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Research on Fault Parameters Modeling Approach of Aircraft IDG

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Abstract: The essence of the faults of the aircraft IDG (Integrated Drive Generator) is the change of its internal structure parameters. In this paper, mathematical models of the exciter and the main generator in aircraft IDG are constructed and the relationship between the parameter change and the faults can be observed directly through the mathematical models. The mathematical models are simulated in MATLAB/Simulink. After modifying certain fault parameters, the relevant fault waveform of aircraft IDG can be acquired. *Copyright © 2013 IFSA.*

Keywords: Aircraft IDG, Mathematical model, MATLAB, Fault parameters.

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1. Introduction

IDG (Integrated Drive Generator) is the onboard electrical power of civil aviation transport aircraft, which has a widely installed in modern age. It is composed of a three brushless AC synchronous generator and a constant speed drive unit. The constant speed drive unit changes the time-variable speed of the aircraft engine into the constant speed by the differential gear and inputs the constant speed to aircraft generator shaft. The permanent magnet generator, excitation generator, rotating rectifier and main generator was installed on the same spindle. They are also connected to the aviation engine shaft, constituting the three aviation brushless alternator. And then the driving engine outputs alternating current (AC) [1].

The PMGs magnetic field is provided by the permanent magnets. It generates an alternating current, and through the rectifier device the current is rectified into DC as the excitation current for the exciter. The exciter generates an alternating current in the exciter magnetic field, which is transferred into DC as the main generator excitation current by rotating rectifier mounted in the spindle. The main generator acquires excitation current for excitation

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magnetic field, and induces a 120/208 V, 400 Hz three-phase AC in the stator armature. The AC is eventually outputted into terminal transport aircraft grid through the main generator output terminal [2]. As the generator has no brush or slip ring, the exciter is designed as a rotating-armature synchronous generator in order for the brushless control. And the main generator is designed as a rotating-pole synchronous generator.

2. Mathematics Model of Aircraft IDG

When the aircraft generator operates in steady state, the exciter and main generator is connected by the rotating rectifier, which has six diodes and six working state. It is assumed that all of the diodes are ideal switches in the model, that the circuit is considered as the passage when diode is biased forward and as open-circuit when diode is biased reversely. For example, when Va>Vb and Vb>Vc, the diodes D1 and D6 are biased forward and the other are biased reversely, and the model state in this case is called state AB. The voltage relationship of six states is shown in Table 1.

Table 1. Rotating rectifier working states list.

State	Forward Biased Diodes	Reverse Biased Diodes
AB	D1D6	Left
AC	D1D2	Left
BC	D3D2	Left
BA	D3D4	Left
CA	D5D4	Left
CB	D5D6	Left

The status of the whole system is discrete when diodes are off and is continuous when is operating in one of the six states. The continuous state of the aircraft generator is only studied in this paper. Provided that the generator is running continuously in state AB. In this case, winding A and winding B ars connected to a passage while the winding C is not [3], as it is shown in Fig. 1.

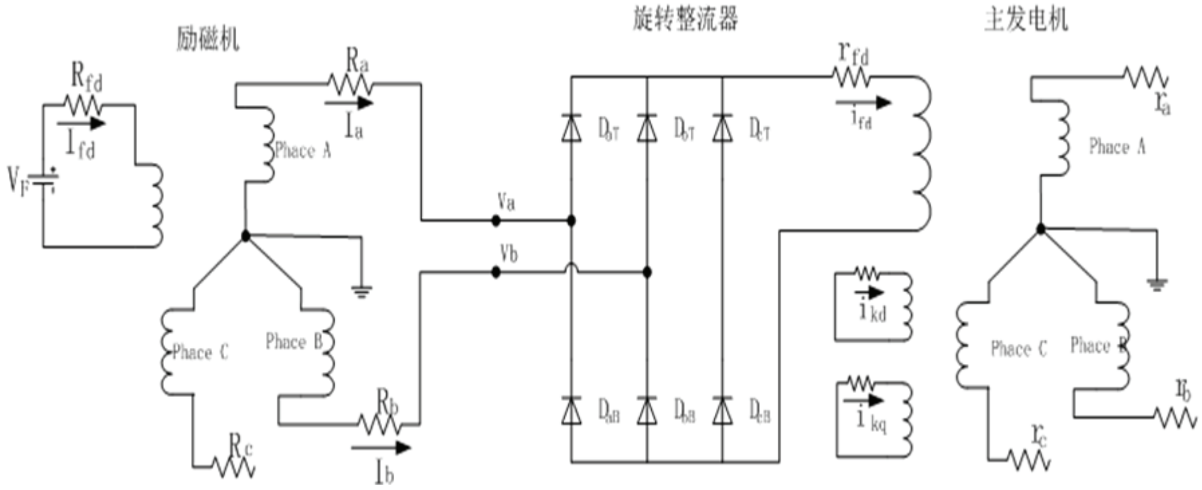


Fig. 1. Steady-state circuit of generator in state AB.

