Calculation of TTC for AC/DC Power Systems Based on Improved Continuation Power Flow

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Abstract. A model of total transfer capability (TTC) for the AC/DC system with multi-terminal voltage source converter DC (VSC-MTDC) system is set up in this paper. As the load and generator power in traditional continuation power flow (CPF) algorithm increased with equal proportion, a novel continuous power flow approach based on economic operation of power grid is proposed. In the method, taking the minimum generation cost as the goal, the distribution of generator output is optimized by economic dispatching based on linear programming method, which can avoid the defects of some existing methods that caused by the piecewise linearization of incremental ratio of generator consumption curve. The distribution of load increment and the parameters of VSC control modes are optimized by mathematical optimization method to minimize the network loss, which can get the TTC under economic conditions. Finally, cases study based on modified IEEE 9-node system and modified IEEE 30-node system verify the rationality and effectiveness of the proposed methods.

1. Introduction

In the electricity market environment, the Total Transfer Capability (TTC) is not only an important indicator of the power system, but also an important technical reference indicator that must be understood by all participants in the market to conduct trading activities [1-2]. With the continuous expansion of the power grid scale and the rapid development of DC transmission technology, it is increasingly important to study the maximum transmission capacity of AC-DC hybrid power grids. According to the North American Electric Power Systems Reliability Council (NERC) 1996 document, TTC refers to the maximum power that a power transmission system can transmit in a system transmission section or an interconnected transmission network without violating any system safety constraints. The TTC subtracts the existing transmission protocol flow, transmission reliability margin, and capacity benefit margin, which is the Available Transfer Capability (ATC). The TTC calculation method is also applicable to ATC calculation, and the TTC calculation is the basis of ATC calculation [3].

With the development of modern power electronics technology, a new generation of high voltage direct current transmission technology--Voltage Source Converter High Voltage DC (VSC-HVDC) based on voltage source converter (VSC) composed of controllable shutdown power electronic devices, with its good operational reliability and flexibility have received increasing attention [4]. Since the

VSC-HVDC is essentially different from the traditional HVDC in physical models, the traditional AC/DC system TTC calculation model and method cannot be directly used in the VSC-HVDC system. The existing power flow calculation methods for AC/DC hybrid systems with VSC include: unified iterative method [4-5] and alternating iterative method [6-7]. Because the unified iterative method is not convenient to deal with the flexible control strategy and operation mode of AC/DC system, this paper chooses AC/DC alternating iterative method to calculate the power flow, and based on its power flow calculation model, the TTC calculation model of AC/DC system with multi-terminal VSC-HVDC is established.

At present, the TTC deterministic calculation methods applicable to AC/DC hybrid systems mainly include continuous power flow method [8-10] and optimal power flow method.

The optimal power flow method solves the optimization model by mathematical algorithm to obtain TTC. The main disadvantage of its existence is that it is impossible to track the process of system state change when the section power gradually approaches the extreme value, and it is inconvenient to find the weakest link that affects the TTC. The Continuous Power Flow (CPF) generally increases the transmission power of the transmission section in steps according to the step size until a certain constraint condition is exceeded. At this time, the transmission section TTC is obtained. This method avoids some shortcomings of the above optimum power flow methods and the calculation result is more practical. But the conventional section power growth mode generally increases the receiving end load according to a fixed power factor and a fixed ratio, and distributes the generated power according to the generator capacity. If the power increments of all load nodes and generator nodes constitute a power increase vector, the power growth direction vector of each step of the conventional CPF is the same, so the method can only calculate the TTC of the system in a specific power growth direction, and still needs Improve. In addition, the above two methods in the solution of TTC and its process only from a technical point of view, without considering economics, such as power generation, network loss and other costs. Literature [8] introduced the discrete control link of transformer ratio and compensation capacitor bank into the continuous power flow method, and the calculation illustrated that the ATC of the AC/DC system would change with the direction of power growth, but it was not pointed out how to determine the power growth direction to get the most economical ATC. Literature [9] proposed a master-slave iteration continuous flow algorithm. From the perspective of static voltage stability, the modal analysis was used to find the most reliable ATC for AC/DC systems. At the same time, the subsection linearization method was used to realize the economic dispatch of the generator, and the ATC of the system power generation cost is obtained, but the method was only applicable to the generator consumption characteristic curve under certain circumstances.

