A Decentralized Optimal Operation of AC/DC Hybrid Microgrids Equipped With Power Electronic Transformer

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ABSTRACT In the AC/DC hybrid microgrids equipped with power electronic transformer (PET), different AC grids and DC grids are connected through multiport PET to operate the entire network in a secure and economic manner. This paper proposes a decentralized optimal power flow model, considering the multiport coordinated control strategy of PET, for running autonomous AC/DC hybrid microgrids. To optimize the power flow in the network, the steady state model of PET is established, including voltage source converter power injection model and Kriging model. By introducing a secondary droop control layer can realize the autonomous operation of AC/DC hybrid microgrids and increase the utilization efficiency of distributed generations. Then using the analytical target cascading approach, each AC/DC sub-microgrid is regarded as different autonomous subjects. The distributed PET is as power coupling node and information interaction node to decompose the optimal problem of AC/DC hybrid microgrids equipped with PET which is solved in parallel. The obtained subproblems for these grid levels are solved with a nested solution process. The simulation results verify the correctness and effectiveness of the proposed model in this paper.

INDEX TERMS AC/DC hybrid microgrids, power electronic transformer, steady state model, autonomous operation, decentralized optimal power flow.

I. INTRODUCTION

The power electronic transformer (PET) is also called solid state transformer (SST) or energy router [1], [2]. As the interface device between the distribution system and the electricity consumers in future smart grid, the PET with the capability to actively manage the power has received widespread attention [3]–[5]. The AC/DC hybrid microgrids equipped with PET provide a new method for the easy connection of the distribution resources in a large scale.

The optimal power flow (OPF) problem has great significance to the optimization and operation of microgrids. To optimize the power flow in the network, the steady state model of PET should be established. It acts as the basic equation for the power flow calculations and optimizations. However, there are few literatures have researched about it. Refer to Fig.1, the power flow model of the energy router is derived based on the circuit equations of the voltage source converter (VSC) [6]. On this basis, the steady state model for PET has been proposed with considering the power loss characterization of VSC, and it can be applied to the AC/DC hybrid microgrids [7]. Recent research has demonstrated that the number of PET power conversion stage can be three-stage, four-stage, and five-stage [8]–[10]. Furthermore, PET has a variety of circuit topologies, in which the low voltage AC and DC ports of mixed frequency modulation PET topology coupled together [11]. Therefore, the PET steady state model based on Fig.1 suffers some open problems such as...
the lack of ability to consider different PET structures, which limits its usefulness in practical applications.

With the intermittent and uncertain renewable energy increasingly penetrates into the hybrid microgrids, great challenges arise for system operators to keep the microgrids safe and reliable. To manage the DGs in the multiport network some existing literatures have studied various control strategies such as master-slave control and droop control. Compared with master-slave control strategy, the droop control strategy, with no critical communication links among the parallel-connected inverters, has been extensively implemented to operate DGs for sharing the powers of the load in autonomous [12].

The droop control strategy is proposed for power sharing between AC/DC hybrid microgrids by the interlinking converter [13]. However, these given strategies might not satisfy different microgrid operational requirements, such as accurate power sharing in DGs, appropriate load sharing among different phases of AC microgrids etc. Notice that the secondary control layer with low communication requirements is adopted to compensate frequency and voltage deviations produced by conventional primary control [14]–[16]. It can attain more complex operational objectives, such as the power and voltage references of each phase set independently and adequate power supply on heavily loaded phases [17]. At present, research on the PET is mainly concentrated on its inner power electronic topology. An appropriate coordinated control strategy for multiport PET can improve the operation effect of AC/DC hybrid microgrids, which has not been researched yet.

Optimal operation strategy is of great importance to the economic and safe operation of the microgrid. Plenty of publications have discussed the optimal operation in AC/DC hybrid microgrids in recent years, including robust optimization approach to address the uncertainties [18]–[20] and optimal scheduling strategy to make multi-source coordination [21], [22]. A few researches have investigated the solve approach in a hybrid AC/DC system, including traditional mathematical programming methods and the intelligent algorithms [23], [24]. However, these works usually solve the optimization problem in a centralized manner, whereas the idea of centralized control in the traditional power system will become impractical once the size of microgrids grows to a certain extent. Because in a centralized control requires a very high communication capacity which can result in communication bottlenecks [25]–[27]. Furthermore, the expanding network scale will make it difficult to solve the optimization problems efficiently [28]–[30]. Notice that the existing decentralized operation models are usually applied in distribution systems, multiple AC microgrid systems or their hybrid systems [31]–[33]. The AC/DC hybrid microgrids and its autonomous operation control strategy are not being considered.

In fact, the AC/DC hybrid microgrids equipped with PETs can integrate DGs in a large scale. The distributed nature of AC/DC microgrid makes its optimal operation problem very suitable to be solved in a decentralized manner. Furthermore, decentralized control for autonomous microgrids can also satisfy the demand of decentralized autonomous and centralized coordinated scheduling mode in the future power grid [34]. Various decomposition solution techniques have been proposed to solve the multi-area distribution networks optimal operation problem, including auxiliary problem principle (APP) [35], alternating direction method of multipliers (ADMM) [36], and analytical target cascading (ATC) [37]. However, considering AC/DC hybrid microgrids equipped with PET is a new form of distribution networks, its network topology and operation scheme are very different from conventional microgrids. To the best of our knowledge, the decentralized optimization problem about it has not been fully researched.

On this basis, this paper proposes a decentralized optimal power flow model for running autonomous AC/DC hybrid microgrids equipped with PET. ATC method provides a hierarchical structure with certain flexibilities on the coordination of subproblems, which is suitable as the framework of decentralized operation scheme for the AC/DC hybrid microgrids equipped with PET.

