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An Optimal Reactive Power Control Strategy for UHVAC/DC Hybrid System in East China Grid

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***Abstract*—During the holidays, the power load of the East China Grid dropped significantly, resulting in excess capacitive reactive power, which makes the grid voltage increase significantly. For ultra-high voltage alternating current/direct current (UHVAC/DC) hybrid system, restricted by the minimum input number of the alternating current filter (ACF) in the dc converter stations, multiple dc stations that operate at a low-power transmission mode will inject a large capacitive reactive power to 500 kV ac grid, leading to a dramatic voltage rise. In addition, the 1000 kV UHVAC system may also transport a large capacitive reactive power to 500 kV ac grid during the holidays. In this paper, an optimal reactive power control strategy based on multi-dc power modulation has been proposed. It includes two steps. First, the minimized reactive power interchange control strategy which minimizes the reactive power interchange (RPI) between the UHVAC grid and the 500 kV ac grid has been executed. After that, if the grid voltage still exceeds the upper limit, the multi-dc power modulation is used to minimize the RPI between the dc converter stations and the 500 kV ac grid. The example analysis shows that the proposed optimal reactive power control strategy can effectively optimize the reactive power distribution in the UHVAC/DC hybrid system, thus reasonably controling the grid voltage.**

***Index Terms*—Multi-dc power modulation, reactive power interchange (RPI), ultra-high voltage alternating current/direct current (UHVAC/DC) hybrid system, voltage control.**

I. Introduction

EAST-CHINA Grid is operating the largest interconnected 500 kV alternating current (AC) grid in China. In load center, several ultra-high voltage direct current (UHVDC $\pm$ 800 kV), converter stations and ultra-high voltage alternating current (UHVAC 1000 kV), substations are centralized located, forming an UHVAC/DC hybrid system [1].

During the holidays, due to the significant decline in power load, the dc transmission power decreased. Restricted by the smallest input group of the alternating current filter (ACF) in the dc converter stations, the capacitive reactive power provided by the ACF are much greater than it is consumed by converter. Therefore, a great amount of capacitive reactive power will be injected from multiple dc converter stations to 500 kV ac grid, which made the grid voltage significantly increased.

The dc power modulation which changes the transmitted active power could reduce the reactive power interchange (RPI) between the dc converter station and the 500 kV ac grid. However, changed the transmitted active power for single dc system would break the power balance for both sending and receiving end, thus impact on the power generation scheduling for 500 kV ac grid. But for UHVAC/DC hybrid system in East China Grid, because of all the dc systems have the same sending grid, so the active power could be transferred freely between multiple dc systems without changing the total transmitted active power. Therefore, it is a good opportunity to decrease the total RPI by using multi-dc power modulation.

Given the worldwide scope of the dc projects, the use of the dc power modulation after the grid fault to provide emergency auxiliary frequency control or emergency power transfer has become a trend [2]–[5]. But for multi-dc power modulation, related researches [6] are still rare. From the present literature, it is the first time to control the ac grid voltage by using multi-dc power modulation.

For 1000 kV UHVAC grid, the capacitive reactive power is usually injected from UHVAC grid to 500 kV ac grid during holidays. The RPI could also largely increase the voltage of 500 kV ac grid. In order to effectively decrease the voltage, this paper seeks to provide a minimized reactive power interchange (MRPI) control strategy to minimize the RPI between the UHVAC and 500 kV ac grid.

II. Impact of Multi-DC Power Modulation on 500 kV AC Grid

A. Reactive Power Consumption of the Converter

While the dc transmission system is running, the converter requires absorbing capacitive reactive power from the ac grid, so that the converter could always be concerned as a reactive power load. The reactive power consumption could be calculated by

$$Q_{\mathrm{dc}} = P_{\mathrm{dc}} \tan \varphi \tag{1}$$

where

$$\tan \varphi = \frac{(\pi/180)\mu - sin\mu \cdot \cos(2\gamma + \mu)}{\sin \mu \cdot \cos(2\gamma + \mu)}. \tag{2}$$

In (2), P_{dc} is the transmitted active power; Q_{dc} is the reactive power consumption of converter; φ is the power-factor angle of

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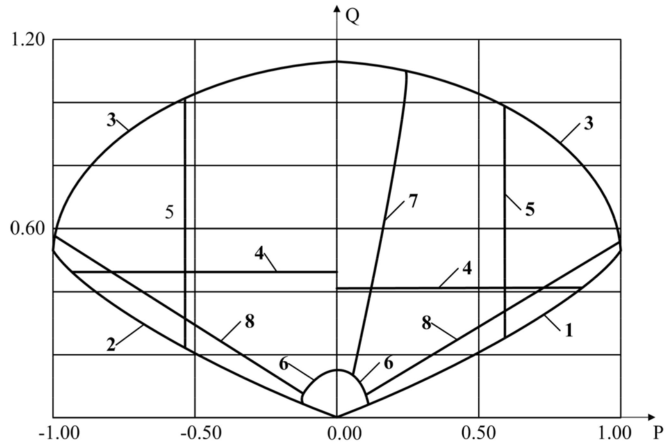

Fig. 1. Reactive power absorbed by the inverter.

converter; μ is the phase-shift angle; γ is the arc extinguishing angle; for the rectifier, γ is replaced by the trigger angle α.