In order to avoid the disadvantages of the fixed direction of power growth in the traditional continuous power flow method, based on the traditional CPF algorithm for calculating AC/DC transmission capacity, this paper adopts economic scheduling based on linear programming method to optimize the distribution of generator output and determine the output direction of the generator. The internal point method is used to optimize the distribution load increment to determine the load growth direction. At the same time, considering the influence of VSC control mode on TTC, the VSC control mode parameter setting value is optimized with the minimum network loss as the target. Furthermore, a method for calculating the total transfer capability of VSC-HVDC AC/DC hybrid system is proposed. The improved continuous power flow method based on grid economic operation improves the economic efficiency of TTC from the aspects of reducing power generation cost and reducing network loss.

2. calculation model of total transfer capability for AC/DC systems with VSC

2.1. The Mathematical Model of Power Flow Calculation for AC/DC systems with VSC
Power flow calculation is the basis of TTC calculation. Alternating iterative method is used to calculate the power flow of AC/DC system with VSC in this paper.
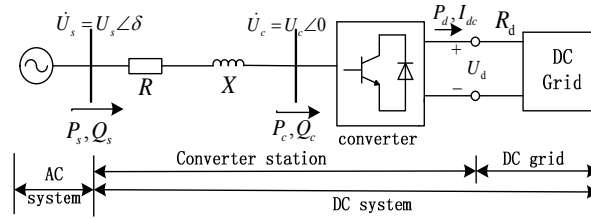
Figure 1. Model of VSC-HVDC.

Fig.1 illustrates the VSC-HVDC system model where R is the equivalent resistance of all active losses inside the VSC converter station. R, X and the inverter together form a VSC converter station. The DC grid and the VSC converter station together form a DC system, and the point s is the boundary point between the DC system and the AC system. According to this VSC-HVDC model, a complete AC/DC decoupling power flow calculation model can be divided into three sub-models as follows.

The DC grid power flow calculation, AC subsystem power flow calculation and inverter equations are the same as Literature [9] shows.

2.2. The calculation model of TTC for AC/DC systems with VSC

2.2.1. The objective function.
According to the TTC definition, the objective function F can be expressed as follow.

$$F = \max\left(\sum_{i \in A, j \in B} P_{ij} + \sum_{v \in A, k \in B} P_{vk} \right) \tag{1}$$

Where P_{ij}, active power transfer between nodes i and j in the AC system; P_{vk}, active power transfer between nodes v and k in the DC system; A, power supply area; B, power receiving area. If all the lines between the supply and receiving areas are AC lines, $P_{vk} = 0$.

2.2.2. Equality constraint.
The AC system equation constraint is the AC subsystem flow equation. The DC system equation constraints include the DC grid equation and the VSC converter equation.

2.2.3. Inequality constraint

$$\begin{cases} U_{si}^{\min} \leq U_{si} \leq U_{si}^{\max}, & i \in N_{ss} \\ Q_{si}^{\min} \leq Q_{si} \leq Q_{si}^{\max}, & i \in N_{ss} \\ S_{ij}^{\min} \leq S_{ij} \leq S_{ij}^{\max}, & i,j \in N_{ss} \\ P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max}, & i \in N_{G} \\ Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}, & i \in N_{G} \end{cases} \tag{2}$$

AC system inequality constraints are show in Eq. (2), where N_G is a collection of all generator nodes, and the superscripts "max" and "min" indicate the maximum and minimum values of the variables.

The DC system inequality constraints are shown in Eq. (3), which include DC voltage constraint, converter AC voltage constraint, modulation ratio constraint, VSC heat capacity constraint and DC line maximum allowable current constraint.

$$\begin{cases} U_{dk}^{\min} \le U_{dk} \le U_{dk}^{\max} & k \in N_d \\ U_{cn}^{\min} \le U_{cn} \le U_{cn}^{\max} \\ M_n^{\min} \le M_n \le M_n^{\max} & n \in N_C \\ I_{cn} \le I_{cn}^{\max} \\ I_{kv} \le I_{kv}^{\max} & v \in k \end{cases} \qquad (3)$$

Where the subscript "n" is the VSC number, and the N_C is the set of VSC.