The contributions of this paper include:

- We proposed a Kriging model for multiport PET, which has not been investigated yet. This power flow model can be applied to the low voltage AC/DC hybrid microgrids to optimize calculations.
- The OPF model of AC/DC hybrid microgrids is proposed with considering the coordinated control strategy of PET ports and DGs. Facilitating an optimization of the operating state of the hybrid microgrids via the coordination of DGs and PET.
- Application of the ATC method to solve the OPF problem of AC/DC hybrid microgrids with considering the autonomous operation strategy. The distributed PET is as power coupling node and information interaction node to realize decentralized autonomous and centralized coordinated scheduling mode for multi-microgrids in a large scale.

The rest of this paper is organized as follows: Section II outlines the generalized steady state mathematical model of the PET and derives the Kriging model. The OPF formulation with the application of PET is proposed in Section III. The decentralized optimal operation problem of hybrid microgrids is given in Section IV. Section V presented the simulation results, and the conclusions are listed in Section VI.

II. STEADY STATE MODEL OF PET

Generally, the configuration of the generalized PET is shown in Fig.1. The PET has multiple ports, including AC port and DC port, that could be connected to different AC grids and DC grids. Each port is made of a flexible AC/DC or DC/DC converter, and they are linked using a DC/DC transformer. In the generalized configuration of the PET, the active and reactive injection power of each AC port are expressed by $P_{ac}^m$ and $Q_{ac}^m$, respectively, and the magnitude of the AC port
voltage is expressed by \( U_{dc}^n \); the equivalent resistance and reactance of the AC/DC converter are expressed by \( R_{ac}^m \) and \( X_{ac}^m \), respectively. The active injection power and the voltage magnitude of each DC port are expressed by \( P_{dc}^n \) and \( U_{dc}^n \), respectively; the equivalent resistance of the DC/DC converter is expressed by \( R_{dc}^m \). \( m, n \) are the numbers of AC and DC port, respectively. The parameters on the AC grid side and DC grid side, including the injection power and the voltage, of each port can be independently controlled by the flexible VSC-based AC/DC and DC/DC converter.

### A. VSC POWER INJECTION MODEL

The current mathematical models for PET proposed in published literatures are the power flow equation of the equivalent circuit of the AC/DC and DC/DC converter. However, the research has demonstrated that using the modular multilevel matrix converters technology the AC/AC converter can replace the conventional AC/DC/AC converter to form AC port [38], [39]. Furthermore, the efficiency of the entire microgrids is improved by optimizing the power injection and the voltage magnitude of each port. Thus, the external performance equivalent model of multipoort PET, with considering the power loss characterization equation of the convert, is proposed in this paper.

The external performance equivalent model of multipoort PET, improved from Fig.1, is shown in Fig.2. Without considering the power flow equation of the VSC equivalent circuit, and it can be applied to a variety of PET topologies. The total power loss of PET is described by \( P_{loss} \).

The active power balance equation of the multipoort PET is described as:

\[
\sum_{i=1}^{m} P_{ac}^i + \sum_{j=1}^{n} P_{dc}^j - P_{loss} = 0
\]  

(1)

Loss model of the converter developed in this paper, including the switching losses and conduction losses of power electronic devices, are written as a function of the phase current magnitude. The overall converter losses can be split up into three aggregated loss components containing no load losses, losses linearly and quadratically depending on the phase current [40], [41].

\[
P_{loss,ac}^i = k_0 + k_1 I_{ac}^i + k_2 (I_{ac}^i)^2
\]  

(2)

\[
P_{loss,dc}^j = k_0 + k_1 I_{dc}^j + k_2 (I_{dc}^j)^2
\]  

(3)

\[
I_{ac}^i = \sqrt{(P_{ac}^i)^2 + (Q_{ac}^i)^2} / U_{ac}^i
\]  

(4)

\[
I_{dc}^j = P_{dc}^j / U_{dc}^j
\]  

(5)

where \( P_{loss,ac} \) and \( P_{loss,dc} \) represent the power loss of the PET AC and DC port, respectively; \( \varphi = \{a, b, c\} \) is the three-phase system; \( k_0, k_1, k_2 \) are the fitting parameters of the loss, the current of PET AC and DC port are expressed by \( I_{ac}^i \) and \( I_{dc}^j \), respectively, and they are defined by (4) and (5), respectively. Actually, the loss model of isolation DC/DC transformer, including the DC/AC converter losses and high frequency transformer losses, also can be written as a function of the phase current magnitude [42], [43]. And the low voltage AC/DC ports of PET are obtained from the low voltage DC bus of DC/DC isolation transformer in general [4], [44], [45]. Thus, loss of isolation DC/DC transformer is added to the high voltage AC port of PET in this paper.

Equation (2), (3) shows the power loss characterization formulation of the PET AC and DC port, respectively. The loss of multiport PET is the sum of each port, which can be defined as:

\[
P_{loss} = \sum_{i=1}^{m} \sum_{\varphi=a}^{c} P_{loss,ac}^i + \sum_{j=1}^{n} P_{loss,dc}^j
\]  

(6)

In summary, the VSC power injection model of the PET can be formulated by using (1)-(6). However, notice that low voltage AC and DC port of the mixed frequency modulation PET are coupled together. The above loss characterization formulation of the PET AC and DC port cannot be applied to it. Moreover, as the research continues to deepen, an increasing number of PET topologies are proposed. This will make it difficult to describe the loss characterization of different PET topologies with a certain formulation. Hence, the Kriging model is derived based on the VSC power injection model of PET in this paper.