In the figure above, the exciter and the main generator are connected through the conducted D_{aT} and D_{bB}, forming a complete loop. Apply the KVL law to this circuit, and you can get the following relationship [4]:

$$\begin{cases} \dot{\psi}_a = r_a i_a + v_a \\ \dot{\psi}_b = r_b i_b + v_b \\ \dot{\psi}_c = r_c i_c + v_c \\ \dot{I}_a = \dot{i}_{fd} \\ \dot{\psi}_{kq} = -r_{kq} i_{kq} \\ \dot{\psi}_{kd} = -r_{kd} i_{kd} \end{cases} \tag{1}$$

$$\begin{cases} \dot{\Psi}_a - \dot{\Psi}_b - \dot{\Psi}_{fd} = (R_a + R_b + r_{fd}) I_a \\ \dot{I}_a + \dot{I}_b = 0 \\ \dot{I}_c = 0 \\ \dot{\Psi}_{fd} = -R_{fd} I_{fd} + V_F \end{cases} \tag{2}$$

$$\begin{cases} \dot{w} = \dfrac{P}{2J}(T_m - T_e - \hat{T}_e - Dw) \\ \dot{\theta}_r = w \end{cases} \tag{3}$$

The mathematical equation of main generator is represented as formula (1), and formula (2) describes the exciter mathematical equation. The "Fd" is the parameters of the exciter. The "Kq, kd" marks damper winding parameters. As the exciter of aircraft

IDG is an undamped generator, damper winding parameters are not included in exciter parameters. Meanwhile, the main generator has only two sets of damper winding, which is also different from the ordinary synchronous generator. The kinematic equation of the generator rotor is represented as equation (3), among which T_e and $\hat{T}_e$ respectively represent the electromagnetic torque of the main generator and the exciter. They can be calculated according to the torque formula:

$$\begin{aligned} T_e = & -p_0 L\left[i_a^2 \sin 2\theta + i_b^2 \sin(2\theta+120^o) + i_c^2 \sin(2\theta-120^o)\right. \\ & \left. +2i_a i_b \sin(2\theta-120^o) + 2i_b i_c \sin 2\theta + 2i_c i_a \sin(2\theta+120^o)\right] \\ & +p_0 M_{afd} i_{fd}\left[i_a \sin\theta + i_b \sin(\theta-120^o) + i_c \sin(\theta+120^o)\right] \end{aligned} \tag{4}$$

There are 12 state variables in equation (1), (2) and (3), including the angular velocity and the angular displacement, which are shown as the following vectors:

$$\begin{cases} \psi = \begin{bmatrix} \psi_a & \psi_b & \psi_c & \psi_{kq} & \psi_{fd} & \psi_{kd} \end{bmatrix}^T \\ i = \begin{bmatrix} i_a & i_b & i_c & i_{kq} & i_{fd} & i_{kd} \end{bmatrix}^T \\ \Psi = \begin{bmatrix} \Psi_a & \Psi_b & \Psi_c & \Psi_{fd} \end{bmatrix}^T \\ I = \begin{bmatrix} I_a & I_b & I_b & I_{fd} \end{bmatrix}^T \end{cases} \tag{5}$$

$$\begin{cases} R = \left[r_a \quad r_b \quad r_c \quad -r_{kq} \quad 0 \right. \\ \left. -r_{kd} \quad R_a + R_b + r_{fd} \quad 0 \quad 0 \quad -R_{fd} \right]^T \\ V = \left[v_a \quad v_b \quad v_c \quad 0 \quad 0 \right. \\ \left. 0 \quad 0 \quad 0 \quad 0 \quad V_F \right]^T \end{cases} \tag{6}$$

As $\Psi = Li$, you can obtain:

$$\dot{\psi} = (\dot{Li}) = \dot{L}i + L\dot{i} \tag{7}$$

Take the equation (7) into (1) and (2), and you can find that:

$$L\begin{bmatrix} \dot{i} \\ \dot{I} \end{bmatrix} = V - (\dot{L} + R)\begin{bmatrix} i \\ I \end{bmatrix} \tag{8}$$

Each variable in the equation (7) is a vector, where L is a matrix composed of the self-inductance and mutual-inductance of the main generator and exciter. Combined with the formula (4), the formula (8) can formulate the mathematical model of aircraft IDG [5].

3. System Faults and Parameter Faults

After early observation of the generator failure, the primary cause of the generator electrical fault is the change of certain internal parameters in the generator. Therefore, the faults can be diagnosed by observing the changes of the internal parameters in the generator. Meanwhile, according to the different results of such generators faults, the generator electrical faults can be divided into two major categories: system faults and parametric faults.

The system faults refer to the electrical failure causing structure change of the generator internal electrical system. It can be classified as follows:

1) The phase fault, that is ground faults of single phase winding, which forms a new loop from winding to the ground, creating additional current component and making loop voltage equal to 0.

2) The external-phase fault, that is ground faults of multiple-phase winding, which change the structure of the generator internal electrical system.

The parameter faults refer to the electrical faults, which do not change the generator internal electrical system structure, however, just change certain structural parameters [3]. It has also two cases: First, the existing ratings of generator parameters are changed, which leads to change of certain electrical variables. Second, the parameters themselves are changed and new physical parameters are introduced due to electro-magnetic induction, which add new electrical variables, leading to imbalance running in the system, and then the faults take place. The internal physical parameters of generator are shown in Table 2.

Table 2. Physical parameters of aircraft IDG.