3. Improved CPF algorithm for VSC AC/DC systems

3.1. Power Growth Mode in Basic CPF Algorithm

The essence of the CPF is to increase the output of the generator in the power supply area and the load on the power receiving area, and find out the maximum power flow feasible solution on the selected transmission section under the constraints of various system safety. Basic CPF algorithms need to introduce a common factor to regulate load and power generation growth.

$$\begin{cases} P_{Li}^{(t)} = P_{Li}^0 + \sum_t \lambda^{(t)} K_{pi} \\ Q_{Li}^{(t)} = Q_{Li}^0 + \sum_t \lambda^{(t)} K_{qi} \\ P_{Gi}^{(t)} = P_{Gi}^0 + \sum_t \lambda^{(t)} K_{Gi} \end{cases} \qquad (4)$$

where: P_{Li} and Q_{Li} are the active and reactive loads of node i respectively; λ is the step size of the cycle in the continuous power flow algorithm; K_{pi} and K_{qi} are the ratio of the active and reactive load increase of node i to the total increment of the corresponding system respectively. When the load increases according to a fixed power factor, K_{pi}/K_{qi} is a fixed value; K_{pi} and K_{qi} are the active and reactive load increments of node i in the t-th cycle; $\lambda^{(t)} K_{pi}$ and $\lambda^{(t)} K_{qi}$ are the active and reactive load increments of node i in the t-th cycle respectively; K_{Gi} is the ratio of the active power increase of generator i to the total increment of system power generation; the superscript "0" represents the initial value and the superscript t indicates the number of iterations.

In the continuous power flow algorithm, the step size λ mainly affects the speed at which the program converges, and the direction of load and generator power growth (determined by K) has a crucial influence on the size of the TTC. The load of each step of the traditional CPF increases in the same direction. Therefore, it can only calculate the TTC of the system in the direction of specific power growth, not necessarily the maximum TTC that the system can achieve. In the traditional CPF, the generator power increase is generally distributed to each generator according to the capacity. This distribution mode is easy to program and calculate, but it does not fully meet the distribution method of the generator output in actual operation, and it does not reflect the potential economic value of TTC. Therefore, this paper intends to adopt the objectives of power generation economic dispatch and minimum network loss, and the growth direction of power generation and load power is determined by optimization calculation, which makes the two defects of traditional CPF improved.

3.2. CPF Algorithm Based on Generator Economic Dispatch (Gen-CPF)

3.2.1. Optimization of power generation growth direction. The generator output is allocated with the lowest power generation cost as the objective function, then the TTC calculation model can be described as a two-layer optimization model, as shown in Eq. (10).

$$\begin{cases} \max(\sum_{i \in A, j \in B} P_{ij} + \sum_{s \in A, k \in B} P_{vk}) \\ \min \sum_{i \in A} f_i(P_{Gi}) \\ s.t. \quad g(x) = 0 \\ \quad\quad h_{\min} \leq h(x) \leq h_{\max} \end{cases} \tag{5}$$

Where $f_i(P_{Gi})$ is the function of the unit i power generation cost.

Applying CPF method to solve the optimization model. The power generation and load can be gradually increased by cyclic iteration to approach the upper target transmission power, and the lower target can be achieved by solving the single objective optimization function Eq.(7) after each step of the load increasing. In this way, the total cost of power generation can be minimized at each load level of continuous power flow, and the economic output of the generator can be obtained, and then the economic dispatching situation of generators under various load levels can be simulated, which is more practical in engineering applications.

In the CPF algorithm model based on genset economic dispatch, the generator power and its increment are obtained by solving the optimization model Eq. (6) and Eq. (7.

$$\begin{cases} \min \sum_{i \in A} f_i(P_{Gi}^0 + \Delta P_{Gi}^{(t)}) \\ s.t. \quad g(x) = 0 \\ \quad\quad h_{\min} < h(x) < h_{\max} \end{cases} \tag{6}$$

$$P_{Gi}^{(t)} = P_{Gi}^0 + \Delta P_{Gi}^{(t)} \tag{7}$$

Where $\Delta P_{Gi}^{(t)}$ represents the incremental output of the generator i relative to the initial value at the *t*-th cycle.

In the improved CPF algorithm based on generator economic dispatch (Gen-CPF), the total increment of generator output in each cycle is no longer allocated according to capacity or fixed ratio, but the variable determined by generator economic dispatch.

$$D_{PG}^{(t)} = [\Delta P_{G1}^{(t)} \cdots \Delta P_{Gi}^{(t)} \cdots \Delta P_{Gm}^{(t)}] \tag{8}$$

Where $D_{PG}^{(t)}$ is the generator power growth direction vector in the *t*-th cycle; *m* is the number of generators in the power supply area.