### B. THE KRIGING MODEL

The power injection and voltage magnitude of each port as well as the loss changes with the operation states for the PET, and there is a complicated function relationship between them. It can be analyzed by the nonlinear fitting method such as the Kriging model, which is suitable for the nonlinear problem and has received extensive attention in published literatures [46], [47]. A Kriging model predicts the response function \( y(x) \) is the linear weighting of known sample function. It can be expressed by [48], [49]:

\[
\hat{y}(x) = \sum_{i=1}^{r} \omega^{(i)} y^{(i)}
\]  

(7)

where \( x \) is the unknown observation point parameters, \( \hat{y}(x) \) is the fitting function, \( r \) is the number of known sampling
points, \( \omega \) is the weighting coefficient, \( y \) is the response value of the known sampling points.

To calculate the weighting coefficient, the Kriging model introduces statistical assumptions and regards the unknown function as a gaussian stochastic process. This stochastic process is defined as:

\[
Y(x) = \beta_0 + Z(x)
\]

\[\text{MSE}[\hat{y}(x)] = E[(\omega^T Y - Y(x))]\]

where \( \beta_0 \) is an unknown constant, representing the mathematical expectation of \( Y(x) \), \( Z(x) \) is a static random process with the mean is 0 and the variance is \( \sigma^2 \). On the gaussian stochastic process basis, the Kriging model can be obtained by minimizing the mean square error with the optimal weighting coefficient, as shown in (9).

The Kriging equivalent process of external characterization for PET is shown in Fig.3. To establish the steady state model of multiport PET, large amount of sampling data related to loss should be obtained during operation. After that the fitting formulation of loss function can be expressed as:

\[
P_{\text{loss}} = f(P_{\text{ac}}^\psi, Q_{\text{ac}}^\psi, U_{\text{ac}}, P_{\text{dc}}, U_{\text{dc}})
\]

It can be seen that the total loss of PET can be calculated with known power injection and the voltage magnitude of each AC and DC port by the fitting formulation. Equation (10), together with (1), form the OPF model of the PET, which is used as a basis in formulating the OPF model in the next section.

The established Kriging model of PET could be adapted to a variety of PET topologies without being affected by changes of the loss characterization curve. Furthermore, it can also be applied to three-phase asymmetric microgrid, which is convenient for multiport PET to optimize and analyze. This paper adopts the DACE toolbox of MATLAB to construct the Kriging model of PET.

**III. OPF FORMULATION OF HYBRID MICROGRIDS**

In the AC/DC hybrid microgrids equipped with PET, different AC grids and DC grids are connected through the multiport to form a network topology in a large scale [50], [2], as shown in Fig.4.

Under the normal condition, the operation goal of the AC/DC hybrid microgrids equipped with PET could be to minimize the operating cost. The PET is able to regulate the network power flow by setting the power injection and voltage of each port, compare with the conventional interlinking converter based microgrids, the PET provides extra flexibility in controlling the distribution. We note that the power injection for the port 1, 3, 6, 7 of PET as well as the port 2, 4, 5, 7 connected to the AC/DC microgrids should be balancing at any time. Therefore, an appropriate coordinated control strategy for multiport PET to operate safely and stably of the hybrid microgrids is particularly important. At present, the constant voltage control is adopted to keep the power balance for a single PET, however it cannot apply to the hybrid networks contain multiple PETs, and which has not been studied yet.

In this section, an OPF model, with considering the coordinated control strategy for multiport PET, is presented.

**A. OBJECTIVE FUNCTION**

PET is composed of power electronic devices, which has higher power loss than the conventional transformer. The maximum efficiency of the PET in operation, proposed by the North Carolina State University [51], was only 94%. Low efficiency is also one of the reasons that limit PET difficulty in large scale application. However, the PET can regulate network power flow to reduce the line power losses in the distribution system. Therefore, an optimal operation model, with considering the power loss of the network, is proposed to improve the utilization efficiency of PET and DGs. The objective function can then be mathematically formulated as:

\[
\min f = P_{\text{loss,PET}} + P_{\text{loss,AC}} + P_{\text{loss,DC}}
\]

where \( P_{\text{loss,PET}} \) is the power loss of the multiport PET; \( P_{\text{loss,AC}} \) and \( P_{\text{loss,DC}} \) are the active power loss of AC microgrid and DC microgrid, respectively. In this paper, the loss of PET is shown in Section II and the loss of AC/DC microgrids can be formulated by the difference between total generation power and sum of load power which is given by:

\[
P_{\text{loss,AC}} = \sum_{N_{\text{ac}}} \sum_{N_{\text{ac}}} P_{\text{ac,dc}}^\psi + \sum_{N_{\text{ac}}} P_{\text{ac,dc}} - P_{\text{load,ac}}
\]

\[
P_{\text{loss,DC}} = \sum_{N_{\text{dc}}} P_{\text{dc}} + \sum_{N_{\text{dc}}} P_{\text{dc,dc}} - P_{\text{load,dc}}
\]

where \( N_{\text{ac}} \) and \( N_{\text{dc}} \) are the number of PET AC port and DGs in AC microgrid, respectively; \( P_{\text{ac,dc}} \) is the power output of DGs.
and the $P_{\text{load,ac}}$ is the sum of load power in AC microgrid. $N_{\text{dc}}$ and $n_{\text{dc}}$ are the number of PET DC port and DGs in DC microgrid, respectively; $P_{\text{dc,dg}}$ is the power output of DGs and the $P_{\text{load,dc}}$ is the sum of load power in DC microgrid.

