A Design Methodology for Installing Reactive Compensation Equipment in Ultra High Voltage AC Transmission System Based on a Modified Particle Swarm Optimisation Method

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Abstracts:
Ultra high voltage (UHV) AC system operates at 1000kV or above and is characterised with having a large transmission capacity (5000MW or above per single circuit) and long transmission distances. It is capable of producing over 4 times more reactive power gains than a conventional 500kV transmission line, and also absorbing a significant amount of reactive power when power flow across the line is high. Managing UHV AC voltage profile across a range of operating conditions is a major design challenge, especially in the early stage of development in UHV AC transmission systems. It requires an appropriate amount of inductive and capacitive compensation equipments with different characteristics installed at appropriate locations. This paper presents a practical method for designing, installing and operating reactive power compensation schemes for UHV AC systems. The method takes into account the cost of different types of reactive power compensation equipment, such as mechanically switched capacitors, static var compensators, fixed shunt reactors, controllable shunt reactors, etc, and minimises the overall cost of reactive compensations such that the system operates satisfactorily across a range of operational conditions whilst satisfying system constraints, including voltage and thermal constraints. The optimisation problem is solved by a modified particle swarm optimisation algorithm. The design framework is applied to a real UHV system design as case study, and is compared with conventional design method.

Key words: System Planning and Development, Optimisation and Mathematical Programming, System Operation

I. INTRODUCTION
Over the past three decades, China’s electric power systems have seen rapid expansion in both installed generation capacity and grid development. For the period of 2000 to 2010, demand growth has averaged about 12% a year. By 2012, total installed generation capacity reached over 1000GW[1], including 76GW of wind and 3GW solar power generation. Peak demand reached about 600GW. It is projected that by 2020 total installed generation will reach 1900GW, of which 160GW would be wind generation and 30GW solar although coal fired generation will still dominate but is on a declining trend with its share falling from present 80% to about 72% in 2020 [1]. Distribution of China’s power energy resources is extremely uneven across the country. Two thirds of coal is located in the north and northwest, and two thirds of hydro power resource is endowed in the south and southwest of the country[1]. On the other hand, major demand centres are situated in the eastern seaboard. Therefore, electricity has to be transmitted in increasingly large quantity over long distances from power generation to demand centres. This necessitated rapid development of power networks in the country over the past two decades[2]. Network operating voltage has increased rapidly from 220kV, to 500kV and 750kV to facilitate bulk transmission of power[2].

The first 1000kV ultra high voltage (UHV) demonstration project in China went into operation in 2009 and has been in commercial operation since 2010. State Grid Corporation of China (SGCC), the owner and operator of 80% national transmission and distribution systems are planning by 2020 to construct a 1000kV national UHV AC transmission network interconnecting and overlaying on the existing 750kV or 500kV regional power systems[1-2]. One of the key challenges in operating an UHV AC transmission system is voltage stability and control. UHV AC transmission lines are characterised with having large transmission capacity and long distances. It can produce 4 to 5 times the amount of capacitive gains on a per kilometre basis as a 500kV line. It can also absorb significant amount of reactive power during heavy loading conditions [2-3]. Therefore, it requires not only significant amount of inductive compensation to suppress overvoltage during switching or light load conditions, but also capacitive compensation to control
Reactive power planning is a complex and nonlinear optimisation problem[3,7,8]. Over the past decade, a number of researchers have developed and applied rigorous optimisation based methods in solving the reactive power compensation problems. [8] conducted a comprehensive review of objectives, constraints and algorithms in reactive power planning. Optimisation algorithms surveyed includes mathematical optimisation method, intelligent search algorithms such as simulated annealing, tabu search, etc. Particle swarm optimisation and its application in power systems including reactive power planning can be found in [6,12,13,15]. A scenario based approach to reactive power planning is reported in [7] which attempts to increase the flexibility in reactive compensation across a range of system operating conditions. The problem of planning and allocating slow and fast reactive compensation is developed in [12] which tries to make an economic trade-off between fast and slow Var compensation whilst meeting reactive control requirements under normal and contingency states. The problem is formulated as a mixed integer optimisation problem and solved by particle swarm optimisation (PSO) method. This paper develops a methodology for identifying and installing fast and slow inductive and capacitive reactive power compensation devices in UHV AC system that meets UHV system voltage regulation requirements under a range of operating conditions.