In literature [9], based on piecewise linearization of the generator consumption characteristic curve, the corresponding consumption micro-increasing rate of each unit consumption characteristic is sorted. It is preferred to increase the output of the generator with a low consumed energy increase ratio, thereby achieving economic dispatch of the generator. This method is simple and fast. However, if this method is applied to every iteration of CPF, all the generator consumption characteristic curves in the system are required to satisfy the second derivative greater than 0 since P_G^0. Otherwise, the economics

of generator power distribution in each iteration will not be guaranteed. This article gives the inverse example as follow.
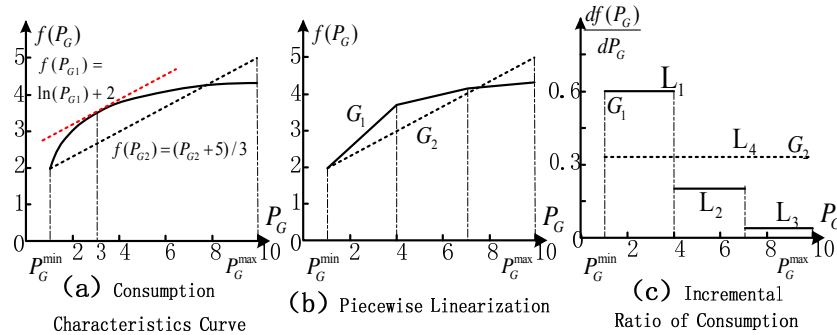

Figure 2. Counterexample of generator economic dispatch solved by piecewise linear method.

The consumption characteristic curves of the two generators G_1 and G_2 in the system are shown by the solid line and the dotted line in Fig. 2(a). Its output range is [1, 10] MW. Consumption characteristics $f(P_{G1}) = \ln(P_{G1}) + 2$ and $f(P_{G2}) = (P_{G2} + 5)/3$ (yuan) respectively

According to the calculation step of the CPF, the output of the two generators is increased from P_G^{min} to 10MW. The growth step for each cycle is set to 3MW. Using The piecewise linearization method to distribute the total output of each new power generation to the generators G_1 and G_2, the generator with low consumed energy increase ratio in Figure 2(c) is preferred to bear the output. The output of the generator must be gradually increased from the initial state. If the generator G_1 output increment is less than 4MW, the second segment consumption micro-increment rate (L_2) cannot be applied to compare with the generator G_2 consumption micro-increment rate (L_4). The consumption rate micro-increasing rate (L_1) of the first segment of G_1 is higher than L_4, so G_1 is never applied. That is to say, when applying the piecewise linearization to realize the economic dispatch of the generator in the above example, G_2 bears 10MW, and G_1 does not bear the new output. However, if the equal consumed energy increase ratio law is applied to economically dispatch the two generators in Figure 2(a), G_1 and G_2 should respectively bear the new output of 3MW and 10-3=7MW (Fig.2 (a) the abscissa of the tangent point of the red dotted line). Obviously, piecewise linearization does not apply in the above case.

By analyzing the above counterexamples, the piecewise linearization method is only applicable to some systems with specific consumption characteristic curves. The fundamental reason is that the power distribution of the unit follows the equal consumed energy increase ratio law, and the piecewise destroys the continuity of the micro-increase rate. The micro-increasing rate is a derivative of the consumption characteristic curve, so the micro-increasing rate corresponding to different power states of the unit (different points on the characteristic curve) is varied. The piecewise linearization method can economically dispatch generators in a certain segment. However, in the next segment, the total power generation of the system has increased, and the system power generation status has changed. Therefore, a simple superposition of optimal allocations in different states of the system may not be able to achieve the most economical allocation of total incremental power generation.

In order to avoid the above drawbacks, this paper directly uses the generation cost curve obtained by the generator consumption characteristic curve and the fuel price to carry out the economic dispatch of the unit to determine the most economical output power distribution of the generator. The generation cost curve can be approximated as a polynomial function as shown in Eq. (4).

$$f(P_G) = aP_G^2 + bP_G + c \tag{9}$$

Where: *a, b, c* are polynomial parameters of power generation costs.

