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Abstract: In order to improve the hybrid simulation speed of AC/DC power grid, it is necessary to improve the simulation method of sub grid parallel. *An electromechanical transient stability simulation system is presented for AC/DC hybrid power grid. The AC/DC sub network module is used to divide the large AC/DC power grid into small AC/DC sub networks, so that each sub network can be simulated in parallel. The numerical calculation method is improved for the efficiency and accuracy of simulation calculation.* Taking IEEE 10-39 bus as an example, the effectiveness of the method is verified in PSCAD (Power Systems Computer Aided Design Software) environment.

Keywords: electromechanical electromagnetic; transient stability simulation system; numerical calculation method; hybrid AC/DC power system

交直流混合电力系统机电电磁暂态稳定仿真系统

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摘要：为了提高交/直流电网的混合仿真速度，有必要使用分网并行的手段改进仿真方法。*提出了一种交/直流混合电网机电暂态稳定仿真系统，交/直流子网模块用于将大交/直流电网划分为小交/直流子网，使每个子网可以并行仿真。同时对数值计算方法进行了改进，提高了仿真计算的效率和精度。*以准新英格兰 IEEE10 机 39 总线为例，在电磁暂态仿真软件 PSCAD (Power Systems Computer Aided Design Software)环境下验证了该方法的有效性。

关键词：机电电磁；暂态稳定仿真系统；数值计算方法；交/直流混合电力系统
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Introduction

The electromagnetic transient simulation of power system is mainly used to study the short time changes of instantaneous values of voltage and current. The electromechanical transient simulation of power system mainly studies the swing process of generator rotors. Separate electromechanical transient

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simulation analysis adopts quasi-steady state simulation when simulating power electronic equipment such as HVDC system and FACTS[1], but cannot reflect the fast transient characteristics. Separate electromagnetic transient analysis is limited by the simulation scale.

The mathematical model of power system transient numerical calculation can be described through a set of differential equations, and can be solved by a certain numerical integration or differential method to obtain various transient responses in time domain. In the late 1960s, reference [2] proposed the basic theories and methods for numerical calculation of electromagnetic transients. Reference [3] first proposed the use of implicit trapezoidal integration method in electromagnetic transient simulation calculations, which has also been most widely used. Reference [4] pointed out the implicit trapezoidal integration method being restricted in terms of integration format and numerical stability. And in the electromagnetic transient simulation, when some sudden changes occur, using the method to calculate will produce. "virtual" numerical oscillation phenomenon[5]. In response to this problem, the critical damping adjustment method is proposed in reference [6]. T. NODA et al.[7] proposed to apply the 2nd order mono-diagonal implicit Runge-Kutta (RK) method to the electromagnetic transient calculation. This method has L-stability, so it can effectively avoid numerical oscillation.

The electromechanical transient process is the pattern of changes in the mechanical motion of the motor rotor caused by changes in the electromagnetic torque of the generator and motor in the power system[8]. The electromechanical transient process simulation mainly studies the transient stability of the power system after being subjected to the large disturbances and the static stability after being subjected to the small disturbances. Common simulation software internationally includes PSS/E[9] of American PTI company, ETMSP of American EPRI company, NETOMAC of German Siemens company[10], PSASP independently developed by China Electric Power Research Institute and Chinese version of BPA program.

Facing various transient problems[11], different numerical calculation methods will produce different calculation effects[12], and the above phenomenon does not occur when using implicit Euler method [13]. In order to improve the accuracy and speed of AC/DC power grid hybrid simulation, an electromechanical-electromagnetic transient stability simulation system for AC/DC power grid is proposed, which can perform parallel simulation calculation on AC/DC power grid transient stability and improve the efficiency of simulation calculation.

1 Electromechanical transient simulation model of AC system

The electromechanical transient simulation model of the AC system is suitable for the electromechanical transient simulation of the AC network in the electromechanical-electromagnetic transient simulation system. It includes an AC subnet module, an electromechanical transient calculation module, and a data transmission and communication module.

1.1 AC system split network module

The AC system split network module is suitable for splitting the large AC power grid into small AC power grids at the beginning of the simulation so that each sub-grid can be simulated in parallel.

