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Research and Improvement of Electromechanical Transient Performance of Power System Based on SIMULINK

Duo Wang *

School of Electrical and Control Engineering, North University of China, Taiyuan, China.

Abstract: The research on electromechanical transient stability of power systems is of great significance. Analyzing the parameters of the simulation system and its improved system with typical short-circuit faults, this paper studies the transient stability of power systems and its improvement. Firstly, based on the SIMULINK of MATLAB, a double-loop simulation with the single-machine-infinite-bus system is built. The simulation experiments of the system under the circumstances of three-phase short circuit and single-phase grounding short circuit faults are then carried out to analyze the parameters such as limit cutting time and voltage. Besides, this paper explores how the controllable series capacitor compensation device and reducing mechanical power output by prime mover improve the transient stability of the system. Experiments show that the stability after fault is under conditions where the fault is removed before the critical clearing time, which can increase the threshold to gain more response time for relay protection devices. Thus, the value of researching and improving system transient stability is proved.

Keywords: Electromechanical Transient Stability; Short Circuit Fault; Critical Clearing Time; MATLAB

1. Basic Theory

1.1 Electromechanical Transient Stability of Power System

The research on electromechanical transient stability of power systems focuses on whether the system can return to the original state or transit to a new stable state after being disturbed in a stable operating mode. The operation of the system before and after disturbance is shown in Fig.1 [1].

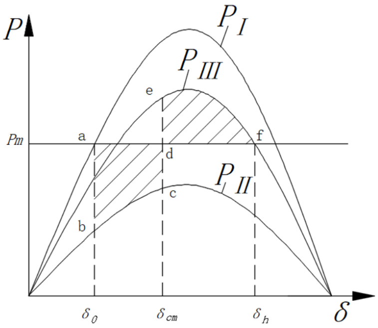

Fig.1 Power Characteristic Curve of Normal Operation, Failure, and Fault Removal of the Simple System

In Fig.1, P_m is the mechanical power output by the prime mover, P_I, P_{II}, and P_{III} are power characteristic curves of the generator during normal operation, after a short circuit fault, and after the timely removal of a short circuit. According to the equal area criterion [1], the system is in transient stability at the critical clearing angle δ_{cm}, and the corresponding fault clearing time is the critical clearing time t_{cm}.

1.2 Common Faults of Power System

Faults such as short and open circuits often occur during the power system operation, with the short circuit as the worst one. Thus, it is most representative to carry out experiments under this condition. In a three-phase system, short circuits are divided into as follows, including the three-phase short circuit $f^{(3)}$, two-phase short circuit $f^{(2)}$, two-phase earth fault $f^{(1,1)}$, and single-phase earth fault $f^{(1)}$. In this paper, the most typical $f^{(3)}$ and $f^{(1)}$ are used for research, as shown in Fig.2 and Fig.3.

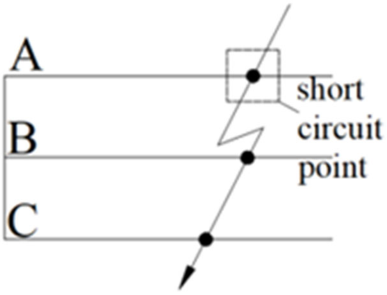

Fig.2 Three-Phase Short Circuit

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[*] Corresponding author: 2015040406@st.nuc.edu.cn

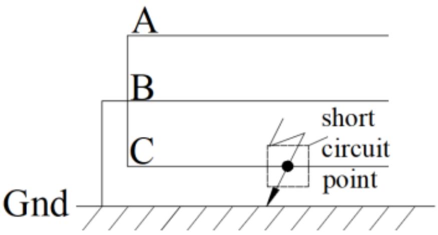


Fig.3 Phase Earth Fault

After the fault occurs, some output mechanical power of the prime mover will be stored in the rotor of the generator [1], which spares more time for the system to recover stability. Therefore, the system will remain stable if relay protection devices such as circuit breakers and automatic reclosure are used to remove the fault before t_{cm}, otherwise, it will lose stability.

