Coordinative Control Strategy for Power Electronic Transformer with Microgrid Connection

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Abstract: Power electronic transformer integrates rich forms of electrical interfaces and is able to realize a flexible, accurate and continuous regulation of the network power flow. It’s a promising power equipment to act as the ‘energy router’ in the energy internet, achieving a large-scale access and efficient utilization of distributed energy resources. To solve the DC-bus voltage fluctuation of PET caused by the randomness of the output power of microgrid, a coordinative control strategy between the input stage, isolation stage of PET and the microgrid is proposed. The frequency-domain analysing method is used compare the characteristics of the power fluctuation response under the proposed coordinative control strategy and a traditional control strategy. The simulation results indicate that the proposed control strategy can achieve the stability and fast convergence of DC bus voltage, which proves the correctness and advancement of the coordinative control strategy.

1. Introduction
To cope with the contradiction between the shortage of fossil energy and the increasing load year by year [1], countries worldwide are now developing Distributed Renewable Energy Technologies. Traditional AC power grid lacks the capability of flexible regulation [2], so it’s incapable to fully absorb and utilize a large penetration of renewable energy. In this context, the concept of “Energy Internet” emerged as the times require. Based on the local consumption of DGs, the energy internet aims to build a bottom-up interconnective energy system, with microgrids, smart communities as energy units, and energy routers as central devices [3]. It’s a feasible solution for the energy crisis.

Power electronic transformer is a novel intelligent power equipment which combines power electronic converter technologies with high-frequency transformation technologies. In addition of having the potential to replace traditional transformers, PET has many ancillary functions like reactive power compensation, fault isolation, power quality adjustment, etc. It also provides a rich form of power interfaces for DGs and microgrids, and is expected to act as the energy router in energy internet.

Presently, there have been many literatures relating to the control strategy of cascaded PET, but most of these strategies are independent control. There are few studies focused on coordinative control between different parts of PET and the power quality control under microgrid connection. To solve the harmonic voltage fluctuation of PET’s DC buses caused by non-linear loads, a strategy combining direct voltage control with virtual impedance control was proposed in document [4], which is essentially based on the harmonic current feed-forward compensation. Document [5] analysed the causes of the secondary ripple voltage from the perspective of energy transmission, and proposed a ripple voltage suppression strategy based on the ripple power path. Document [6] proposed a two-
stage coordinated control strategy that feeds back the working state of the inverter to the control link of the rectifier, improving the response speed of the DC bus voltage. There is certain reference significance in these new control strategies, but none of them take the access of microgrid into account. This paper is focused on the coordinative control strategy of PET. Firstly, the frequency response method is used to analyse the influence of microgrid on the DC voltage fluctuation of PET under a traditional control strategy. Based on this, a co-operating control strategy between the input stage and isolation stage is proposed to enhance the voltage stability of the LVDC bus. The microgrid and AC load current feed-forward controller is also introduced to eliminate their influence on DC bus voltage. The simulation results substantiate the correctness and effectiveness of the proposed control strategy.

2. PET model and traditional independent control strategy

2.1. Mathematical model of PET

![Figure 1. Topology of the power electronic transformer](image)

The topology of PET adopted in this paper is shown in Fig. 1. It’s composed of a three-phase modular multilevel converter as the input stage, an input-series output-parallel CLLC resonant converter as the isolation stage and a three-phase four-leg inverter as the output stage. The structure of the PET-based grid-connected microgrid system is shown in Fig. 2. Considering the advantages of DC microgrids over AC microgrids in system cost, control simplicity, and number of converters, a DC microgrid with 700V voltage bus is selected and connected to the LVDC port of the PET. The DC microgrid consists of photovoltaic power supply, battery and DC load.

