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STATE ESTIMATION OF AC/DC HYBRID DISTRIBUTION NETWORK WITH PET

Jia Si[1], Yunfei Mu [1], Hongjie Jia[1], Qian Xiao[1], Tianjiao Pu[2], Ye Li[2], Xiaohui Wang[2]

1 Key Laboratory of Smart Grid of Ministry of Education (Tianjin University), Tianjin 300072, China

2 China Electric Power Research Institute, Beijing 100192, China

ABSTRACT

In AC/DC hybrid distribution network with power electronic transformer (PET), the topology is more complex and the operation mode is more flexible. As a result, it is of significance to study the state estimation method of hybrid network. This paper starts from PET steady state model considering the converter loss, and then analyses its control method for AC/DC hybrid network. By adding the virtual nodes, a unified state estimation model for power electronic equipment is established. The pseudo-measurement equation is formulated according to the control equation of power electronic equipment to improve the redundancy of data. Finally, a state estimation method for AC/DC hybrid networks with PET is proposed. A test case of an AC/DC hybrid network with PET is used to verify the effectiveness of the proposed method.

Keywords: power electronic transformer (PET), steady state model, hybrid AC/DC network, three-phase state estimation, pseudo-measurements

1. INTRODUCTION

In recent years, more and more distributed generation (DG) has been applied in power system, especially at the distribution level. However, this situation brings the problem of power grid security operation and efficient energy consumption. The loss of the AC/DC converters is huge, since DGs are usually connected to the AC network. On the other hand, the flexible regulation and interconnection capabilities of the current power grid are not flexible enough to realize the economic use and full consumption of DGs[1]. To solve the above problems, the power electronic transformer (PET) is introduced to build an AC/DC hybrid network. The PET is the combination of power electronic circuit and traditional high frequency transformers, which has both AC interface and DC interface[2]. It has the function of power regulation, which can accurately coordinate the power distribution between AC subsystem and DC subsystem. As a result, the PET can significantly improve electricity efficiency and realize the interconnection of distributed energy, which is the future development trend.

However, the structure of AC/DC hybrid network based on PET is complex, and its operation is more flexible. To obtain its real operation state is the premise of realizing complementary optimization and coordinated control. As a vital part of Energy Management System, state estimation can provide reliable real-time data of operating state[3][4]. Therefore, it is of great significance to study the state estimation of hybrid AC/DC distribution network with PET.

Many researches have already been carried out on PETs. However, the existing papers are mainly focused on the design and control strategy of PET. The state estimation of AC/DC hybrid network with PET has not been fully studied yet. An alternative iteration algorithm to solve the power flow of distribution network with PET was proposed in [5], but the multiport interconnection is not considered. A steady-state power flow model of PET was formulated in [6], but the DC subsystem and the unbalance situation is not considered. Considering the problem of the low data redundancy in low-voltage networks, a method to add pseudo-measurement equation based on the control equation of power electronic equipment was introduced in [7]. The interface of PET also has high precision voltage and power control capability. How to use this information to improve the state estimation accuracy needs to be further studied.

In this paper, a state estimation method for AC/DC hybrid networks with PET is proposed, and the least

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square method is used to solve the problem iteratively. Considering the three-phase unbalance of voltage in low-voltage network, this paper establishes a three-phase model of low-voltage AC network. By adding the virtual nodes, a unified state estimation model for power electronic equipment is established. To solve the problem of insufficient measurement information in low-voltage network, a method of adding pseudo-measurement equation according to the control mode of power electronic equipment is proposed. Finally, an AC/DC hybrid network with PET is used to verify the effectiveness of the proposed method.

2. CONFIGURATION AND CONTROL MODE OF PET

2.1 The structure of PET

The main circuit of PET is based on a three-stage structure, containing high-voltage (HV) input stage, high frequency isolation transformer and low-voltage (LV) output stage, as shown in Figure 1[13][14]. Firstly, input AC/DC converter converts high voltage alternating current (AC) to high voltage direct current (DC). Then through high frequency isolation transformer, the square wave is coupled to the transformer vice side. Thirdly, according to the power demand, the LV side is linked to the DC network, or convert to AC voltage through an AC/DC converter.