The paper is organised as follows: UHV AC transmission system characteristics are described in Section II with reactive power planning problem formulated in Section III. Section IV describes solution process, followed by case studies in Section V, and finally, Section VI provides conclusions.

II. CHARACTERISTICS OF UHV AC TRANSMISSION SYSTEMS

UHV AC transmission system operates at 1000kV or above and is used for bulk transmission of electricity power over long distances (over 200km), the charging capacitive gains of the UHV line can be calculated as [2,3]

\[ Q_c = \frac{B V^2}{2} \]

(1)

Where \( Q_c \) is capacitive gain of the line, \( B \) is the line susceptance and \( V \) is voltage magnitude.

Table below compares key parameters of typical 1000kV, 750kV and 500kV overhead transmission lines[2].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Voltage Level (nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500kV</td>
</tr>
<tr>
<td>conductor</td>
<td>4×300</td>
</tr>
<tr>
<td>Diameter of bundled conductor (cm)</td>
<td>42.0</td>
</tr>
<tr>
<td>Phase to phase distance (m)</td>
<td>13</td>
</tr>
<tr>
<td>( R_0 ) (pu/km)</td>
<td>1.05×10^{-5}</td>
</tr>
<tr>
<td>( X_0 ) (pu/km)</td>
<td>1.14×10^{-4}</td>
</tr>
<tr>
<td>( B_0 ) (pu/km)</td>
<td>0.00978</td>
</tr>
</tbody>
</table>

Table 1 Comparison of typical 500kV, 750kV, and 1000kV overhead lines.

It can be seen from Table 1 above that the capacitive gain of an UHV overhead line is about 4.4 times that of a 500kV one.

For an UHV overhead line of 300km, the capacitive gain on the line is over 1300MVAR. This also represents the no-load or switching gains, which, if not compensated, would produce unacceptable level of overvoltage. This is usually managed by connecting fixed shunt reactors (FSR) to both ends of the overhead line. The size of FSR is determined by no-load and switching overvoltage regulation requirements.

The net reactive power gains/losses an UHV overhead line produces is the difference between capacitive gain and reactive power losses across the line. Assuming that the active power transmitted is significantly larger than the reactive power, it can be approximated as:

\[ Q_{net} = B(\frac{E^2}{2} + \frac{V^2}{2}) - P^2X/V^2 \]

(2)

Where \( Q_{net} \) is the net reactive power produced by the UHV line, \( P \) is the active flow across the line, \( X \) is line reactance, \( E \) and \( V \) are voltage at the sending and receiving end, respectively.

Figure 1 below compares the net reactive power produced by typical 500kV, 750kV and 1000kV transmission lines with a length of 200km.
For a 200km 1000kV transmission line, its transfer capability due to voltage stability limit is well over 8000MW. It can be seen from Figure 1 above that significant amount of reactive compensation is required to manage voltage regulations across a range of power flow conditions.

There are broadly 4 types of reactive compensation devices that can be used to control the UHV voltage regulation. They are

- Fixed shunt reactor (FSR)
- Controllable shunt reactor (CSR)
- Mechanically switched capacitors (MSC or MSCDN)
- Static Var Compensators (SVC)

FSRs are required to manage no-load or switching overvoltage and are determined by the overvoltage regulation. They are typically connected to both ends of the UHV transmission lines, and are likely to be in-service all the time. CSRs are new types of shunt reactors that can vary its output smoothly and rapidly as the power flow increases[14]. MSCs are capacitive compensation equipment used to regulate steady state voltage profiles and can be switch in/out in blocks depending on the system conditions. SVCs can provide dynamic voltage response.

