Benefit analysis of using multi-port and multi-function power electronic transformer connecting hybrid AC/DC power grids

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Abstract: This study proposes a generalised configuration of the multi-port and multi-function power electronic transformer (MPMF-PET) based mixed AC/DC power grids, and the equivalent circuit and mathematical model of the MPMF-PET are established. To illustrate the benefits of using MPMF-PET to improve the integration and power control ability of a distributed energy resource in an existing distribution network, an iterative algorithm is proposed for system power flow calculations. Case studies are carried out on a real distribution system modified with MPMF-PET. Results show that the performance of the hybrid AC/DC distribution system is increased by MPMF-PET through proper control and optimal operation, which realised the renewable energy in the AC system to power the DC system and increased the renewable energy acceptance.

1 Introduction

The integration of a large-scale distributed energy resource (DER) is a great challenge for a modern distribution power system. The application of a power electronic transformer (PET) is drawing much attention because it can reduce AC/DC and DC/AC converter amount and conversion losses and improves the DER integration [1–2]. PET with multi-port and multi-function (MPMF-PET) is a new power electronic device that can connect distribution network, microgrid, and distributed generation (DG) to realise highly flexible power flow controllability and energy complementarity for more DER integration.

The research and development of PET has attracted much attention in research institutions and industries. The typical structure and operation of PET used in distribution network are analysed in [3–7]. For the medium distribution grid, there exist two types of circuits of the PET: one is based on single-phase converter cascaded topology and the other is modular multilevel converter (MMC)-based three-phase PET. Compared with the single-phase cascaded topology, the MMC-based three-phase PET can increase the quality of the output DC voltage and reduce the number of the power switches [3, 4]. A comparative analysis of different PET topologies has been discussed in this paper [5], including the popular CHB-based approach and MMC-based topologies. The design, control, component level simulations and operation strategies of MMC-based PET have been proposed in the paper [6, 7].

The power flow method for hybrid AC/DC systems has been developed in the recent literature [8–10]. Two different models and strategies have been developed for the AC/DC interface and power flow, as the unified and the sequential approach. In the unified approach, the AC and DC equations are dealt with simultaneously as one single problem. In the sequential approach, the AC and DC systems are solved separately through an iterative process [8]. As a new power control and conversion device, there is very little research on the power flow model and the method of MPMF-PET-based mixed AC/DC power grids. There is a big difference between the VSC and MPMF-PET power flow calculation models due to the inner structure complexity and multiple ports coupling characteristics of MPMF-PET.

However, at present, all of these studies are limited by the PET inner structure design, component-level simulations and control strategies. From the distribution system level, it has great value to investigate how the MPMF-PET can be used to improve the mixed AC/DC distribution system operation and how much benefit it can bring to the distribution system. However, the research and development of MPMF-PET from the distribution system level is less discussed.

To fill these gaps, this paper explores the benefit of using MPMF-PET in the mixed AC/DC distribution network. The typical MPMF-PET structure and its model are derived base on the control and operation analysis. The power flow calculations and optimisation of MPMF-PET-connected AC/DC distribution system are discussed, which is beneficial to evaluation of MPMF-PET application. The overall contributions of this paper are summarised as follows:

I. The typical MPMF-PET structure, equivalent circuit and mathematical model are derived, which can be used for MPMF-PET-connected AC/DC distribution system analysis.
II. An alternating iterative algorithm is proposed for the MPMF-PET-connected AC/DC distribution system power flow calculations.
III. To illustrate the potential benefit of using MPMF-PET to improve the performance of the distribution network, we propose a probabilistic evaluation method and optimise the MPMF-PET operation, which can make load transfer and balancing in different power supply areas, as well as increase the renewable energy acceptance.

The remainder of the paper is as follows. Section 2 presents the generalised structure and model of the MPMF-PET. Section 3 proposes the power flow model of MPMF-PET-based mixed AC/DC power grids and a method of evaluating the benefits of using MPMF-PET. Section 4 presents a case study of using a modified distribution system, showing the effectiveness of the proposed method and the benefit of using MPMF-PET. Finally, Section 5 concludes this paper.