1.3 Measures to Improve the Transient Stability of the System

It is of great engineering significance to improve transient stability. Generally, the following measures can be adopted.

Realize quick fault removal and adopt an automatic reclosing device.

Reduce the difference in generator power after disturbance, such as decreasing the mechanical power output by the prime mover.

Control dynamic elements that can be controlled in the system. For example, a controllable series capacitor compensation device is used in the line [2].

The generator's difference between mechanical power and electromagnetic power is the main cause of failing transient stability after a large disturbance, so it is usually considered to reduce such a difference first [1]. Meanwhile, the controllable series capacitor compensation device can reduce the total equivalent reactance of the system and improve the transfer capability. Thus, both methods can improve transient stability. This paper will focus on the effects of two methods on improving the transient stability of power systems.

2. Construction of Simulation Model

2.1 Overall Design Framework of Simulation Model

The simulation model is constructed by SIMULINK in MATLAB, consisting of the main module with a double-loop power system featuring a single machine infinite bus, the fault module for setting short circuits, and the observation module for parameter measurement. The overall design framework diagram is shown in Fig.4.

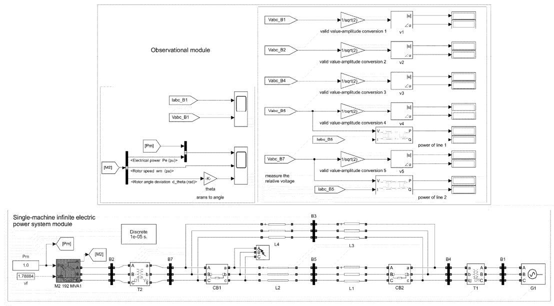


Fig.4 Overall Design Framework Diagram of the Simulation

2.2 Module of Single-Machine-Infinite-Bus Power System

The single-machine-infinite-bus power system constructed in this paper has two parallel lines, each of which is divided into two sections, with the fault point set in one of them. The two ends of the line are transformed by two D-Yg transformers to realize voltage transmission from *M2* to *G1*, as shown in Fig.5.

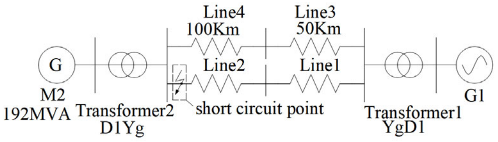


Fig.5 System Diagram

In Fig.5, the installed capacity of generator *M2* is 192MVA, the length of *Line4* and *Line2* is 100*Km*, and the length of *Line3* and *Line1* is 50*Km*. The short circuit point is on the side of *Line2* near *Transformer 2*, which is shown by a dashed box in Fig.5. The impedance parameters of the line are shown in Tab. 1.

Tab.1 Impedance Parameters of the Line

Impedance Parameters of Lines	*Line1*	*Line2*	*Line3*	*Line4*
Resistance (Ω)	0.1058	0.16928	0.1058	0.16928
Inductance (W)	2.3854e-3	2.2592e-3	2.3854e-3	2.2592e-3
Capacitance (F)	17.65e-9	15.24e-9	17.65e-9	15.24e-9

2.3 Fault Module

The short-circuit in the three-phase system is set by the component "*Three-Phase Fault*", and the short circuit type is set by checking the options in "*Fault between*". "*Phase A*", "*Phase B*", "*Phase C*" can be checked to set the three-phase short circuit. "*Phase A*" and "*Ground*" can be checked to set the Phase *A* earth fault. Set the total running time of the system to 10 seconds in "*Switching time*", and the failure occurs in the sixth second.

The setup and description of the fault are shown in Tab. 2.