Parameter	Description
r	Average air-gap radius
l	Air-gap axial length of generator
α1,α2	Mechanical geometry parameters of generator
N_s	Turns of stator winding
N_{fd}	Turns of excitation winding
N_{kq}	Turns of q-axis damper winding
N_{kd}	Turns of d-axis damper winding
L_{ls}	Leakage flux of stator winding
L_{lf}	Leakage flux of field winding
L_{lkq}	Leakage flux of q-axis damper winding
L_{lkd}	Leakage flux of d-axis damper winding
r_a	Winding resistance of a-phase stator
r_b	Winding resistance of b-phase stator
r_c	Winding resistance of c-phase stator
r_{fd}	Field winding resistance
r_{kd}	d-axis damper winding resistance
r_{kq}	q-axis damper winding resistance

It should be noted that physical parameters of synchronous generators shown in Table 2 hold meaning only when the generator is in normal operation, as the normal operating state of generator is assumed to be symmetric operation. Meanwhile, it is also assumed that all the winding turns is N_S, and there is self-inductance of the stator windings and mutual-inductance with the other windings. When fault symptoms occur, however, parameters of different windings have changed inevitably and cannot be represented by the same parameter size. For example, as a-phase winding gets a fault, fault parameters shown in Table 3 will be introduced and the original self-inductance of winding will be changed. It is worth noting that the inherent mechanical geometry parameters of generator-r, L, α1, α2, etc. will not be changed when the electrical faults of windings occur.

Table 3. New parameters introduced for a-phase winding fault.

Parameter	Description
N_{sa}	Equivalent turns of a-phase winding
L_{safd}	Mutual inductance of a-phase winding and excitation winding
L_{sakd}	Mutual inductance of a-phase winding and d-axis damper winding
L_{sakq}	Mutual inductance of a-phase winding and q-axis damper winding
L_{sas}	Mutual inductance of a-phase winding and b/c-phase damper winding

In most cases, the parameter faults and the system faults are not mutually independent. For example, an obvious parameters fault of winding occurs due to a short-circuit fault of several turns of coil, while the generator's normal operation may not be interrupted according to the margin designed for the synchronous generator. However, if the generator operates with fault in a long-term, making the core of the generator winding overheated, the winding-grounded system fault will occur. In this case, it will interrupt the normal operation of the generator, even make it damaged. Therefore, the parameter fault is a pre-incentive of system fault and an initial characterization of change of some certain structural parameters before system fault occurs. The parameters that can describe the system fault symptoms are collectively known as the fault parameters. As can be seen from the above, it is only necessary to input a small amount of testing and maintenance costs to guarantee the long-term normal operation of the generator, if the change of the fault parameters can be diagnosed before system fault occurs and then the trend of a certain type of fault is determined.

4. Simulation

4.1. Construction of Simulation Models

According to analysis of the structure of the aircraft IDG, the Simulink model [7] is shown in Fig. 2.

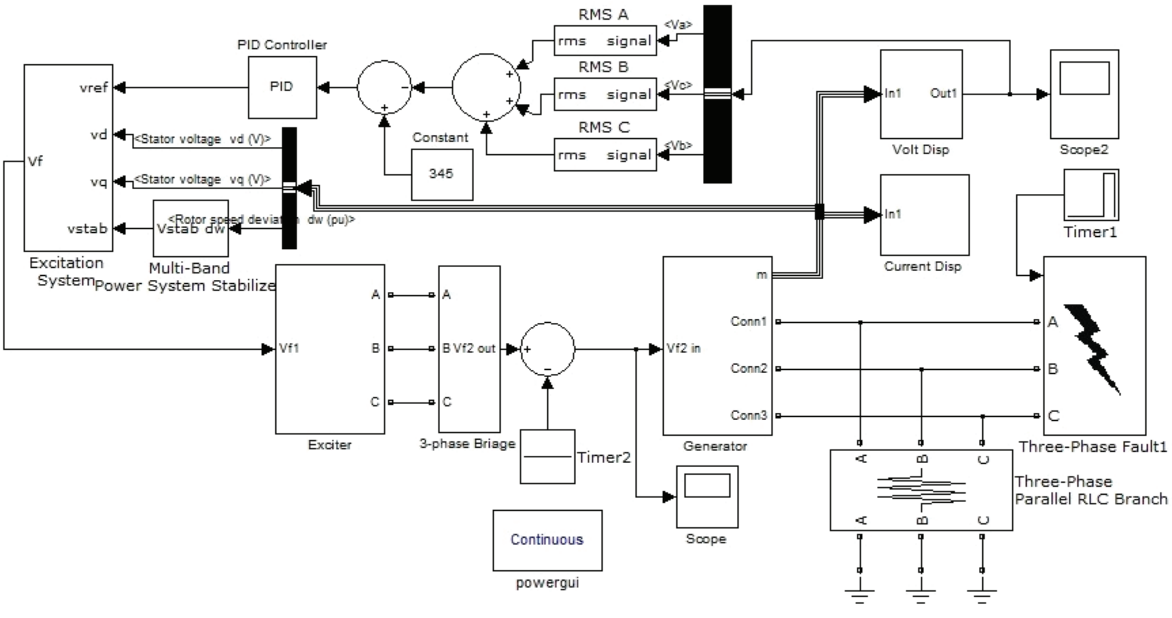


Fig. 2. Simulink model of the aircraft IDG.

