Linear Robust Optimal Dispatch of AC/DC Active Distribution Network with PET

Ruizhi Wang*, Lei Dong*
School of North China Electric Power University, Beijing, China

*Corresponding author e-mail: 414389572@qq.com, *hbddll@126.com

Abstract. By considering the uncertainty of renewable energy in AC/DC active distribution network with power electronic transformer (PET), this paper proposes a linear robust optimized dispatch method with PET contained. Firstly, a steady-state model that only takes into account the characteristics of PET port is established. Secondly, we linearize the power flow equations of the AC/DC distribution network, and derive the expressions for the voltage safety at network nodes and for the current safety of lines, then establish the robust optimized dispatch model of the AC/DC distribution network containing PET. Finally, the nonlinear constraints such as port capacity in the network are linearized, and the robust optimized dispatch model is transformed into a quadratic programming model without uncertain variables using dual optimization theory, so that the model can be solved in an efficient and fast way. The two modified IEEE33 node systems have constructed the AC/DC active distribution network with PET. The simulation verified the accuracy and effectiveness of the proposed method.

1. Introduction
Along with development of the dc distribution system and the increase of the penetration of distributed generations, an intelligent transformer with the capability to actively manage the power and allowing for the easy connection of the distribution resources becomes indispensable [1]. Power electronic transformer (PET), also known as solid state transformer (SST) or intelligent universal transformer, is a kind of electric equipment that combines power electronics technology and high frequency power conversion technology to achieve flexible power conversion [3]. With a lot of advantages such as small size, voltage sag compensation, current and voltage control etc., the PET can dispatch the power among distribution system, ac grid, and dc grid. Therefore, it can play the role of the so-called energy router in the distribution power grid analogous to what the router does for the Internet. In recent decade, the PET has caught increasingly more attention and been extensively investigated for the distribution system. Compared to traditional transformer, the three-stage PET has been analyzed, the simulations as well as a working prototype have confirmed that the PET can provide the desirable features [5]. For the three-stage PET, the system design and performance demonstration of a high-voltage PET lab prototype and the integration issues of PET with dc microgrid are presented in [6]. In [7], a promising microgrid architecture that integrates the PET with zonal dc microgrid and a centralized power management algorithm are proposed, and the simulation results shows the feasibility of the proposal. The hardware integration of PET and dc microgrid is presented in [8], and a
hierarchical power management strategy is created for the system to enable the disconnection of the dc microgrid. However, the researches of PET in the distribution power are mainly focused on topology evaluation and controller development. The power interconnection realized by PET as an energy router is not analyzed from the point of view of system level.

AC/DC hybrid active distribution network will be an important form of intelligent distribution network in the future. One of the key technologies is the energy management technology with optimal dispatch strategy as the core [9]. From the aspect of optimal dispatch of AC/DC active distribution network, in order to avoid the nonlinear constraints of network power flow, a second-order cone relaxation method must be applied to the model to obtain the global optimal solution [10]. The security-constrained coordinated economical dispatch method of energy storage systems and converter stations for hybrid AC/DC distribution networks is presented in [11], and by the linearization technique, the mixed integer nonlinear programming model, which is difficult to solve, is transformed into linear programming model. The power dispatch strategy in microgrid integrated with PET is presented in [12], and the immune particle swarm optimization is adopted to find the Pareto solution.[13] proposes a method to optimize AC/DC hybrid distributed energy system with PET, and the results show that by the power regulation function of the PET, the full consumption of the distributed power generation can be effectively realized. Such deterministic optimal scheduling model, however, does not consider the randomness of renewable energy output in AC/DC active distribution network. The real-time security of distribution network may not be satisfied in the actual operation process.

