A Method of Dynamic Extended Reactive Power Optimization in Distribution Network Containing Photovoltaic-Storage System

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Abstract. The grid-integration of Photovoltaic-Storage System brings some undefined factors to the network. In order to make full use of the adjusting ability of Photovoltaic-Storage System (PSS), this paper puts forward a reactive power optimization model, which are used to construct the objective function based on power loss and the device adjusting cost, including energy storage adjusting cost. By using Cataclysmic Genetic Algorithm to solve this optimization problem, and comparing with other optimization method, the result proved that: the method of dynamic extended reactive power optimization this article puts forward, can enhance the effect of reactive power optimization, including reducing power loss and device adjusting cost, meanwhile, it gives consideration to the safety of voltage.

1. Introduction

Recent years, the short of traditional energy and the gradual opened of power market, makes the Distributed Generator (DG) get a large number of applications. As the penetration of DG become higher in power network, distribution network will be more complex. Therefore, scholars do a lots research in relevant content, and the problem of reactive power optimization become a hot content [1,2,3].

Dynamic reactive power optimization is a complex mixed-integer nonlinear programming problem, and it commonly increase the maximum action frequency of control variable as constraints to avoid control equipment frequent operate [4]. So far, distributed energy storage technology receive a lots of attentions and has made considerable development [5]. The Energy Storage System (ESS) can reduce the cost and increase the flexibility of the system[6]. ESS offers an ideal economic dispatch[7]. If ESS combined with photovoltaic (PV) connect to the grid, the active power of ESS will be able to two-way adjust, effectively relieve the problem of voltage over limit and equipment overload after distributed photovoltaic access, it can act as a buffer in power system [8]. From the control point of view, if ESS be used in distributed network, ESS’s active power can be treated as control variable and it will be able to enhance the adjusting ability of network. Therefore, installing Photovoltaic-Energy Storage Hybrid System (PESHS) in the operation of distribution network as additional will become the main trend.

For this reason, towards distributed network containing PESHS, this paper puts forward a kind of dynamic reactive power optimization model. This model add the minimum adjusting cost of ESS as one of objective, use 24-hour as an optimization period, and optimizing in chronological order.
2. Mathematical Model of Dynamic Reactive Power Optimization

2.1. Problem formulation

The proposed model adopts the method of time decoupling, the dynamic reactive power optimization is transformed into static reactive power optimization.

1. Minimum active loss of network

Active loss is an important index of power grid operation economical efficiency, adjusting the state of transformer and reactive power equipment, or the active and reactive output of PESHS, the load flow distribution would be improved, so as to effectively reduce the active loss of power grid. Its mathematical expression is as follows:

\[ P_{\text{loss}} = \sum_{i=1}^{n} \sum_{j=1}^{n} V_i V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \]  

(1)

2. Minimum adjusting cost of transformer and compensating capacitor

\[ C_{TQ} = C_t \sum_{i=1}^{n_t} (T_i' - T_i^{-1}) + C_Q \sum_{j=1}^{n_Q} (Q_j' - Q_j^{-1}) \]  

(2)

Where \( t = \text{time} \); \( i = \text{transformer} \); \( j = \text{compensating capacitor} \); \( C_{TQ} \) is the total adjusting cost of transformer and compensating capacitor; \( C_t \) and \( C_Q \) are the unit adjusting cost of transformer and compensating capacitor; \( T \) is transformer tap notch and, \( Q \) is group number of operational capacitor; \( n_t, n_Q \) are number of transformer and compensating capacitor.