In the figure above, a three-phase rotating rectifier (3-phase Bridge) is between the exciter and the main generator. The load is a three-phase resistance-balance load (Three-phase Parallel RLC Branch), whose internal options can be selected for a comprehensive load by a certain ratio of RCL. The PID module is used for exciter regulation. The three-phase short-circuiter and timer are used in combination. The generator short-circuit time is pre-set and then its sudden short-circuit fault of internal winding during simulation can be observed. In aircraft IDG, the exciter is an armature-rotating synchronous generator and the main generator a pole-rotating synchronous generator, whose structures are basically of the same, except that the exciter has no damper winding. The electrical module and the mechanical module compose the main generator module. The electrical module is shown in Fig. 3.

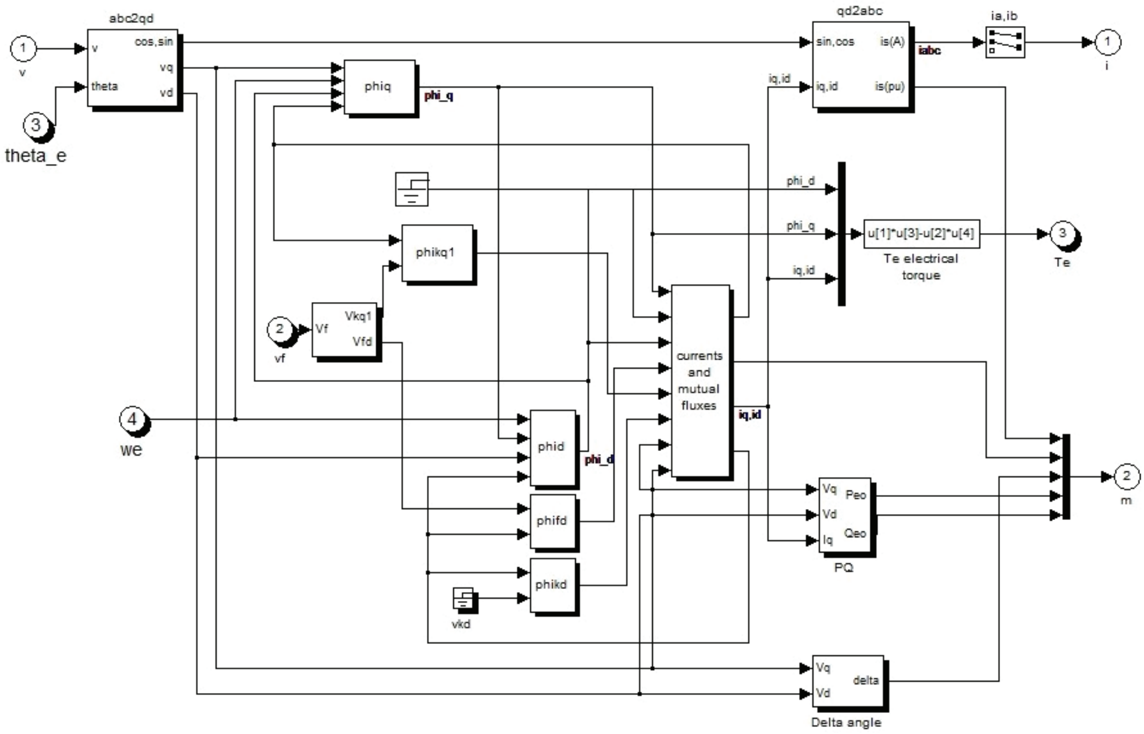


Fig. 3. Electrical module of the main generator.

The electrical module of main generator is composed of the current module, the mutual-inductance calculation module and the coordinate transformation module. The current and mutual-inductance calculation module is the key parts of the electrical module, even the whole generator. The fluxes are input into the module, and the mutual-inductance and dq-axis current of each winding are outputted. The Simulink model of the current and mutual-inductance calculation module is shown in Fig. 4.

The principle of Park transform is used in coordinate conversion module. The three-phase voltage-current can be transformed into dq0 coordinates and vice versa. The module is shown in Fig. 5.

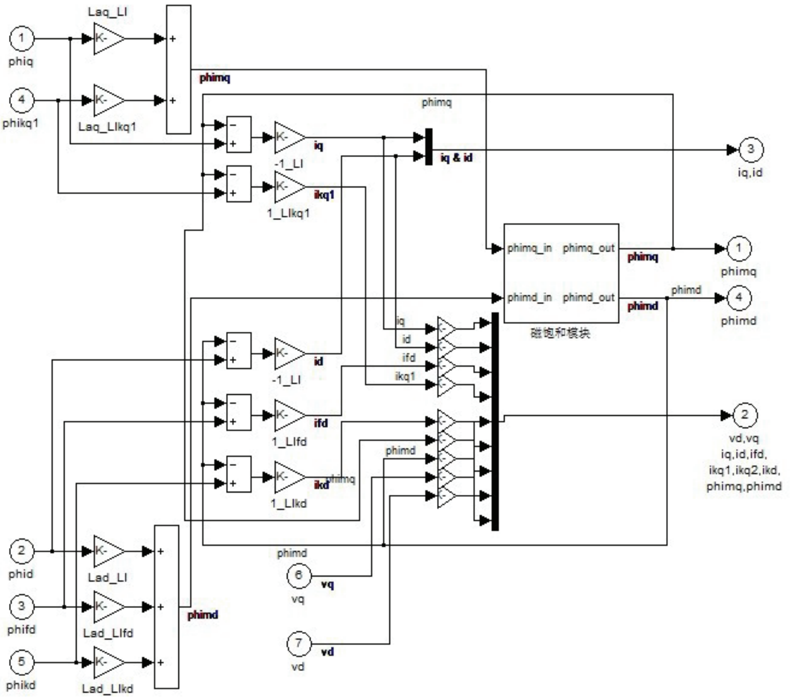


Fig. 4. Current and mutual-inductance calculation module.