**B. CONSTRAINTS**

This formulation is subject to the following constraints:

1) **POWER FLOW EQUATIONS**

For an unbalanced AC microgrid comprising $M$ set of buses, the phase active powers $P_i^\phi$ and reactive powers $Q_i^\phi$ injected at any phase of an arbitrarily selected bus $i$ can be given by (14) and (15), where $G_{ik}^m$, $B_{ik}^m$ are the bus admittance matrix element’s conductivity and admittance, respectively, $\theta_{ik}^m$ is the voltage phase angle. Meanwhile, for a DC microgrid comprising $N$ buses, the power $P_i$ injected at any arbitrary bus $i$ can be obtained by (16), where $U_{\text{dc}}$ is the DC bus $i$ voltage, $G_{ij}$ is the conductance of the DC bus admittance matrix.

$$P_i^\phi = \left|U_i^\phi\right| \sum_{k=1}^{M} \sum_{m=a}^{c} \left|U_k^m\right| (G_{ik}^m \cos \theta_{ik}^m + B_{ik}^m \sin \theta_{ik}^m) = 0$$

(14)

$$Q_i^\phi = \left|U_i^\phi\right| \sum_{k=1}^{M} \sum_{m=a}^{c} \left|U_k^m\right| (G_{ik}^m \sin \theta_{ik}^m - B_{ik}^m \cos \theta_{ik}^m) = 0$$

(15)

$$P_i - U_{\text{dc}} \sum_{j=1}^{N} G_{ij} U_{\text{dc}} = 0$$

(16)

2) **COORDINATED CONTROL EQUATIONS OF PET**

To maintain power balance in a multiport network formed by several VSC stations, the master-slave control and droop control, have been investigated in current literatures. Compared with the former, the droop control, without communication, can operate DGs for sharing the powers of the load. This makes the microgrid operate autonomously and increase the absorption level of DGs. Furthermore, because the renewable energy generation is intermittent and uncertain, all fluctuations are caused by DGs or loads, result in the deviation of the power, should be supplied by PET under the master-slave control. Notice that the PET with an intermediate DC/DC link separates the high and low voltage AC systems to operate at different frequencies. A coordinated control strategy for multiport PET is proposed in this paper. The high voltage AC port of PET is connected with the main grid, and the frequency is determined by it. Constant voltage control is adopted to provide power support for low voltage networks. The low voltage AC/DC ports of PET are connected to the hybrid microgrids, and the droop control is adopted to operate autonomously.

The droop control characterization curve for AC and DC port of PET is shown in Fig.5. In this paper the secondary control layer with low communication requirements is adopted to attain more complex operational objectives. The droop characterization of PET AC port is obtained as:

$$P_{\text{ac}}^\phi = k_{\text{pet}}^p (\omega_0 + \delta \omega_{\text{pet}}^q - \omega)$$

(17)

$$Q_{\text{ac}}^\phi = k_{\text{pet}}^q (U_{\text{pet,0}} - U_{\text{ac}} + \delta U_{\text{pet}}^q - U_{\text{ac}})$$

(18)

$$k_{\text{pet}}^p = \frac{P_{\text{ac, max}}}{\omega_{\text{ac, max}} - \omega_{\text{ac, min}}}$$

(19)

$$k_{\text{pet}}^q = \frac{U_{\text{ac, max}} - U_{\text{ac, min}}}{Q_{\text{ac, max}}}$$

(20)

where $k_{\text{pet}}^p$ and $k_{\text{pet}}^q$ are the active and reactive power droop coefficients, respectively, $\omega_0$ and $\omega$ are the PET AC port no load and output angular frequencies, respectively, $\omega_{\text{ac, min}}, \omega_{\text{ac, max}}$ are the minimum and maximum permissible angular frequencies of AC microgrid, respectively, $U_{\text{pet,0}}, U_{\text{ac}}$ are the PET AC port no load and output voltage, respectively, $U_{\text{ac, min}}, U_{\text{ac, max}}$ are the minimum and maximum permissible voltage magnitude of AC port, respectively, $\delta \omega_{\text{pet}}^q$ and $\delta U_{\text{pet}}^q$ are the bias values that can be optimized, $P_{\text{ac, max}}, Q_{\text{ac, max}}$ are the maximum output active and reactive power of the PET AC port, respectively. Since the controller can bias the active and reactive power references of each phase individually, the power can be set flexibly which can improve the utilization efficiency of DGs.

The droop characterization of PET DC port is obtained as:

$$P_{\text{dc}} = k_{\text{pet}}^{\text{dc}} (U_{\text{pet,0}} - U_{\text{dc}}) + \delta U_{\text{pet}}^{\text{dc}}$$

(21)

$$k_{\text{pet}}^{\text{dc}} = \frac{U_{\text{dc, max}} - U_{\text{dc, min}}}{P_{\text{dc, max}}}$$

(22)

where $k_{\text{pet}}^{\text{dc}}$ is the power droop coefficients of DC port, $U_{\text{pet,0}}$, $U_{\text{dc}}$ are the PET DC port no load and output voltage, respectively, $U_{\text{dc, min}}, U_{\text{dc, max}}$ are the minimum and maximum permissible voltage of DC port, respectively, $\delta U_{\text{pet}}^{\text{dc}}$ is the bias values, $P_{\text{dc, max}}$ is the maximum output power of the DC port.

3) **DROOP CONTROL EQUATIONS OF DGs**

The DGs in the AC/DC microgrid that controlled by power electronics converters are all adopted droop control strategy to make the sub-microgrid operate autonomously. They can be described as:

$$P_{\text{ac,dg}} = \sum_{\psi=a}^{c} P_{\text{ac,dg}}^\psi = k_{\text{ac}}^p (\omega_0 + \delta \omega_{\text{ac}} - \omega)$$

(23)
The active power of the DGs in the DC microgrid can be optimized; $U_{ac,0}$, $U_{ac,dg}$ are the AC DGs bus no load and output voltage, respectively; $\delta U_{dc}$ is the voltage bias values of DGs in DC microgrid that can be optimized; $U_{dc,0}$, $U_{dc,dg}$ are the DC DGs bus no load and output voltage, respectively.