3. Minimum adjusting cost of ESS

\[ C_E = \sum_{i=1}^{n_E} C_{\text{OMM}} (P_{ci} + P_{di}) + C_{\text{Dep}} U_{di} (1 - U_{di}^{i-1}) \]  

(3)

Where \( t = \text{time} \); \( i = \text{ESS} \); \( C_E \) is the operating cost of ESS; \( C_{\text{OMM}} \) is the maintain cost coefficient of ESS; \( P_{ci}, P_{di} \) are the charging and discharging power of ESS, \( U_{di} \) is the state of charge; \( C_{\text{Dep}} \) is the ESS’s cost of depreciation, as in (4):

\[ C_{\text{Dep}} = \frac{\eta_{\text{Dep}}}{N} (C_P P_N + C_E E_N) \]  

(4)

Where \( \eta_{\text{Dep}} \) is the depreciation coefficient of ESS; \( P_N \) is the maximum output of ESS; \( E_N \) is rated capacity of ESS; \( C_P \) and \( C_E \) are the corresponding installing cost coefficient, \( N \) is cycle index of accumulator. In order to make units unified, using electrical power form to express adjusting cost of ESS, as in (5):

\[ C_E^{\prime} = \frac{C_E}{\alpha \Delta t} \]  

(5)

Where \( \alpha \) is electricity price; \( \Delta t \) is unit time of optimization.

Synthesizing these optimization goals above, the objective function can be concluded:

\[ \min P^{\prime} = P_{\text{loss}}^{\prime} + C_{TQ} + C_E^{\prime} \]  

(6)

Control variable include:

- \( Q_{ci} \) = reactive power output of compensating capacitor;
- \( T \) = voltage regulator;
- \( \lambda_{\text{PV}} \) = power factor of photovoltaic system;
- \( P_E \) = active power output of ESS;

2.2. Constraint condition

The objective function is restricted by the following factors.
Limit on unit capacitor capacity:
\[ Q_{\text{Cmin}} < Q_i < Q_{\text{Cmax}} \]  
(7)

Limit on tap position of transformer:
\[ T_{K_{\text{min}}} < T_i < T_{K_{\text{max}}} \]  
(8)

Limit on PSS active power output:
\[ [V_{\text{Di}} + P_{\text{Di}}] < V_i < [V_{\text{Di}} + P_{\text{Di}}] \]  
(9)

Voltage magnitude limits at PQ nodes:
\[ 0.95 \leq V_{pq} \leq 1.05 \]  
(10)

Power factor limit of PV generation:
\[ \lambda_{\text{min}} \leq \lambda_{\text{PV}} \leq \lambda_{\text{max}} \]  
(11)

Where \( Q_{\text{Cmin}}, Q_{\text{Cmax}} \) are the minimum and maximum capacity of unit capacitor \( i \); \( T_{K_{\text{min}}}, T_{K_{\text{max}}} \) are the minimum and maximum tap position of transformer \( i \); \( \lambda_{\text{min}}, \lambda_{\text{max}} \) are the minimum and maximum power factor of photovoltaic; \( V_{\text{Di}} \) is the active power output of photovoltaic \( i \); \( P_{\text{Ui}} \) and \( P_{\text{Di}} \) are the minimum and maximum active power output of ESS \( i \), they can be obtained as:

\[
\begin{align*}
P_{\text{Ui}} &= \min(E_{\text{max}}/\eta_{\text{Ci}}, E_{\text{Ui}} - E_i) \\
P_{\text{Di}} &= \max(E_{\text{min}}/\eta_{\text{Di}}, E_{\text{Di}} - E_i/\eta_{\text{Di}})
\end{align*}
\]  
(12)

Where \( \Delta t \) is the unit time of optimization; \( E_{\text{Di}}, E_{\text{Ui}} \) are the minimum and maximum capacity of ESS \( i \); \( E_{\text{min}}, E_{\text{max}} \) are the maximum discharge-charge power network receive from ESS; \( \eta_{\text{Ci}}, \eta_{\text{Di}} \) are the efficiency of charge-discharge power; \( E_i \) is the remainder capacity of ESS, the calculating method can be described as in (13):

\[
E_i^t = E_{i}^{t-1} + (P_{\text{C}}/\eta_{\text{Ci}} - P_{\text{Di}}/\eta_{\text{Di}})\Delta t - E_i(1 - U_{\text{C}}')(1 - U_{\text{Di}}')
\]  
(13)

Where \( t = \text{time} \); \( P_{\text{C}}/\eta_{\text{Ci}}, P_{\text{Di}}/\eta_{\text{Di}} \) are the charge-discharge power of ESS; \( U_{\text{Ci}}, U_{\text{Di}} \) are the state of ESS charge; \( E_i \) is the wastage of the energy storage resting.