With the increasing penetration of renewable energy in the distribution network, to ensure the reliability and security of optimal dispatch, the optimal dispatch model needs to take into account the uncertainty of renewable energy. Robust optimization (RO) is a modeling framework for optimization under uncertainty. Unlike stochastic optimization [14] or probabilistic power flow [15] approaches, RO only requires moderate information of underlying uncertainties. It provides immunity against all possible realizations of uncertain data within the uncertainty bounds [16]. [17] propose the robust optimization base scheduling of multi-microgrids considered in both renewable energy sources and electric load. The developed linear model provides immunity against the worst-case realization within the provided uncertainty bounds. [18] propose the robust optimal dispatch in AC active distribution network with the linear power flow after the Taylor Expansion, but it does not contain the DC distribution network. As for the AC/DC network,[19] proposes a novel bi-level two-stage robust optimal scheduling model considering the source-load uncertainties, and converting the Min-Max-Min problem into mixed-integer linear programming problem, which can be solved quickly and effectively.[20] introduces an optimal dispatch model for simultaneous reduction of cost and emission from generation activities in an AC/DC hybrid microgrid under load and generation uncertainties. Particle swarm optimization, and fuzzy max-min technique are employed to obtain the nonlinear model’s optimal solution. [21] proposes a robust optimal dispatch model with the PET, but this linear optimization model only considers the power balance constraint and does not consider the linearization of the PET’s port capacity, etc.

In order to avoid that the nonlinear programming problem in the AC/DC active distribution network with PET cannot be solved in a fast and effective way, we have considered the uncertainty of renewable energy output and linearized the constraints of AC/DC power flow equations and the port capacity in PET, etc. Then, a linear robust optimized dispatch model is established for the AC/DC active distribution network with PET. At the same time, the robust optimized dispatch model is transformed into a quadratic programming model without uncertain variables through the dual optimization theory, so that the robust optimized dispatch model can be solved in a fast and effective way.
2. AC/DC Active Distribution Network With PET

2.1. Steady-state model of PET

With the advantages of flexible control, PET can not only flexibly provide AC/DC bus interface, but can also realize the voltage conversion and bidirectional power transfer through power electronic technology and high-frequency transformer. Although there are many different topologies in PET, according to the external port characteristics of PET [24], the steady-state model of PET can be equivalent to a three-port power electronic device with power loss, as shown in Fig. 1.

Fig 1. The three-port equivalent model of PET, Main network, DC distribution network, AC distribution network.

Also shown in Fig. 1, $P_M$ and $Q_M$ represent the active power and reactive power exchanged between PET and the main network. $P_{AC}$ and $Q_{AC}$ represent the active power and reactive power exchanged between PET and AC distribution network, respectively. $P_{DC}$ represents the power exchanged between PET and DC distribution network. $S_M$, $S_{AC}$ and $S_{DC}$ represent the maximum access capacity of PET on the main network side, the AC distribution network side, and the DC distribution network side, respectively.

The PET in the AC/DC hybrid active distribution network plays the role of “power router” due to its capability of controlling the port power. Therefore, power complementation can be realized between the AC and DC distribution networks to fully absorb the output of distributed renewable energy in the system. Besides, the AC/DC distribution network will have less dependence on the power of the main network, which improves the autonomy of the AC/DC distribution network.

A PET can be simplified to a node by defining a constant of power loss coefficient $k_{pet}$. The product of the active power injected into this node and the power loss coefficient is equal to the active power output from this node. Considering that the distributed renewable energy had better be fully absorbed in situ, and the electrical power had not better be transported from the AC/DC system to the main network, the steady-state model of PET can be expressed as:

$$P_M + P_{DC,in} + P_{AC,in} = k_{pet} (P_{DC,out} + P_{AC,out})$$  \hspace{1cm} (1)

Where $P_{DC,in}$, $P_{AC,in}$, $P_{DC,out}$ and $P_{AC,out}$ are the active power of the DC and AC distribution network that flows into and out of PET, respectively. $P_M$ is the active power that flows into the PET from main network.

At the same time, due to the limitations of the PET capacity, the following constraints are obtained:

$$\sqrt{P_M^2 + Q_M^2} \leq S_M$$  \hspace{1cm} (2)

$$\sqrt{P_{AC}^2 + Q_{AC}^2} \leq S_{AC}$$  \hspace{1cm} (3)

$$P_{DC} \leq S_{DC}$$  \hspace{1cm} (4)
2.2. Linearized model of AC power flow

The power of the branch in the AC distribution network is expressed as:

\[ S_{ij} = V_i \cdot \left( \frac{(V_i - V_j)}{z_{ij}} \right)^* = \frac{V_i^2 - V_i V_j \cos \delta_{ij} - j V_i V_j \sin \delta_{ij}}{r_{ij} - j x_{ij}} \]  

(5)

Where \( i \) is the initial node of the branch, \( j \) is the end node of the branch, \( z_{ij}, r_{ij} \) and \( x_{ij} \) are the impedance, resistance and reactance of the branch, respectively, \( V_i \) and \( V_j \) are the voltage amplitude of the initial and end node of the branch as well as the phase angle difference, respectively.