In this module, first input the original parameters

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and information of the AC power grid, and the DC power grid connected to it is equivalent to the injected current source, and the power flow calculation is performed to obtain the voltage V_0 of each node under stable operating conditions, current at the first end of each line I_{start} and current at the end of each line I_{end}.

Secondly, the preliminary screening of the segmented network is conducted, and the long-distance transmission lines connecting multiple AC subnets are selected according to the two orders of voltage level from high to low and the length of the transmission line from long to short. When formula (1) is satisfied, use this line as the cutting point to separate the two connected subnets, where C and L are capacitance and inductance per unit length of the long-distance transmission line. S and f are respectively the distance and frequency of the current line. Δt is the step size of electromechanical simulation.

$$(2\pi\sqrt{LC} / f) > 0.062\,8 \times \Delta T \tag{1}$$

The above-mentioned lines satisfying the conditions are equivalent to two equivalent circuits. The equivalent injection current source of its equivalent circuit injection current terminal to the connected subnet is $I_{\text{es}}(t) = -i_{\text{start}}(t)$. The equivalent admittance is $G_{\text{es}} = 1/\sqrt{L/C}$. The equivalent injection current source of its output current terminal to the connected subnet is $I_{\text{ee}}(t) = -i_{\text{end}}(t)$. The equivalent admittance is $G_{\text{ee}} = 1/\sqrt{L/C}$.

Finally, each equivalent circuit is merged into the divided sub-grid as part of the injection current and admittance of the sub-grid network. Each equivalent circuit participates in the simulation calculation of the sub-grid.

1.2 AC grid electromechanical transient calculation module

AC grid electromechanical transient calculation module is suitable for the simulation calculation of transient stability of each subnet after AC grid division. The module has the following calculation steps:

Step 1: Assign a dedicated computing unit to each AC subnet, and enter the parameters and information of the AC subnet (including the equivalent circuit of the DC power grid connected to it and the equivalent circuit of the adjacent AC subnet). Perform power flow calculation to obtain the voltage V_1, current I_1, electromagnetic power P_{e1} of each generator, the initial value of power angle of each generator δ_0 under stable operating conditions and the initial value of each generator angular frequency ω_0;

Step 2: Form the transient differential-algebraic equation of the AC subnet:

$$\begin{aligned} \dot{x} &= f(x, y) \\ 0 &= g(x, y) \end{aligned} \tag{2}$$

Set the initial value of electromechanical transient stability simulation $t = 0$ and the electromechanical simulation step size Δt. Set the maximum time of electromechanical simulation $T_{\max}$;

Step 3: Determine whether there is a fault or operation; if not, go to step 5; if there is a fault or operation, go to step 4;

Step 4: Modify the network algebraic equation according to the fault and operation;

Step 5: Calculate the network algebraic equation and find variables such as operating parameters at time t;

Step 6: Calculate the assumed one-value $x_1(t+\Delta t)$ and assumed two-value $x_2(t+\Delta t)$ of the state variable at $t+\Delta t$ and the assumed one-value $y_1(t+\Delta t)$. This step is as follows:

Step 6.1: Knowing the state variable *x*(*t*) at time *t*, including power angle *δ*(*t*), angular frequency *ω*(*t*), generator electromagnetic power $P_e(t)$, calculate the assumed value $x_1(t+\Delta t)$ of the state variable $x(t+\Delta t)$ as follows:

$$\begin{aligned} & l_1=\Delta T\times f(x(t)) \\ & l_2=\Delta T\times f\left(x(t)+l_1/2\right) \\ & l_3=\Delta T\times f\left(x(t)+k_2/2\right) \\ & l_4=\Delta T\times f\left(x(t)+k_3\right) \\ & x_{(1)}(t+\Delta T)=x(t)+\frac{1}{6}\left(l_1+2l_2+2l_3+l_4\right) \end{aligned} \tag{3}$$

Bring $x_1(t+\Delta t)$ into the algebraic equation calculation, and obtain the assumed value of the running variable $y_1(t+\Delta t)$;

Step 6.2: Calculate the hypothetical binary value $x_2(t+\Delta t)$ of the state variable $x(t+\Delta t)$ (the assumed value of the running variable $y_1(t+\Delta t)$ is brought into the running variable during calculation):

$$\begin{aligned} & x_2(t+\Delta T)= \\ & x(t)+\frac{\Delta T}{2}(f(x(t))+f(x_1(t+\Delta T)) \end{aligned} \tag{4}$$