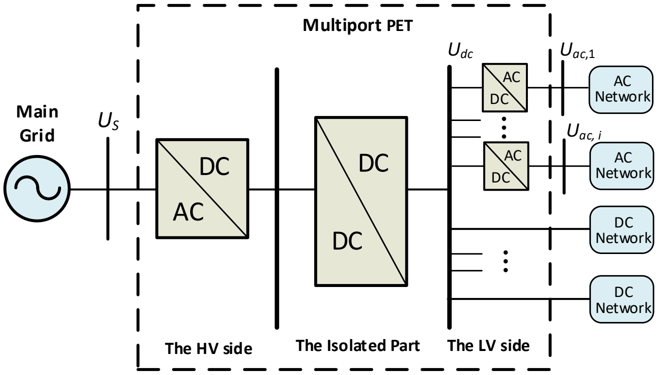

Fig. 1 Topological structure of multiport PET

2.2 The model of AC/DC converter

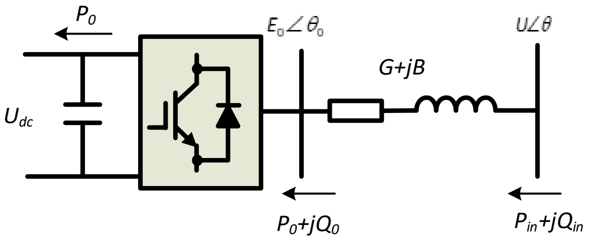

Fig. 2 Equivalent circuit of AC/DC converter

Each AC interface of PET can be considered as an AC/DC converter, whose equivalent circuit is shown in Figure 2. The $E_0\angle\theta_0$ is the voltage phasor at the AC side of the converter. The equivalent loss of each converter is described by $G+jB$. U_{dc} represents the voltage of the DC side of the converter.

The active power P_{in} and the reactive power Q_{in} exchanged between the system and the converter are expressed as:

$$\begin{cases} P_{in} = GU^2 - UE_0(G\cos(\theta-\theta_0) + B\sin(\theta-\theta_0)) \\ Q_{in} = -BU^2 + UE_0(B\cos(\theta-\theta_0) - G\sin(\theta-\theta_0)) \end{cases} \tag{1}$$

The active power P_0 and the reactive power Q_0 injected into the converter are written as:

$$\begin{cases} P_0 = -GE_0{}^2 + UE_0(G\cos(\theta_0-\theta) + B\sin(\theta_0-\theta)) \\ Q_0 = BE_0{}^2 - UE_0(B\cos(\theta_0-\theta) - G\sin(\theta_0-\theta)) \end{cases} \tag{2}$$

The HV side of PET, which is connected to the main grid is analyzed as a balanced system. However, in the low-voltage AC network, as the three-phase is usually unbalanced, the power needs to be calculated in each phase. The method is the same as (1)-(2).

2.3 The loss and power constraint of PET

The active power loss of the isolated DC/DC converter mainly consists of 1) dynamic loss, which is related to actual power exchange; 2) static loss, which has no relevance to the operating state of PET. For the power loss of distribution network itself is considerable, only static loss ΔP_{st} is considered in this paper. The active power balance constraint of PET is formulated as:

$$P_M + \sum_{j=1}^{S}\sum_{\varphi=a}^{c} P_{ac,j}^{\varphi} + \sum_{k=1}^{T} P_{dc,k} = \Delta P_{st} \tag{3}$$

where P_M represents the power injected from the main grid. S, T are the number of AC interfaces and DC interfaces, respectively. The power of each phase of the j-th AC interface is described as $P_{ac,j}^{\varphi}$. The power of the k-th DC interface is described as $P_{dc,k}$.

Therefore, by combing (1)-(3), the steady model of PET is formulated, which is suitable to the analysis of AC/DC hybrid network.

