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A novel system operation mode with flexible bus type selection method in DC power systems

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ABSTRACT

With the development of power electronics technology, the DC power system shows great advantages to improve the power system performance. However, the research on DC power system is far from enough, and there is great demand for the improvement of system flexibility and renewable energy integration ability. Thus, the new flexible system operation mode which can satisfy the requirements is of interest. This paper carefully analyzes and discusses the power flow problem of DC power systems first. Then, some new bus types are proposed to construct new system operation modes which can improve the system flexibility (includes friendly renewable energy sources integration ability and flexible power flow ability). The proposed power flow calculation method can solve the power flow problem with the new operation modes and new bus types. However, the feasibility of system operation may be broken by arbitrary selection of new bus types. Thus, the flexible bus type selection method is further proposed to select proper bus types. As a result, the system flexibility can be improved and the feasibility of system can be assured. At last, the numerical experiments results are presented to verify the effectiveness of proposed method.

1. Introduction

The clean and sustainable energy is an irreversible trend of human society to solve the energy crisis. In recent years, more and more the RESs (Renewable Energy Sources) are integrated into power systems [1,2]. The penetration of RESs changes some typical characteristics of power systems. For example, the unidirectional power flow in radiational system cannot be assured and the uncertainty is brought into power system. In addition, the RESs also bring more power electronics converters and interfaces [3,4].

In recent years, the power system capacity of big city especially in developing countries suffers severe challenges. Due to the limited space and tremendous reconstruction cost, how to improve the transmission capacity of existed infrastructure becomes an attractive subject.

As to loads, some new types of loads such as data centers, electrical vehicles, and communication centers have widely appeared in recent years. According to nowadays development trends, these loads will have deep influence on future city power systems. These loads are supplied by DC power, and additional power converters are needed in AC distribution system [5].

Considering the aforementioned facts and problems, the DC power technology provides a new way to solve them together. Some primitive researches on DC power system have been done to appraise the potential. If the DC distribution systems are fused into traditional AC distribution systems, the lower losses, more capacity and higher compatibility can be got [6–10]. The distribution system with DC zone is also much more friendly to RESs and DC loads, as it can decrease some inverters for integration. The traditional shortcomings of DC system such as voltage transformation are overcome by advanced power electronics technology. With the help of sensor and communication technology, the DC distribution system also will contribute to construct more advanced smart grid [11–13]. The DC zone may be very large which can be treated as a complete DC distribution system which should be deeply researched before more complicated coupling analysis with AC distribution system. However, the protection of DC systems may be more hard and expensive than AC systems. The cost of DC systems may also be larger. With more research works and development, the problems may be gradually overcome in the future.

In system level, the flexibility is mainly reflected on power flow flexibility, which contribute to the system losses, stability and lines loads. Another meaning of flexibility is in the level of components (RES, ESS, EV, etc.). Different components have different operations requirements for maximum profits. However, their operations are limited by the grid. If the DC power system can support the flexible operations

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of different components, the system flexibility will be improved and the system-level benefit can be increased. However, the flexibility of power flow and flexibility requirements of system components may cause the conflict of bus type selection in DC power analysis.

The aforementioned flexibility requirements construct a challenging but meaningful problem in DC power system. To solve this problem, the power flow in DC power system should be further researched to support the requirements. The bus types of DC power system also need to be reconsidered carefully to adapt to the future DC power system development and construct a new system operation mode to improve flexibility. Thus, this paper focuses on the system operation mode with flexible bus type selection method which is critical to future smart DC power systems.

Blaabjerg et al. [14] gives a review of the recent researches on design, control and analysis of DC distribution systems, and some advantages of DC distribution technology are also pointed out. Mackay et al. [15] discusses the benefits and application of universal DC distribution systems. Hamad et al. [16] proposes a control scheme for the voltage regulation of DC distribution systems. Mohamad and Mohamed [17] studies an island detection technique in DC distribution systems to cooperatively operate with AC systems. Marano-Marcolini et al. [18] proposes an operational strategy to assure the normal operation of DC links when communication circumstance deteriorates. Suryanarayana and Sudhoff [19] provides a design paradigm for performance optimization of DC distribution systems with lots of power electronics devices. Alacano et al. [20] proposes a multivariable modeling approach to better design and analyze power-electronics based DC distribution systems. van der Blij et al. [21] gives an algebraic derivation of the stability analysis in DC distribution systems. Liang et al. [22] studies the power flow algorithm in distribution systems including both AC and DC zones. Chen et al. [23] gives the systematic control and protection structure of DC power networks, and the novel adaptive DC power stabilizer is proposed. However, the DC distribution here is only seen as an interface to AC grid. Some finished researches can help DC distribution system to friendly integrate DGs and cooperate with AC systems. Tabari and Yazdani [24] proposes an energy management strategy which can friendly integrate plug-in electric vehicles in DC distribution systems. However, all the aforementioned researches are limited by the traditional bus types and operation modes whose flexibility potentiality is not enough. To improve the system-level performance of DC distribution system, this paper proposes a novel system operation mode with flexible bus type selection method of DC power systems.