$$U_{ac, dg}^a = U_{ac, dg}^b = U_{ac, dg}^c$$

Generally, the three-phase voltages at the DG bus are strictly balanced by employing negative sequence compensators. Therefore, the output power of DGs in AC microgrid is the three-phase total power $P_{ac,dg}$, $Q_{ac,dg}$. The droop coefficients $k^p_{ac}$, $k^q_{ac}$, $k_{dc}$ of DGs are obtained as:

$$k^p_{ac} = \frac{\omega_{max} - \omega_{min}}{P_{max, ac}}$$

$$k^q_{ac} = \frac{U_{ac, max} - U_{ac, min}}{Q_{max, ac}}$$

$$k_{dc} = \frac{U_{dc, max} - U_{dc, min}}{P_{max, dc}}$$

where $P_{max, ac}$, $Q_{max, ac}$ are the maximum output active and reactive power of the DGs in AC microgrid, respectively; $U_{ac, max}$, $U_{ac, min}$ are the maximum and minimum of the AC DGs bus output voltage, respectively; $P_{max, dc}$ is the maximum output active power of the DGs in DC microgrid; $U_{dc, max}$, $U_{dc, min}$ are the maximum and minimum of the DC DGs bus output voltage, respectively.

### 4) INEQUALITY EQUATION

The problem must satisfy the set of (30)-(35), which describe the AC/DC bus voltages, DGs output power for both AC/DC microgrid and the AC microgrid frequency as inequality constraints.

$$U_{i, min}^p \leq U_i^p \leq U_{i, max}^p$$

$$U_{i, min}^q \leq U_i^q \leq U_{i, max}^q$$

$$P_{ac, min} \leq P_{ac, dg} \leq P_{ac, max}$$

$$\sqrt{(P_{ac}^2) + (Q_{ac}^2)} \leq S_{ac}$$

$$P_{dc, min} \leq P_{dc, dg} \leq P_{dc, max}$$

$$\omega_{min} \leq \omega \leq \omega_{max}$$

where $U_{i, max}$, $U_{i, min}$ are the maximum and minimum of the AC nodes, respectively; $U_{i, max}$, $U_{i, min}$ are the maximum and minimum of the DC nodes, respectively; $P_{max, ac}$, $P_{min, ac}$ are the maximum and minimum of the DGs active power output in AC network, respectively; $Q_{max, ac}$, $Q_{min, ac}$ are the maximum and minimum of the DGs reactive power output in AC network, respectively; $P_{max, dc}$, $P_{min, dc}$ are the maximum and minimum of the DGs active power output in DC network, respectively; $\omega_{max}$, $\omega_{min}$ are the maximum and minimum of the frequency, respectively.

Moreover, the output power for both AC and DC port of PET should be accounted for by inequality constraints represented by:

$$P_{ac, min}^\phi \leq P_{ac}^\phi \leq P_{ac, max}^\phi$$

$$\sqrt{(P_{ac}^\phi)^2 + (Q_{ac}^\phi)^2} \leq S_{ac}^\phi$$

$$P_{dc, min} \leq P_{dc} \leq P_{dc, max}$$

where $P_{ac, max}$, $P_{ac, min}$ are the maximum and minimum of the active power output of PET AC port, respectively; $S_{ac}$ is the power capacity of PET AC port; $P_{dc, max}$, $P_{dc, min}$ are the maximum and minimum of the active power output of PET DC port, respectively.

The overall OPF formulation is discussed above. To solve it, a decentralized optimization algorithm can be adopted to satisfy the demand of decentralized autonomous and centralized coordinated scheduling mode in the future power grid.

### IV. FORMULATION OF DECENTRALIZED PROBLEM

#### A. GENERAL DESCRIPTION OF ATC METHOD

In this section, a hierarchical architecture to solve decentralized OPF in AC/DC hybrid microgrids equipped with PET via ATC is proposed in which the centralized network is split into sub-networks including the AC grid, DC grid, and PET. Fig.6 shows the ATC top-down and bottom-up target and response iterative process.

The design target problem is partitioned into a hierarchical set of sub-problems associated with the systems, subsystems, and components. Given the initial values of targets from components, the subsystems run OPF and determine responses for the components. Then, given the responses from subsystems and targets from systems, the components run OPF to assign targets for subsystems and responses to systems. Finally, using responses from components the systems run OPF to determine targets for components. The iterative process is repeated until targets and responses converge for all the sub-networks [52].

![FIGURE 6. ATC top-down and bottom-up process.](image-url)
respectively, the coupling variables \( P \) and \( Q \) of subproblem PET, AC microgrid, and DC microgrid, are decomposed into target variables \( \eta \) and response variables \( \mu \) in the proposed OPF model.

The target and response variables of hybrid grids.

**FIGURE 7.** The target and response variables of hybrid grids.

**B. PET SUBPROBLEM**

The two-hierarchy of AC/DC hybrid microgrids equipped with PET is illustrated in Fig.7 to clearly show the optimize variables with the proposed OPF model.

As shown in Fig.7, the \( Y_{\text{pet}}, Y_{\text{ac}} \) and \( Y_{\text{dc}} \) are the local variables of subproblem PET, AC microgrid, and DC microgrid, respectively, the coupling variables \( \{P_{\text{ac}}, Q_{\text{ac}}, U_{\text{ac}}, P_{\text{dc}}, U_{\text{dc}}\} \) are decomposed into target variables \( \eta_{\text{ac}}, \eta_{\text{dc}} \) and response variables \( \mu_{\text{ac}}, \mu_{\text{dc}} \), and a set of consistency constraints are described as:

\[
c = \eta - \mu = 0
\]  

We relax the consistency constraints in the objective function using a penalty term. Now the optimization objective of the PET subproblem is formulated as:

\[
\min f_{\text{PET}} = \sum_{\text{ac}, \text{dc}} P_{\text{ac,dc}}^\psi + \sum_{\text{ac}} P_{\text{ac,dc}}^\psi + \sum_{\text{dc}} P_{\text{ac,dc}}^\psi
\]

where, the target variables \( P_{\text{ac,dc}}^\psi \), \( Q_{\text{ac,dc}}^\psi \), \( U_{\text{ac,dc}}^\psi \), and \( P_{\text{ac}}, P_{\text{dc}} \) are the optimization variables and the response variables \( \mu_{\text{ac}}, \mu_{\text{dc}} \) are the constant variables. \( v \) is the vector of Lagrangian multipliers, and \( w \) is the vector of penalty weight. The equality constraints including (1) and the inequality constraints including (36)-(38).

