Research on VSC-MTDC Robust Optimal Power Flow Based on the Uncertainty of Wind Farm Output

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Keywords: VSC-MTDC, Uncertainty, Power flow optimization, Differential evolution, Newton iteration, Robust optimization.

Abstract. Multi-terminal flexible direct current transmission based on voltage source converter (VSC-MTDC) is an effective measure to solve the problem of wind power consumption. In this paper, a method called robust optimization is proposed to calculate power flow in VSC-MTDC system with uncertain wind power. The model of uncertain output of wind farm is described by bounded uncertainty set. Besides, with differential evolution (DE) algorithm as a framework, reference value of VSC voltage and power control under uncertain wind power are solved by DE fitness evaluation function which comes from the combination of Newton-Raphson (NR) iteration power flow solution method and VSC-MTDC dynamic multi-objective power flow optimization model. At the end of this paper, the validity and superiority of this method is proved by comparison among a number of examples.

Introduction

Large-scale wind power transmission technology has undergone the development process from AC grid to flexible DC transmission. In recent years, with the development of full-controlled semiconductor devices, flexible high voltage direct current transmission technology based on voltage source converter (VSC-HVDC) enables long-distance transmission of large-scale wind power. However, VSC-HVDC is a two-terminal system, if one VSC terminal is out of operation due to malfunction, the entire system will be paralyzed. Therefore, VSC-MTDC Technology has been proposed. VSC-MTDC system is a flexible HVDC system with three or more converters operating in parallel, which has better economy, flexibility and controllability than two-terminal HVDC system [1]. Currently, research on VSC-MTDC mainly focuses on control strategy and improvement of VSC, the aspect of system power flow optimization is involved fewer. Determination of command value of power and voltage control in VSC is lack of certain basis [2], optimal economy and stability of MTDC network cannot be guaranteed.

In addition, traditional study on power flow optimization in electric system with wind farms are mostly based on the identified wind power forecast, but the natural attributes of wind energy make wind power prediction exist a big error compared to the actual, so the traditional power flow optimization cannot timely cope with random fluctuations of wind power which impact the safe operation of the system.

To solve these problems, this paper considers the uncertainty of wind power, uses robust optimization techniques dealing with uncertain variables, builds multi-objective optimal model of MTDC network, uses differential evolution algorithm combined with Newton iterative method to solve power flow of VSC-MTDC on steady state, provides a reasonable reference value of voltage and active power control for VSC, achieve safe, stable and economical operation of VSC-MTDC system.
Uncertainty Wind Power Model

Results of conventional wind speed prediction is time-varying predictive value of certain point, which are exist some errors between the actual wind speed, bounded uncertainty sets can be used to describe the above error[3]. That is, adding uncertainties on the basis of the wind speed prediction data, so the wind speed varies at any time in an uncertain neighborhood based on the forecast wind speed at this point. Mathematical model of uncertain wind speed can be simplified as the following expression:

\[ V = \left\{ v \in \mathbb{R}^{N_T} : v_{N_T}^{\text{fit}} - D_{N_T}^{\text{fix}} \leq v_{N_T} \leq v_{N_T}^{\text{fit}} + D_{N_T}^{\text{fix}}, \forall N_T \right\} \tag{1} \]

It can be seen that the size of the wind speed uncertain interval set is decided by the parameters \( D_{N_T}^{\text{fix}} \) and \( D_{N_T}^{\text{fix}} \). The function between output active power of fan \( P(v) \) and wind speed \( v \) can be approximately described as:

\[ P(v) = \begin{cases} 0 & v < v_{ci} \text{ or } v > v_{co} \\ k_1 v + k_2 & v_{ci} \leq v < v_{rate} \\ P_{rate} & v_{rate} \leq v < v_{co} \end{cases} \tag{2} \]

where: \( k_1 = \frac{P_{rate}}{(v_{rate} - v_{ci})} \); \( k_2 = -k_1 v_{ci} \); \( P_{rate} \) is the rated power of wind turbine; \( v_{ci}, v_{rate}, v_{co} \) are cut-in speed, rated wind speed and cut-out wind speed respectively.

Uncertainty fan mathematical model can be obtained by substituting mathematical model of uncertain wind speed into the above certain fan equation, which is shown in the following formula:

\[ W = \left\{ P \in \mathbb{R}^{N_T} : P_{N_T} (v_{N_T}^{\text{fit}} D_{N_T}^{\text{fix}}) \leq P_{N_T} \leq P_{N_T} (v_{N_T}^{\text{fit}} D_{N_T}^{\text{fix}}), \forall N_T \right\} \tag{3} \]