2.4 PET control method for AC/DC hybrid network

Since the lacking of generator bus to support voltage stability inside the low-voltage network, the LV sides of PET are designed using constant voltage control. The PET keeps constant voltage and frequency at low-voltage AC side and constant voltage at low-voltage DC side within rating limit. Therefore, the PET is equivalent to a constant voltage source for the low-voltage network. As a high precision power electronic equipment, the PET implements individual phase control of the voltage amplitude $U_{ac}^{a,b,c}$ and the voltage phase angle $\theta_{ac}^{a,b,c}$, in order to keep the independence of three phase voltage.

On the HV side, the PET keeps the voltage and current in same phase, making the PET is equivalent to a "resistivity load" or a "constant-current source" for the main grid. By relaxing the control of active power on HV side, main grid balances the surplus or shortage.

3. STATE ESTIMATION ALGORITHM FOR AC/DC NETWORK WITH PET

3.1 Weighted least squares estimation

Weighted least squares estimation is one of the most common methods in power system state estimation, which is described as:

$$\min J = [\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})]^{\mathrm{T}} \boldsymbol{W} [\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})] \tag{4}$$

where $\boldsymbol{x}$ denotes the system state variable. In this paper, the amplitude and phase angle of node voltage are chosen. The measurements are arranged in vector $\boldsymbol{z}$ and are composed of real-time measurements, zero injection virtual measurements and pseudo-measurements. ***h(x)*** describes the nonlinear relation between system state variable and measurement. The $\boldsymbol{W}$ is the weight coefficient matrix of the measurement.

The nonlinear equations ***h(x)*** is solved iteratively with Gauss-Newton method.

$$\Delta\hat{\boldsymbol{x}}^{(l)} = [\boldsymbol{H}(\hat{\boldsymbol{x}}^{(l)})^{\mathrm{T}} \boldsymbol{W} \boldsymbol{H}(\hat{\boldsymbol{x}}^{(l)})]^{-1} \boldsymbol{H}^{\mathrm{T}}(\hat{\boldsymbol{x}}^{(l)}) \boldsymbol{W} [\boldsymbol{z} - \boldsymbol{h}(\hat{\boldsymbol{x}}^{(l)})] \tag{5}$$

$$\boldsymbol{x}^{(l+1)} = \hat{\boldsymbol{x}}^{(l)} + \Delta\hat{\boldsymbol{x}}^{(l)} \tag{6}$$

The ***H(x)*** is the Jacobian matrix of function vector, whose elements are expressed as:

$$H_{ij}(x^{(l)}) = \left.\frac{\partial h_i}{\partial x_j}\right|_{x=x^{(l)}} \tag{7}$$

3.2 The characteristic of state estimation for AC/DC hybrid network with PET

As an energy transfer station among main grid, AC subsystem and DC subsystem, PET is applied to coordinate power flow. The state estimation needs to calculate not only the state of each system, but also the state variable on each interface of PET, as well as its power flow distribution. As a result, a state estimation method for AC/DC hybrid network with PET need to be formulated, considering the steady model of PET and its control equation.

Low-voltage networks are equipped with a large number of DGs. Commonly, the DGs connect to the DC subsystem through DC/DC converter, and connect to the AC subsystem through DC/AC converter or AC/DC/AC converter. Since real-time measurements are limited in low-voltage networks, the control equations of converters can be used as available pseudo-measurements with high precision, in order to enhance the observability.

3.3 Virtual node

Through equations (1) and (2), the power flow expression of each AC/DC converter is similar to that of traditional AC network. Therefore, a unified power flow model can be formulated, in order to establish an integrated state estimation algorithm. For the AC/DC converter described in Figure 3, the virtual node is added to each interface. As a result, the model of converters could be included into the existing system.