3.2.2. Generators economic dispatch based on successive linear programming. The successive linear programming method has better convergence for the optimization model with linear constraints. The method is simple and easy to program [15]. Therefore, it can be applied to solve the generator scheduling model.

Solving the generators economic dispatch by successive linear programming. For convenience of explanation, the optimization model (6) is expressed as the form shown in the Eq. (10).

$$\begin{cases} \min \quad f(x_2) \\ s.t. \quad g(x_1, x_2) = 0 \\ \qquad h(x_1, x_2) \le 0 \end{cases} \tag{10}$$

Where: x_1 is the state variable, which represents the voltage amplitude and phase angle of the system; x_2 is the control variable, which represents the active and reactive output of the unit; g is the optimization model equality constraint, and h is the optimization model inequality constraint.
The algorithm calculation process is as follows:

1) Set the cycle flag n=0. Select the initial value for the control variable x_2^0.

2) Substituting x_2^n into the equality constraint $g(x_1^n, x_2^n) = 0$ yields x_1^n.

3) Linearize the optimization model near x_1^n and then apply linear programming to solve for Δx.

$$\begin{cases} \min_{\Delta x} \left[\frac{\partial f}{\partial x} \big|_{x=x^n} \right] \cdot \Delta x \\ s.t. \quad \left[\frac{\partial g}{\partial x} \big|_{x=x^n} \right] \cdot \Delta x \le g(x^n) \\ \qquad -\Delta \le \Delta x \le \Delta \end{cases} \tag{11}$$

Where: x = [x₁, x₂]. The superscript represents the number of iterations; Δ is the step limit.
4) Let n=n+1, $x_2^n = x_2^{n-1} + \Delta x$.
5) If the inequality constraint h is satisfied and the Eq. (17) is established, then go to step 6. Otherwise, the iteration is stopped and the result is output.

$$\frac{\partial f}{\partial x} + \Gamma^n \cdot \frac{\partial g}{\partial x} \le e* \tag{12}$$

Where Γ is the Lagrangian multiplier vector of linear programming. e* is the slope limit.
6) Adjust the step size limit Δ and go to step 2.

3.3. CPF algorithm for optimizing load and power distribution (GenLoad-CPF)
On the basis of the traditional CPF algorithm, if the total load increment of the power receiving area does not change during each cycle, changing the load growth direction will change the distribution of the power flow, then the system network loss and the power generation in power supply area will also change. Therefore, the economical efficiency of the section transmission power can be further improved by the optimized distribution of the load increment.

In this paper, the load increment of each node in each step cycle of CPF is set as the independent variable, and the minimum loss of system network is taken as the goal to optimize these independent variables, so as to realize load optimization allocation.

After adopting generator economic dispatch and load optimization allocation, the overall TTC calculation model becomes the three layer optimization model shown in Eq. (13).

$$\begin{cases} \max(\sum_{i \in A, j \in B} P_{ij} + \sum_{s \in A, k \in B} P_{vk}) \\ \min P_{loss}(\Delta P_{Li}^{(t)}, \Delta Q_{Li}^{(t)}) \\ \min \sum_{i \in A} f_i(P_{Gi}) \\ s.t. \ \ g(x) = 0 \\ \qquad h_{min} \le h(x) \le h_{max} \end{cases} \qquad (13)$$

Where P_{loss} is the system active network loss.

In Eq. (13), the maximum transmission capacity of the section is the first layer objective function. Approaching the optimal solution by gradually increasing the load on the power receiving area and generating electricity in the power supply area (as shown in Eq. (14)); The system network loss is minimum as the second layer objective function. In each cycle of continuous power flow, the optimal load distribution mode is obtained by solving the Eq. (15) through the optimization algorithm; the minimum total power generation cost is the third layer objective function. In each cycle of the second layer objective function solving optimization, the model (6) is solved by the method described in Section 2.2.2 to obtain the optimal power generation and its increment. The three layer objective functions are sequentially nested, and the parameter transfer relationship between them is as shown in Fig. 3. In the figure, O_{LP} and O_{LQ} represent the optimized active and reactive load growth direction vectors, respectively.
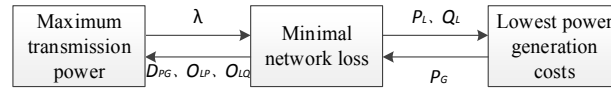

Figure 3. Objective function and parameter transfer coordination diagram.