Step 7: According to Step 6, calculate the assumed one-value $x_1(t+2\Delta t)$ and the assumed two-value $x_2(t+2\Delta t)$ and the assumed value of the running variable $y_1(t+2\Delta t)$;

Step 8: Calculate the calculated value of the state variable $x_3(t+\Delta t)$ and the calculated value of the operating variable $y_3(t+\Delta t)$:

$$\begin{aligned} x_3(t+\Delta T)=\frac{1}{2}[& x_2(t+\Delta T)+x(t)+ \\ & \frac{\Delta T}{3}(f(x(t))+f(x_2(t+\Delta T))+ \\ & f(x_2(t+2\Delta T))] \end{aligned} \tag{5}$$

Bring $x_3(t+\Delta T)$ into the algebraic equation calculation, and obtain the calculated value of the running variable $y_3(t+\Delta T)$;

Step 9: Use the calculated value of the calculated state variable $x_3(t+\Delta T)$ and the calculated value of the running variable $y_3(t+\Delta T)$ as the simulation result. Upload the result to the communication center;

Step 10: Let the current simulation time $t=t+\Delta t$. When $t\geqslant T_{\max}$, go to step 12. When $t<T_{\max}$, go to step 11;

Step 11: Load the data uploaded by the adjacent subnet and DC subnet from the communication center. Update the injection current and admittance matrix of the subnet, and return to step 5 to continue the simulation calculation;

Step 12: Output the result, and the calculation ends.

2 DC system electromagnetic transient simulation model

The electromagnetic transient simulation model of the DC system is suitable for the electromagnetic transient simulation of the DC network in the electromechanical-electromagnetic transient simulation system. It includes a DC sub-network module and an electromagnetic transient calculation module. Every Δt (electromechanical transient step), the DC side electromagnetic transient simulation part will interact with the AC power grid through the data communication module described in the AC side electromechanical transient part.

2.1 DC grid split network module

The DC grid segmentation network module is suitable for dividing multiple DC lines into multiple DC subnets at the beginning of the simulation, so as to calculate the parallel simulation of each sub-grid.

First input the original parameters and information of the DC and AC grids. According to the principle that each DC transmission line is divided into a DC subnet, the network is divided, and the AC line connected to the DC subnet is equivalent to the injection current source, and the equivalent injection current value is injected into the DC circuit three-phase current of the inverter. Secondly, an electromagnetic transient simulation calculation module is assigned to each DC subnet for parallel calculation.

2.2 DC grid electromagnetic transient calculation module

The electromagnetic transient calculation module of DC power grid includes three parts: converter monitoring module, electromagnetic transient calculation module A and electromagnetic transient calculation module B. It is used to simulate the electromagnetic transient stability of each subnet after the DC power grid is divided.

2.2.1 Inverter monitoring module

The converter monitoring module is suitable for monitoring the commutation of the converter during the working process, identifying the working condition of the converter, so as to allocate the calculation tasks under different working conditions to the electromagnetic transient calculation module A and the electromagnetic transient calculation module B to calculate.

At the beginning of the monitoring process, a calculation unit is assigned to each converter valve, a determination unit is assigned to each converter, and the parameters and information of the control system and communication center are input. Between every two converter valve trigger pulses, each converter valve judges the converter valve's working condition through the calculation unit. The specific steps are as follows:

Step 1: At the moment when the trigger pulse of a certain converter valve is issued, it is judged whether the valve voltage u_i is less than zero. If $u_i > 0$, the converter valve is judged to be a commutation situation and then go to step 2; if $u_i \leqslant 0$, the converter valve determines that the previous situation remains unchanged, and continues to step 1 at the time of the next pulse issuance;

Step 2: Calculate the end time of the commutation valve, establish the mathematical model of the commutation valve according to the current working conditions, and calculate the time when $i_1(t) = 0$, which is the end time of the commutation valve $t_{\mathrm{i}}^{\mathrm{E}}$;

Step 3: When $(t_{\mathrm{i}}^{\mathrm{E}} + 0.00376\Delta T_i) \geqslant t_i^{u_1}$, the commutation valve succeeds in commutation; when $(t_i^{\mathrm{E}} + 0.003\ 76\Delta T_i) < t_i^{u_1}$, the commutation valve fails in commutation. Then upload the information judged by the converter valve to the converter judgment unit. In the above formula, Δt_i is the interval period of the trigger pulse of the converter valve, and $t_i^{u_1}$ is the forward recovery time of the converter valve voltage.