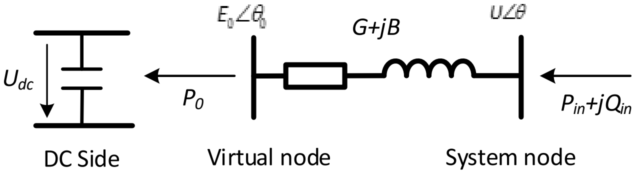

Fig.3 Diagram of virtual node

Since that the amplitude and phase angle of node voltage are used as state variable, the amplitude E_0 and phase angle θ_0 of virtual node need to be added into the state variable. As a result, the state variable $\boldsymbol{x}$ will be extended to equation (8):

$$\boldsymbol{x} = \begin{bmatrix} U \\ \theta \\ E_0 \\ \theta_0 \end{bmatrix} \tag{8}$$

3.4 Adding pseudo-measurements for PET

On LV side of PET, each converter should be set as voltage control, i.e. amplitude and phase angle of the voltage at AC interface, the amplitude of the voltage at DC interface. The pseudo-measurement equations are formulated according to the control method:

$$\begin{cases} 0 = u_{dc}^{ref} - u_{dc} + v_{u_{dc}} \\ 0 = U_{ac}^{\varphi,ref} - U_{ac}^{\varphi} + v_{U_{ac}^{\varphi}} \\ 0 = \theta_{ac}^{\varphi,ref} - \theta_{ac}^{\varphi} + v_{\theta_{ac}^{\varphi}} \end{cases} \tag{9}$$

where superscript *ref* denotes the reference of controlled object. v represents measurement error of corresponding equation.

On HV side of PET, the power control is relaxed to satisfy the power balance constraint. In addition, the reactive power is controlled to zero, and the voltage and current are kept in same phase. A pseudo-measurement equation and a virtual measurement equation are formulated:

$$\begin{cases} 0 = P_M + \sum_{j=1}^{S} \sum_{\varphi=a}^{c} P_{ac,j}^{\varphi} + \sum_{k=1}^{T} P_{dc,k} - \Delta P_{st} \\ 0 = Q_{1s} + v_{Q_{1s}} \end{cases} \tag{10}$$

3.5 Adding pseudo-measurements for DGs

3.5.1 DGs connected to AC network

The converter, used to connect the DGs and AC network, is assumed that its structure and output voltage is three-phase balanced. The corresponding pseudo-measurement equations can be obtained:

$$\left|E_{0,i}^{a}\right|-\left|E_{0,i}^{b}\right|=0 \tag{11}$$

$$\left|E_{0,i}^{a}\right|-\left|E_{0,i}^{c}\right|=0 \tag{12}$$

$$\theta_{0,i}^{a}-\theta_{0,i}^{b}-\frac{2\pi}{3}=0 \tag{13}$$

$$\theta_{0,i}^{a}-\theta_{0,i}^{c}+\frac{2\pi}{3}=0 \tag{14}$$

There are many different kinds of controlling strategies for DGs. In this paper, the *PQ* control and $U_{dc}Q$ control are taken as an example to analyze.

In the *PQ* control, the pseudo-measurement equations are formulated:

$$P_{Gi}^{ref}=P_{Gi}^{a}+P_{Gi}^{b}+P_{Gi}^{c} \tag{15}$$

$$Q_{Gi}^{ref}=Q_{Gi}^{a}+Q_{Gi}^{b}+Q_{Gi}^{c} \tag{16}$$

In $U_{dc}Q$ control, the injected active power in DC side needs to be calculated in advance. Therefore, equation (15) needs to be rewritten as:

$$P_{dc}(U_{dc}^{ref})=P_{Gi}^{a}+P_{Gi}^{b}+P_{Gi}^{c} \tag{17}$$

3.5.2 DGs connected to DC network

Some DGs, such as photovoltaic, always operate in MPPT mode, and all the electric value are inconstant. Others, such as the energy storage battery, the current or voltage is set to the constant value, which is formulated as:

$$0=U_{dc}^{ref}-U_{dc}+v_{U_{dc}} \tag{18}$$

$$0=I_{dc}^{ref}-I_{dc}+v_{I_{dc}} \tag{19}$$

4. CASE STUDY

The proposed method is applied to a typical AC/DC hybrid network with PET. As shown in Figure 4, the case includes a 750V 9-bus DC subsystem and a 400V 13-bus AC subsystem. There are four DGs in the case. The micro-turbine at bus 6 is connected to grid directly and the rest DGs are connected through converters. The control methods are shown in Table 1.