According to (1) and (2), the capacitive reactive power absorbed by the inverter is affected by many operating parameters. One of the most sensitive is the arc extinguishing angle γ. At different dc operation modes, the reactive power absorbed by the inverter shows different trajectories, as illustrated in Fig. 1.

In Fig. 1, P is the transmitted active power, Q is the reactive power consumed by inverter. Curves 1–8 represent the following control mode.

1) *Curve 1:* Minimum rectifier α control.
2) *Curve 2:* Constant arc extinguishing angle control.
3) *Curve 3:* Constant dc current control.
4) *Curve 4:* Constant reactive power control.
5) *Curve 5:* Constant active power control.
6) *Curve 6:* Minimum dc current control.
7) *Curve 7:* Maximum rectifier α control.
8) *Curve 8:* Constant dc voltage control.

The constant arc extinguishing angle control mode is mainly used for the dc inverter stations in UHVAC/DC hybrid system. In the actual operation, the operating parameters are rarely changed, therefore the phase-shift angle and arc extinguishing angle will not be used in the reactive power optimization. The reactive power absorbed from the inverter could be determined by the transmitted active power.

B. Reactive Power Control of DC Converter Station

The RPI between the dc converter stations and the 500 kV ac grid is not only determined by the reactive power absorbed from the inverter, but also closely related with the reactive power control strategy of dc converter station.

In the UHVDC or HVDC converter stations in East China Grid, the capacity of a single group ACF is usually 240–290 MVar. During the holidays, switched a group of ACF may cause the voltage fluctuation over 5 kV in 500 kV ac grid. Therefore, for the reactive power control of the dc converter station, the decisive factor is the number of input ACF.

In order to meet the filter requirements, the minimum input number of the ACF must be guaranteed. The RPI between the dc converter stations and the 500 kV ac grid could be calculated using

$$Q_{I\mathrm{dc}} = Q_{\mathrm{dc}} - nQ_f = P_{\mathrm{dc}} \tan\varphi - nQ_f \tag{3}$$

where

$Q_{I\mathrm{dc}} =$ RPI between the dc stations and the ac grid;
$Q_f =$ the capacity of a single group of ACF;
$n=$ the number of input ACF.

For the reactive power control strategy, the minimum input number of the ACF has the highest priority. Before the inverter unlocked and the current detected, the ACF control module input the minimum number of the ACF into operation according to the predetermined ACF input sequence. In the entire operation of the dc system, the minimum filter condition would be monitored, once it reaches a preset dc power, a new group ACF must be switched on or off. Therefore, the minimum input number of the ACF (n_f) is represented as the function of P_{dc}, as shown in

$$n_f = n(P_{\mathrm{dc}}) = \begin{cases} n_{f\,\min}, P_{\mathrm{dc}} \le P_{t\,\min} \\ n_{f\,\min}+1, P_{t\,\min} < P_{\mathrm{dc}} \le P_{t1} \\ \vdots \qquad \vdots \\ n_{f\,\max}, P_{t\,\max} < P_{\mathrm{dc}} \end{cases} \tag{4}$$

where

$n_{f\,\min} =$ input number of ACF at minimum dc power;
$n_{f\,\max} =$ input number of ACF at maximum dc power;
$P_{t\,\min}$, P_{t1}, $P_{t\,\max} =$ preset dc power, by which a new group of ACR must be switched on or off.

C. Multi-DC Power Modulation

From the foregoing analysis, for a single dc converter station, whether the reactive power absorbed by the inverter or the input number of the ACF are mainly depended on the active power transmitted by the dc system. Therefore, the RPI between dc converter station and 500 kV ac grid could be represented as a function of P_{DC}

$$Q_{\mathrm{Idc}} = Q_{\mathrm{dc}} - nQ_f = f(P_{\mathrm{dc}}). \tag{5}$$

During the holidays, if the grid voltage exceeds the upper limit, the multi-dc power modulation could be a good choice to reallocate the active power for several dc systems, thus largely decreases the RPI between dc converter stations and the 500 kV ac grid.