![Figure 2. Topology of PET-based DC microgrid](image)

Ideally, the common DC bus current is divided equally among three phases of MMC and the three phases should be completely symmetrical. In this case, the three-phase MMC can be equivalent to three single-phase systems. The dynamic equation in dq frame is shown in equation 1.
\[
\begin{align*}
\begin{aligned}
\frac{d}{dt}(L_S + \frac{L_a}{2})i_q &= E_d - U_d + \omega \left( L_S + \frac{L_a}{2} \right) i_q \\
\frac{d}{dt}(L_S + \frac{L_a}{2})i_d &= E_q - U_q - \omega \left( L_S + \frac{L_a}{2} \right) i_d \\
C_{He} \frac{dU_{dc}}{dt} &= \frac{3E_d i_d}{2U_{dc}} - \sum_{i=1}^{N} i_{1i} = \frac{3E_d i_d}{2U_{dc}} - i_1
\end{aligned}
\end{align*}
\] (1)

Where, \(E_d\) and \(E_q\) are the voltage of the distribution network; \(i_q\) and \(i_d\) are the current of MMC on the AC side; \(U_q\) and \(U_q\) are the AC outlet voltage of MMC; \(L_s\) and \(L_a\) are the filter inductance and arm inductance on the grid side; \(\omega\) is the fundamental frequency of the system; \(U_{dc}\) is the HVDC voltage of MMC; \(C_{He}\) is the equivalent series inductance of MMC; \(i_{1i}\) is the primary current of the isolation sub-module \(i\), where \(i=1,2,3,...,N\), \(N\) denotes the submodule number; \(i_1\) is the sum of the primary side currents.

The input-series output-parallel CLLC resonant converter is chosen as the isolation stage. The structure of a single submodule of it is shown in Fig. 3:

![Figure 3. The structure of a single submodule of the isolation stage](image)

When single-phase-shift control is adopted [7], the dynamic models of input, output current and output voltage of the sub-module can be expressed as follows:

\[
\begin{align*}
\begin{aligned}
\dot{i}_{1l} &= \frac{8nU_{dc}}{\pi^2 Z_{eq}} \cos \varphi_i \\
\dot{i}_{2l} &= \frac{8nU_{dc}}{\pi^2 Z_{eq}} \cos \varphi_i \\
NC_i \frac{dU_o}{dt} &= \sum_{i=1}^{N} \frac{8nU_{dc}}{\pi^2 Z_{eq}} \cos \varphi_i - i_{inv} - i_{mc}
\end{aligned}
\end{align*}
\] (2)

Where, \(U_{dc1}\) and \(U_o\) are the primary and secondary side DC voltage of the sub-module \(i\); \(i_{1l}\) and \(i_{2l}\) are the currents on both sides; \(i_{lc}\) is the output current of the whole isolation stage; \(i_{inv}\) and \(i_{mc}\) are the currents of the output stage and microgrid; \(C_i\) is the capacitance on the primary side; \(NC_i\) is the equivalent parallel capacitance of the LVDC bus; \(n\) is the ratio of the high frequency transformer; \(\varphi_i\) is the phase shift angle of the sub-module.

2.2. Traditional hierarchical independent control strategy

Traditional control strategy of PET is generally the three-stage independent control [8], that is, the voltage and current double-loop is adopted in input-stage to regulate the HVDC bus voltage and the current on the grid side; the single-phase-shift control based on a single voltage loop is adopted in the isolation stage to stabilize the LVDC bus voltage; and also the double-loop control is used in the output stage to adjust the magnitude and frequency of the AC voltage. The control diagram under traditional strategy is shown in Fig. 4. The balance control for the CLLC converters are not considered in this paper.
Under traditional control, the control objectives of different parts of the PET are independent, which not only ignores the inherent coupling characteristics of the internal electrical quantity, but also increases the fluctuation of bus voltage when occurring the power swing. Especially when the microgrid is connected to the distributed network through the LVDC port of the PET, the uncertainty of the output power needs to be compensated by the fast response of the DC-DC stage to maintain the stability of the voltage bus. Normally, under the grid-connected operation, the power of the DC-DC converter comes from the HVDC bus of the input stage, but the power response speed of the input stage is far slow than that of the isolation stage in traditional control, resulting in the unstable of the system voltage. Therefore, the traditional control strategy is not suitable for the case that PET is used as a grid connection device.