In the interval between adjacent trigger pulses, the converter judgment unit integrates the working conditions of each converter valve. It judges the working condition of the converter, and assigns all the converter valves that have not failed to the electromagnetic transient calculation module A; The situation where the commutation valve commutation failure occurs is assigned to the electromagnetic transient calculation module B.

2.2.2 Electromagnetic transient calculation

The electromagnetic transient calculation module A is suitable for the electromagnetic transient stability calculation of the DC subnet in which the converter works normally. This module performs simulation calculation as follows:

Step 1: Use the steady-state response of the DC subnet as the initial value of the electromagnetic transient simulation calculation process. Load the information of the adjacent AC subnet from the communication center. Determine the working condition of the subnet according to the information given by the converter monitoring module, and input the current parameters and information of the DC subnet (including the AC bus connected to it) such as three-phase voltage and current, control system information, converter equivalent circuit and DC transmission line equivalent circuit. According to the parameters and information, a steady-state mathematical model is formed, and the state variable xt_i^{start} at the start time is calculated, which is used as the initial value of the transient stability simulation calculation;

Step 2: Establish the transient differential equation of the DC subnet

$$\frac{\mathrm{d}x}{\mathrm{d}t}=\dot{x}=h(t,x) \tag{6}$$

$$x(t_0)=x(t_i^{\text{start}}) \tag{7}$$

Set the initial value of electromagnetic transient stability simulation $t_0=0$, and the electromagnetic transient simulation step size ΔT_{ia};

Step 3: Determine whether there is a fault or operation; if not go to step 5. If there is a fault or operation go to step 4;

Step 4: According to the fault and operation, modify the differential equation and state variable value of the network at the current step;

Step 5: Solve the assumed Q value and assumed W value of the state variable at time $t+\Delta T_{ia}$. This step is as follows:

Given the state variable $x(t)$ at time t, calculate the assumed Q value $x_Q(t+\Delta T_{ia})$ of the state variable $x(t+\Delta T_{ia})$ as follows:

$$\begin{aligned}
&l_1=\Delta T_{ia}\times h(x(t))\\
&l_2=\Delta T_{ia}\times h(x(t+\frac{l_1}{2}))\\
&l_3=\Delta T_{ia}\times h(x(t)+\frac{k_2}{2}(x)\\
&l_4=\Delta T_{ia}\times h\left(x(t)+k_3\right)\\
&x_Q\left(t+\Delta T_{ia}\right)=x(t)+\frac{1}{6}\left(l_1+2l_2+2l_3+l_4\right)
\end{aligned} \tag{8}$$

Calculate the assumed W value $x_W(t+\Delta T_{ia})$ of the state variable $x(t+\Delta T_{ia})$:

$$x_W(t+\Delta T_{ia})=$$
$$x(t)+\frac{\Delta T_{ia}}{2}(h(x(t)+h(x_Q(t+\Delta T_{ia}))) \tag{9}$$

Step 6: Follow Step 5 to calculate the assumed Q value $x_Q(t+2\Delta T_{ia})$ and the assumed W value $x_W(t+\Delta T_{ia})$ of the state variable at $t+2\Delta T_{ia}$, where the state variable at time $t+\Delta T_{ia}$ is brought into the value of $x_W(t+\Delta T_{ia})$;

Step 7: Calculate the calculated value of the state variable $x_R(t+\Delta T_{ia})$ at time $t+\Delta T$:

$$x_R(t+\Delta T_{ia})=\frac{2}{3}x_W(t+\Delta T_{ia})+\frac{1}{3}[x(t)+$$
$$\frac{\Delta T_{ia}}{3}(h(x(t))+h(x_W(t+\Delta T_{ia}))+$$
$$h(x_W(t+2\Delta T_{ia})))] \tag{10}$$

Step 8: Use the calculated state variable $x_R(t+\Delta T_{ia})$ as the simulation result and upload it to the communication center and inverter monitoring module to determine whether the system is stable. If it is stable, go to Step 10, if unstable, go to step 9;

Step 9: Let the current simulation time $t=t+\Delta T_{ia}$, when $t\geqslant\Delta T_i$, go to step 10, and when $t<\Delta T_i$ return to step 5 to continue the simulation calculation;

Step 10: Output the electromagnetic transient simulation results of the DC subnet under the current working conditions (within the ΔT_i period), and the

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calculation is completed.

