 2 shows the detail of the power and load changes.

After the simulation, the power and voltage of several typical devices are analysed. In Fig. 8, the output powers and voltages of the wind turbine (WT) and the energy storage system ESS) change at 1.5 s because of the dispatch shown in Table 2. It is clear that the power of WT increases from 1 to 1.5 MW and the voltage is also
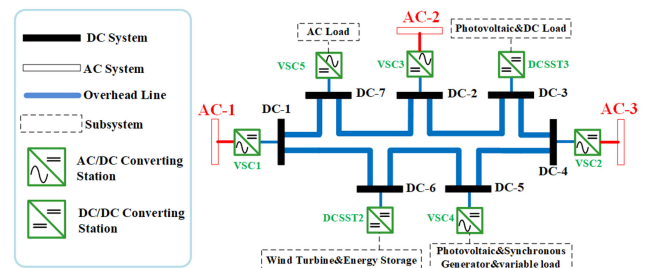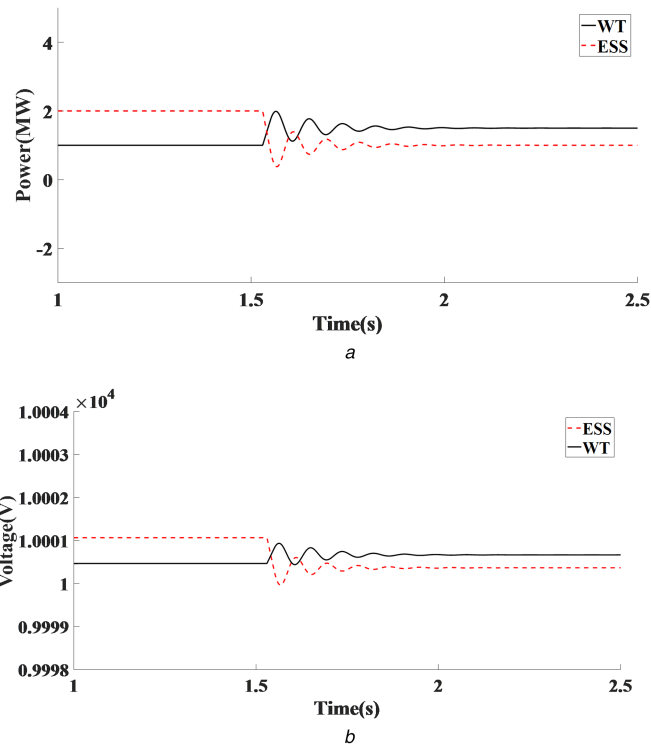

Fig. 7 *Topology of the testing DC distribution network*
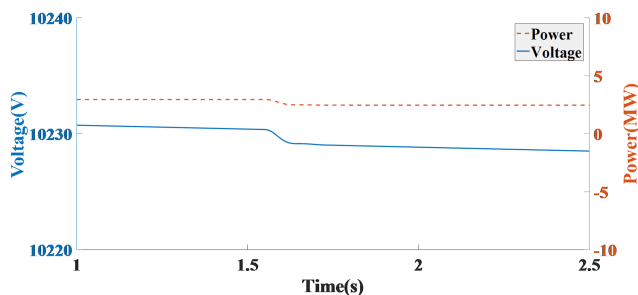
Table 1 Network data of DC distribution network

Bus	No.	Control type	Power capacity, MW	Slope, V·W⁻¹	Line	Resistance, Ω
DC-1	1	1	±10	0	1–7	0.1554
DC-2	2	2	±10	10^{-2}	7–2	0.1166
DC-3	3	2	/	10^{-2}	2–3	0.1554
DC-4	4	2	±10	3×10^{-3}	3–4	0.3108
DC-5	5	2	5	3×10^{-3}	4–5	0.3885
DC-6	6	2	3	10^{-2}	5–6	0.1554
DC-7	7	2	/	10^{-2}	6–1	0.0777

Table 2 Dispatch of distributed generations and loads

Bus	Devices	Power, MW
DC-3	photovoltaic	6 to 3
	DC load	7
DC-5	microgrid	1
	variable load	5 to 2
DC-6	WT	1–1.5
	energy storage system	2 to 1
DC-7	AC load	8

Fig. 8 *Power and voltage of WT and ESS*
(a) Powers of WT and ESS, *(b)* Voltages of WT and ESS

Fig. 9 *Power and voltage of the DC/DC converter SST2*

Fig. 10 *Power and voltage of the bus DC-2*

going up. Likewise, there is a drop in both the power and voltage of ESS.