With the same two assumptions in [22], the matrices \( B_1 \) and \( B_2 \) are defined as:

\[
B_1(i, j) = -\frac{r_{ij}}{r_{ij}^2 + x_{ij}^2}, \quad B_2(i, j) = -\frac{x_{ij}}{r_{ij}^2 + x_{ij}^2}, \quad i \neq j, \quad B_1(i, i) = \sum_{j=1, j \neq i}^{N} \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2}, \quad B_2(i, i) = \sum_{j=1, j \neq i}^{N} \frac{x_{ij}}{r_{ij}^2 + x_{ij}^2}
\]

(6)

For the AC distribution network, except the slack node, the injected power of the other nodes can be expressed by:

\[
\begin{bmatrix}
P_{AC} \\
Q_{AC}
\end{bmatrix} \left[ B_1^C - B_2^C \right] \begin{bmatrix} \delta \end{bmatrix} = \begin{bmatrix} B_1^C \\
B_2^C
\end{bmatrix} \begin{bmatrix} V_{i,AC} \end{bmatrix} - \begin{bmatrix} B_1^C \\
B_2^C
\end{bmatrix} \begin{bmatrix} V' \end{bmatrix}
\]

(7)

Where \( P' \), \( Q \), \( \delta \) and \( V \) are the injected active power, reactive power, phase angle and amplitude of node voltage except slack node, respectively. \( B_1^C \) and \( B_2^C \) are the sub-matrix formed by deleting the first row and the first column of \( B_1 \) and \( B_2 \), respectively; vectors \( B_1^C \) and \( B_2^C \) are the column vectors formed by deleting the first element in the first column of \( B_1 \) and \( B_2 \), respectively; \( \delta_1 \) is the phase angle of the voltage at slack node; \( V_{i,AC} \) is the voltage amplitude of the slack node in the AC distribution network. In the power flow calculation, \( V' \) is always set as 1.0 to 1.1 p.u. Therefore, the phase angle and amplitude of the node after linearizing the power flow equations can be expressed as:

\[
\begin{bmatrix}
\delta \\
V
\end{bmatrix} = \begin{bmatrix}
B_2 & B_1 \\
-B_1 & B_2
\end{bmatrix}^{-1} \begin{bmatrix}
P_{AC} \\
Q_{AC}
\end{bmatrix} = \begin{bmatrix}
E & -F \\
F & E
\end{bmatrix} \begin{bmatrix}
P_{AC} \\
Q_{AC}
\end{bmatrix}
\]

(8)

\[
\begin{bmatrix}
P_{AC} \\
Q_{AC}
\end{bmatrix} = \begin{bmatrix}
P_{AC} \\
Q_{AC}
\end{bmatrix} - \begin{bmatrix} B_1^C \\
B_2^C
\end{bmatrix} \begin{bmatrix} \delta \end{bmatrix} - \begin{bmatrix} B_1^C \\
B_2^C
\end{bmatrix} \begin{bmatrix} V_{i,AC} \end{bmatrix}
\]

(9)

Then the amplitude of the AC voltage is expressed as:

\[ V' = E Q_{AC} - F P_{AC} \]

(10)

The AC line current can be expressed as:

\[ I_{AC} = L_{AC} A_{AC} (E Q_{AC} - F P_{AC}) \]

(11)
Where $L_{ac}$ is the diagonal matrix composed of the absolute values of the admittances of all branches in the AC distribution network, $A_{ac}$ is the correlation matrix of the node branches in the AC distribution network.