Tab.2 Fault Description

Factor	Fault DC Line	Location of Fault	Type of Fault	Fault Clearing Mode
Setting Description	*Line2*	*Bus7*	*Phase A* Earth Fault, Three-Phase Short Circuit	Circuit Breaker *CB1*

2.4 Observation Module

The specific simulation settings of the observation module are shown in Tab. 3. The component “Gain” is used to convert the power angle of the generator from radian to angle, and the amplitude of each voltage to root-mean-square value. Besides, the component “Fourier” is used to convert the root-mean-square value to modulus and phase, with the component “Power” used to calculate the line power.

Tab.3 Observed Parameter

Object of Observation	Observation Parameter	Angle of Observation	Observation Instrument
Busx	*Vabc_Bx(x=1,2,4,5,7)*	Modulus value, phase angle	*Display*
Linex	*Px=Vabc_By*Iabc_By(x=1,2,y=5,7)*	Power	
M2	*d_theta*, *wm*, *Pe*, *Pm*	Power angle （δ）, speed, power	*Scope*
G1	*Vabc_B1*, *Iabc_B1*	Voltage, current	

3. Fault Simulation

3.1 Overall Design of Simulation Experiment

The main design of the simulation experiment is divided into two sections. One is the study of electromechanical transient stability, which is mainly divided into stable operation experiments and experiments of fault and fault removal, constituting the content of Chapter 3. In addition, based on the experimental results in Chapter 3, two improved methods are proposed in Chapter 4, and the results of improving transient stability are analyzed. The flow chart of the simulation experiment is shown in Fig.6.

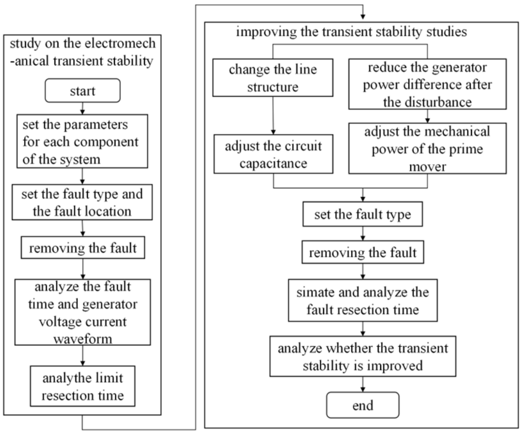


Fig.6 Simulation Flow Chart

3.2 Stable Operation

Stable operation of a power system is the state when the system works normally. If the system fails, the system will enter the transient process from stable operation [1]. When P_m is set to 1.632, a set of stable operation parameters of the system can be measured according to the simulation model, as shown in Tab. 4.

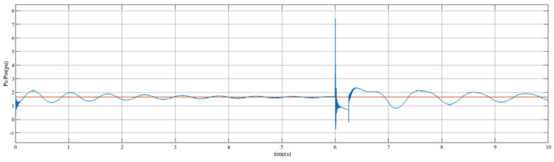
Tab.4 System Parameters at the Stable Operation

Object of Observation	*Vabc_B1*	*Vabc_B2*	*Vabc_B3*	*Vabc_B5*	*Vabc_B7*
Observation Value (pu)	0.075 ∠-7.3°	0.093 ∠14.8°	1.143 ∠33.3°	1.191 ∠36.8°	1.258 ∠43.0°
Object of Observation	*P2*	P_e	*P1*	*d_theta (°)*	*wm*
Observation Value (pu)	0.283+j0.519	1.637	0.319+j0.460	-24.8	0.999

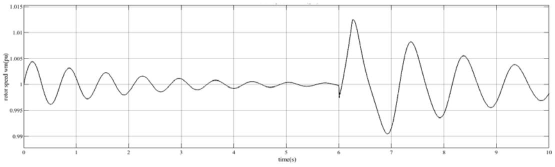
The data shown in Tab. 4 are all standard values except the generator power angle, and the reference voltage and reference power are rated for the generator. Observing the waveform of the oscilloscope, it can be seen that the electromagnetic power of the generator is basically stable near 1.632, the mechanical power output by the prime mover. Besides, the rotating speed of the generator is kept near the rated value and the power angle of the generator tends to be a constant value with time. Therefore, this paper judges whether the fault is removed by whether the system can keep a stable state after the fault.