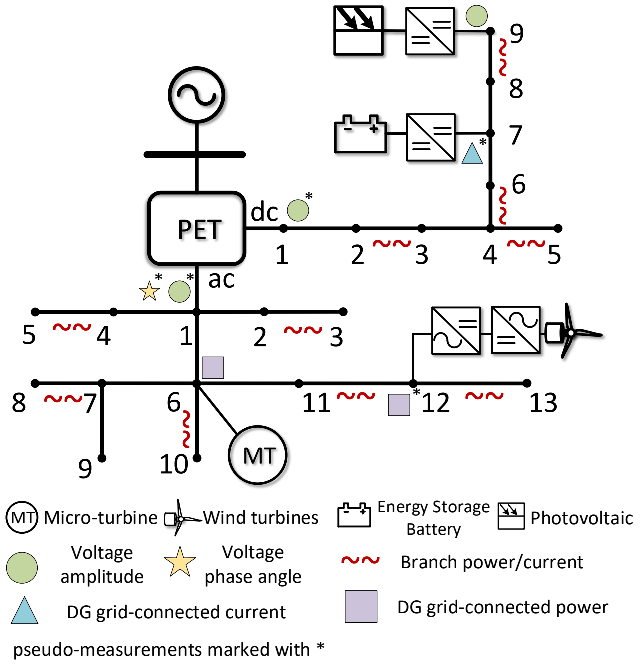

Fig. 4 AC/DC hybrid network with PET

The pseudo-measurement is generated on each load node based on historical data and real-time weather forecast. The pseudo-measurements of PET and converters are formulated according to the control method. In addition, some real measurement devices are configurated in this system, which are shown in Table 2.

The measurement data is generated by superimposing a normal distribution noise with an average value on the power flow calculation. The real measurement error is 0.002, and the load pseudo-measurement error is 0.05.

Virtual nodes are added into AC network according to 3.3. The AC LV side is marked with node 0 and the wind turbines interconnection node is marked with node 14.

The results of the absolute errors of voltage amplitude and phase angle are shown in Figure 6 and Figure 7, respectively. Each group of data represents a, b and c phase from left to right.

The maximum absolute errors of the voltage amplitude and phase angle are 4.75e-05 and 1.96e-03, respectively. The average absolute errors are 1.83e-05 and 4.74e-04, respectively. According to the results, the proposed method shows good performance.

Table 1 DGs' control methods

	DG	Converter type	Control method
DC network	Photovoltaic	DC/DC	MPPT control
	Energy Storage Battery	Bidirectional DC/DC	Constant-current control
AC network	Wind turbine	AC/DC	*PQ* control
		DC/AC	$U_{dc}Q$ control

Table 2 System real measurement configuration

System	Measurement type	Measurement number
AC subsystem	DG grid-connected power	1
	Branch active power	6
	Branch reactive power	6
DC subsystem	Voltage amplitude	1
	Branch current	4