Based on the above linearized power flow equations, it is approximated that the amplitude and phase angle of node voltage are equal to the real and imaginary parts of the corresponding voltage [21], respectively. Therefore, the power loss of the AC distribution network is expressed as:

$$P_{loss} = (A_{ac}V_{ac})^T G_{ac} (A_{ac} V_{ac}) + (A_{ac} \delta_{ac})^T G_{ac} (A_{ac} \delta_{ac})$$

(12)

Where $G_{ac}$ is the diagonal matrix composed of the conductance of each branch. $V_{ac}$ and $\delta_{ac}$ are the amplitude and phase angle of all the node voltage in the AC distribution.

### 2.3. Linearized model of DC power flow

In the DC distribution network, all the node voltages are considered to approximate the reference value. A matrix $D$ is defined in which the elements satisfy:

$$D(i,j) = \frac{-1}{r_{ij}} , \; D(i,i) = \sum_{j \neq i, j \neq 1} \frac{1}{r_{ij}}$$

(13)

The linearized DC power flow can be expressed as:

$$V'_{dc} = D_e^T (P'_{dc} - D_c V_{1,dc})$$

(14)

where $P_{dc}$ and $V_{dc}$ are the injected active power and the magnitude vector of node voltage except the slack node, $D_e$ is the column vector formed by deleting the first element in the first column of the matrix $D$, $D_c$ is the sub-matrix formed by deleting the first row and the first column of the matrix $D$, $V_{1,dc}$ is the voltage amplitude of the slack node in the DC distribution network.

Then the current of the DC line is expressed as:

$$I_{dc} = L_{dc} A_{dc} V_{dc}$$

(15)

Where $L_{dc}$ is the diagonal matrix composed of conductance of all branches in the DC distribution network, $A_{dc}$ is the correlation matrix of the node branches in the DC distribution network. $V_{dc}$ is the amplitude of all the node voltage in the DC distribution.

The power loss of the DC distribution network can be expressed as:

$$P_{loss} = (A_{dc} V_{dc})^T G_{dc} (A_{dc} V_{dc})$$

(16)

Where $G_{dc}$ is the diagonal matrix composed of the conductance of each branch.

### 3. Nonlinear Robust Model With PET

#### 3.1. Objective function

In this paper, minimizing the cost of purchasing electricity and the cost of AC/DC network loss are used as the objective function. The cost of purchasing electricity includes the cost of purchasing
electricity from the main network, the cost of power generation by micro turbine (MT), the cost of energy storage operation, and the cost of demand response (DR). Specifically, it can be expressed as:

$$F = \min C_{\text{loss}} + C_{\text{Main}} + C_{\text{MT}} + C_{\text{ESS}} + C_{\text{DR}}$$  \hspace{2cm} (17)$$

where $C_{\text{loss}}$ is the cost of AC/DC network loss, $C_{\text{Main}}$ is the cost of purchasing electricity from the main network, $C_{\text{MT}}$ is the cost of power generation by MT, and $C_{\text{ESS}}$ is the cost of energy storage system(ESS). $C_{\text{DR}}$ is the cost of DR. The detailed cost of power generation by MT, ESS and DR can be found in Reference [18].

3.2. Constraints on the distribution side

The constraints of power flow equations: the power flow equations of AC/DC active distribution network are shown in Eq. (7) and Eq. (14), which satisfies:

$$
\begin{align*}
    P_A &= P_{AC,CG} + P_{AC,RDG} - P_{AC,Load} \\
    Q_A &= Q_{AC,CG} - Q_{AC,Load} \\
    P_D &= P_{DC,CG} + P_{DC,RDG} - P_{DC,Load}
\end{align*}
$$  \hspace{2cm} (18)$$

where $P_{AC,RDG}$ and $P_{DC,RDG}$ are the output active power of the renewable energy in the AC and DC distribution network during the period of $t$, respectively; $P_{AC,CG}$, $Q_{AC,CG}$ and $P_{DC,CG}$ are the output active and reactive power, respectively, of the controllable resources in the AC and DC distribution network during the period of $t$, and the reactive power of controllable resource is controlled according to the constant power factor; $P_{AC,Load}$, $Q_{AC,Load}$ and $P_{DC,Load}$ are the predicted loads, respectively, of the AC and DC distribution network during the period of $t$.