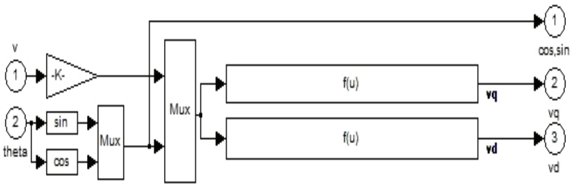


Fig. 5. Current and mutual-inductance calculation module.

The function outputting V_q is

$$f(u) = \frac{1}{3}[\cos\ \theta(2 v_b + v_b) + (\sqrt{3} v_b \sin\ \theta)]$$

and the function outputting V_d is

$$f(u) = \frac{1}{3}[\sin\ \theta(2 v_b + v_c) + (-\sqrt{3} v_c \cos\ \theta)]$$

The mechanical characteristics module of aircraft IDG is shown in Fig. 6.

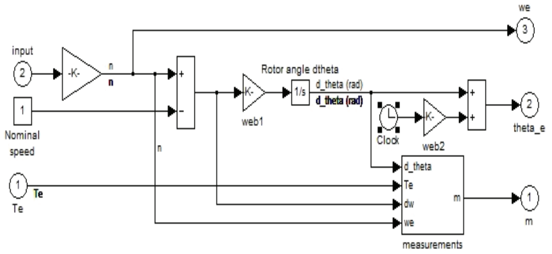


Fig. 6. Mechanical characteristics module of aircraft IDG.

The mechanical characteristics module of the main generator is constructed based on the motion equations of the rotor. The input is the rotating speed in radians and the outputs are the angular speed of rotor, the angular displacement and the electromagnetic torque.

4.2. The Initial Parameter Setting

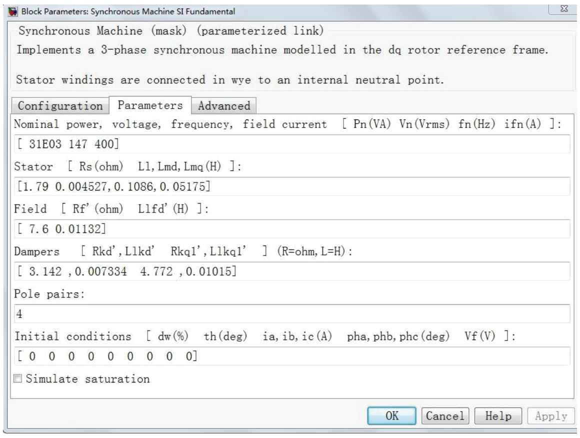
All the initial parameters of the generator Simulink model are shown in Table 4.

According to the basic parameters of the aviation generator, such as the rated voltage, rated current, rated frequency, the pole pair number and the rotating speed, simulation parameters such as the resistance of three-phase winding, the resistance of field winding and the inductance can be determined. However, the initial parameters of system must be set correctly in order to ensure the simulation running from a steady state during the dynamic simulation of power system based on MATLAB. If there is no initial setting or the setting is unreasonable, the system will operate in an unstable state in a long term, making the simulation results distorted and the simulation meaningless. A solution is the Power GUI in MATLAB PSB unit, which has a function of steady flow calculation and setting initial value. The option "Load Flow and Machine Initialization" is used to run with the new load, drawing the steady-state value of the prime mover, the excitation system and the synchronous generator under this load. Input the mechanical power, the excitation voltage, the terminal voltage and the stator current in steady state into the appropriate boxes as the initial value of the system, and then the setting of steady-state initial value is completed.

Table 4. Initial physical parameters settings of the Simulink model of aircraft IDG.

Parameter	Description	Value
L_{ls}	Self-inductance of stator winding	0.004527 H
L_{md}	Mutual-inductance of d-axis winding	0.1086 H
L_{mq}	Mutual-inductance of q-axis winding	0.05175 H
L_{lkq}	Self-inductance of q-axis damper winding	0.01015 H
L_{lfd}	Self-inductance of field winding	0.01132 H
L_{lkd}	Self-inductance of q-axis damper winding	0.007334 H
r_a	Resistance of a-phase stator winding	1.62 Ω
r_b	Resistance of b-phase stator winding	1.62 Ω
r_c	Resistance of c-phase stator winding	1.62 Ω
r_{kq}	Resistance of q-axis damper winding	7.772 Ω
r_{fd}	Resistance of field winding	7.6 Ω
r_{kd}	Resistance of d-axis damper winding	3.142 Ω
N_s	Turns of stator winding	100
N_{fd}	Turns of field winding	100
N_{kq}	Turns of q-axis damper winding	100
N_{kd}	Turns of d-axis damper winding	100
D	Damping coefficient	0.009 $kg.m^2.s^{-1}$
J	Instantaneous inertia	0.0093 $kg.m^2$

When the module based on MATLAB / Simulink is running, it is necessary to adjust parameters and assign values specifically, according to the actual memory of the PC, the operational performance and the software version [8]. The actual parameter assignment page of aircraft IDG based on MATLAB/Simulink simulation is shown in Fig. 7.



