# Optimal Reactive Power Dispatch Considering Power Loss of Transformer

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**Abstract.** A large proportion of power loss in distribution system is from transformer, which is not considered in the traditional Distribution network Reactive Power Optimization (DRPO). This paper proposes a DRPO model considering the power loss of transformer. The optimization method includes reactive power compensation with capacitor, tap adjusting with On-Load Tap Changer (OLTC) transformer. Simulation on the modified IEEE 33-bus test system with Differential Evolution Algorithm (DEA) is testified, the different load level is also analyzed and compared with the traditional optimization model, the test results show that the DRPO considering power loss of transformer is very necessary for light-loaded system. DRPO considering power loss of transformer is more reasonable and adaptable.

## Introduction

The traditional Distribution network Reactive Power Optimization (DRPO) can be defined as optimizing operating status of the distribution network equipment at some point or within a certain period in the future to ensure the safe, economical and stable operation of the entire distribution system through adjusting all kinds of reactive power compensation equipment or other means which can change the system reactive power flow when satisfying various constraint conditions in the network.

The reactive compensation with capacitor bank include the centralized compensation in the substations, ring main unit and other places, distribution line dispersion compensation, and user terminal dispersion compensation. The ideal capacitor in the circuit does not cost power loss in the circuit. As a medium of energy transfer, large-capacity transmission of reactive power in distribution network can be avoided by the capacitor reactive power compensation. Therefore, a reasonable capacitor reactive power compensation can reduce the power loss of transmission line and transformer, improve power factor, and also reduce power generation costs. On-Load Tap Changer Transformer (OLTCT) can regulate the output voltage by changing the tap position. The fundamental principle is to adjust the reactive transmission between the primary side and secondary side of the transformer which does not change reactive power capacity of the total distribution system.

In actual operation, a large proportion of power loss in distribution system comes from transformer, which is not considered in the traditional DRPO. Although the DRPO can optimize the operating network voltage, reduce network power loss, but it also may increase the power loss of the transformer. As an important component in distribution network, the transformer loss needs to be taken into consideration in the process of optimization, especially when the power loss of transformer is large in the distribution network.

In this paper, the DRPO strategy and model will be fully improved, including the reactive power compensation with capacitor, tap position adjusting with On-Load Tap Changer Transformer

 

(OLTCT). At the same time in order to get close to the actual distribution network operation, the transformer loss has been taken into account in the comprehensive optimization model in this paper which can provide a more comprehensive strategy for DRPO.

## Distribution Network Reactive Power Optimization

**The Traditional Distribution Network Reactive Power Optimization Model.** The traditional DRPO is in order to implement the objective of minimum active power loss, optimal voltage quality and the minimum running costs and so on by adjusting the reactive power compensation equipment and transformer tap under the premise of the radial distribution network constraint conditions.

The optimized objective function of minimum active power loss and optimal voltage quality is as follows: [1-2]

$$\min f_1 = P_{loss} \tag{1}$$

$$\min f_2 = \sum \left( \frac{V_i - V_{i,0}}{\Delta V_{i,\max}} \right)^2 \tag{2}$$

where $P_{loss}$ is the power loss of the distribution network; $V_i$ is the voltage amplitude of node $i$; $V_{i,0}$ is the ideal voltage amplitude of node $i$. $\Delta V_{i,max}$ is the maximum allowable voltage deviation of node $i$. Except the regular power balance, node voltage and branch current constraint condition, the constraints also include:

The constraint condition of the capacitor bank switching:

$$Q_{C,j}^{\min} \le Q_{C,j} \le Q_{C,j}^{\max} \qquad j=1\sim m \tag{3}$$

The tap adjusting constraint condition of OLTCT:

$$OLTC_k^{\min} \le OLTC_k \le OLTC_k^{\max} \qquad k=1\sim n \tag{4}$$

where the $m$ is the number of nodes at which capacitors are installed. The $n$ is the number of nodes at which OLTCTs are installed. $Q_{C,j}$ is the switching capacity of the reactive compensation equipment at node $j$. $Q_{C,j}^{\max}$ and $Q_{C,j}^{\min}$ respectively represents the upper limit and lower limit of the reactive compensation capacity at node $j$. $OLTC_k$, $OLTC_k^{\max}$ and $OLTC_k^{\min}$ are respectively the tap position, the upper limit and lower limit of the tap adjusting range of the transformer $k$.

**The Comprehensive DRPO Model Considering the Power Loss of Transformer.** The comprehensive DRPO model considering the power loss of transformer proposed in this paper uses two optimization methods includes reactive power compensation capacitor and OLTCT tap adjusting. The objective function is the minimum power loss of entire distribution network includes network loss and transformer loss, which is as follows:

$$\min F = P_{loss\_net} + P_{loss\_Mtf} + P_{loss\_Ltf} \tag{5}$$

where $P_{loss\_net}$ is network loss. $P_{loss\_Mtf}$ is power loss of medium voltage transformer which is 110/10kV transformer in this paper. $P_{loss\_Ltf}$ is power loss of distribution transformer which is 10/0.38kV load bus transformer in the paper.