III. Reactive Power Balance of UHVAC Substation

A. Reactive Power Balance Requirements

For a 1000 kV UHVAC line with the length of $x = l$, consider the voltage of the receiving end $UR = UR\angle 0^{\circ}$ and the natural power $Sn = U_R^2/Zc$ as the base value, the voltage

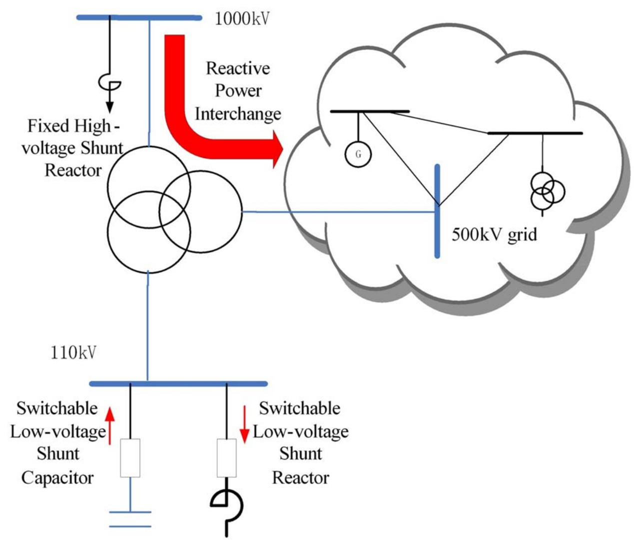

Fig. 2. FHSR + SLSCR compensation mode.

modulus ratio (VMR) of the sending side to the receiving end could be defined by [7], [8]

$$k = \frac{\left|\dot{U}_{s*}\right|}{\left|\dot{U}_{R*}\right|} = \sqrt{(\cos\beta l + Q_{R*}\sin\beta l)^2 + (P_{R*}\sin\beta l)^2} \quad (6)$$

where
$\dot{U}_{s*}$, $\dot{U}_{R*}$ = voltage of the sending side and receiving end;
P_{R*} = transmitted active power at the receiving end;
Q_{R*} = transmitted reactive power at the receiving end;
β = phase constant, Zc = wave impedance.

If the transmission power ($PR*$) is known, the reactive power balance requirements of the receiving end ($Q_{\mathrm{req}R*}$) is a function of k, as shown in

$$Q_{\mathrm{req}R*} = Q_{R*} = \frac{\sqrt{k^2 - (P_{R*}\sin\beta l)^2} - \cos\beta l}{\sin\beta l} = f_R(k). \quad (7)$$

Likewise, the reactive power balance requirements of the sending side ($Q_{\mathrm{req}S*}$) could also be expressed by a function of k, as shown in

$$Q_{\mathrm{req}S*} = \frac{\sqrt{k^2 - (P_{R*}\sin\beta l)^2} - k^2\cos\beta l}{\sin\beta l} = f_s(k). \quad (8)$$

B. Reactive Power Compensation for UHVAC Substation

Nowadays, the commercial UHVAC projects mainly adopt the fixed high-voltage shunt reactor (FHSR) + switchable low-voltage shunt capacitor or reactor (SLSCR) compensation mode, as shown in Fig. 2.

The capacity of a single SLSCR in UHVAC substation is usually 200–240 MVar, much greater than that in 500 kV ac substation. The RPI between UHVAC and 500 kV ac grid would be significantly changed by switching SLSCR.

C. RPI Between UHVAC Grid and 500 kV AC Grid

The RPI between UHVAC grid and 500 kV ac grid could be expressed as a function of the k (k = VMR), as shown in [9]

$$Q_{I\mathrm{ac}*} = Q_{\mathrm{req}*} - \left(Q_{cph*} + NQ_{cpl*}\right) - Q_{t*} \quad (9)$$

where
$Q_{I\mathrm{ac}}$ = RPI between UHVAC grid and 500 kV ac grid;
Q_{req} = reactive power balance requirements at the high voltage side of the UHV transformer, here is actually the $Q_{\mathrm{req}}R*$ in (7) or $Q_{\mathrm{req}S*}$ in (8);
Q_{cph} = reactive power compensation provided by FHSR;
N = a real integer, it indicates the number of SLSCR;
Q_{cpl} = reactive power compensation provided by SLSCR;
Q_t = reactive power loss of the UHV transformer

$$Q_{cph*} + NQ_{cpl*} = \frac{Q_{cph} + NQ_{cpl}}{U_{cpn}^2} Z_c k^2 = g_s(k) \quad (10)$$

$$Q_{t*} = \frac{P_{t*}^2 + \left(Q_{\mathrm{req}*} - Q_{cph*}\right)^2}{\left|U_{h*}^2\right|} \times \left(x_{h*} + \frac{x_{m*}x_{l*}}{x_{m*} + x_{l*}}\right) = f_t(k) \quad (11)$$

$$N = f_{\mathrm{round}}\left\{\frac{Q_{\mathrm{req}*} - Q_{cph*} - Q_{t*}}{Q_{cpl*}}\right\} = n(k) \quad (12)$$

where
U_{cpn} = nominal voltage;
P_t = active power transmitted through the UHV transformer;
U_h = high side voltage of the UHV transformer;
x_h, x_m, x_l = equivalent reactance for the high, middle and low voltage side of the UHV transformer respectively;
f_{round} = function rounds a number to the nearest integer.