Synchronous Machine (mask) (parameterized link)

Implements a 3-phase synchronous machine modelled in the dq rotor reference frame.

Stator windings are connected in wye to an internal neutral point.

Nominal power, voltage, frequency, field current [Pn(VA) Vn(Vrms) fn(Hz) ifn(A)]:
[31E03 147 400]

Stator [Rs(ohm) L1,Lmd,Lmq(H)]:
[1.79 0.004527,0.1086,0.05175]

Field [Rf'(ohm) Llfd'(H)]:
[7.6 0.01132]

Dampers [Rkd',Llkd' Rkq1',Llkq1'] (R=ohm,L=H):
[3.142 ,0.007334 4.772 ,0.01015]

Pole pairs:
4

Initial conditions [dw(%) th(deg) ia,ib,ic(A) pha,phb,phc(deg) Vf(V)]:
[0 0 0 0 0 0 0 0 0]

☐ Simulate saturation

Fig. 7. Initialization of parameter assignment of the main generator.

As can be seen, the power of the main generator is 31 KVA, and the outputted rated voltage is closed to 115 V, and the frequency maintains at 400 Hz, a slight change with the initial setting. The resistance of no-load excitation winding is 7.6 ohms. According to provisions of CMM manuals [9], it is normal that the resistance of no-load excitation winding remains at 6.7 to 9.0 ohm.

4.3. No-Fault Simulation

The following is no-fault simulation of the Simulink model of the aircraft IDG. The duration is 2 seconds.

The initial parameter is set according to the requirements of generator steady-state operation, and the three-phase balanced resistive load is added. The output waveforms of the generator are shown in the following diagrams.

As is shown in Fig. 8, after the voltage-buildup process of the generator, the steady-state output reaches the effective value of 115 V (line voltage about 150 V), and the voltage-buildup time is 0.8–1 s.

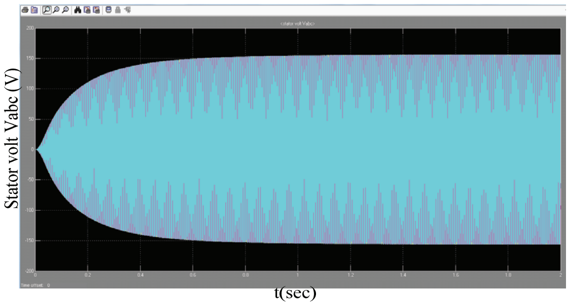


Fig. 8. Three-phase output of the main generator stator.

After being zoomed in, the three-phase output voltage waveform of the aircraft generator is shown in Fig. 9. As can be seen, the output waveform is a stable three-phase sinusoidal AC voltage. The frequency is 400 Hz.

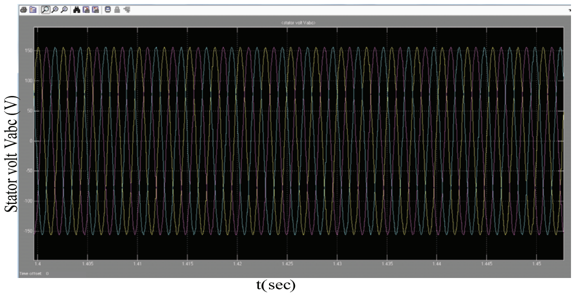


Fig. 9. The enlarged three-phase output of the main generator stator.

The stator-side currents of the main generator, including the three-phase output current and the excitation current waveform diagrams are shown in Fig. 10.

The damper winding current is shown in Fig. 11. The three-phase output current non-rated current, as the load is not rated. The excitation current is increasing from 0 to 1.65 A steadily, matching the CMM manual requirement that the excitation current does not exceed 1.9 A [9]. The dq-axis damper winding current increases significantly in the beginning, and then reduces to zero gradually.

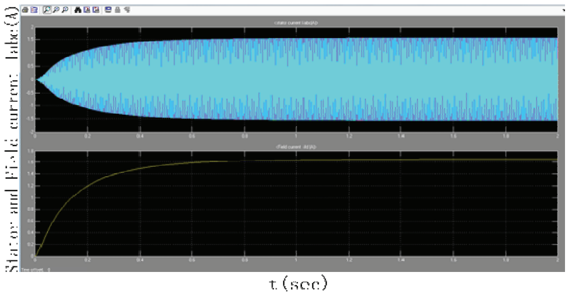


Fig. 10. The stator current and the excitation current of the main generator.

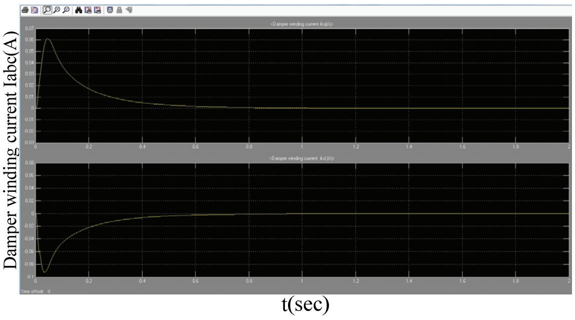


Fig. 11. The damper winding current of the main generator.