Multi-objective Dynamic Power Flow Optimization Model

Multi-objective Dynamic Power Flow Optimization Function

a) Fan output optimization model

Wind power consumption has become the key issues affecting the healthy development of Chinese wind power, thus VSC-MTDC supply side should be optimized to achieve the goal of enhancing the absorptive capacity of wind power and minimizing the wind power curtailment. Maximum power tracking model of fan is:

\[ \min f_1 = \sum_{t=1}^{T} \sum_{w=1}^{W} \left| \frac{P_t - \hat{P}_t}{\hat{P}_t} \right| \tag{4} \]

where: \( T \) represents optimization period; \( W \) represents the number of MTDC wind farms; \( P_t \) indicates the fan output; \( \hat{P}_t \) represents the maximum allowable output fan.

b) Transmission loss optimization model

Because VSC transmission power is controllable, reasonable power flow of MTDC network is beneficial to reduce network losses, optimal model of transmission losses is:

\[ \min f_2 = \sum_{t=1}^{T} \sum_{i=1}^{M} S_{ik} \alpha \% + \sum_{j=1}^{N_d} \sum_{k=1}^{N_d} \frac{(U_{j} - U_{k})^2}{R_{jk}} \tag{5} \]

where: the transmission losses including the loss of the converter station and DC network losses. Assuming converter station losses are \( \alpha \% \) proportional to its transmission capacity [4]; \( N_d \)
represents the number of converter DC link nodes; \( U_j \) represents converter DC bus voltage, \( U_N \) represents its rated voltage.

c) Voltage violation optimization model

Voltage is limited within reasonable range:

\[
\min f_3 = \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{|U_j - U_N|}{U_N}
\]

Transforming above multiple objective optimization function (4) to (6) into single objective optimization problem through linear weighting method [5]:

\[
\min F = \phi_1 f_1 + \phi_2 f_2 + \phi_3 f_3
\]

\[\sum_{p=1}^{5} \phi_p = 1 \text{ and } \phi_p \in [0,1] \text{ represents weighting factors.}\]

Constraints

a) Equality Constraints

For complex multi-terminal DC network:

\[s Pi di dij dj f_i dih \Phi_i = 0 \quad i \in \Phi_d\]

where: \( \Phi_d \) represents connection, node set between AC and DC power grid; when the converter is a rectifier, \( s_p = 1 \); when the converter is an inverter, \( s_p = -1 \); \( g_{ij} \) is node conductance matrix of DC network; \( I_d \) is DC current vector; \( V_{dj} \) is DC voltage vector.

b) Inequality Constraints

Fan output restrictions:

\[P_{min} \leq P_i \leq P_{max} \quad i \in W\]

Node voltage, current, power limits of DC network:

\[U_{imin} < U_i < U_{imax} \quad i \in \Phi_d\]

\[I_{imin} < I_i < I_{imax} \quad i \in \Phi_d\]

\[P_{imin} < P_i < P_{imax} \quad i \in \Phi_d\]

Capacity limits of converter station:

\[S_{imin} < S_i < S_{imax} \quad i \in W\]

VSC-MTDC Robust Optimal Power Flow Calculation Based on the Wind Farm Output Uncertainties

Solution of VSC-MTDC Dynamic Optimal Power Flow

Solution of VSC Independent Variables Based on Differential Evolution Algorithm. DE, which based on swarm intelligence theory, guides the optimization search through group generated from cooperation and competition between individuals within populations. Compared to traditional optimization algorithm, DE not only has simple principles, strong robustness, but also with the optimal solution of memory individuals and information sharing within the population, the process of this algorithm can be seen in [7]:

MTDC Power Flow Calculation Based on NR Iterative Method

a) Construct nonlinear equations of the n node MTDC network power flow

In MTDC network, the power flow is determined by the amplitude of the voltage differences between buses. Assuming there are \( n \) nodes in DC network, \( m \) nodes connected to the VSC within the \( n \) DC nodes, there are \( n-m \) no energy injected nodes. Node current vector in MTDC network can be expressed as [8-9]:

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\[ I_{dc} = \left[ I_{dc1}, I_{dc2}, \ldots, I_{dcn} \right] \arah^{T} \tag{8} \]

Balance node number is set to 1, \( U_{dc1} \) is independent variable, node voltage vector in MTDC network can be expressed as:

\[ U_{dc} = \left[ U_{dc1}, U_{dc2}, \ldots, U_{dcn} \right] \arah^{T} \tag{9} \]

For symmetric DC ground VSC-MTDC network, node power can be expressed as:

\[ P_{dc} = 2U_{dc1}I_{dc} \quad \forall i \leq k \tag{10} \]

Node power vectors in MTDC network can be expressed as:

\[ P_{dc} = \left[ P_{dc1}, P_{dc2}, \ldots, P_{dcm}, 0, \ldots, 0 \right] \arah^{T} \tag{11} \]

Among the 2\(~m\) nodes, active power track wind farm output in real time. Combing formula (8) and (10) can obtain results as follows:

\[ P_{dc} = 2U_{dc1} \sum_{j=1 \atop j \neq i}^{n} Y_{dci} (U_{dc} - U_{dij}) \quad \forall i \leq k \tag{12} \]