At present, only CSRs and FSRs are capable of operating at 1000kV and above and are directly connected to the UHV buses for overvoltage regulation. However, at present, there are no capacitive compensators, such as MSCs, MSCDNs, SVCs, etc., that can operate at the UHV voltage level and therefore must be installed at lower voltage levels, connected directly at busbars or tertiary winding of an inter-bus transformer[2,4]. CSRs can respond rapidly to system disturbances by changing its output, thereby providing voltage support[4,14].

The cost of these four types of reactive compensation devices vary significantly and the purpose of this paper is to develop an optimal planning method that minimises total compensation costs whilst satisfying system voltage constraints across a range of operating conditions.

### III. FORMULATION OF UHV REACTIVE POWER PLANNING PROBLEM

At the early stage of UHV system construction, the reactive power planning is based on the principle of achieving a balanced reactive power at each voltage level on the zonal/nodal basis so as to minimise the reactive power flow between different zones/nodes of UHV system and also between UHV and other voltage levels. [4] developed a practical method of calculating and identifying appropriate amount of shunt reactors (FSRs & CSRs) against the expected power flow conditions. The method is being used in actual reactive power planning of UHV systems. However, it could not take into account the reactive power compensation requirements under different power flow conditions and also may lead to over-invest as it cannot identify the overall optimal siting and sizing of compensations.

This paper develops an optimal reactive power planning method that takes into account of different power flow conditions and minimise total costs of reactive compensation required.

**Objective Function**

Although the main objective of reactive power planning is to minimise total cost of reactive compensation, many variants exist to take into account of transmission losses, generation production, etc, and can be formulated as a multi-objective optimisation problem[8,9]. For reasons of practicality and characteristics of UHV system as described previously, we consider the UHV reactive power optimisation as the one to minimise the total cost of reactive compensation.

The objective function for compensation investment cost can be described as follows.

\[
\min f = \sum_{i=1}^{n} (C_{CSR}Q_{CSR} + C_{MSC}Q_{MSC} + C_{SVC}Q_{SVC})
\]

(3)

Where, the \( f \) is the cost function; \( C_{CSR}, C_{MSC}, C_{SVC} \) are the unit cost of CSR, MSC, SVC, respectively; \( Q_{CSR}, Q_{MSC}, Q_{SVC} \) are quantities of CSRs, MSCs, and SVCs, at substation \( i \), respectively. \( n \) is the number of nodes. Please note that the above objective function does not contain operational cost.

As FSRs are usually required for managing no-load and switching voltage and are normally determined as a first step of UHV reactive power planning. Therefore, for simplicity, they are assumed in this paper to have been determined separately and before the optimisation process[4]. However, they can be considered in the future studies as part of overall optimisation.

**Constraints**

Optimisation must satisfy the following equality and inequality constraints.

\[
V_{i}^{\min} \leq V_{i}^T \leq V_{i}^{\max}
\]

(4)

\[
Q_{G}^{\min} \leq Q_{G}^T \leq Q_{G}^{\max}
\]

(5)

\[
P_{G}^{\min} \leq P_{G}^T \leq P_{G}^{\max}
\]

(6)

\[
v_{i}^{T} \leq V_{i} \leq v_{i}^{T}
\]

(7)

\[
\left| V_{i}^{\max} - V_{i}^{\min} \right| \leq \delta
\]

(10)

\[
Q_{G}^{\min} \leq Q_{G} \leq Q_{G}^{\max}
\]

(11)

\[
Q_{CSR}^{\min} \leq Q_{CSR} \leq Q_{CSR}^{\max}
\]

(12)

\[
Q_{SVC} = Q_{MSC} + Q_{SVC}
\]

(13)

Where, superscript, \( S \), in equations (4)-(10) has the value of 0 and 1 which, respectively, denotes steady state and N-1 contingency conditions. Similarly, superscript, \( T \), represents the different load conditions studied, e.g. minimum, peak demand conditions, etc. It is specified by the user. \( V_{i}^{\min} \) and \( V_{i}^{\max} \) are minimum and maximum voltage allowed at node \( i \), etc, that can operate at the UHV voltage level and therefore are typically connected to both ends of the UHV transmission lines, and are likely to be in-service all the time. CSRs are new types of shunt reactors that can vary its output smoothly and rapidly as the power flow increases[14]. MSCs are capacitive compensation equipment used to regulate steady state voltage profiles and can be switch in/out in blocks depending on the system conditions. SVCs can provide dynamic voltage response.