$P_{loss\_net}$ is the calculation result of distribution network power flow. $P_{loss\_Mtf}$ and $P_{loss\_Ltf}$ both include variable loss and fixed loss of the transformer. When operating voltage is raised by OLTCT in the distribution network, the transformer loss will also increase.

$$P_{loss\_Mtf} = \Delta P_{kb} + \Delta P_{gd} \tag{6}$$

$$P_{loss\_Ltf} = \sum_{i=1}^{ln} \left( \Delta P_{kb,i} + \Delta P_{gd,i} \right) \tag{7}$$

where the variable loss of transformer is $\Delta P_{kb}=(P^2+Q^2)/U^2\times R$; the fixed loss of transformer is $\Delta P_{kb}=U/U_e \times\Sigma\Delta P_0$; $P$ and $Q$ is respectively active and reactive transmitted power of the transformer; $U$ is the actual operating voltage of the transformer. $U_e$ is the nominal voltage. $\Delta P_0$ is unloaded loss; $R$ is the equivalent resistance of the transformer; $ln$ is the total number of transformers in the distribution network; $\Delta P_{kb,i}$ is the variable loss of transformer $i$; $\Delta P_{gb,i}$ is the fixed loss of transformer $i$.

**The Constraint Conditions of DRPO Considering the Transformer Loss.** The constraint conditions of comprehensive DRPO include power balance constraint, node voltage constraint, power flow constraint of branch, the capacitor bank switching constraints and the tap adjusting constraint of OLTCT. The *distflow* method is used to process power balance constraint in this paper.

$$\sum_{k:(j,k)\in\psi_b} P_{jk} = P_{ij} - r_{ij} \cdot \left( P_{ij}^2 + Q_{ij}^2 \right) \big/ U_i^2 - P_j^L \tag{8}$$

$$\sum_{k:(j,k)\in\psi_b} Q_{jk} = Q_{ij} - x_{ij} \cdot \left( P_{ij}^2 + Q_{ij}^2 \right) \big/ U_i^2 - Q_j^L + Q_j^C \tag{9}$$

$$U_j^2 = U_i^2 - 2\left( r_{ij}P_{ij} + x_{ij}Q_{ij} \right) + \left( r_{ij}^2 + x_{ij}^2 \right)\left( P_{ij}^2 + Q_{ij}^2 \right) \big/ U_i^2 \tag{10}$$

where $P_j^L$ and $Q_j^L$ are respectively original active and reactive load power of node $j$; $Q_j^C$ is reactive power of capacitors installed at node $j$. $r_{ij}$ and $x_{ij}$ are respectively the resistance and reactance of the branch $(i, j)$. $P_{ij}$ and $Q_{ij}$ are respectively active and reactive power of at the head of the branch $(i, j)$. $U_i$ and $U_j$ are voltage amplitude of node $i$ and $j$ respectively. $P_{jk}$ and $Q_{jk}$ are active and reactive power at the head of branch *(j, k)* respectively.

## The Example and Result Analysis

**Example.** The IEEE 33-bus system is a 12.66 kV distribution network with single power supply, including 33 bus nodes and 5 transmission lines, and the total load is 3715kW, 2300kvar. The diagram of distribution network structure is shown in Figure 1, and the specific parameter is in the literature [3]. In order to verify the proposed model, the example system has been modified as follow in this paper.

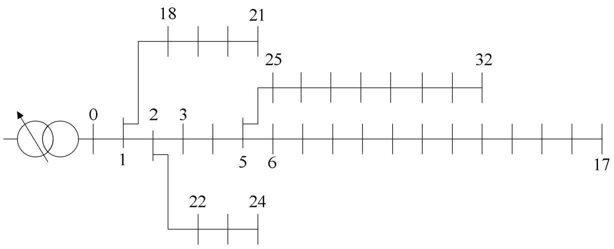


**Fig. 1 Network structure of IEEE 33-bus case**

The eight capacitor banks are respectively installed in the node 5, 7, and 21. The each group is 50kvar. The 110/10kV OLTCT is three-phase duplex winding transformer, the capacity is 31.5MVA, the ratio is 110±8×1.25% kV, the connection mode is YNd11, the number of tap changers is 17, the rated no-load loss is 33.8kW, the rated loaded loss is 133kW, the no-load current percentage is 0.64%, the short circuit impedance percentage is 10.5%. The 10/0.38kV distribution transformer is three-phase duplex winding no-load tap changer transformer, the capacity is 1000kVA, the connection mode is Dyn11, the rated no-load loss is 1.7kW, the rated loaded loss is 10.3kW, the no-load current percentage is 1.0%, the short circuit impedance percentage is 4.5%.

The distribution transformers are installed in every load nodes. The allowed band of the node voltage is 0.95~1.05p.u. The rated long-term running capacity is 5MVA.