Therefore, (9) could be simplified as

$$Q_{I\mathrm{ac}} = F(k) - \mathrm{N} \cdot G(k) \quad (13)$$

where
$F(k) = Q_{\mathrm{req}*} - Q_{cph*} - Q_{t*}$, redundant reactive power which flowed through the UHV transformer;
$G(k) = Q_{cpl*}$, reactive power compensation provided by a single SLSCR.

IV. Optimal Reactive Power Control Strategy

A. Reactive Power Control Process

By using the conventional voltage control methods such as leading phase operation of generator, adjustment of transformer tap or switching reactor/capacitors, only the reactive power flow in the ac grid will be changed. But the multi-dc power modulation will not only change the reactive power flow, but also significantly change the active power flow in the ac grid, making the power flow control tends to be complex. Therefore, the conventional voltage control methods which have smaller impact on ac grids should be firstly utilized. The MRPI control strategy which uses only the conventional voltage control methods is proposed here to minimize the RPI between UHVAC grid and the 500 kV ac grid. After that,

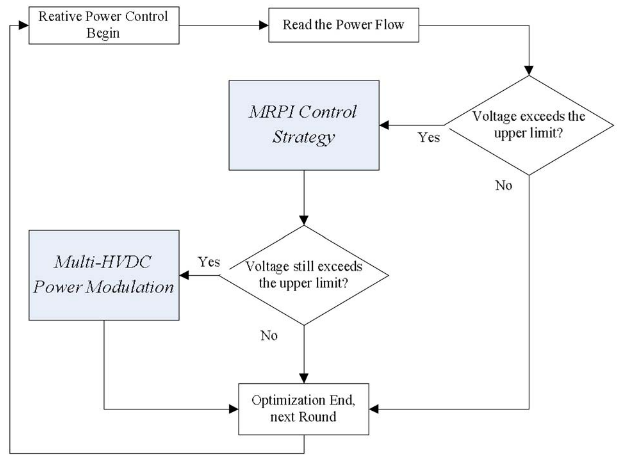

Fig. 3. Process of optimal reactive power control strategy.

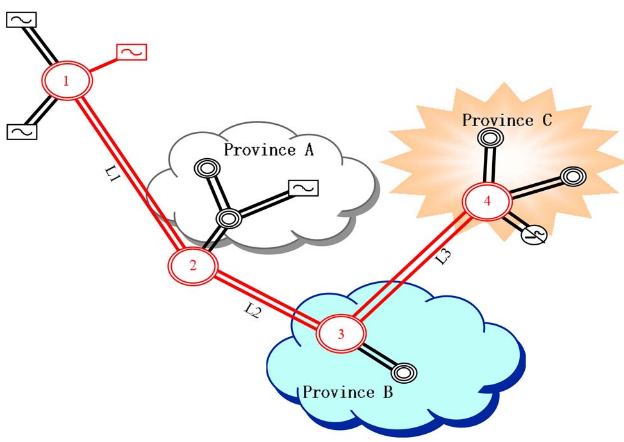

Fig. 4. Simplified electric wiring diagram for a UHVAC project.

if the grid voltage still exceeds the upper limit, the multi-dc power modulation must be used.

The process of the optimal reactive power control strategy based on multi-dc power modulation is shown in Fig 3.

B. Reactive Power Optimization Model

1) MRPI Control Strategy: As mentioned in Introduction, the existence of RPI between UHVAC grid and 500 kV ac grid could lead the voltage largely increased. Therefore, an MRPI control strategy is proposed here to minimize the RPI.

Fig. 4 presents a simplified electric wiring diagram for an UHVAC transmission system in East China Grid. The four UHV substations have the numbers of $i = 1, 2, 3, 4$. The transmission lines between the substations are numbered as $L_i, i = 1 - 3$.

Consider ignoring the active loss of the UHVAC transformer, we can get

$$Q_{Ii} = (Q_{Ri-1} + Q_{si}) - Q_{cphi} - Q_{ti} - N_i Q_{cpli} \tag{14}$$

where

$Q_{Ii} =$ RPI at the substation number *i;*

$Q_{Ri} =$ reactive power balance requirements at the receiving end of the line L_i;

$Q_{Si} =$ reactive power balance requirements at the sending side of the line L_i;

$Q_{cphi} =$ reactive power compensation provided by FHSR at the substation number *i;*

$Q_{ti} =$ reactive power loss of the UHV transformer at the substation number *i;*

$N_i =$ the number of SLSCR which put into operation at the substation number *i;*

$Q_{cpli} =$ reactive power compensation provided by a single SLSCR at the substation number *i;*