3.3 Fault Simulation of Three-Phase Short Circuit

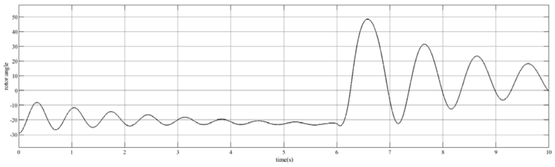
An abnormal power supply will cause inconvenience and serious consequences to production and life, so it is vital to remove faults in time. When the fault occurs in the 6th second of the experiment, the parameters of *M2* and line are measured, so as to obtain the timely critical clearing time of the system. “Dichotomy” [3] is used to approximate the critical resection time. That is to say, if the system is just stable when the fault is removed at t_1, it is unstable when it is removed at t_2 with little difference between t_1 and t_2, then $t_{cm}=(t_2+t_1)/2$. We set the circuit breaker to clear the fault at 10/60 seconds, then accumulate the resection time for 5/60 seconds in turn repeatedly until it is observed that the system is no longer stable at 20/60 seconds. Then the critical resection time is calculated in [15/60, 16/60] by dichotomy approximation. The curves of generator parameters corresponding to t_1 and t_2 are shown in Fig.8 and Fig.9 respectively.



(a) Electromagnetic Power Pe

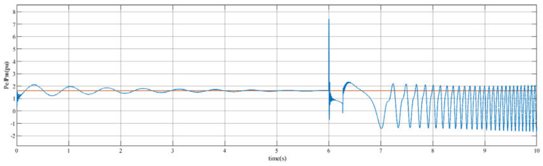


(b) Rotational Speed wm

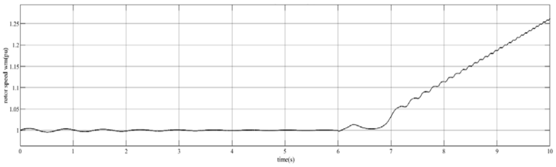


(c) Power Angle δ

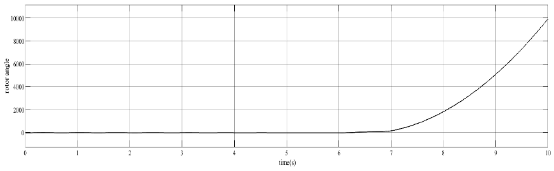
Fig.8 Parameters of the Generator at 15 / 60 s



(a) Electromagnetic Power Pe



(b) Rotational Speed wm



(c) Power Angle δ

Fig.9 Parameters of the Generator at 16 / 60 s

When the fault is removed at 15/60 seconds, the electromagnetic power of the generator is still stable at around 1.632, the speed is stable at about 1, and the power angle tends to be constant at 6°. In other words, the system can return to stability after self-adjustment. When the fault is removed at 16/60 seconds, the electromagnetic power of the generator is no longer stable at a fixed value. Besides, the changing speed and power angle of the generator tend to infinity with time, that is, the system is unstable at this time. Other parameters of the system at time t_1 and t_2 are shown in Tab. 5 respectively.

Tab.5 Parameters of the System at 15 / 60s and 16/60s

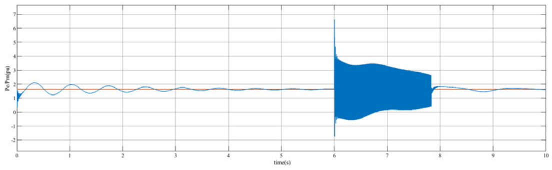
time (s)	*Vabc _B1*	*Vabc _B2*	*Vabc _B4*	*Vabc _B5*	*Vabc _B7*	P_1	P_2
15 / 60	0.075 ∠-7.3°	0.080 ∠30.0°	1.071 ∠33.0°	0.001 ∠94.5°	1.113 ∠55.0°	0.005-j0.040	0.001-j0.001
16 / 60		0.035 ∠-86.0°	0.915 ∠22.7°	0.001 ∠88.6°	0.382 ∠-39.0°	Amino 0	-0.001+j0.001