2 MPMF-PET structure and model

2.1 MPMF-PET structure

Due to the fast development of power electronics technology, several PET configurations have been proposed to achieve the functions of voltage conversion and energy transmission. The three-phase PET circuit for the medium-voltage distribution grid is shown in Fig. 1, and it consists of three parts, namely, the high...
2.2 MPMF-PET mathematical model

2.2.1 Input MMC part: Equivalent circuit, mathematical model and power loss are discussed in this subsection.

The equivalent circuit of the MMC [11] is shown in Fig. 3a; the arm voltages can be approximated by a sinusoidal voltage source. The upper and the lower arms drive half of the grid currents $i_d$ and the converter legs and power from the dc link are modelled through the $i_{dc}$ currents. The MMC equivalent circuit in Fig. 3a is modelled according to the KVL as follows:

$$\begin{align*}
    u_{dc} - u_d(t) - R_i i_d(t) - L \frac{di_d(t)}{dt} - u'_j(t) &= 0 \\
    -u_{dc} + u_d(t) + R_i i_d(t) + L \frac{di_d(t)}{dt} - u'_j(t) &= 0 \\
    u'_j(t) &= R_i i_j(t) + \frac{di_j(t)}{dt} + u_j(t)
\end{align*}$$

The interactions between the converter output voltage $e_j$ and the ac grid voltage $u_j$ are modelled as follows:

$$e_j = \left( Z_e + \frac{1}{j} \right) i_j + u_j \quad (2)$$

The MMC power losses $P_{\text{Loss-MMC}}$ can be calculated using a quadratic function of the AC current:

$$P_{\text{Loss-MMC}} = a + b \cdot i_j + c \cdot i_j^2 \quad (3)$$

2.2.2 Middle DAB part: The DAB circuits on the HV side and on the LV side can be replaced by the respective voltage sources $V_1$ and $V_2$ to simplify the investigations on the DAB converter. Fig. 4 shows the DAB equivalent analysis of the circuit modelling used, which is developed in [12]:

$$\eta_{\text{DAB}} = \frac{\left| P_{\text{out}} \right|}{P_{\text{in}} + P_{\text{Loss-DAB}}} \quad (4)$$

2.2.3 Output DC/AC part: The DC/AC converter is connected to the AC grid and the DC bus of MPMF-PET. The AC side of the DC/AC converter is modelled by a voltage source coupled to the AC bus through impedance $Z_{ac}$ and capacitor $C_p$ and the DC side of DC/AC converter is modelled by a current injected into the DC bus, as shown in Fig. 5. The converter losses $P_{\text{Loss-DCAC}}$ can be calculated using a quadratic function of the converter AC current the same as (3).

2.2.4 Output DC/DC part: The DC/DC converter is connected to the DC grid and the DC bus of MPMF-PET. The DC grid side of the DC/DC converter is modelled by a voltage source coupled through $R_{dc}$. The DC bus side of the DC/AC converter is modelled by a current injected into the DC bus, as shown in Fig. 6. The converter losses $P_{\text{Loss-DCDC}}$ can be calculated using a quadratic function of the converter DC current.

3 Evaluation of the benefits of using MPMF-PET

3.1 Power flow approach of AC/DC power grid based on MPMF-PET

After modelling the four parts MMC, DAB, DC/DC and DC/AC of the MPMF-PET, we establish its equivalent circuit as shown in Fig. 7. The MPMF-PET input and output sides are coupled by the energy conservation equations (5) and (6). The PET losses $P_{\text{Loss}}$ can be calculated by each part and are then summed together:

$$P_S = P_{\text{DC}} + P_{\text{AC}} + P_{\text{Loss}} \quad (5)$$
acceptance. In this paper, we set the objective function as follows:

\[
P_{\text{Loss}} = P_{\text{LossMMC}} + P_{\text{LossDAB}} + P_{\text{LossDCDC}} + P_{\text{LossDCAC}}
\]  

(6)

The sequential approach proposed in [13] has been used for the mixed AC/DC power flow because it can be easily implemented. This method starts with an initial guess of the active power injected into the AC grid, and the bus of PET connected is seen as a PQ bus because the MMC normally controls the DC bus voltage rather than the AC bus voltage; then, the AC power flow is calculated. After that, the PET losses can be calculated. Then, the power injected into the output DC grid and AC grid2 is calculated, and the result can be used for next iteration.

3.2 Evaluation of benefits of using MPMF-PET

The benefits of using MPMF-PET for the distribution system include load transfer and balancing of different power supply areas, increase in renewable energy acceptance, improvement in power quality and so on. In this paper, we set the MPMF-PET transfer real power \(P_{\text{pet}}\) and reactive power \(Q_{\text{pet}}\) as optimisation variables, which reduce the fluctuation of renewable energy and increase its acceptance. In this paper, we set the objective function as follows:

\[
\min \sum_{i} (V_{\text{pet},i} - V_{\text{nom}})^2 + \sum_{j} (V_{\text{DG},i} - V_{\text{nom}})^2
\]  

(7)

This objective function leads to an optimal dispatch of the MPMF-PET’s active and reactive power values to bring the nodal voltages of PET and DG connected as close as possible to the target value. The nominal voltage, i.e. 1 pu, was taken as the target voltage, because this is considered as a midpoint of the complicated scenarios, given that the integration of DG results in voltage rise and the electrification transport leads to low voltages.

Constraints of the MPMF-PET-based distribution system include MPMF-PET operation constraints, AC distribution network constraints and DC distribution network constraints.