3. The coordinative control strategy of PET and the comparative analysis

3.1. Coordinative control strategy of PET

In order to reduce the impact of the microgrid power fluctuation on the voltage stability of PET, a coordinative control strategy between the input stage, isolation stage of PET and the microgrid is proposed in this paper. The overall control diagram is shown in Fig. 5. Due to the access of microgrid, the LVDC bus voltage of PET has a tendency of fluctuating. The output-stage inverter and DC microgrid are simulated to current sources in this paper, and the influence of the current fluctuation of DC microgrid on the output voltage of isolation stage is eliminated by a feed-forward control branch. Moreover, the control objective of maintaining a high-quality LVDC bus voltage is achieved by the input stage and isolation stage jointly, realizing a co-operating among all parts of the PET.

Figure 4. Traditional Control Strategy of PET

(a)Control of the input stage  (b)Control of the isolation stage  (c)Control of the output stage

Figure 5. The coordinative control strategy proposed in this paper

In Fig. 5, $G_{uo}$ is the PI transfer function for the isolation-stage voltage controller; $G_{id}, G_{q}$ and $G_{iq}$ are the transfer functions for the input stage double-loop controller; $U_{dcref}, Q_{ref}$ are the reference values of HVDC bus voltage and reactive power of the input stage; $i_{dref}$ and $i_{qref}$
are the reference values of the inner-loop current of the input stage; \( I_{ref} \) is the reference value of the LVDC bus voltage; \( G_{ps} \) is the transfer function from the phase shift angle to the secondary side current \( i_2 \), which is determined by the expression (2-2). It can be seen that the formula (2-2) is non-linear, and the range of the phase shift angle \( \phi \) in the actual system is 0–\( \pi \), so (2-2) is linearized to obtain:

\[
\begin{align*}
    \dot{i}_2 & = a + b\phi \\
    a & = \frac{8nU_{dc}}{\pi^2|Z_{eq}|} \\
    b & = \frac{16nU_{dc}}{\pi^3|Z_{eq}|}
\end{align*}
\]

(3)

In Fig. 5, control branch 1 feeds the sum of the microgrid current and output stage current forward to the isolation stage as a new control variable, aiming to improve the current response speed of the isolation stage and eliminate the bus voltage fluctuation caused by the power swing of the microgrid. Control Branch 2 not only feeds the control variables of the isolation stage back to the the inner loop of the input stage, bringing the input stage and isolation stage together to maintain the stability of the LVDC bus voltage, but also feeds the output current forward, which eliminates the impact of the isolation stage current on the HVDC bus voltage to a certain extent. In the formula: \( k_1 \) and \( k_2 \) are the control coefficient; \( G_{fb} \) is the feed-forward transfer function; \( G_{cc} \) is the coordinated control transfer function. The corresponding expressions are as follows:

\[
\begin{align*}
    G_{fb} = \frac{1}{b} \\
    G_{cc} = \frac{2bU_{dc}(G_{id} + sL_0)}{3nE_dG_{id}}
\end{align*}
\]

(4)

3.2. Comparative analysis of the response to the power fluctuation in microgrid

From Fig. 4 and Fig. 5, the disturbance response function of the HVDC and LVDC bus voltage to the output current \( I_L \) under the traditional control strategy after the control branch 1 is added is obtained as follows:

\[
\begin{align*}
    \frac{U_{dc}}{I_L} & = -\frac{U_{out}}{I_L} = -\frac{1}{bG_{uo}-NC_{LS}} \\
    & \frac{1}{bG_{uo}-k_1NC_{LS}} \\
    & = \frac{n(G_{uo}-NC_{LS})(sC_{He}+\frac{3E_dG_{id}G_{idd}}{2U_{dc}})}{G_{id}+sL_0}
\end{align*}
\]

(5)