$$\begin{cases} P_{Li}^{(t)} = P_{Li}^0 + \sum_t \Delta P_{Li}^{(t)} \\ Q_{Li}^{(t)} = Q_{Li}^0 + \sum_t \Delta Q_{Li}^{(t)} \\ P_{Gi}^{(t)} = P_{Gi}^0 + \Delta P_{Gi}^{(t)} \end{cases} \qquad (14)$$

$$\begin{cases} \min P_{loss}(\Delta P_{Li}^{(t)}, \Delta Q_{Li}^{(t)}) \\ s.t. \ \sum_{i \in A} \Delta P_{Li}^{(t)} = \lambda^{(t)} \\ \qquad \Delta Q_{Li}^{(t)} / \Delta P_{Li}^{(t)} = \tan\varphi_i \\ \qquad g(x) = 0 \\ \qquad h_{min} < h(x) < h_{max} \end{cases} \qquad (15)$$

Where $\Delta P_{Li}^{(t)}$ and $\Delta Q_{Li}^{(t)}$ respectively represent the increments of active and reactive loads on node i in *t*-cycles relative to *t-1* cycles; φ_i is the power factor angle of the load i.

Let $O_{LP}^{(t)}$ and $O_{LQ}^{(t)}$ represent the t-th cycle active and reactive load growth direction vectors respectively, as shown in Eq.(16) and Eq.(17), if node i is not in the power receiving area, then $\Delta P_{Li}^{(t)}=0$, $\Delta Q_{Li}^{(t)}=0$.

$$O_{LP}^{(t)} = [\Delta P_{L1}^{(t)} \cdots \Delta P_{Li}^{(t)} \cdots \Delta P_{LN}^{(t)}] \tag{16}$$

$$O_{LQ}^{(t)} = [\Delta Q_{L1}^{(t)} \cdots \Delta Q_{Li}^{(t)} \cdots \Delta Q_{LN}^{(t)}] \tag{17}$$

It can be seen from Eq. (15) that in the CPF algorithm for optimizing load distribution, the total load increased by each iteration is still the cycle step size λ, but there is no longer a fixed proportional relationship between the load increments on each node and λ. That is, the direction of load growth is a variable determined by solving the optimal power flow model (15).

The original-dual interior point method has good robustness and convergence, and has mature applications in the calculation of transmission capacity. In this paper, the original-dual interior point method is used to solve the model (15). The key lies in the processing of the simple correction matrix. The detailed solution process is described in literature [17].

3.4. CPF algorithm based on economic operation applied to AC/DC power grid (Opt-CPF for short)
The two improved CPF algorithms mentioned in sections 2.2 and 2.3 of this paper are applicable to both pure AC systems and AC/DC hybrid systems. However, for AC/DC hybrid systems with multi-terminal VSC-HVDC, the parameter setting of the VSC control mode will affect the TTC, so how to optimize and select the appropriate setting value becomes a problem that must be considered.

In the same way as the analysis of the load-optimized allocation to reduce the network loss in Section 2.3, the VSC control parameters can be optimized with the minimum network loss as the goal, and the economics of the TTC can be further improved. Replace the objective function in model (20) with Eq. (18).

$$\min \; P_{loss}(\Delta P_{Li}^{(t)}, \Delta Q_{Li}^{(t)}, C_{VSC}^{(t)}) \tag{18}$$

Where $C_{VSC}^{(t)}$ is the parameter setting value of VSC control mode, the specific optimization amount included is determined by the control mode of each VSC in the hybrid system, see the example for specific settings.

After the introduction of DC system parameters, the traditional CPF "prediction-correction" link needs to be adjusted. The key to the prediction process is to solve the following prediction equation:

$$\begin{bmatrix} J_{P\theta} & J_{PU} - J_{PcU} & S_{dP} \\ J_{Q\theta} & J_{QU} - J_{QcU} & S_{dQ} \\ 0 & e_p & 0 \end{bmatrix} \begin{bmatrix} d\theta \\ dU \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \pm 1 \end{bmatrix} \tag{19}$$

where J_{PcU}, J_{QcU} are the partial derivative of the active and reactive power to the AC node voltage injected into the converter by the AC node. For the meaning of the remaining elements, see the literature [18]. S_{dP}, S_{dQ} respectively indicate the change direction of active and reactive power injected into the node, they satisfy Eq. (20) and Eq. (21), respectively.

$$S_{dP} = [D_{PG}^{(t)} - D_{PG}^{(t-1)} - O_{LP}^{(t)}]^T \tag{20}$$

$$S_{dQ} = [-O_{LQ}^{(t)}]^T \tag{21}$$

In order to obtain the accurate power flow solution of the hybrid system, the alternating iteration method is used to correct the estimated value in the correction link [10].