In this paper, basic power flow analysis problems corresponding to traditional AC systems which include bus types, power flow equations, and Jacobian matrix in DC power systems are analyzed first. Then, considering the new requirements in DC power systems, bus types problem is discussed and a novel operation mode with flexible bus type selection is proposed. At last, the numerical experiments results are given to verify the effectiveness of proposed method.

2. Power flow in DC power systems

The traditional AC power flow analysis procedure mainly consists of:

1. Build the relationship between injected currents and buses voltages through the bus admittance matrix;
2. Determine the bus types according to physical condition and mathematical analysis convenience;
3. Form the power flow equations according to bus types and variables relationship;
4. Solve the equations with proper numerical methods.

The AC power flow analysis is well-known. As to DC power flow analysis, it is not difficult to understand that the DC power flow analysis is similar to AC. The power flow equations in DC power systems have similar mathematical characters with AC power systems. In view of mathematics, power flow equations in DC and AC system are both two order nonlinear equations (or more specifically, quadratic forms) about bus voltages. They are all derived with similar workflow including formation of bus admittance matrix, power flow equations and numerical solution computation [25,26]. However, there are still some differences which need further researches on DC power flow. Without reactive power and reactance, the power flow should be reconsidered. In this section, only the critical different parts of power flow analysis in DC power systems are studied to get the power flow analysis method. To improve the system-level flexibility, the new bus types and the power flow calculation method with new bus types should be studied which will be presented in following sections.

2.1. Bus conductance matrix in DC power system

Without susceptance, the admittance in AC system should be replaced by conductance in DC system. In this paper the bus conductance matrix is denoted as G_D, the component of G_D is denoted as G_{ij}

$$G_D = \begin{pmatrix} G_{1,1} & G_{1,2} & \dots & G_{1,n-1} & G_{1,n} \\ G_{2,1} & G_{2,2} & \dots & G_{2,n-1} & G_{2,n} \\ \dots & \dots & \dots & \dots & \dots \\ G_{n-1,1} & G_{n-1,2} & \dots & G_{n-1,n-1} & G_{n-1,n} \\ G_{n,1} & G_{n,2} & \dots & G_{n,n-1} & G_{n,n} \end{pmatrix} \tag{1}$$

Similar to AC bus admittance matrix, the diagonal term $G_{i,i}$ is equal to the sum of primitive conductance of all transmission lines connected to bus i. The off-diagonal element $G_{i,j}$ is equal to the negative of the primitive conductance of transmission line between bus i and bus j. Obviously, the symmetric property of the AC bus admittance matrix is reserved.

2.2. The buses types in DC power system

The power flow analysis in AC power system has three typical bus types.

- Vθ bus;
- PV bus;
- PQ bus.

As to bus types, it can be explained by following aspects:

1. The bus types correspond to the system freedoms. A bus type in fact specifies what variables can vary freely (whether actively or passively). For PV bus, the active power and voltage magnitude are constant values in each calculation. For PQ bus, the active and reactive power are constant values in each calculation. Other state variables must vary to satisfy the requirements specified by the values. It means that every kind of bus type must corresponds to a physical realization. For example, the PV bus must have generators whose output voltage can be regulated by exciting system and output power can be regulated by turbine power. For PQ bus, their loads consume the constant active and reactive power no matter how the bus voltage changes.
2. The bus type is the abstract mathematical model of all devices connected to a bus. It determines the form of one power flow equation. For AC power system, every equation is in complex domain. One complex equation will be converted to two real equations to simplify calculation.

In DC power systems, there are no reactive power and reactance, and all equations are established in real domain. Thus reactive power Q and voltage angle θ will not appear in DC power system, and the power flow equations are different. As a result, the bus types need to be