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This paper develops an optimal reactive power planning method that takes into account of different power flow conditions and minimise total costs of reactive compensation required.
\( Q_{Gi}^{\text{min}} \) and \( Q_{Gi}^{\text{max}} \) are minimum and maximum MVAR range of generators connected at node \( i \); \( t_i^{\text{min}} \) and \( t_i^{\text{max}} \) are lower and upper tap ratios of on-load tap changers at node \( i \); \( Q_{CSi}^{\text{min}} \) and \( Q_{CSi}^{\text{max}} \) are minimum and maximum amount of capacitive compensation equipment than can be installed at node \( i \); \( Q_{Gi}^{\text{min}} \) and \( Q_{Gi}^{\text{max}} \) are minimum and maximum quantities of CSRs that can be installed at node \( i \); \( V_i^{0,T} \) and \( V_i^{5,T} \) are voltage magnitude at node \( i \) under pre-fault steady state, and after the fault occurring (for N-1, about 4 seconds after the fault) (for more details, please see below). \( V_i^{5,T} \), \( Q_{Gi}^{5,T} \), \( P_{Gi}^{5,T} \) are voltage magnitude, generator reactive and active power output at node \( i \) under demand condition, \( T \), and security state \( S \) (\( S \) being 0 for pre-fault steady state, 1 for N-1), respectively. \( t_i^{5,T} \) is the tap ratio of on-load tap changer at node \( i \).

Equation (10) is the dynamic voltage constraint and is considered as an alternative for voltage stability limit. Figure 2 below shows the voltage response at node \( i \) following a fault.

![Fig.2 Voltage curve following a N-1 fault](image)

In order to prevent dynamic voltage instability, sufficient dynamic reactive power reserve must be provided. This is usually provided by generators and SVCs. A number of studies on reactive power planning has included voltage stability limit as one of the multi-objective optimisation functions[8,6], which usually requires performing continuous power flow calculations as the true critical point of P-V curve is very difficult to find for a large and complex system. In this paper, we propose to use voltage dynamic response curve as a practical criterion for identifying dynamic reactive power requirements. For the purpose of this study, \( \delta \) of 0.5% is considered as appropriate.

Let \( \mathbf{h}^{0,T} \) be the vector of pre-fault steady state constraints under demand condition, \( T \), as represented by equation (4) – (13), and \( \mathbf{h}^{5,T} \) be the vector of constraints for N-1 contingency under demand condition \( T \). The above optimisation problem can be re-arranged as follows

\[
\min f' = \sum_{i=1}^{N_p} (C_{CSR, i} Q_{CSR, i} + C_{MSC, Q_{MSC, i}} + C_{SVC, Q_{SVC, i}}) + \lambda_1 h_0^{0,T} + \lambda_2 h_i^{5,T}
\]

Where, \( \lambda_1 \) and \( \lambda_2 \) are Lagrange weighting factors, penalising the violation of constraints during the optimisation process. In this paper a value of \( 10^3 \) is found appropriate.

IV. SOLUTION PROCESS

PSO is a type of evolutionary algorithm and has found wide applications in power systems [15]. It achieves efficient search through a population of randomly generated particles. Each particle is a candidate solution to the optimisation problem which has its own position and velocity. Since this method imitates the behaviours of biomes it fits well for parallel computing[15] which is important in improving optimisation performance, especially for large and complex systems, such as UHV reactive power planning.

This paper developed a modified PSO for the proposed reactive power planning method. The method is codified in C++ and calls a commercial power system analysis package for load flow and transient voltage analysis.

Detailed process is described below:

1) Initialisation. This includes setting the number of particles \( N_p \), maximum number of generations and convergence criterion \( \varepsilon \)

2) Initialisation of first generation particles. This is generated randomly as \( x=x_{\text{min}}+\alpha(x_{\text{max}}-x_{\text{min}}) \), where \( \alpha \) is a random number in \([0,1] \) and \( x \) is current position of the particle; calculates and updates the best value of the particle (pbest) and also group best values (gbest).