3.5. TEST RESULTS
In this paper, the modified IEEE 9 nodes systems are used to verify the effectiveness of the proposed model and algorithm.

3.6. Modified 9 Nodes System
The modified IEEE 9-node system structure is shown in Figure 4. The left side of the red dotted line is the receiving area, and the right side is the power supply area.AC and DC voltage reference value U_s^*=345kV , U_d^*=690kV .The power reference value is 100MW.The parameters of the consumption characteristics (Eq. (9)) of the 3 generators are shown in Table 1.

The 3 converter stations and 3 DC lines constitute the DC subsystem, and the equivalent impedance values of the converter stations are the same. $Z_{VSC} = 0.259 + j0.0085$ .The resistance values of DC lines are respectively as follows: $Z_{d12} = 0.031$, $Z_{d13} = 0.029$ and $Z_{d23} = 0.019$ .DC voltage $U_d \in [1.0,1.1]$, AC side voltage of converter $U_c \in [0.85,1.1]$, Converter modulation ratio $M \in [0,1]$,Permissible current of converter $I_c \leq 1.2$ p.u. There are 0.5 p.u. DC load on node 3d. VSC control mode and initial setting value are in Table 2.

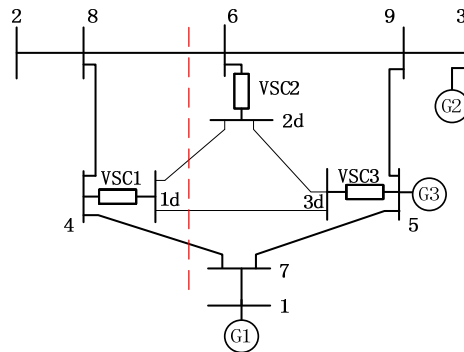**Figure 4.** Diagram of an AC/DC power system based on IEEE 9 nodes test system.

Table 1. Generator cost parameter.

Generator number	a	b	c
1	0.11	5	150
2	0.1225	1	335
3	0.1225	1	335

Table 2. VSC control mode and its initial parameters.

VSC number	control mode	Initial value of control parameter /p.u.
VSC1	Pd, Qs	-0.4, 0.259
VSC2	Ud, Qs	1.05, 0.436
VSC3	Pd, Us	0.9, 1.024

Table 3. Comparison of TTC results calculated in four ways.

	Basic CPF	**Gen-CPF**	**GenLoad-CPF**	**Opt-CPF**
TTC/MW	281.163	370.596	379.342	386.515
P_{G1}/MW	57.667	239.986	232.103	234.651
P_{G2}/MW	141.000	95.166	106.206	22.272
P_{G3}/MW	146.000	98.617	94.361	135.334
Generation cost /10^4¥	0.681	1.085	1.058	1.051
P_2/MW	56.987	87.002	76.059	76.000
P_4/MW	156.987	187.002	207.363	190.968
P_8/MW	55.987	87.002	86.650	108.022
Total load of receiving area/MW	267.961	361.006	370.072	374.989

TTC is calculated according to the above 4 methods, and the result is shown in Table 3. According to TTC calculation results, Opt-CPF is the largest, GenLoad-CPF and Gen-CPF are the second, and basic CPF is the smallest. From the point of view of total generation cost, the basic CPF is the smallest. However, the TTC, generation power and total load of the latter three methods are significantly different from the basic CPF. Therefore, it is difficult to compare the economy of each method from the index of generation cost. For this reason, the system state of the 60-th cycle in Gen-CPF is intercepted as shown in Table 5. The TTC at this time has just increased to almost equal to the basic CPF, so it is comparable economically.

Table 4. The system status of the 60th cycle by Gen-CPF.