The electromagnetic transient calculation module B is suitable for the electromagnetic transient stability calculation of the DC subnet where the commutation of the converter fails. The algorithm of module B is similar to that of module A.

2.3 Data transmission communication module

The data transmission and communication module is suitable for information exchange among AC subnets, AC subnets and DC subnets. It is characterized by collecting and distributing calculation data of each subnet every electromechanical transient simulation moment. It is used for simultaneous data exchange among subnets.

3 Simulation verification

In this paper, in the PSCAD environment, based on the standard New England IEEE10 machine 39 nodes, the DC network is added, as shown in Fig.1. The parameters of the DC network are: AC and DC interface capacity 250 MW, DC energy storage power 250 MW, and DC/AC load 50 MW.

Divide the topology into 4 partitions as shown. Among them, it is divided from the busbars 1~2, 3~4, 16~17, 14~16, and between the DC interfaces.

Ground fault is applied at node 14 and the fault is removed after 0.1 s. Extract the voltage of each node and the power flow of each line for comparative study, especially for the nodes and lines at the partition interface. Compare the calculation time before and after the partition, and compare the simulation time of each partition.

The simulation compares the dynamic characteristic curves of the two simulation methods before and after the partition. Since the voltage is not only closely related to the dynamic characteristics of the system, but also has a great impact on the DC commutation process, in order to make the index not single, this paper selects the node voltage amplitude and power at the same time. Angle is used as a quantitative indicator to measure the dynamic error. The relative root mean square in formula (11) is used to calculate and analyze the error of each point of the dynamic curve before and after the equivalent, so as to reflect the overall average deviation.

$$\Delta u_{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(u_{\mathrm{p}} - u_{\mathrm{a}})^2} \Big/ \sqrt{\frac{1}{N}\sum_{i=1}^{N}u_{\mathrm{p}}^2} \qquad (11)$$

Among them, Δx_{RMS} is the relative root mean square error value of the sampling points of the dynamic curve before and after the partition; u_{p} and u_{a} are the value of the i^{th} sampling point of the dynamic characteristic curve before and after the partition; N is the number of sampling points.

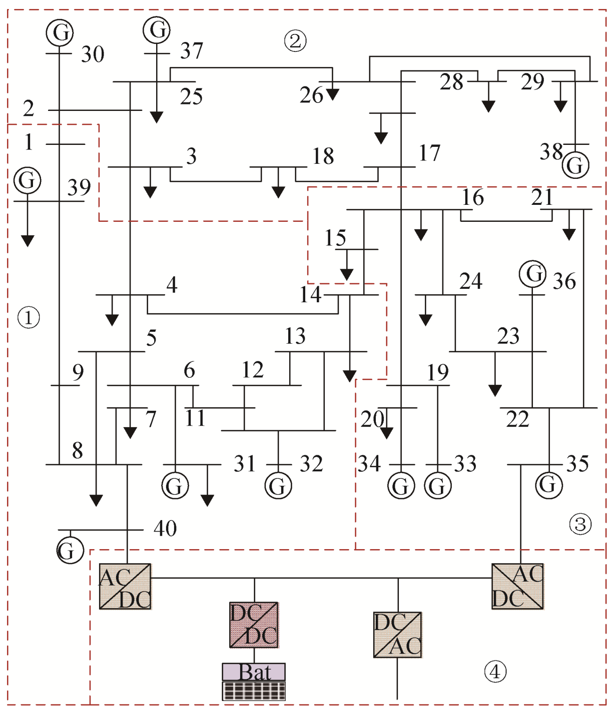

Fig. 1　IEEE 39-node 10 machine improved AC/DC hybrid simulation system

Due to different partition sizes and categories, the calculation time of each partition is different. The calculation time of the partition after the network is divided is shown in Tab. 1. The calculation time of the serial and parallel simulation methods before and after the division is shown in Tab. 2. After partitioning, for this example, the overall calculation time is reduced by 1/3~1/4 compared to before partitioning.