The differential evolution algorithm is used to solve this example. The Parameter setting is as follows: the scaling factor F and crossed factor CR are 0.8 and 0.8 respectively. The Population size NP is 30, the maximum iterations is 80.

According the following formulas:

$$R_T = P_k \cdot U_N^2 \Big/ \left(1000 \cdot S_N^2\right) \tag{11}$$

$$X_T = U_k\% \cdot U_N^2 \Big/ \left(100 \cdot S_N\right) \tag{12}$$

The impedance of 110kV transformer can be calculated: $R_T$ =0.6437Ω, $X_T$ =25.41Ω; The impedance of distribution transformer can be calculated: $R_T$=1.03Ω，$X_T$=4.5Ω.

**The Analysis of Result.** The example is calculated by Matlab 8.1, the two scenarios are set to analyze the results of comprehensive DRPO proposed in this paper, which include:

Scenario 1: The traditional DRPO of distribution network which doesn't consider the transformer loss.

Scenario 2: The DRPO proposed in this paper considering the power loss of the 110/10KV transformer and distribution transformer.

The result of DRPO considering transformer loss at different load level is shown in Table 1. We can see that along with the reducing of the load, the percentage of the no-load loss in the total loss is increasing, the proportion of load loss is greatly reducing.

**Table 1 The Result of DRPO Considering The Power Loss From Transformer**

| Result | The System Total Loss [kW] | Network Loss [kW] | 110kV No-load Loss [kW] | 110kV Load Loss [kW] | 10kV No-load Loss [kW] | 10kV Load Loss [kW] |
|---|---|---|---|---|---|---|
| The original load | 268.435 | 163.618 | 35.490 | 22.190 | 54.603 | 12.505 |
| 50% Load | 131.063 | 37.658 | 34.856 | 0.511 | 54.958 | 3.08 |
| 10% Load | 86.389 | 1.567 | 32.532 | 0.02 | 52.134 | 0.136 |

The results of traditional DRPO and DRPO considering transformer loss with original load are shown in Table 2. We can see that with the original load the results of traditional DRPO and DRPO considering transformer loss are almost the same. It's because of under the original load level, no-load loss and load loss of the transformer are almost the same, combined with the network loss, the DRPO results will increase the voltage as far as possible in order to decrease network loss and load loss.

**Table 2 The DRPO Results with the Original Load**

| Result | The system total power loss [kW] | The number of switching capacitor groups（5/17/21） | OLTC tap position |
|---|---|---|---|
| Original Network | 202.677 | / | / |
| Scenario 1 | 268.437 | 10/10/9 | +8 |
| Scenario 2 | 268.435 | 10/10/10 | +8 |

The results of traditional DRPO and DRPO considering transformer loss with 50% load are shown in Table 3 from which we can see that the results have some differences. It's due to the proportion of the transformer no-load loss increases, and the proportion of load loss and network loss reduces, for the total system loss, the higher voltage isn't better. Although the total losses are similar, in scenario 1 the high OLTC tap position raises the voltage to reduce the network loss which is inversely proportional to the square of the voltage, in scenario 2 the reasonable tap position can reduce the no-load loss of the transformer.

 

**Table 3 The DRPO Results with the 50% Load**

| Result | The system total power loss [kW] | The number of switching capacitor groups（5/17/21） | OLTC tap position |
|---|---|---|---|
| Original Network | 47.071 | / | / |
| Scenario 1 | 131.112 | 10/10/4 | +8 |
| Scenario 2 | 131.063 | 10/10/4 | +5 |

The results of traditional DRPO and DRPO considering transformer loss with 10% load are shown in Table 4. When the distribution network is in light load condition, the power loss of scenario 2 is 7.96% lower than scenario 1. The number of switching capacitor groups and OLTC tap position are different. Because the transformer no-load loss is much larger than the sum of load loss and network loss, the reducing the system loss is mainly depending on the reducing of transformer no-load loss. When satisfying the precondition of the system security, the lower voltage is better. The OLTC tap position is -6, the capacitor can keep the voltage of the node isn't out-of-limit.

**Table 4 The DRPO Results with the 10% Load**

| Result | The system total power loss [kW] | The number of switching capacitor groups（5/17/21） | OLTC tap position |
|---|---|---|---|
| Original Network | 1.786 | / | / |
| Scenario 1 | 93.860 | 6/2/1 | +8 |
| Scenario 2 | 86.389 | 7/2/1 | -6 |

## Conclusion

In this paper, a DRPO model considering transformer loss is proposed, the optimization methods include capacitor reactive power compensation, transformer on-load voltage regulation. An improved IEEE 33-bus system at different load level is used for simulation calculation, the results show that after considering the transformer loss, with 10% load level system, the total loss was reduced by 7.96%. When the distribution network is in light load condition, it is very necessary to consider transformer loss in DRPO. In terms of the applicability, the DRPO considering the transformer loss is suitable for various load levels, can provides a new method for reducing the total ditribution system loss.

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