The constraints of voltage safety: in order to ensure the safe operation of the distribution network, the voltage of each node cannot exceed the allowable range of safe operation, i.e.:

$$V \leq V' = EQ_{AC} + FP_{AC} \leq \bar{V}$$  \hspace{2cm} (19)$$

$$V \leq V' = D_{\text{DC}}(P_D - D_{\text{DC}}V_{DC}) \leq \bar{V}$$  \hspace{2cm} (20)$$

Where $\underline{L}$ and $\overline{L}$ are the vectors of upper and lower limits of the node voltage, respectively.

The constraints of line safety: in order to avoid line overload, the line current should meet the constraints of line capacity, i.e.:

$$L \leq I_{AC} = L_{AC}A_{AC}V_{AC} \leq \bar{I}$$  \hspace{2cm} (21)$$

$$L \leq I_{DC} = L_{DC}A_{DC}V_{DC} \leq \bar{I}$$  \hspace{2cm} (22)$$

Where $\overline{L}$ and $\underline{L}$ are the vectors of the upper and lower limits of the branch current, respectively.

3.3. Uncertainty in renewable energy

In this paper, the deviation between the actual output and the predicted output of renewable energy is taken as the uncertain variable which is described by the box uncertainty set:
\[
\begin{align*}
\{ P_{RDG,r}^i &= P_{RDG,p}^i + \sigma_i \\
-\sigma &\leq \sigma_i \leq \sigma
\end{align*}
\] (23)

Where \(P_{RDG,r}^i\) and \(P_{RDG,p}^i\) are the actual output and predicted output of renewable energy during the period of \(t\); \(\sigma^i\) is the deviation between the actual output and the predicted output during the period of \(t\); \(-\sigma\) and \(\sigma\) are the upper and lower limits of the predicted deviation.

Therefore, the established model can be expressed as:

\[
\begin{align*}
&\text{obj} : (17) \\
&\text{ST} : (1-4),(7),(14),(18-24)
\end{align*}
\] (24)

Obviously, the model cannot be solved efficiently due to the existence of uncertain variables, the introduction of nonlinear constraints on controllable resources and PET port capacity.

4. Linear Robust Model With PET
The robust nonlinear optimized dispatch model with PET introduced in Section III takes into account the randomness of renewable energy output. The obtained optimized dispatch results can effectively deal with the uncertainty of renewable energy output in actual operation. However, due to the existence of uncertain variables as well as the introduction of nonlinear constraints on controllable resources and PET port capacity in the model, the model cannot be solved in an effective way. Therefore, based on the dual optimization theory, the model is transformed into a deterministic optimization model without uncertain variables, and the regular inscribed polygon of a circle is used to approximate the nonlinear constraint of port capacity. Therefore, a linear robust optimized dispatch model with PET is established.

4.1. Dual optimization theory
Taking the constraint of node voltage safety in the AC distribution network as an example, the actual output of the renewable energy with uncertain variables is substituted into the constraint of node voltage safety which can be then described as:

\[
\begin{align*}
\sum_{i=1}^{m} \max_{\sigma^i} F\sigma^i \leq \overline{V} - F(P^i - B_c^i \delta - B_c^i V_{AC}) - EQ_{AC} \\
\sum_{i=1}^{m} \min_{\sigma^i} F\sigma^i \geq \underline{V} - F(P^i - B_c^i \delta - B_c^i V_{AC}) - EQ_{AC} \\
F^i = P_{RDG,p} + P_{AC,CG} - P_{AC,Load}
\end{align*}
\] (25)

Where \(m\) is the number of installed renewable sources in the network, \(\sigma^i\) is the uncertain variable of the predicted deviation of the \(i^{th}\) renewable energy in the \(t^{th}\) period.

According to the linear dual optimization theory, the following equation can be obtained:
For $\min_{\sigma_{i,j}}$, under the predictive bias constraint in Eq. (25), the corresponding Lagrange function is constructed as:

$$L = -\sigma_{i,j} + z^i \sigma_{i,j} + \alpha (\sigma_{i,j} - \bar{\sigma}_{i,j}) + \beta (\sigma_{i,j} - \bar{\sigma}_{i,j})$$

(27)

Where $\alpha$, $\beta$, and $z^i$ are the corresponding Lagrange coefficients. Partial derivation is performed on the Lagrange function to $\sigma_{i,j}$:

$$-1 + z^i + \alpha + \beta^i = 0$$

(28)