We use (15) and (16) to calculate the total amount of the RPI for the UHVAC transmission system in Fig. 4

$$\begin{cases} Q_{I2} = (Q_{R1} + Q_{s2}) - Q_{cph2} - Q_{t2} - N_2 Q_{cpl2} \\ Q_{I3} = (Q_{R2} + Q_{s3}) - Q_{cph3} - Q_{t3} - N_3 Q_{cpl3} \\ Q_{I4} = Q_{R3} - Q_{cph4} - Q_{t4} - N_4 Q_{cpl4} \end{cases} \tag{15}$$

$$Q_{I\text{ac}} = |Q_{I2}| + |Q_{I3}| + |Q_{I4}|. \tag{16}$$

$|Q_{Ii}|$ is the absolute value of the RPI which flow through the UHV transformer at the UHV substation number i. If the RPI between UHVAC and 500 kV ac grid is too large, the trip fault of the UHV main transformer which disconnect the UHVAC power grid from 500 kV ac grid may cause a great fluctuation of voltage in 500 kV ac grid, which could lead the voltage exceeds the upper/lower limit. Therefore, the RPI must be minimized no matter it is capacitive or inductive.

The UHV substation number 1 has no direct electrical connection to the lower 500 kV power grid, therefore its RPI would be excluded in (16).

On the basis of (15) and (16), let $(|U_{hi*}|/|U_{h(i+1)*}|) = k_i$ $i = 1, 2, 3$, now we can obtain the following equations:

$$\begin{aligned} Q_{I4*} &= F_4(k_3) - N_4 G_4(k_3) \\ Q_{I3*} &= F_3(k_2, k_3) - N_3 G_3(k_2, k_3) \\ Q_{I2*} &= F_2(k_1, k_2) - N_2 G_2(k_1, k_2). \end{aligned} \tag{17}$$

In (17), $N_2\sim$ N$_4$ can be expressed as the function of k_i. The minimized RPI can be presented as the following mathematical model:

$$\begin{aligned} \min Q_{I\text{ac}} &= \min\left(|Q_{I4*}| + |Q_{I3*}| + |Q_{I2*}|\right) \\ &= \min f\left(k_1, k_2, k_3\right) \end{aligned} \tag{18}$$

where

$k_1, k_2, k_3 =$ VMR of the line L_1 L_3;

$Q_{I\text{ac}} =$ total RPI of three UHV substations.

Equation (18) is essentially a high order multivariate nonlinear function, in which k_1, k_2, k_3 are decision variables. The aim of the MRPI control strategy is to find the optimal $k_1 - k_3$ which could minimize the sum of the absolute value of RPI at three UHV substations.

In addition, the conventional voltage control methods such as leading phase operation of generator, adjustment of transformer tap or switching reactors/capacitors should be also used to decrease the voltage in 500 kV ac grid. In the optimization, the 500 kV ac grid is modeled by the ac power flow model.

The bus voltages are selected as one of the optimization target in the MRPI control strategy, as presented in

$$f(x) = \begin{cases} \min(Q_{I\text{ac}}) \\ \min(\Delta V) \end{cases} \tag{19}$$

$$\Delta V = \sum_{j=1}^{\mathrm{m}} \left[\frac{\Phi\left(V_j - V_{j\mathrm{desired}}\right)}{\Delta V_j \max} \right]^2. \tag{20}$$

V_j is the voltage amplitude of node j in 500 kV ac grid; $V_{j\mathrm{desired}}$ is the ideal voltage of node j; $V_{j\max}$ is the voltage upper limit of node j; ΔV_j max is the difference between upper limit and lower limit; m is the total number of nodes; The function $\Phi(x) = \begin{cases} 0 & if\, x \le 0 \\ x & if\, x > 0 \end{cases}$

subject to

$$\begin{aligned} V_{g\min} &\le V_g \le V_{g\max} \\ T_{t\min} &\le T_t \le T_{t\max} \\ C_{j\min} &\le C_j \le C_{j\max} \\ U_l &\le U_{l\max} \\ N_{i\min} &\le N_i \le N_{i\max} \\ S_{ti} &\le S_{ti\max} \end{aligned}$$

where

$V_g =$ the terminal voltage of the generator;
$T_t =$ the transformer tap of the main transformer;
$C_j =$ the capacity of the reactor/capacitors at node *j;*
$U_l =$ voltage along the UHVAC line, must satisfy the restriction of steady state over-voltage requirements;
$N_i =$ the number of SLSCR which put into operation at the UHVAC substation number *i;*
$S_{ti} =$ apparent power which flow through the UHV transformer at the UHVAC substation number i, must smaller than the transformers' rated capacity.

2) Multi-DC Power Modulation: The capacitive reactive power injected from the dc converter stations to the 500 kV ac grid is the main reason which causes the grid voltage increased. Therefore, the minimization of RPI between dc converter stations and the 500 kV ac grid is one of the optimization targets.

Secondly, the voltage of the 500 kV ac grid should be controlled as low as possible during the holidays, so the voltage deviation from its ideal value of each node has also been selected as the optimization target.