According to Fig. 7, it can be found out that WT and ESS are connected to the DC distribution network by the DC/DC converter SST2, whose power and voltage are shown in Fig. 9. Since the total output power of WT and ESS decrease from 3 to 2.5 MW, the power of SST2 also falls off, and so does the voltage.

Fig. 10 illustrates the power and voltage of the voltage source converter-based superior system, which is referred to as AC-2. After the dispatch in Table 2, the distribution network can balance the power demand by means of the buses connected to the superior systems, manifested as absorbing power from and delivering power to the superior systems. It is clear that the distribution network absorbs power from the AC-2, and the power remains basically constant after the dispatch, which is determined by the power flow and topology of the network.

Here, limited to space, the results of the other devices are not analysed in detail.

In order to validate the accuracy of the model developed, the traditional physical model of the distribution network in Fig. 7 is constructed, the dispatch flow in Table 2 applies to the traditional model, and the results of the model developed are compared with the traditional model. As shown in Table 3, the expected power, the actual power, the actual voltage, and the voltage deviation of each bus before and after the dispatch is recorded. It is clear that the steady results of the traditional model are roughly the same as the data in Figs. 8–10. The total power generated by WT and ESS is from 3 to 2.47 MW in Fig. 8, which is from 2.9565 to 2.4667 MW in Table 3. Also the voltage of the bus DC-6 is from 10,231 to

Table 3 Steady results of the traditional model

Case	No.	Expected power, MW	Actual power, MW	Actual voltage, V	Voltage deviation, V
before	1	/	9.0215	9995.5	4.5
	2	0	−1.801	9999.7	0.3
	3	−1	−0.9422	10,051.5	51.5
	4	0	5.4678	10,009.94	9.94
	5	−4	−3.3768	10,245.3	245.3
	6	3	2.9565	10,230.2	230.2
	7	−8	−7.8388	9972.2	27.8
after	1	/	9.7589	9995.6	4.4
	2	0	−1.524	9999.7	0.3
	3	−4	−3.8763	10,049.1	49.1
	4	0	5.3408	10,009.92	9.92
	5	−1	−0.9945	10,150.3	150.3
	6	2.5	2.4667	10,228.5	228.5
	7	−8	−7.8388	9971.8	28.2

10,229 V in Fig. 9, which drops from 10,230.2 to 10,228.5 V in the traditional model. Meanwhile, the power of the bus DC-6 changes from 2.98 to 2.49 MW after the dispatch in the model developed, and it goes from 2.9565 to 2.4667 MW in the traditional model. Similarly, for the bus DC-2, the bus voltage and power in Fig. 10 are totally in agreement with the data in Table 3.

To summarise, the simplified model can accurately and rapidly simulate the transient process and steady states of the testing DC distribution network.

5 Conclusion

In this paper, the droop control of the DC distribution network is introduced. Then the simplified modelling of DC distribution network considering droop control is studied emphatically, and the model of the testing DC distribution network is presented for simulation analysis. Finally, the following conclusions are drawn:

- The models proposed based on the power–voltage characteristic curve of the bus in the paper can accurately simulate the transient process and steady states of the DC distribution network.
- The simplified model proposed can avoid the complex modelling of power electronic components and reduce the calculation burden of simulation software, making it possible to simulate large-scale DC system.
- The dynamic process during the power dispatch of DC distribution network is simulated and analysed. By adjusting the expected power of each bus, the power flow of the network can be directly changed.

6 Acknowledgments

7 References

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