3) Update position and velocity of each particle

\[
v_{i+1} = k \cdot (w \cdot v_i + \phi_1 \cdot \text{rand}(\cdot)(p_{\text{best}}-x_i) + \phi_2 \cdot \text{rand}(\cdot)(g_{\text{best}}-x_i))\]

\[
x_{i+1} = x_i + v_{i+1}
\]

Where \( x_i \) and \( v_i \) are the current position and velocity of the \( i \)th generation. \( w \) is the inertia factor, \( \phi_1 \) and \( \phi_2 \) are acceleration factors, \( \text{rand}(\cdot) \) is random number in \([0,1] \), \( k \) is the convergence factor and is given as follows:

\[
k = \frac{2}{|2 - \phi - \sqrt{\phi^2 - 4\phi}|}
\]

Where \( \phi = \phi_1 + \phi_2 > 4 \). Generally speaking, inertia factor, \( w \), is determined as

\[
w = w_{\text{max}} - \frac{w_{\text{max}} - w_{\text{min}}}{i_{\text{max}}} \times i
\]

Where \( i_{\text{max}} \) is the maximum number of iterations, \( i \) is the current iteration, \( w_{\text{max}} \) and \( w_{\text{min}} \) are the upper and lower limit of the inertia factor.
In order to further improve the speed and robustness of PSO, wavelet variance method is introduced to the randomness of the particles as follows: assuming each particle of the group has the opportunity to mutate randomly, let the probability of mutation be \( p_m \) \( (p_m \in [0, 1], \text{ defined by the user}) \). During the iteration, each particle generates a random number in \([0,1]\), if it is greater than \( p_m \), then the particle is mutated

\[
x'(i+1) = \begin{cases} 
  x'(i) + \sigma \times (x_{\text{best}}(i) - x'(i)) & \sigma > 0 \\
  x'(i) + \sigma \times (x'(i) - x_{\text{best}}(i)) & \sigma \leq 0 
\end{cases}
\]

where

\[
\sigma = \frac{1}{\sqrt{a}} e^{-\left(\frac{\gamma}{2}\right)^2} \cos\left(5 \left(\frac{\gamma}{a}\right)\right)
\]

\[ a = e^{-\ln(g) \times (1 - \frac{1}{T})^T + \ln(g)} \]

5) For the new generation of particles, calculates their pbest and group gbest. Check whether the convergence criteria are met, if not, go to Step 3).

The optimisation process can be stopped if the maximum number of iterations, or the convergence criteria have reached.

V. CASE STUDIES

The reactive power planning method developed in this paper is applied to the planning of actual UHV transmission project in China. Figure below shows the illustrative configuration of the project.

![Figure 3. UHV transmission project – case study](image)

It can be seen from Figure 3 that there are five UHV substations “A to E” with four thermal plants “P1 to P4”. Each of the substations is connected to the local area grids with substation “E” connected to existing UHV network. Although the number of UHV nodes is relatively limited the study has to take into account 750kV and 500kV networks which are connected to the UHV system. In total, there are over 21000 nodes and 26000 branches in the study.

Due to considerations of time and for the purpose of proving the validity of the proposed approach, only heavy load conditions are considered in the study. As described previously, there are currently no capacitive compensations, e.g. MSCs, MCDNs, and SVCs, that can operate and connect at 1000kV and above, therefore, it is assumed in this paper that MSCs with capacity of 210MVAr are connected to 110kV (usually at the tertiary winding of the UHV transformers), MSCs with capacity of 60MVAr are connected at 66kV or lower voltage levels. SVCs are assumed to be installed at 500kV nodes, and CSRs are connected directly to the UHV busbars or transmission lines. The unit cost of SVCs and CSRs are assumed to be 138% and 150% of MSCs, respectively.

Two power transfer conditions are considered: 6000MW and 10000MW power transfer between substations A and B.

For PSO, the number of particles is chosen as 60; and the maximum number of generations is set as 200.