The reactive power optimization based on multi-dc power modulation could be represented as

$$f(x) = \begin{cases} \min\left(Q_{I\mathrm{dc}}\right) \\ \min(\Delta V) \end{cases} \tag{21}$$

where

$$Q_{I\mathrm{dc}} = \sum_{z=1}^{r} |Q_{Iz}| \tag{22}$$

$$\Delta V = \sum_{j=1}^{\mathrm{m}} \left[\frac{\Phi\left(V_j - V_{j\mathrm{desired}}\right)}{\Delta V_j \max} \right]^2. \tag{23}$$

Q_{Iz} is the RPI between the dc converter station number z and the 500 kV ac grid, the size of the Q_{Iz} could be calculated by (5); r is the total number of dc systems.

When the multi-dc power modulation applied, the step of MRPI control strategy which uses the conventional voltage control methods has been already executed. Therefore, the reactive power optimization based on multi-dc power modulation does not include the conventional voltage control methods such as leading phase operation of generator, adjustment of transformer tap or switching reactor. Only dc related control variables are considered. The inequality and equality conditions can be expressed as

$$\begin{cases} P_{\mathrm{dc}^z} \min \le P_{\mathrm{dc}^z} \le P_{\mathrm{dc}^z} \max \\ \mathrm{n}_f z \le n_z \le n_z \max \\ L_e \le L_e \max \\ V_j \le V_j \max \end{cases} \tag{24}$$

$$\Delta \mathrm{P_{dc}} = \sum_{z=1}^{r} P_{DC^z} - P_{\mathrm{total}} = 0. \tag{25}$$

P_{dc^z} is the transmitted active power for the dc converter station number z; n_z is the input number of ACF in the dc converter station number z, must be equal or greater than the $\mathrm{n}_f z$(minimum input number of ACF); L_e is the current on transmission line e, which must be lower than its thermal stability limit L_e max; V_j is the voltage amplitude of node j in 500 kV ac grid. P_{total} is the total transmitted active power for all dc systems, it should remain constant during the multi-dc power modulation process.

C. Optimization by Using the Immune Genetic Algorithm (IGA)

The solution of the MRPI control strategy in (19) and the multi-dc power modulation in (21) is actually a multiobjective optimization problem with several inequality and equality conditions. All these two processes are difficult to solve by traditional method.

IGA [10]–[13], one of the artificial intelligent algorithms, has been successfully applied in the field of power system. In East China Grid, an automatic voltage control (AVC) [11], [14] system has been deployed to control the reactive power resources, such as SLSCR, generators, on-load voltage regulating tap, etc. The cycle of the instruction issued by the AVC system is 5 min. Through the simulation verification, if the IGA is adopted, the time of one reactive power optimization process is still less than 1 min. Therefore, the IGA is suitable for our purpose to solve the reactive power optimization problem. In our research, IGA is used for both MRPI control strategy and multi-dc power modulation.

The recognition process of the immune system to foreign antigen is looking for the antibody which has the largest affinity (or called binding force) with the antigen. According to the recognition process of the immune system, IGA could be formed by combining some characteristics of the immune system with genetic algorithm. The main idea of IGA is using the antigen as the objective function, and using the antibodies as the search space. The coding technique used for IGA is similar as for GA, such as the decimal integer coding. The antibodies in IGA are also equivalent to the chromosomes in GA.

Both MRPI control strategy and multi-dc power modulation have two objectives. In order to solve the multi objective optimization problem, the local affinity and the global affinity are used in this paper.

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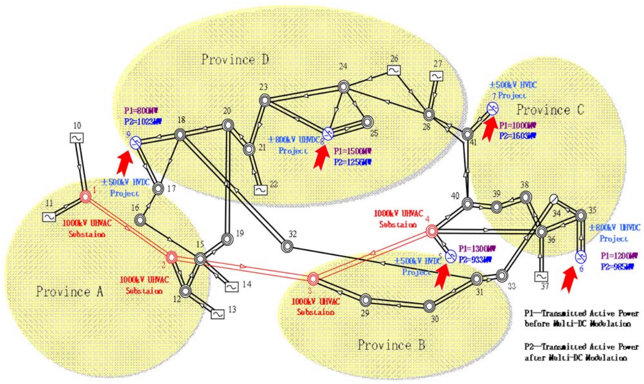

Fig. 5. UHVAC/DC hybrid system.