**C. AC/DC MICROGRID SUBPROBLEM**

The AC and DC microgrids exchange power with the multiport PET, and the optimization objective can be formulated as:

The AC sub-problem

\[
\min f_{\text{AC}} = \sum_{\text{ac}} P_{\text{ac,dc}}^\psi + \sum_{\text{ac}} P_{\text{ac,dc}}^\psi - P_{\text{load,ac}}
\]

Note that the target variables \( P_{\text{pet}}, Q_{\text{pet}}, U_{\text{pet}} \) is the constant variables and the response variables \( P_{\text{pet}}, Q_{\text{pet}}, U_{\text{pet}} \) is the optimize variables here. The equality constraints include (14), (15), (17)-(20), (23), (24), (26)-(28) and the inequality constraints include (30), (32), (33), (35).

The DC sub-problem

\[
\min f_{\text{DC}} = \sum_{N_{\text{dc}}} P_{\text{dc}} + \sum_{N_{\text{dc}}} P_{\text{dc,dc}}^\psi - P_{\text{load,dc}}
\]

As mentioned, the target variables \( P_{\text{pet}}, Q_{\text{pet}}, U_{\text{pet}} \) is the constant variables and the response variables \( P_{\text{pet}}, Q_{\text{pet}}, U_{\text{pet}} \) is the optimize variables in the DC sub-problem. And the equality constraints are the (16), (21), (22), (25), (29). The inequality constraints are the (31), (34).

**D. DECENTRALIZED SOLUTION PROCEDURE**

A nested solution process which consists of an inner loop and an outer loop is adopted to solve the decentralized OPF problem is shown in Fig.8 [53]. Note that as there is no direct links between AC and DC microgrid, their optimization problems can be solved in parallel.

The process is explained as follows:

**Step 1:** Set the iteration indexes \( k_o, k_l = 0 \). Given the initial values for the penalty parameters \( v, w \), and the target variables \( \eta_{\text{ac}}, \eta_{\text{dc}} \).

**Step 2:** Update \( k_l = k_l + 1 \). Solve the AC and DC microgrid sub-problem with response variables \( \mu_{\text{ac}}, \mu_{\text{dc}} \) as optimize variables and the target variables \( \eta_{\text{ac}}, \eta_{\text{dc}} \) from the previous iteration.

**Step 3:** Solve the PET sub-problem with target variables \( \mu_{\text{ac}}, \mu_{\text{dc}} \) as optimize variables and response variables from \( \mu_{\text{ac}}, \mu_{\text{dc}} \). Step 2. The solution process of subproblem is shown in Fig.9.

**Step 4:** Check the inner loop convergence criterion (43). If satisfied, go to step 5; otherwise, return to step 2. The \( f_{k_l}, f_{k_l-1} \) are the objective functions between two consecutive inner loop iterations and the \( \varepsilon_1 \) is the predefined tolerance.

\[
|f_{k_l} - f_{k_l-1}| \leq \varepsilon_1
\]  

**Step 5:** Check the output loop convergence criterion (44), (45). If it is satisfied, the optimal solution is obtained and
iteration is stopped; otherwise, go to step 6.

\[
\begin{align}
\|c^k - c^{k-1}\| &\leq \varepsilon_2 \\
\|c^k - c^{k-1}\| &\leq \varepsilon_3
\end{align}
\]  

(44)  
(45)

**Step 6:** Set \(k_0 = k_0 + 1\). Update the values of the penalty function parameters according to:

\[
\begin{align}
\nu^{k_0+1} &= \nu^{k_0} + 2 \ast \beta \nu^{k_0} \circ c^{k_0} \\
\omega^{k_0+1} &= \begin{cases}
\beta \omega^{k_0} , & \|c^{k_0}\| \geq \gamma \|c^{k_0-1}\| \\
\omega^{k_0} , & \|c^{k_0}\| \leq \gamma \|c^{k_0-1}\|
\end{cases}
\end{align}
\]

(46)  
(47)

where, \(\beta, \gamma\) are the constant, and “\(\circ\)” represents the Hadamard product.

**V. SIMULATION RESULTS**

In this section, an AC/DC hybrid microgrids equipped with PET system is used to investigate to test the effectiveness of the proposed operation approach. The MATLAB 2017a software with YALMIP toolbox is employed and all testing cases in this paper are run on a PC with Intel(R) Core(TM) i7-8550CPU @1.8GHz with 8GB RAM.

**A. HYBRID MICROGRIDS SYSTEM**

Fig.10 shows the test AC/DC hybrid microgrids equipped with PET where the 380V unbalanced AC 24-bus grid and the 750V DC 10-bus grid are connected through the PET. The high voltage AC port of PET is connected to the main grid and provides power support for low voltage AC/DC microgrids.

The impedance of the line conductor of each phase in AC microgrid is \(Z_1 = (0.240 + 0.077j)\Omega/km\), and the resistance of the line conductor in DC microgrid is \(R_1 = 0.0754\Omega/km\).