### 3. Calculating method

This paper uses Cataclysmic Genetic Algorithm (CGA) to solve reactive power optimization. CGA based on genetic algorithm and adds catastrophe operator, so as to improve the efficiency of optimization, and avoid the optimization calculation into the local optimum. Using MATLAB to write relevant program, and is used to optimize calculation.

In order to satisfy the voltage constraint, this paper use a Voltage Risk Index, it is regard as a penalty term join in the objective function, it is obtained as:

\[
V_{\text{LIM}} = \sum_{i=1}^{n} \left| \frac{V_i - \text{Sat}(V_i)}{V_{\text{max},i} - V_{\text{min},i}} \right|
\]  
(14)

Where \( V_i \) is magnitude of Voltage on node \( i \); \( \text{Sat}(x) \) is saturation function, it can be obtained as:

\[
\text{Sat}(x) = \begin{cases} 
\lambda_{\text{min}}, & x < \lambda_{\text{min}} \\
\lambda_{\text{max}}, & \lambda_{\text{min}} \leq x \leq \lambda_{\text{max}} \\
\lambda_{\text{max}}, & \lambda_{\text{max}} < x
\end{cases}
\]  
(15)
Meanwhile, in order to make the energy of ESS balance between the beginning and end of optimization period, this paper use Storage Energy Balance Index to be regard as a penalty term appended in objective function, it can be obtained as:

\[
E_{cdi} = \begin{cases} 
E_i^b - E_i^e, & (E_i^b - E_i^e) > \varepsilon \\
0, & (E_i^b - E_i^e) \leq \varepsilon 
\end{cases}
\]  \quad (16)

Where \(E_i\) is the remainder capacity of ESS \(i\) at the time of \(t\), \(\varepsilon\) is value of allowable deviation.

After adding penalty terms to objective function, the extended objective function is:

\[
\min F'' = P_{\text{LOSS}} + C_{\text{T-Q}}^t + C_{E}^t + \lambda_{V} V_{\text{V}} + \lambda_{E} \sum_{i=1}^{N} E_{cdi}
\]  \quad (17)

Where \(\lambda_{V}, \lambda_{E}\) are penalty divisor, and \(\lambda_{V}\) is a positive number, the value of \(\lambda_{E}\) increase gradually, it can be obtained as:

\[
\lambda_{E} = \begin{cases} 
0, t \leq t_1 \\
k_1 \cdot t^2, t_1 < t \leq t_2 \\
k_2 \cdot t, t_2 < t \leq T 
\end{cases}
\]  \quad (18)

In order to ensure that \(\lambda_{E}\) increase gradual, equation (18) is subject to \(k_1 < k_2 / t_2\).

4. Test systems
This paper uses a distributed network as an example, the topological structure as shown in Fig.1, it has 108 nodes. Forecast of load rate as shown in Fig.2, 3 p.m. reach the maximum load 6.246MW. There are three peak load periods: 9 a.m. - 11 a.m., 1 p.m. - 5 p.m. and 8 p.m. - 10 p.m.

**Figure 1.** A topological structure of one distributed network.

**Figure 2.** Forecast of load rate.
There are three PESHS access network through nodes 43, 44, 45 respectively, the configuration and index of PESHS shown in Table 1. A voltage regulator in the power system contains 17 tap position (UN±8×1.25%, capacitors installed in node 4, 10, 16, 22, 25, 28, 33, capacity of unit group are 20kvar, 10kvar, 10kvar, 10kvar, 15kvar, 75kvar, all capacitors have 2 groups to operate.