Results produced by PSO optimisation process are continuous. However without losing validity of the results, the programme developed in this paper further processes the PSO output to give discrete number of reactive power compensation sets by rounding PSO output to the nearest available compensation capacity as would be the case in actual reactive power planning.

Figure 4 below shows the convergence process of PSO for the studied two power transfer conditions.

![Figure 4. Optimization process](image)

It can be seen from Figure 4 that the optimisation converges after about 50 generations.

Table 2 below shows results of reactive compensation required under two different power transfer conditions.

<table>
<thead>
<tr>
<th>Types of Compensation</th>
<th>Substation</th>
<th>6000MW Transfer (A-B)</th>
<th>10000MW Transfer (A-B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSC</td>
<td>UHV A</td>
<td>2x210MVAr</td>
<td>16x210MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>UHV B</td>
<td>5x210MVAr</td>
<td>7x210MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>UHV C</td>
<td>5x210MVAr</td>
<td>5x210MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>UHV D</td>
<td>8x210MVAr</td>
<td>8x210MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>UHV E</td>
<td>12x210MVAr</td>
<td>12x210MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>500kV B1</td>
<td>5x60MVAr</td>
<td>13x60MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>500kV B2</td>
<td>8x60MVAr</td>
<td>8x60MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>500kV B3</td>
<td>6x60MVAr</td>
<td>6x60MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>500kV E1</td>
<td>8x60MVAr</td>
<td>8x60MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>500kV C2</td>
<td>1x60MVAr</td>
<td>1x60MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>500kV C3</td>
<td>8x60MVAr</td>
<td>8x60MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>500kV E1</td>
<td>12x60MVAr</td>
<td>12x60MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>500kV E2</td>
<td>3x60MVAr</td>
<td>3x60MVAr</td>
</tr>
<tr>
<td>MSC</td>
<td>500kV E3</td>
<td>4x60MVAr</td>
<td>4x60MVAr</td>
</tr>
<tr>
<td>SVC</td>
<td>500kV A1</td>
<td>1x60MVAr</td>
<td>1x60MVAr</td>
</tr>
<tr>
<td>SVC</td>
<td>500kV E3</td>
<td>2x60MVAr</td>
<td>2x60MVAr</td>
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<tr>
<td>SVC</td>
<td>500kV A3</td>
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</tr>
<tr>
<td>SVC</td>
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<td>1x30MVAr</td>
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<tr>
<td>SVC</td>
<td>500kV B2</td>
<td>2x60MVAr</td>
<td>2x60MVAr</td>
</tr>
<tr>
<td>SVC</td>
<td>500kV B3</td>
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<tr>
<td>SVC</td>
<td>500kV E1</td>
<td>1x30MVAr</td>
<td>2x60MVAr</td>
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<td>SVC</td>
<td>500kV E2</td>
<td>2x60MVAr</td>
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<tr>
<td>SVC</td>
<td>500kV E3</td>
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<td>2x60MVAr</td>
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<tr>
<td>CSR</td>
<td>UHV D</td>
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<td>Line E</td>
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</table>
It can be seen from Table 2 that the amount of reactive compensation required increases significantly if the planned transfer between substations A and B changes from 6GW to 10GW.

It is intended that further studies will be carried out considering a wider range of operating conditions, and also to improve the efficiency of PSO in the future.

VI. CONCLUSIONS

An optimal reactive power planning method based on improved PSO has been developed for UHV reactive power planning. It minimises total cost of all reactive power compensation equipment, including CSRs, MSCs and SVCs, against a range of system operating and demand conditions and satisfy both steady state and N-1 security requirements. Limits on transient voltage deviation (as percentage of pre-fault steady state value) are considered in the PSO optimisation process and is used as the basis for dynamic reactive power compensation such as SVCs. The method has been tested using an actual UHV project in China with the test network consisting of over 21000 nodes and 26000 branches. Results show the robustness and validity of the proposed method. Further work will be carried considering a wider range of system operating and demand conditions, and also to further improve the efficiency of PSO method. Results will be reported separately in the future.

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VII. REFERENCES


VIII. BIOGRAPHIES

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