The total loads of the AC and DC grid are \(S_{ac} = (1.547 + 0.805)\text{MVA}\) and \(P_{dc} = 0.47\text{WM}\), respectively. As shown in Table 1 and Table 2.

In this paper the no load voltage \(U_{dc,0} = 1.05\text{pu}\) and \(U_{ac,0} = 1.02\text{pu}\); no load angular frequency \(\omega_0 = 1.004\text{pu}\). The permissible voltage of AC and DC microgrid are [0.95, 1.05]pu and [0.95, 1.02]pu, respectively.
TABLE 1. The load of unbalanced AC microgrid (kW, kVar).

| Bus No | P_A | Q_A | P_B | Q_B | P_C | Q_C |
|--------|-----|-----|-----|-----|-----|-----|
| 1      | 30  | 18  | 15  | 8   | 20  | 14  |
| 2      | 10  | 5   | 20  | 13  | 30  | 15  |
| 3      | 15  | 7   | 35  | 18  | 30  | 15  |
| 4      | 30  | 15  | 30  | 18  | 25  | 14  |
| 5      | 15  | 7   | 30  | 18  | 20  | 10  |
| 6      | 0   | 0   | 0   | 0   | 0   | 0   |
| 7      | 35  | 18  | 15  | 8   | 20  | 10  |
| 8      | 30  | 13  | 28  | 14  | 20  | 10  |
| 9      | 25  | 10  | 30  | 18  | 16  | 10  |
| 10     | 19  | 10  | 24  | 10  | 32  | 15  |
| 11     | 20  | 10  | 30  | 15  | 25  | 13  |
| 12     | 25  | 15  | 35  | 20  | 10  | 5   |
| 13     | 20  | 8   | 15  | 9   | 10  | 5   |
| 14     | 10  | 5   | 20  | 10  | 33  | 17  |
| 15     | 0   | 0   | 0   | 0   | 0   | 0   |
| 16     | 35  | 20  | 18  | 9   | 30  | 18  |
| 17     | 28  | 14  | 18  | 10  | 28  | 10  |
| 18     | 35  | 18  | 20  | 10  | 20  | 9   |
| 19     | 38  | 19  | 30  | 18  | 18  | 10  |
| 20     | 14  | 8   | 20  | 16  | 35  | 17  |
| 21     | 14  | 8   | 20  | 16  | 35  | 17  |
| 22     | 19  | 9   | 20  | 10  | 30  | 18  |
| 23     | 18  | 10  | 30  | 10  | 30  | 5   |
| 24     | 29  | 12  | 25  | 15  | 18  | 10  |

FIGURE 12. The power loss in different networks.

TABLE 2. The load of DC microgrid (kW).

| Bus No | P  |
|--------|----|
| 1      | 80 |
| 2      | 50 |
| 3      | 60 |
| 4      | 50 |
| 5      | 50 |

FIGURE 13. The results of Kriging model with variable parameters.

TABLE 3. The permissible output power of PET and DGs (kW, kVar).

| Micro source | Active power | Reactive power |
|--------------|--------------|----------------|
|              | upper | lower | upper | lower |
| PET AC port  | 300   | -300  | 150   | -150  |
| AC DGs       | 60    | 0     | 40    | 0     |
| PET DC port  | 200   | -200  | -     | -     |
| DC DGs       | 100   | 0     | -     | -     |

**B. EFFECTIVENESS ANALYSIS OF PET KRIGING MODEL**

At present, the research on the PET is still in the laboratory stage, and it has not been applied to the distribution network to operate. In this paper the proposed Kriging model is compared with the VSC power injection model of multiport PET, in order to validate its effectiveness. Large amount of sampling data \( \{x, y\} = \{(P_{AC,ac}^P, Q_{AC,ac}^P, U_{AC,ac}^P, P_{DC}, U_{DC})\} \)
can be obtained by Monte-Carlo method according to the (1)-(6). On this basis, the simulation results of the steady state model are as follows:

The 100 test points have been selected randomly to compare the Kriging model with the VSC power injection model. The results are shown in Fig.11, where the horizontal coordinate-axis $X$ is the sampling data $x = (P_{ac}, Q_{ac}, U_{ac}, P_{dc}, U_{dc})$, and the vertical coordinate-axis $Y$ is the power loss of PET $y = P_{loss}$. We observed that the simulation results of the Kriging model agree with the VSC power injection model. The average error between them, show in Fig.11(b), is only 0.39%. This shows that the proposed Kriging model has good fitting accuracy to the loss characterization formulation which is a quadratic function.

For the more complex loss characterization functions, considering the quadratic fitting parameters is not a constant during the operation. The power loss curve of AC microgrid, DC microgrid, and PET varying with the quadratic fitting parameters is shown in Fig.12. Losses in different networks increase as the quadratic fitting parameters increase.
However, the fitting parameters have different effects on the subgrid. Furthermore, the variable fitting parameters mean that the steady state model formulation of PET is a piecewise function, which is difficult to solve. We assumed that when the transmission power of PET is more than 0.4pu, the quadratic fitting parameters of the loss changes from 0.018 to 0.02. The results of Kriging model are as follows:

As shown in Fig.13, the Kriging model still has good fitting accuracy, with only 2.6% average error, to the complex loss characterization functions. Therefore, the steady state model, Kriging model, proposed in this paper can apply to different topologies PET with various loss characterization. The Kriging model of PET can be established as long as there is large amount of sampling data, which is convenient to optimize and analyze.

C. ANALYSIS OF COORDINATED CONTROL STRATEGY

The secondary control layer with low communication requirements can attain more complex operational objectives. The results are shown as follows:

Fig.14 shows the output active power of DGs in AC/DC microgrids. Case1, the DGs in AC/DC microgrids and the AC/DC ports of PET are all without secondary control layer. Case 2, the DGs in AC/DC microgrids without secondary control layer and the AC/DC ports of PET with secondary control layer. Case 3, the DGs in AC/DC microgrids and the AC/DC ports of PET are all with secondary control layer. It is worth mentioning that the secondary control layer can satisfy the power interaction needs by moving the droop curves. By introducing the secondary droop control layer, the output power of DGs in AC/DC microgrids in case3 is more than 32.7% that in case1.