It can be seen from the above table that the voltage at the end of the line is always unchanged. After the fault is removed in 15/60 seconds, the voltage of Bus5 and the power of Line1 and Line2 decrease sharply compared with the steady state. It is caused by the circuit breaker clearing Line1 and Line2. However, when the fault is removed in 16/60 seconds, the parameters of the system change greatly and cannot be stable. The critical clearing time (t_{cm}) of 0.258 seconds can be approximately obtained by dichotomy and mean value method after 4 experiments with resection time of 10/60 s, 15/60 s, 30/60 s, and 16/60 s, with the calculation formula shown in formula (1). That is to say, after the three-phase short circuit occurs in the power system, the circuit breaker must remove the fault within no more than 0.258 s before the system returns to a stable state.

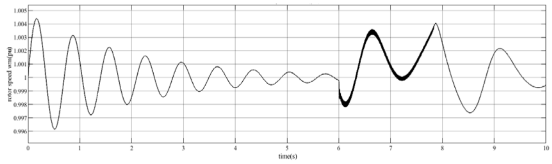
$$t_{cm} = \frac{t_1 + t_2}{2} = \frac{15/60 + 16/60}{2} = 0.258 \qquad (1)$$

3.4 Simulation of Single-Phase Earth Fault

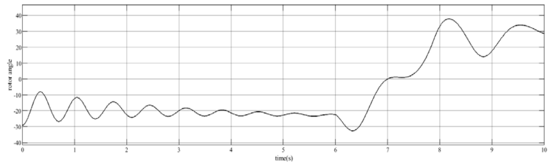
Single-phase earth fault is common in power systems. For example, a branch falling between phase A and the earth forms phase A earth fault. The circuit clearing time interval is [110/60, 115/60] by using the dichotomy method. The generator parameter curves corresponding to time t_1 and t_2 are shown in Fig.10 and Fig.11.



(a) Electromagnetic Power Pe

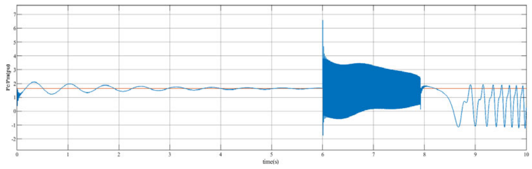


(b) Rotational Speed wm

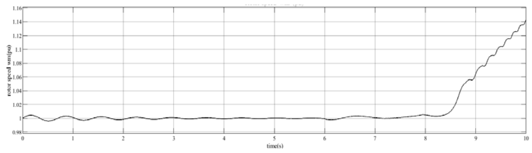


(c) Power Angle δ

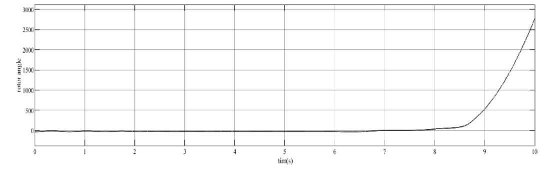
Fig.10 Parameters of the Generator at 110 / 60 s



(a) Electromagnetic Power Pe



(b) Rotational Speed wm



(c) Power Angle δ

Fig.11 Parameters of the Generator at 115 / 60 s

When the fault is removed at 110/60 seconds, the electromagnetic power of the generator is stable at around 1.632, the speed is stable at about 1, and the power angle tends to be constant at 20°, which shows that the system can remain stable after removing the fault. However, when the fault is removed at 115/60 seconds, a situation similar to that when the three-phase short circuit is removed at 16/60 seconds occurs, and the system is unstable. Other parameters at time t_1 and t_2 are shown in Tab. 6.