The MPMF-PET operation constraints include real power balance constraints and boundary constraints of real and reactive power outputs of each port, as shown in the following equations:

\[
\sum_{i} P_{\text{pet},i} + P_{\text{Loss}} = 0
\]  

(8)

\[
P_{\text{pet},i}^{\text{min}} \leq P_{\text{pet},i} \leq P_{\text{pet},i}^{\text{max}}
\]  

(9)

\[
Q_{\text{pet},i}^{\text{min}} \leq Q_{\text{pet},i} \leq Q_{\text{pet},i}^{\text{max}}
\]  

(10)

The AC distribution network constraints include power flow equation constraints and voltage constraints of nodes, as shown in the following equations:

\[
P_{g_i} + P_{\text{pet,act}} - P_{d_i} = V_i \sum_{j} V_j \left[ G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j) \right]
\]  

(11)

\[
Q_{g_i} + Q_{\text{pet,act}} - Q_{d_i} = V_i \sum_{j} V_j \left[ G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j) \right]
\]  

(12)

Fig. 6 DC/DC output equivalent circuit

The case study based on the three-port MPMF-PET distribution system is carried out to verify the validity of the MPMF-PET system. For each scenario, we use the particle swarm optimisation algorithm to find the optimal value of the MPMF-PET operation variables, as shown in Fig. 8.

The DC distribution network constraints include power flow equation constraints and voltage constraints of nodes, as shown in the following equations:

\[
P_{\text{dc}} - P_{\text{pet,dc}} = U_{\text{dc}} \sum_{j \neq i} Y_{\text{dc},ij} \left( U_{\text{dc}j} - U_{\text{dc}i} \right)
\]  

(14)

\[
U_{\text{dc,min}} \leq U_{\text{dc}} \leq U_{\text{dc,max}} \quad \forall i \in n_{\text{dc}}
\]  

(15)

The consideration of renewable energy stochastic variations is achieved through the use of a Monte-Carlo simulation technique, which is a widely used method for handling uncertainty in the power system [14]. For each scenario, we use the particle swarm optimisation algorithm to find the optimal value of the MPMF-PET operation variables, as shown in Fig. 8.

4 Case study

The case study based on the three-port MPMF-PET distribution system is carried out to verify the validity of the MPMF-PET system.
function and previously discussed benefit evaluation. The input port of PET is of 10 kV and is connected to the 17th node of the 10-kV distribution feeder; the DC output port of PET is of 750 V and is connected to the first node of the 750-V DC distribution system; the AC output port of PET is of 380 V and is connected to the fourth node of the 380-V microgrid. The PET DC output port is operated in voltage control mode; the PET AC input and output ports are operated in power control mode, and then, renewable energy can be transferred to the DC grid to achieve power balance and renewable energy consumption. The capacity of PET is set no more than 500 kW due to branch current and economic restriction.

The test system is shown in Fig. 9.

The simulation scenario for one day of 15-min data curves is shown in Fig. 10, and includes load, wind power and photovoltaic power.

Using the methods described in this paper to optimise the active and reactive powers of MPMF-PET, the results are shown in Figs. 11–14 (10-kV AC node 12–20 is rearranged as 1–9). As can be seen from the figures, the MPMF-PET port 1 and port 2 transport active power to the DC grid, realising the renewable energy in the AC system to power the DC system; at the same time, the MPMF-PET through reactive power control controls the AC node voltages to not exceed the upper limit, which can increase the renewable energy acceptance.

The comparison of voltage distribution without MPMF-PET and with MPMF-PET optimisation for the 10-kV distribution feeder at node 16 is shown in Fig. 15, and the voltage distribution of all nodes at t = 13:30 is shown in Fig. 16. As we can see, the voltage level is greatly improved through MPMF-PET control.
5 Conclusion

In this paper, we proposed the benefits of using MPMF-PET in the hybrid AC/DC distribution system. We establish the four parts MMC, DAB, DC/DC and DC/AC of the equivalent circuit and also proposed a mathematical model of the MPMF-PET. After that, the MPMF-PET equivalent circuit for power flow is given, and the sequential approach is used for the mixed AC/DC power flow calculation. In order to analyse the benefits of load balancing of different power supply areas and the increase in renewable energy acceptance, we propose an optimisation model for the evaluation of benefits. The nodal voltages of MPMF-PET and DG-connected buses are brought to the target value through optimal dispatch of the MPMF-PET's active and reactive power values. A case study based on a practical power system is used to verify the functions of MPMF-PET and our optimisation method. The simulation results show that the performance of the entirely hybrid AC/DC distribution system is increased by MPMF-PET through proper control and optimal operation, which released the renewable energy in the AC system to power the DC system and increase the renewable energy acceptance.

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7 References

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