To facilitate the flow calculation, using equation (12) to configure Newton nonlinear equations \( f(x) \):

\[ f(x) = \Delta P_{dc} = P_{dc} - 2U_{dc1} \sum_{j=1 \atop j \neq i}^{n} Y_{dci} (U_{dc} - U_{dij}) = 0 \]

\[ f(x) = [f(x_1), f(x_2), \ldots, f(x_n)] \arah^{T} \tag{13} \]

b) Iteration

The \( g + 1 \)-th iteration solution of unknown variable is consists of the \( g \)-th iteration solution and \( g \)-th correction solution \( \Delta x(g) \):

\[ x(g+1) = x(g) + \Delta x(g) \tag{14} \]

The \( g \)-th correction solution \( \Delta x(g) \) of unknown variable is:

\[ \Delta x(g) = J_{DC}^{-1} f(x(g)) \tag{15} \]

where: \( J_{DC}^{-1} \) is inverse matrix for the Jacobi matrix in the nonlinear equations.

c) Termination condition

Stopping the search when the number of iterations \( g \) exceeds the maximum number of iterations \( G_m \) or accuracy of solution meets the requirement.

Solving optimal objective function \( \min F \) after obtaining MTDC network power flow through Newton iterative method, the result is taken as value of fitness function in this iteration process of DE algorithm.

Robust Optimization Based on Uncertainty of Wind Power Output

Robust optimization is a new method to deal with optimization problems with uncertain information, parameters of random problems are put into a pre-determined uncertain set which including the worst-case scenario, so it has a certain immunity ability to uncertain factors [10].

Since the wind speed at any time is uncertain, the uncertainty of wind power output is derived by the formula (3), cost of MTDC system will increase because of the uncertainty of wind power output for a long-time scale, in other words, the economy of system is reduced and the safe
operation of the system is impacted. Therefore, there are two core points about robust optimization in this article: 1. Deciding uncertain wind power output rationally at any time, seeking an optimal solution in the range of uncertain wind power output, so that optimal results satisfy all the limits under uncertainty at this time; 2. In a long time scale, robust optimization can be summarized as min-max thought in mathematics, that is, value of independent variable is economic optimum conservative result which comes from all the maximum conservative solutions in the long time scale within all uncertain sets satisfied optimal objective function.

VSC-MTDC robust optimization model based on uncertainties of wind power output can be expressed as [11]:

\[
X = \min_{re T} \left( \max_{PcW} (\min F) \right)
\]

The solving process of VSC-MTDC Robust Optimal Power Flow Based on the Uncertainty of Wind Farm Output is shown in Fig.1.

![Diagram of VSC-MTDC robust optimal power flow based on the uncertainty of wind farm output.](image)
Analysis of Example

Taking the VSC three-terminal flexible HVDC transmission system as an example, the topology diagram is shown in Fig.2.

Number 1 converter as the balance node.

Forecast wind speed every 10 minutes of the next 12 hours using Weibull random number generator, establish the uncertainty wind power output model according to (1)~(3). Using the robust power flow optimization method proposed in this paper and the traditional method based on certainty wind power output model respectively to calculate the power flow of the VSC three-terminal flexible HVDC transmission network, the independent variable $U_i$ over time is shown in Fig.3.

It can be seen from Fig.3 that the robust optimization results are more stable than the traditional optimization, so robust optimization method used to solve the uncertainty of wind turbine output can improve the stability of the system to some extent.

There is always a deviation between the actual wind speed and the forecast wind speed owing to the uncertainty of wind speed. At present, average error of wind power forecast 24 hours ahead in leading level country can reach 10% [12], so we can simulate the actual wind speed by adding 10% random deviation to the wind speed forecast sample. Control the system in Fig.2 with the
In Fig. 3, the objective function average value is 0.101 and 0.097 when the system is controlled by independent variables of traditional and robust optimization respectively, the latter is lower than the former by about 4%. Thus, robust optimization is more economical and safe than the traditional optimization, and more suitable for the VSC-MTDC system with large wind field.

Summary

Aiming at VSC-MTDC system, a robust method is proposed for solving optimal power flow considering the uncertain wind farm output. Uncertainty sets were used to describe uncertainties of wind farm output, and robust optimization methods were used to improve the immunity of system to the uncertainties of wind power output. Comparing to the command values of voltage and active power which are formulated in accordance with the operation mode and experience in general terms in current study of flexible DC transmission system based on voltage source converter, the method proposed in this article utilizes DE algorithm to solve VSC independent variables. In each DE iteration process, after solving power flow of MTDC in steady-state operation by NR methods, the fitness function is acquired from established multi-objective optimization function, in order to ensure safe, stable and economical operation of VSC-MTDC system under instruction values given from DE algorithm. Finally, the feasibility of the proposed method is verified through examples.

Acknowledgement

This research was financially supported by the “National Natural Science Foundation of China” (61271001), the “Fundamental Research Funds for the Ministry of Education of Central Universities “ (14CX05039A) and the “Sinopec Science and Technology Project” (315120).

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