Tab.6 Parameters of the System at 15 / 60s and 16 / 60s(pu)

time (s)	*Vabc _B1*	*Vabc _B2*	*Vabc _B4*	*Vabc _B5*	*Vabc _B7*	*P1*	*P2*
110 / 60	0.075 ∠-7.3°	0.068 ∠46.3°	1.024 ∠33.8°	0.001 ∠-25.6°	0.943 ∠65.6°	Amino 0	-0.001-j0.001
115 / 60		0.052 ∠-26.1°	1.020 ∠26.1°	0.001 ∠-47.7°	0.713 ∠17.0°	Amino 0	Amino 0

The analysis shows that the system parameters of a single-phase earth fault in critical conditions are similar to those of a three-phase fault. When the fault is removed at 110/60 s, the system is in a steady state, but when the fault is removed at 115/60 s, the system is unstable. When the resection time was 25/60 s, 50/60 s, 70/60 s, 90/60 s, 120/60 s, 100/60 s, 110/60 s, and 115/60 s, the critical clearing time was 1.875 seconds as shown in the formula (2).

$$t_{cm}=\frac{t_1+t_2}{2}=\frac{110/60+115/60}{2}=1.875 \tag{2}$$

By comparison, the critical clearing time of a single-phase earth fault is much longer than that of a three-phase short circuit, which shows that the fault bearing capacity of a three-phase short circuit is weaker and the requirements for relay protection devices are higher [4]. Therefore, it is necessary to further study how to improve the critical clearing time of three-phase short circuits.

4. Measures to Improve the Transient Stability of the System

The measures to improve the transient stability of the system are adding a controllable series capacitor compensation device and reducing the mechanical power output by the prime mover. The former is realized by increasing the capacitance of the line, that is, the capacitance of the four lines is slightly increased to 3e-8F. The latter is realized by modifying the mechanical power Pm of the prime mover, that is, adjusting the value of Pm from 1.632 to 1.55.

Then, simulations of the three-phase short circuit and single-phase earth fault are carried out for these methods, so as to obtain the corresponding critical clearing time. The recorded data are shown in Tab. 7.

Tab.7 Contrast Data (s)

Type Fault	Original System	System After Series Capacitance	System After Pm Reduction
*Phas*e *A* Earth Fault	1.875	3.083	2.417
Three-phase Short Circuit	0.258	0.375	0.417

It can be seen from the table that using the series capacitor compensation method, the critical clearing time is increased by 64.43% when a *Phase A* earth fault occurs, and by 45.35% when a three-phase short circuit occurs. In addition, by reducing the mechanical power of the prime mover, the critical clearing time is increased by 28.91% when a *Phase A* earth fault occurs, and by 61.63% when a three-phase short circuit occurs. Thus, these two methods are effective in improving the transient stability of the system. The specific choice should consider factors such as cost and convenience according to the actual situation [5].

5. Conclusion and Prospect

In this paper, the transient stability simulation model of the power system is constructed to simulate single-phase short circuits and three-phase short circuits. Besides, the changes in mechanical power, critical clearing angle, and other parameters of the system are studied. It is proven that the three-phase short circuit is the most serious fault, and the system will remain stable if the fault is removed before the critical clearing time corresponding to the critical clearing angle.

In addition, two methods improving the transient stability of the power system are simulated, which are reducing the mechanical power output of the prime mover and adding a controllable series capacitor compensation device.The correctness and effectiveness of these two methods are verified.

The conclusion is based on the ideal data, which can be used to further explore their application through the energy function method [6], artificial intelligence method [6], and so on in complex practical situations. With the universal application of artificial intelligence and big data analysis in the electrical field, the transient stability prediction method based on artificial intelligence came into being [6], which further promoted the data-driven artificial intelligence method and electric big data, deserving further in-depth study.

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