TABLE I
REACTIVE POWER COMPENSATION SCHEME

Node Number	Total Reactive Power (Mvar) (Capacitve/Inductive)	ACF (Number*Mvar)	Capacitor (Number*Mvar)	Reactor (Number*Mvar)
1	0 / 480	/	/	2 * 240
2	840 / 480	/	4 * 210	2 * 240
3	840 / 480	/	4 * 210	2 * 240
4	840 / 480	/	4 * 210	2 * 240
5	1890 / 0	9 * 210	/	/
6	3900 / 0	15 * 260	/	/
7	1890 / 0	9 * 210	/	/
8	3900 / 0	15 * 260	/	/
9	1890 / 0	9 * 210	/	/

For the multiobjective function $\min F(x) = [f_1(x), f_2(x), \ldots, f_n(x)]^T$,the local affinity of a feasible solution x_i with each objective function $f_k(x)$ could be calculated by using

$$A_{F_k}(x_i) = \sum_{j=1}^{N} A_k\left(x_j\right) \tag{26}$$

$$\begin{cases} A_k\left(x_j\right) = 1 \quad if\, f_k(x_i) \le f_k\left(x_j\right),\ j = 1, 2, \ldots, N \\ A_k\left(x_j\right) = 0 \quad if\, f_k(x_i) > f_k\left(x_j\right),\ j = 1, 2, \ldots, N \end{cases} \tag{27}$$

where

$A_{F_k}(x_i) =$ the local affinity of x_i with $f_k(x)$;

$N =$ the number of antibodies.

The global affinity of the antibody x_i is calculated by adding all local affinities of x_i with $F(x)$, as shown in

$$A_F(x_i) = \sum_{k=1}^{n} A_{F_k}(x_i). \tag{28}$$

The antibody with larger global affinity is closer to the optimal solution of multiobjective functions.

V. EXAMPLE ANALYSIS

Fig. 5 illustrates a simplified UHVAC/DC hybrid system in East China Grid, it include two ±800 kV UHVDC converter stations, three ±500 kV HVDC converter stations, six UHVAC lines, four 1000 kV UHVAC substations, 84 500 kV ac lines, 24 500 kV substations, and 8500 kV power plants. Among them, nodes 1–4 are 1000 kV UHVAC substations and nodes 5–9 are dc converter stations. The reactive power compensation scheme for each UHVAC substation and dc converter station are listed in Table I.

TABLE II
IGA OPTIMIZATION RESULTS FOR MRPI CONTROL STRATEGY

Number of Antibodies	$Q_{i\,AC}$	ΔV	Local Affinity to $\min(Q_{i\,AC})$	Local Affinity to $\min(\Delta V)$	Global Affinity
1	133.2	10.1	37	39	76
2	132.5	10.7	38	36	74
3	132.4	10.8	39	35	74
4	133.6	10.2	36	38	74
5	133.9	10.6	35	37	72
6	136.4	10.9	34	34	68
7	137.2	11.2	33	32	65
8	139.2	11.1	31	33	64
9	137.4	11.5	32	30	62
10	140.2	11.3	30	31	61

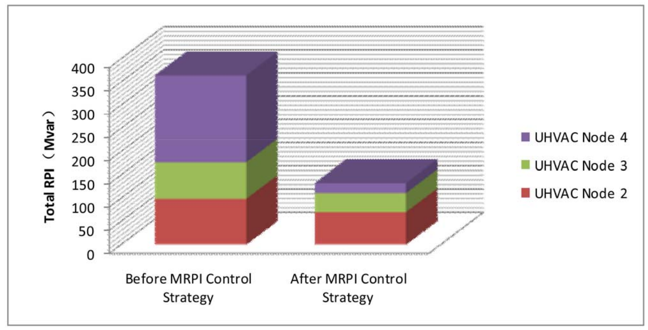

Fig. 6. RPI for each UHVAC substation.

In order to control the voltage below the upper limit, the proposed two-step multiobjective optimization process with several inequality and equality conditions has been executed. The variables include not only the conventional voltage control methods such as leading phase operation of 21 generators, adjustment of 59 transformer taps or switching 178 capacitor/reactors, but also the power settings on the five dc systems. The IGA which mentioned in Section IV is used here to solve the optimization problem.

According to the optimization process in Fig. 3, the MRPI control strategy is firstly implemented to decrease the RPI between 1000 kV UHVAC grid and 500 kV ac grid.

Table II lists the first ten antibodies with larger global affinities obtained by the IGA. The first antibody which has the largest global affinity is selected as the optimization result.

The comparison of the RPI for each UHVAC substation before and after the execution of the MRPI control strategy is shown in Fig. 6, and the voltage value for 500 kV bus at nodes 1–12 are shown in Fig. 7. The voltage values of remaining nodes which have a similar trend are not listed here. The detailed calculation results could be found in Table III.

After the MRPI control strategy, the RPI between 1000 kV UHVAC grid and 500 kV ac grid is largely decreased, resulting voltage drop at all nodes. But there are some nodes whose voltage are still higher than their upper limit, so the multi-dc power modulation is executed subsequent.

Before and after the multi-dc power modulation, the voltage of nodes 1–12 and the RPI between the dc converter stations and 500 kV ac grid are shown in Figs. 7 and 8.