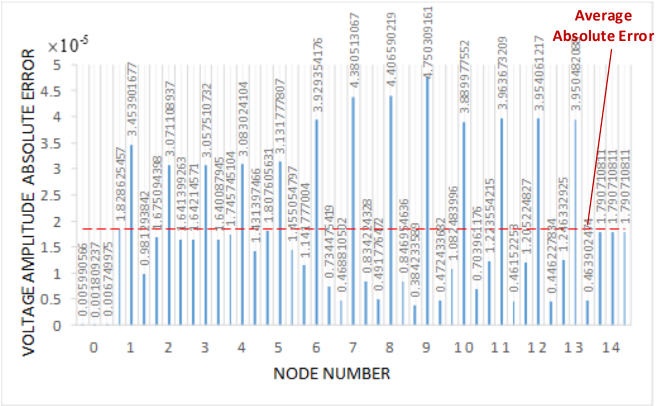

Fig. 5 Voltage amplitude absolute error

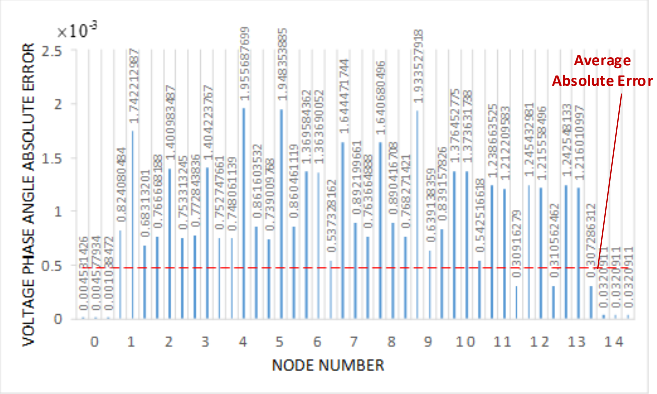

Fig. 6 Voltage phase angle absolute error

In addition, some electrical quantities are determined, which are shown in Figure 7.

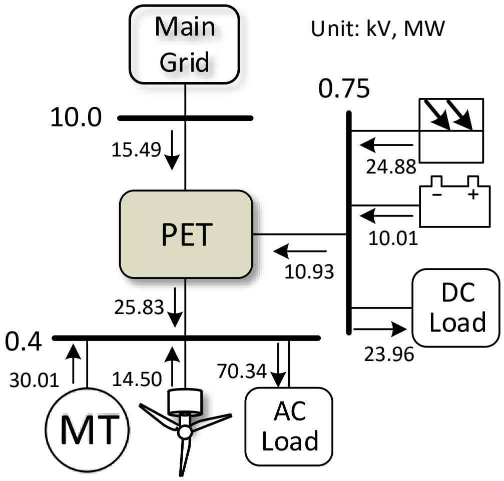

Fig. 7 Calculation result of AC/DC hybrid network

The arrows and figures represent the direction and quantity of active power. The rest figures denote the voltage amplitude. In this case, the load in subsystem is large, and main grid provides the power shortage.

Changing the load demand and DGs output, the PET will operate in different state, as shown in Table 3.

Table 3 The operating state at various ports of PET

State	Low-voltage network	P_{ac}	P_{dc}	P_M
1	Power consumption	Two-way	Two-way	Forward
2	Power feedback	Two-way	Two-way	Backward

In Table 3, P_M denotes the power flow on the HV side. The inflow of PET is positive and the outflow of PET is negative. P_{ac} and P_{dc} denote the power flow on the LV side.

According to the calculation results, when the output of distributed generation fluctuates, PET can quickly and accurately coordinate the power flow among the main network, DC subsystem and AC subsystem to ensure the stable operation of AC/DC network.

5. CONCLUSION AND DISCUSSION

A state estimation method for AC/DC hybrid networks with PET is proposed in this paper, and the least square method is utilized to solve the problem iteratively. An example of an AC/DC hybrid network with PET is given to verify the effectiveness of the proposed method.

The PET steady state model proposed in this paper is not only suitable for power flow algorithm and state estimation, but for security and stability analysis, optimization and other research direction. Furthermore, an application scenario of AC/DC hybrid system based on PET is built, considering the control strategies and operation characteristics of different renewable energy. Besides, if the multiple PETs are adopted in the system, the networks with different voltage level will be connected. Therefore, the interconnection of electric energy can be realized in a wider range. Also, the multi-PET coordinated control will be more flexible. Besides the constant voltage control analyzed in this paper, there will also be droop control, master-slave control and other control modes. In the follow-up work, we will concentrate on the state estimation of AC/DC hybrid networks with different voltage level under the multi-PET coordinated control.

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