According to Fig. 5, the disturbance response function under the coordinative control strategy can be obtained as follows:

\[
\begin{align*}
    \frac{U_{dc}}{I_L} & = -\frac{U_{out}}{I_L} = -\frac{1-k_1}{bG_{uo}-NC_{LS}} \\
    & \frac{(1-k_1)(bG_{uo}+NC_{LS})}{n(G_{uo}-NC_{LS})(sC_{He}+\frac{3E_dG_{id}G_{idd}}{2U_{dc}})}
\end{align*}
\]

(6)

By comparing (5) and (6), it can be seen that the proposed control strategy can greatly reduce the impact of power fluctuation of the microgrid on the bus voltage of PET. When the feed-forward coefficient \( k_1 = 1 \), the effect of the power fluctuation on the bus voltage can be completely eliminated theoretically. In addition, the introduction of the feedback branch brings the input stage and isolation stage together to maintain the stability of the LVDC bus voltage, which is a further insurance for the voltage quality.
According to the simulation parameters listed in Table 1, the bode diagram of the disturbance response of the bus voltage can be plotted in Fig. 6. It can be seen from the figure that the introduction of the extra control branches can greatly reduce the disturbance gain of the DC voltage bus, and ensure a high-quality voltage under the condition of microgrid access.

4. Simulation results

PSCAD/EMTDC is used to build the simulation model of the PET-based grid-connected system as described in Fig. 2 above. The rated capacity of the PET is 1.2MVA, and the output stage is connected with 1MW line frequency AC load. The other simulation parameters of the whole system are shown in Table 1.

| Distribution network voltage | AC side filter inductor (L_s) | Arm inductance of MMC (L_m) | Number of submodules of MMC | Reference value of HVDC voltage (U_{dc ref}) | Isolation-stage module number(N) |
|-----------------------------|-------------------------------|-----------------------------|-----------------------------|--------------------------------------------|----------------------------------|
| 10kV                        | 10mH                          | 20mH                        | 6                           | 20kV                                       | 6                                |

When simulating, the unity power factor is realized on the AC side of the PET. The output power of microgrid increases from 0.2MW to 1.9MW at 2 seconds. The responses of the whole system under traditional control strategy and the coordinative control strategy proposed in this paper are compared in the case of a large bidirectional fluctuation of the output power of PET. The simulation results are shown in Figs. 7 and 8.
Figure 8. The comparison of the power following

It can be seen from the figures above that, when suffering the same level of power swing, the maximum voltage fluctuation of the LVDC bus and the HVDC bus under the traditional control strategy are about 23V and 380V respectively, and the dynamic response time is about 0.3 seconds; while the maximum voltage fluctuation under coordinative control strategy proposed in this paper are about 10V and 150V respectively, and the response time is about 0.1 seconds, which is far more better than the traditional strategy. Through comparative analysis, it can be seen that the coordinative control strategy can significantly reduce the voltage fluctuation of the DC buses on the condition of a two-way large-range output power fluctuation of the load, and improve the response speed difference between the input stage and isolation stage of PET at the same time, enabling the input stage and isolation stage to operate as a whole to maintain a high-quality bus voltage.

5. Conclusion
In this paper, a PET-based grid-connection equipment is studied. At first, the mathematical model of PET is established, and its traditional hierarchical independent control strategy is introduced. To solve the voltage fluctuation of the DC buses caused by the randomness of the microgrid output power, a coordinative control strategy between the input stage, isolation stage of PET and the microgrid is proposed. In this strategy, the sum of the microgrid and load current are fed forward as a control directive, and so the response speed of the isolation stage to microgrid power fluctuation will be improved and the influence of the power swing on the LVDC bus will be eliminated to a certain extent. The introduction of the composite feedback branch of the isolation stage enables the input stage of PET to respond to the control requirements of the isolation stage, and realize the joint control of the LVDC bus voltage between both stages. The simulation results indicate that, when occurring a two-way large-range output power fluctuation of the load, the coordinative control strategy proposed in this paper can significantly reduce the fluctuation amplitude and response time of the DC bus voltage of PET, improve the dynamic speed difference between the two stages and enhance the voltage quality and the stability of the whole system.

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