TABLE III
CALCULATION RESULTS FOR MRPI CONTROL STRATEGY

Control Strategy	Item	"Low Hours" Operation Mode in Holidays			
		UHVAC Station1	*UHVAC Station2*	*UHVAC Station3*	*UHVAC Station4*
Before MRPI Control Strategy	High Side Voltage (kV)	1074	1078	1072	1074
	Middle Side Voltage (kV)	531.0	525.9	529.0	535.9
	Low-voltage Reactor/Capacitor	1/0	2/0	2/0	1/0
	Capacitive Reactive Power Injection	/	99.4	78.2	187.4
	Total RPI (Mvar)	$Q_{\Sigma um}=\lvert Q_{12}\rvert+\lvert Q_{13}\rvert+\lvert Q_{14}\rvert=365$			
	VMR	$k_1=0.9963,\ k_2=1.0056,\ k_3=0.9981$			
After MRPI Control Strategy	High Side Voltage (kV)	1070	1075	1067	1068
	Middle Side Voltage (kV)	528.9	523.6	526.1	531.5
	Low-voltage Reactor/Capacitor	1/0	2/0	2/0	2/0
	Capacitive Reactive Power Injection	/	70.8	40.9	21.5
	Total RPI (Mvar)	$Q_{\Sigma um}=\lvert Q_{12}\rvert+\lvert Q_{13}\rvert+\lvert Q_{14}\rvert=133.2$			
	VMR	$k_1=0.9953,\ k_2=1.0075,\ k_3=0.9991$			

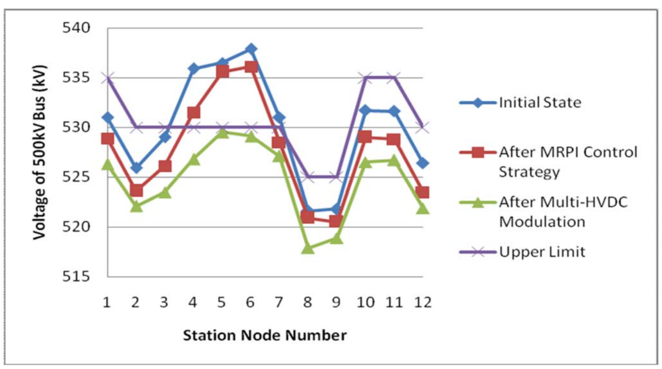

Fig. 7. Voltage before and after multi-dc modulation.

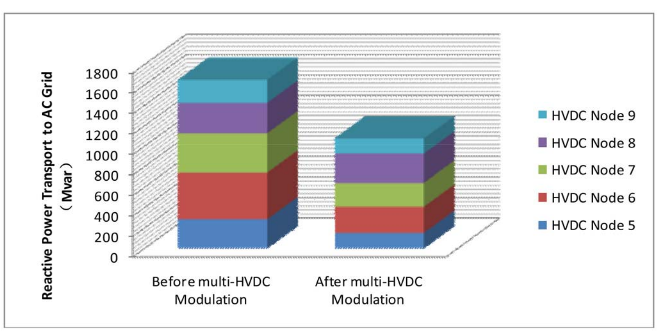

Fig. 8. RPI before and after multi-dc modulation.

According to Fig. 7, there are two dc converter stations (nodes 5 and 6) and one UHVAC substation (node 4) whose voltage still exceeds the upper limit after the MRPI control strategy. After the multi-dc power modulation, the total transmitted active power from dc systems remains unchanged, as shown in Fig. 5, but the voltage of all UHVAC substations and dc converter stations could be controlled lower than their upper limit.

Fig. 8 illustrates the change of the RPI between the dc converter stations and the 500 kV ac grid. Through the rational reallocation of the dc transmission power, the capacitive reactive power injection was largely decreased from 1655 to 1079 MVar, leading up to 5 kV voltage reduction in the nearest 500 kV ac grid.

VI. CONCLUSION

During the holidays, a great amount of capacitive reactive power will be injected from 1000 kV UHVAC grid and multiple dc converter stations to 500 kV ac grid, which exceeds the maximum regulation capacity of the conventional voltage control methods in 500 kV ac grid, made the grid voltage significantly increased.

An optimal reactive power control strategy based on multi-dc power modulation is proposed to solve this problem. The impact of multi-dc power modulation on 500 kV ac grid is illustrated in Section II. The RPI between UHVAC grid and 500 kV ac grid is demonstrated to be a function of VMR in Section III. The optimal reactive power control strategy is presented as a combination of MRPI control strategy and multi-dc power modulation in Section IV. The UHVAC/DC hybrid system in East China Grid is used as an example in Section V. It shows that the optimal reactive power control strategy based on multi-dc power modulation can effectively decrease the voltage of UHVAC/DC hybrid system during the holidays.

In the actual engineering practice, the reallocation of the transmitted active power between several dc systems without changing the total amount of the transmitted active power has made full application in East China Grid during the Spring Festival and National Holiday in the year of 2013 and 2014. It is proved that the power transfer between multiple dc converter stations could effectively decrease the grid voltage.

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