4.4. The Fault Simulation of Sudden Increase of the Field Winding Resistance

The original value of R_{fd} 7.6 Ω is increased to 10 Ω. The internal parameters of the existing components in MATLAB/Simulink cannot be modified due to its characteristics. As the change of the field winding resistance results in the change of the excitation current of the main generator, it can be simulated by modifying the external excitation current. Meanwhile, it can be seen from experiments that the excitation module interferes with the characteristic details of the fault obviously, so remove it and the voltage regulating process by regulator for this change can be well observed. The Simulink simulation diagram of this system is shown in Fig. 12. The change of the output waveform is shown in Fig. 13.

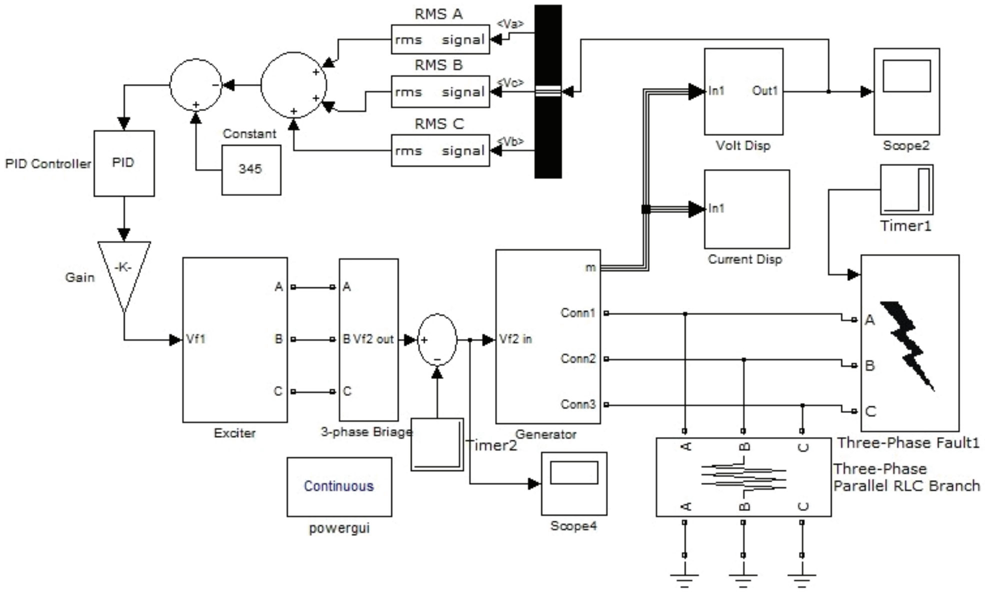


Fig. 12. The Simulink diagram of the whole generator when the excitation fails.

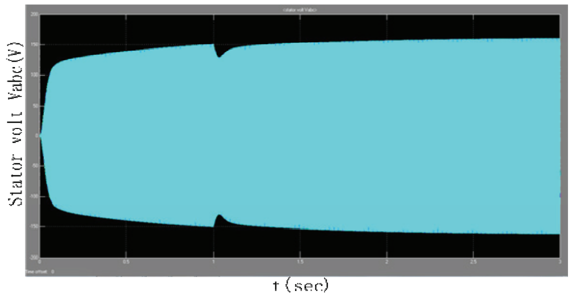


Fig. 13. The three-phase output of the main generator stator when the excitation fails.

As can be seen, the moment a fault occurs, the voltage output begins to distort but returns to normal after a while. This is because the excitation regulating module of the system adjusts the excitation current to the required values. The degree of distortion of the voltage waveform can be observed clearly in Fig. 14.

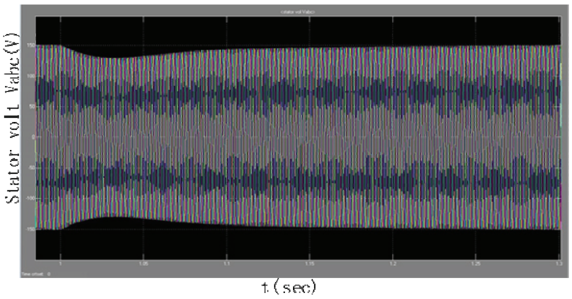


Fig. 14. The enlarged three-phase output of the main generator stator.

Similar fault waveforms can also be found in the current of the main generator, as is shown in Fig. 15 and Fig. 16. The excitation current can be clearly seen in Fig. 15. The current of the damper winding is shown in Fig. 16, in which an opposite spike is generated during the fault.

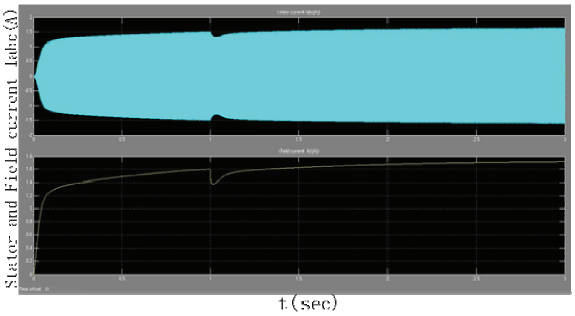


Fig. 15. The stator current and excitation current of the main generator when the excitation fails.

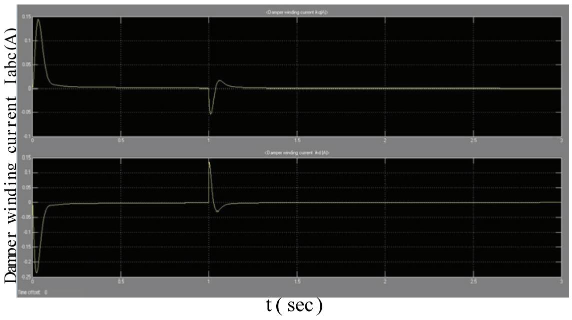


Fig. 16. The current of the damper winding of the main generator when the excitation fails.