	TTC/MW	P_{G1} **/MW**	P_{G2} **/MW**	P_{G3} **/MW**	**Generation cost /10^4¥**	**Total load of receiving area/MW**
Gen-CPF	281.6	112.6	116.5	116.5	0.633	280.612
Basic CPF	281.2	57.7	141.0	146.0	0.681	267.961

As can be seen from Table 4, the total load (280.612 MW) in the receiving area is 12.651 MW higher than that of the basic CPF (267.961 MW) when the Gen-CPF is used for 60 cycles, while the generation cost is reduced by 0.048 million yuan (0.681-0.633 = 0.048). Therefore, compared with the basic CPF algorithm, Gen-CPF based on economic dispatch of generating units can not only improve the transmission capacity of the system, but also reduce the generation cost at each level of load.

Compared with Gen-CPF, the GenLoad-CPF method in Table 3 shows that the load ratio on node 2 which is farther away from the generation area is reduced, while the load ratio on node 4 which is nearer to the generators is obviously increased. The total load increase by about 9MW while the generation cost reduce by about 270 yuan. Therefore, the TTC calculated by GenLoad-CPF is more economical.

The Opt-CPF algorithm further optimizes the VSC control parameters $C_{VSC}^{(t)}$ with the minimum network loss. VSC2 is chosen as the constant DC voltage control mode, node 2d is the slack bus of DC subsystem, VSC1 control parameters $P_{d1}^{(t)}$ and $Q_{S4}^{(t)}$, VSC3 control parameters $P_{d3}^{(t)}$ and $U_{S5}^{(t)}$ participate in optimization.

After optimization, the setting value of VSC1 is P_d=0.437 p.u., Q_s=0.331 p.u., VSC3 setting value P_d=2.092 p.u., U_s=1.007p.u. Now, the power flow state of the hybrid system has changed significantly: in G2 and G3 generators with the same consumption characteristics, the output of G2 far from the receiving area decreases greatly; at the same time, the load proportion on node 8 increases, and the

load proportion on node 4 decreases. Opt-CPF is better than GenLoad-CPF because the load in the receiving area (374.989) increases about 5 MW compared with GenLoad-CPF (370.072).

Based on the above analysis, the TTC obtained by Opt-CPF algorithm is more economical than that by other methods. The generation power growth direction, load growth direction and VSC setting value calculated by this method can be used as an important reference for dispatching operation. Therefore, this paper recommends the use of OPT-CPF algorithm based on power grid economic operation to calculate system TTC.

Table 5 shows the state of each VSC at the end of the 4 algorithms.

Table 5. Parameters of the VSC.

Computing methods	VSC	U_c/p.u.	I_d/p.u.	M	θ/(rad)
Basic CPF	1	0.9225	-0.5079	0.7179	-0.0334
	2	0.9055	0.4764	0.7049	0.0086
	3	1.0184	0.8789	0.7968	0.0617
Gen-CPF	1	0.9583	-0.4895	0.7460	-0.0309
	2	0.9474	0.4568	0.7374	0.0079
	3	1.0951	0.8178	0.8559	0.0534
GenLoad-CPF	1	0.9547	-0.4913	0.7427	-0.0312
	2	0.9486	0.4446	0.7376	0.0002
	3	1.0946	0.8182	0.8545	0.0535
Opt-CPF	1	0.9360	0.5296	0.7181	0.0349
	2	0.9878	-2.0505	0.7546	-0.1491
	3	1.0925	1.9022	0.8424	0.1239

4. Conclusion

In order to obtain the maximum transmission capacity under the condition of system economic operation, this paper proposes three improved CPF algorithms for the fixed defects of power generation and load power in the traditional continuous power flow algorithm, and the logic is progressive.

(1)The Gen-CPF algorithm enhances the economics of the TTC from the perspective of reducing power generation costs through generator economic dispatch.

(2)The GenLoad-CPF algorithm applies the interior point method to optimize the allocation of load based on the above algorithm, and improves the economics of TTC from the perspective of reducing network loss. This method has better economic optimization effect for pure AC system TTC calculation, but it needs to be improved in the application of TTC calculation in AC/DC system.

(3) The Opt-CPF algorithm takes into account the characteristics of the VSC-MTDC system based on the GenLoad-CPF algorithm. By optimizing the parameters of the VSC control mode, the TTC economy is further improved from the perspective of reducing the network loss.

The calculation example verifies that for the AC-DC hybrid system with VSC, the Opt-CPF algorithm obtains the best TTC economy. This paper recommends using this algorithm to calculate the AC/DC system TTC.

Acknowledgments

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