Tab. 1　Calculation time of each partition after network segmentation

Partition number	Calculation time at 5s simulation /s
1	50.0
2	60.5
3	48.5
4	16.0

Tab. 2　Comparison of computing time before and after network segmentation

Serial/Parallel	Calculation time at 10s simulation /s
Serial	201.0
Parallel	60.5

Taking the voltage of node 13 as an example, through simulation, the amplitude and phase angle of the voltage before and after the partition are shown in Fig. 2~3. It can be seen that there are some errors, but the overall trend is consistent. According to formula (11), the degree of similarity before and after partitioning reaches 97%.

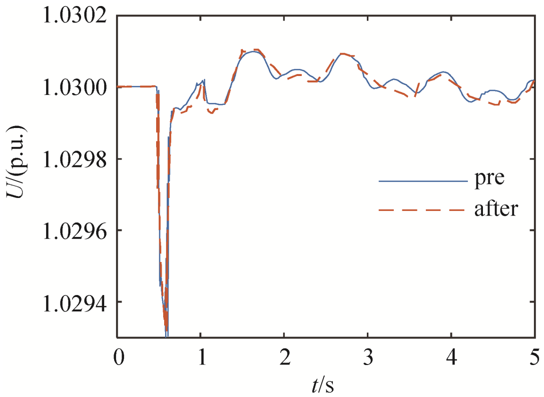

Fig. 2　Comparison of voltage amplitude of node 13 before and after partitioning

Taking the power between nodes 13~14 as an example, through simulation, the power comparison before and after the partition is shown in Fig. 4. It can be seen that the simulation result is similar to the voltage, and the overall trend is consistent. Through formula (11), it can be calculated that the simulation similarity before and after the partition reaches 92%.

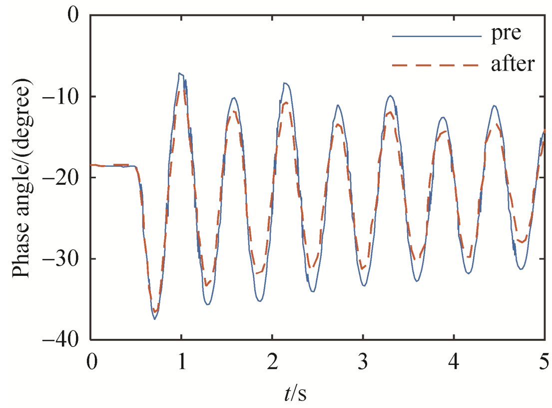

Fig. 3　Comparison of voltage phase angle of node 13 before and after partitioning

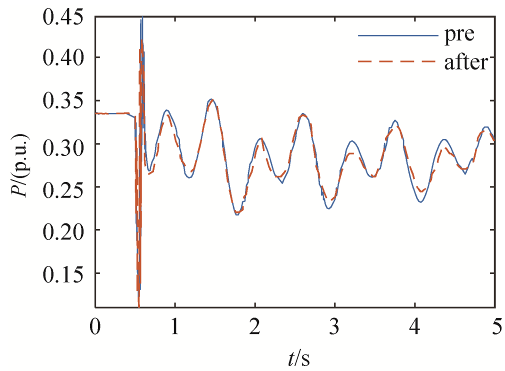

Fig. 4　Power comparison between nodes 14~15 before and after partitioning

The root-mean-square errors of the voltages, phase angles, and power between the nodes of all the partitions are shown in Tab. 3, which are within the acceptable range.

Tab. 3　Relative root mean square error before and after equivalence

Node	Voltage error/%	Line	Power error/%
1	0.3	1~2	8.1
14	0.25	16~17	9.2
8	0.32	14~15	8.3
14	0.26	8~40	4.5
35	0.1	22~35	6.7

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4 Conclusion

This paper proposes an electromechanical-electromagnetic transient stability simulation system for AC/DC hybrid power grids. It improves the transient stability simulation calculation of AC grid and DC grid by dividing the AC/DC hybrid grid and introducing the calculation assumptions of variables. It improves the numerical calculation method and can perform parallel simulation calculations on the AC/DC power grid transient stability. The method can improve the efficiency of simulation calculation.

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