4.5. The Simulation of Short-Circuit Fault

The high level is triggered at t=1.4 s and is cutoff at t=1.8 s by setting the timer. The timer and the circuit breaker (Three-phase Fault) are used in combination. When the high level is triggered by the timer, the circuit breaker starts to work. The two phases – a and b of the generator is set at short-circuit by the circuit breaker at the same time. The three-phase voltage waveform output by the stator when the two phases – a and b are at short-circuit is shown in Fig. 17. Its enlarged diagram is shown in Fig. 18.

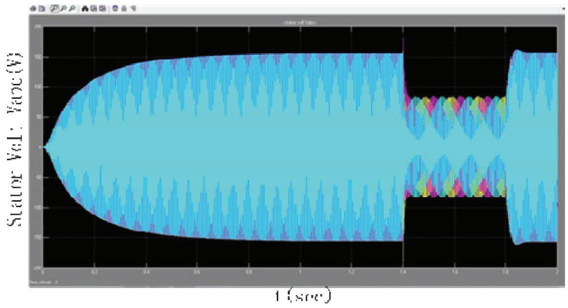


Fig. 17. The three-phase voltage waveform output by the stator when the two phases – a and b are at short-circuit.

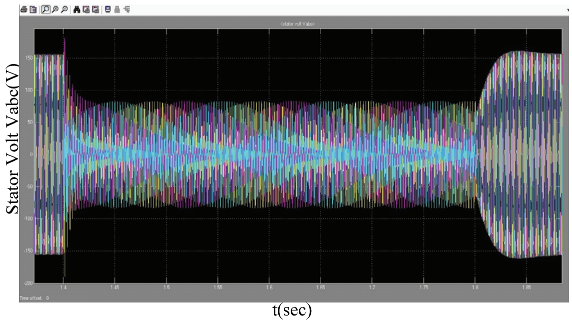


Fig. 18. The enlarged diagram of Fig. 17.

As can be seen from the Fig. 4-17, the three-phase output changes drastically when fault occurs. Although it is a two-phase short circuit, the output of the third phase will also change. When the fault ceases, the generator outputs voltage normally again after a voltage-buildup process.

The current waveform of stator winding and the excitation winding distorts severely when the two-phase short circuit fault of the generator occurs, as is shown in Fig. 19. The current waveform of the damping winding is shown in Fig. 20.

As can be seen from Fig. 20, when the short-circuit fault occurs in generator, the current of damper winding no longer just fluctuates slightly in one direction while generates a electromagnetic response in a high frequency instead.

According to above fault simulations, the internal complex winding structure in aircraft IDG leads to various electrical phenomena. The three-phase output of the main generator stator terminal can not fully reflect the specific level and the exactly damaged parts of the fault sometimes. Therefore, some other waveforms of fault parameters, such as the excitation current and the damping current, need observation to determine the condition of the fault.

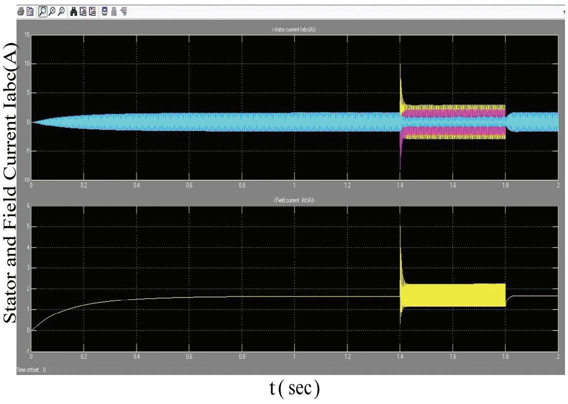


Fig. 19. The current waveform of stator winding and the excitation winding when the two-phase short circuit fault occurs.

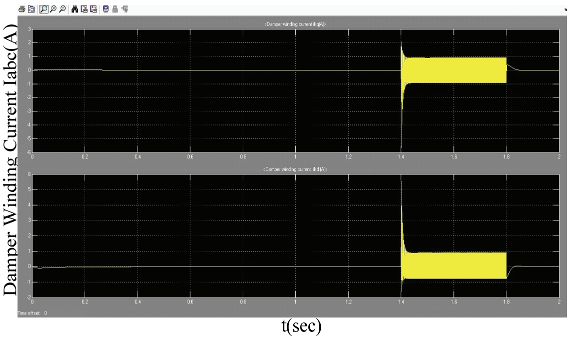


Fig. 20. The current waveform of the damping winding when the two-phase short-circuit fault occurs.

5. Conclusion

In this paper, the characteristics of the phase-field mathematical model of the aircraft IDG is studied and the overall structures of the exciter and the main generator are constructed, making a more accurate description of the running state of the aircraft IDG with asymmetric fault. The normal operation, the excitation failure and the phase-to-phase short-circuit fault are simulated by the mathematical model in MATLAB/Simulink. It turned out that the running status of aircraft IDG can be accurately described in this model. The simulation results and the actual ground testing system aircraft IDG can be combined in further studies, composing the automatic testing system of internal faults for the aircraft IDG, and this can be optimized in practical application.

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