The power loss of AC/DC hybrid microgrids equipped with PET is shown in Table 4. We observed that improving the utilization efficiency of DGs in AC/DC microgrids helps to reduce the power loss. Therefore, the loss of the hybrid microgrid is 94kW in case 3, which is the lowest.

### Table 4. The power loss of AC/DC hybrid microgrids (kW).

| Case | \(P_{\text{loss, PET}}\) | \(P_{\text{loss, AC}}\) | \(P_{\text{loss, DC}}\) | \(P_{\text{loss, SUM}}\) |
|------|-----------------|-----------------|-----------------|------------------|
| 1    | 59.2            | 48.9            | 2.1             | 110.2            |
| 2    | 55              | 46.2            | 2               | 103.2            |
| 3    | 49.2            | 42.2            | 2.6             | 94               |

D. RESULT OF THE ATC APPROACH

Fig.15 (a)-(e) shows the coupling variables between PET and AC/DC hybrid microgrids in each outer loop. It can be seen that the target variables and response variables converge to the same operating point after 9 iterations. The case system in this paper contains 2 PETs with 22 coupling variables. The simulation results show that the ATC algorithm has good convergence to AC/DC hybrid microgrids equipped with PET, which can be applied to the large-scale networks with large amounts of renewable energy.

The results of the decentralized approach and centralized approach are shown in Table 5. In scenario 1, PET adopts VSC power injection model and the AC/DC hybrid microgrids equipped with PET adopts centralized OPF. In scenario 2, PET adopts VSC power injection model and the AC/DC hybrid microgrids equipped with PET adopts decentralized OPF. In scenario 3, PET adopts Kriging model and the AC/DC hybrid microgrids equipped with PET adopts decentralized OPF.

Table 5 shows the loss of AC, DC, and PET subgrid, average output power of DGs in AC/DC microgrid, frequency of AC microgrid and output power of PET AC/DC port. We observed that the results are very close among three scenarios. These results show the effectiveness of the decentralized approach.

### Table 5. Results of variables in decentralized and centralized OPF.

| Scenario | \(P_{\text{loss, PET}}\) | \(P_{\text{loss, AC}}\) | \(P_{\text{loss, DC}}\) | \(P_{\text{loss, SUM}}\) |
|----------|-----------------|-----------------|-----------------|------------------|
| 1        | 157.8           | 155.5           | 159             | 480.2            |
| 2        | 158.2           | 155.6           | 158.6           | 480.4            |
| 3        | 157.8           | 155.5           | 159             | 480.2            |

E. AC/DC HYBRID MICROGRIDS WITH MORE PETS AND DGs IN A LARGE SCALE

In order to verify the method proposed in this paper can be applied to systems with different number of PET ports and DGs, the AC/DC hybrid microgrids simulation with more PETs and DGs in a large scale is analyzed here. In fact, the research on the PET is still in the laboratory, and there is currently no actual operating system or demonstration project for AC/DC hybrid microgrids equipped with PET. Therefore, the simulation case based on the structure of Fig.4 is shown as follows:

As shown in Fig.16, the AC/DC hybrid microgrids consists of 4 multiple PETs and 8 sub-microgrids, where the 380V AC microgrid, 750V DC microgrid and 1500V DC microgrid are connected through the 4-port PET to integrate DGs in a large scale. The simulation results are shown as follows:

The coupling variables, including the voltage, active power of 8 DC ports and the voltage, active power and reactive power of 4 AC ports, between PET and AC/DC microgrid in each outer loop iteration are shown as Fig.17 (a)-(e). It is obvious that all target variables and response variables...
converge to the same operating point after 8 iterations. This shows that the method proposed in this paper can be applied to the microgrid system with more PETs and DGs. It provides ideas for the decentralized optimization operation of the new network structure of AC/DC hybrid autonomous microgrids equipped with PET to consume renewable energy in a large scale.

Actually, the AC/DC hybrid microgrid with multiport PET is conducive to the integration of distributed renewable energy sources in a large scale. Compared with the centralized optimization approach the subnet in decentralized optimization approach can be optimized independently without communication bottlenecks. It will improve the stability of the hybrid system. The different subnets are coupled together through multiport PET, decentralized algorithm requires more iterations in order to obtain the optimum. However, the AC and DC microgrid subproblem can be solved in parallel, this can
improve the efficiency of solution while in a large hybrid network.

VI. CONCLUSION

The AC/DC hybrid microgrids equipped with PET is a multiple region network which is composed of interconnected AC and DC microgrids. As the plug-and-play ports for DGs, PET allows convenient control of active and reactive power and provides flexibilities on the coordination of AC/DC microgrid. This paper proposed a decentralized OPF approach based on ATC frame to optimize the operation of autonomous AC/DC hybrid microgrids equipped with PET. The simulation results refer to conclusions which can be summarized as follows:

- The proposed Kriging model of PET has good fitting accuracy to the complex loss characterization functions which can be applied to different topologies PET with various loss formulations.
- The coordinated control strategy for multiport PET, with low communication requirements, presented in this paper can realize the microgrid operate autonomously and improve the utilization efficiency of DGs in AC/DC microgrids.
- The ATC method is adopted to solve the decentralized optimization problem and coordinate the operating points of the interconnected autonomous AC/DC hybrid microgrids equipped with PET in a large scale. It can satisfy the demand of decentralized autonomous and centralized coordinated scheduling mode in the future power grid.

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