### Table 1. Configuration and Index of PESHS

| Index | Parameter  | Parameter  |
|-------|------------|------------|
| $E_N$ | 3MW·h      | $C_p$      | 667 CNY / kW |
| $p_N$ | 800kW      | $C_r$      | 1200 CNY / (kW·h) |
| $\eta_e$ | 85%      | $C_{arb}$ | 0.01 CNY / kW |
| $\eta_d$ | 85%      | $n_{op}$  | 0.1% |
| $E_i$ | 2(kW·h)/h | $\alpha$  | 0.8 CNY / (kW·h) |
| $E_{ds}$ | 0.6MW·h  | $C_7$     | 3kW |
| $E_{ui}$ | 3MW·h    | $C_0$     | 2kW |

Installed capacity of PV1, PV2 and PV3 are 350kW, 300kW and 250kW, range of power factor are all from lag 0.85 to lead 0.85. Fig.3 displays the 24 hours forecast for the PV power output.

![Figure 3. Forecast for the PV power output.](image-url)

Different optimization method has been set so as to find different optimization effect. In order to compare the effects of the reactive power output of photovoltaic inverter and energy storage on distribution network operation, the control variable of each method as shown: Method 1: $Q_C$, $T_k$; Method 2: $Q_C$, $T_k$, $\lambda_{PV}$; Method 3: $Q_C$, $T_k$, $\lambda_{PV}$, $P_{ES}$. By using CGA, we can calculate the optimal solution and get the results. Objective value of different method are shown as Fig.4, and power loss is shown as Fig.5.

![Figure 4. Objective value.](image-url)
Figure 5. Power loss.

According to Fig.4 and Fig.5, comparing method 1 with 2, we can see that after the photovoltaic inverter provides reactive power, power loss is obviously reduced. Relative to methods 1 and 2, method 3 is the best optimization method. Because of the enough original energy of ESS, in the first several time ESS provide active power to reduce power loss. At noon time, ESS absorb extra photovoltaic power and reduce power loss. In the remaining time, due to energy storage charge and discharge balance constraints, in order to ensure the normal operation of the next optimization cycle, energy storage device in keeping the capacity close to the initial capacity and then tend to stop run, so the optimization result is the same as the other methods.

Sum up the 24 hours calculation results, total objective value and total power loss of different method as shown in the Table 2.

| Method | Total Objective Value (MW) | Improve Ratio | Total Power Loss (MW) | Improve Ratio |
|--------|---------------------------|---------------|-----------------------|---------------|
| 1      | 3.3614                    | —             | 3.3184                | —             |
| 2      | 3.1634                    | 5.89%         | 3.1264                | 5.79%         |
| 3      | 2.8963                    | 13.84%        | 2.6693                | 23.4%         |

Compare method 2 with 1, the former can reduce more objective value and power loss. According to the optimization effect of method 3, the combined control of reactive power output of photovoltaic inverter and storage energy can achieve better optimization results. Therefore, in the reactive power optimization which consider PESHS, add active power output of ESS and power factor of PV unit as the expansion control variable, better results can be achieved in the grid economy.

5. Conclusion

This paper puts forward an extended reactive power optimization model, which based on PESHS. The model via time decoupling to turn dynamic reactive power optimization to static reactive power optimization. In the optimization, the power loss and the adjustment cost of the equipment are taken into consideration. By setting different optimization methods, we can draw the following conclusions:

1. The reactive power provided by the PV inverter can effectively reduce power loss and total objective value without any other cost.
2. ESS can improve the ability to regulate the distribution network. In a distribution network with photovoltaic systems, ESS can provide enough active power to make up for the shortage of photovoltaic power, and can absorb excess PV active power. Although this may increase the operating cost of the equipment, it is superior in overall economic performance.
3. PESHS access to the distribution network will increases the controllable variables, improves the reactive power control capability of the distribution network, and further excavate the potential of energy saving.
The research done in this paper can be further improved, the influence of PV access uncertainty on active distribution network can be considered, and the effect of ESS on regulating voltage can be further studied. These will be improved in the future research.

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