Then for the uncertain variables in Eq. (28), the following equation is obtained:

$$\sum_{i=1}^{m} \max_{\sigma_{i,j}} F\sigma_{i,j} = F \sum_{i=1}^{m} \alpha_i \sigma_{i,j} - \beta^i \bar{\sigma}_{i,j}$$

$$\begin{cases}
-1 + z^i + \alpha^i + \beta^i = 0 \\
st., \\
\alpha^i \geq 0 \\
\beta^i \geq 0
\end{cases}$$

(29)

Thus, according to the dual optimization theory, the robust optimized model containing uncertain variables is transformed into a robust equivalence model without uncertain variables.

### 4.2. Linearization of the port capacity

For the AC/DC active distribution network with PET, the PET ports have the ability to actively control power flow, and the AC/DC port has the capacity constraint, as shown in Eq. (2)-(4). Simultaneously, the controllable distributed power supply in the AC/DC distribution network also has a capacity constraint, as shown in Eq. (23)-(24). Such capacity constraints mathematically can represent that a circle is inscribed with a regular polygon to approximate the circle to avoid such nonlinearities. Therefore, such nonlinear constraints can be replaced by a series of linear constraints:

$$\left[ \begin{array}{c}
\alpha_x P + \beta_x Q + \delta_x S \leq 0 \\
\forall w \in \left[ 1, 2, \cdots, n_w \right]
\end{array} \right]$$

(30)

Where $\alpha_x$, $\beta_x$, and $\delta_x$ are the coefficients of the linearized capacity constraint, $P$, $Q$, and $S$ are the output active power, reactive power, and port capacity of the corresponding port, respectively. $n_w$ is the number of edges of regular polygon. In this paper, we use the regular tetradecagon.

In summary, the dual optimization theory is used to eliminate the uncertain variable and the port capacity constraint is linearized. Then, the robust optimized dispatch model for AC/DC active distribution network with PET is transformed into an equivalent linear robust optimized dispatch.
model without uncertain variables. The obtained model is a quadratic programming model and can be efficiently and reliably solved using CPLEX.

5. Example Analysis
The modified IEEE33 system constitutes the AC/DC active distribution network with PET.

5.1. Robustness Analysis
Taking the predicted renewable energy output as the actual renewable energy output, the optimized dispatch scheme with PET can be calculated, i.e., the deterministic optimized dispatch.

It can be seen from Table 1 and Fig. 2 that the costs of the AC MT and ESS in the AC distribution network do not show much difference under different dispatch schemes, but their output curves have a large difference at some moments. Overall, the output of ESS in the DC distribution network shows quite difference. This is because, in the proposed robust optimized dispatch scheme, in order to ensure the safety of the network node and the safety of the line, the ESS device in AC/DC active distribution network and the AC MT are required to absorb or supplement the power fluctuation caused by the randomness of the renewable energy at a higher power value at the corresponding moment.

In order to reflect the advantage of the proposed robust optimized dispatch scheme in dealing with the uncertainty of renewable energy output, the node voltage in the network under different schemes is compared under the extreme conditions of intermittent renewable energy output (that is, the error of ±30% in the output of renewable energy).

Fig. 3 shows that for the extreme conditions of the deterministic optimized dispatch scheme, the AC/DC network faces the problem of the voltage exceeding the upper and lower limits. In the proposed robust optimized dispatch scheme, the node voltage of the network is within the security range, which guarantees safe operation of AC and DC distribution networks. The above results have verified the robustness of the proposed method in ensuring the safe operation of the distribution network even with the fluctuation of renewable energy output.

| COST TYPE | Deterministic optimized dispatch/RMB | The proposed robust optimized dispatch/RMB |
|-----------|--------------------------------------|------------------------------------------|
| AC MT     | 4384.54                              | 4794.80                                  |
| AC ESS    | 299.26                               | 355.69                                   |
| AC DR     | 1086.12                              | 1086.12                                  |
| DC ESS    | 94.48                                | 376.60                                   |
| main grid | 7598.92                              | 9539.32                                  |

Table 1. Comparison of costs for different optimized dispatches

![Fig. 2. Result of different dispatches for AC ESS.](image-url)
Fig. 3. Voltage distribution of AC and DC networks

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