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AN INTEGRATED CONTROL SCHEME FOR STARTER/GENERATOR SYSTEM IN MORE ELECTRIC AIRCRAFT

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Abstract

With the development of more electric aircraft, higher demands for electrical energy are put forward in generation systems. The concept of the starter/generator system (SGS) as a promising approach has been widely accepted for its capability to combine starter with generator in aircraft. In this paper, an integrated control scheme is proposed to regulate the engine and output voltage of aircraft when starter/generator operates in different modes. In starting mode, the controller can accelerate the engine high pressure compressor rotor to reference values. In transition mode, the smooth switching control strategy is provided to improve the dynamic performance and reliability of system. In generating mode, the main DC bus voltage can be regulated to the rated value and meet requirements of aircraft when all loads connected to the system. Finally, extensive simulation results are provided to confirm the validity and effectiveness of the proposed control scheme for SGS in more electric aircraft.
Keywords: More electric aircraft, starter/generator system, integrated control, smooth switching, Transition mode.

1. Introduction

The more electric aircraft (MEA) concept is one of the major trends in modern aerospace engineering aiming for reduction of the overall aircraft weight, operation cost, and environmental impact [1-7]. With the increasing electrical power capacity in MEA, it is possible to use the original electrical machine to start the engine, namely starter/generator system (SGS) [5-11]. The starter/generator (SG) needs to satisfy two basic requirements, namely to accelerate the engine and to generate electrical power. In starting mode, the electrical machine operates as a starter to start the engine, and the SG accelerates the engine to the self-sustaining speed [13-17]. In this situation, the customized air turbine starter can be removed. In generating mode, the SG in turn driven by aircraft engine, the SG operates as a generator to supply power to the onboard loads in generating mode. In this scenario, the weight and reliability of generation system are improved effectively by the SGS [17-19]. However, the traditional control methods of SGS are not optimized which makes SGS be prone to failure in the switching process.

This paper presents a comprehensive control strategy to regulate the engine and output voltage of aircraft when SG operates in starting mode, transition mode and generating mode. In starting mode, the engine high pressure compressor rotor can be regulated to reference values. In transition mode, improved smooth switching control strategy is provided to improve the dynamic performance and reliability of SGS. In generating mode, the main DC bus voltage can be regulated to the rated value and meet requirements of aircraft when all loads connected to the system. Therefore, the safety of aircraft can be further ensured.

The rest of this paper is organized as follows. In Section 2, the review of the structure of SGS is presented. The detailed integrated control scheme of SGS is proposed in Section 3. The simulation test results of the SGS are provided to verify the feasibility of the presented method in Section 4. Finally, the concluding remarks are given in Section 5.

2. Review of a typical architecture of starter/generator system

Fig. 1 shows typical architecture of a Starter/Generator (SG) system, which consists of a permanent magnet synchronous SG, a bi-directional converter and a controller. The SG needs to accelerate the engine and to generate electrical power. In starting mode, the SG operates as a starter to start the engine, and the SG accelerates the engine to the self-sustaining speed [17-23]. The SG is energized directly by the DC power from ground power supply or batteries. When the speed of SG reaches to the cut-off rotate speed, the Switch 1 (SW1) is disconnected and then the engine drives the ISGS. In generating mode, the SG in turn driven by aircraft engine, the SG operates as a generator to supply power to aircraft through the bi-directional converter. When the output voltage is regulated to 270V, the Switch 2 (SW2) is connected and SG supplies power for aircraft loads. The basic function of ISGS controllers are utilized to start the engine smoothly in starting mode, and regulate output voltage of ISGS in generating mode.

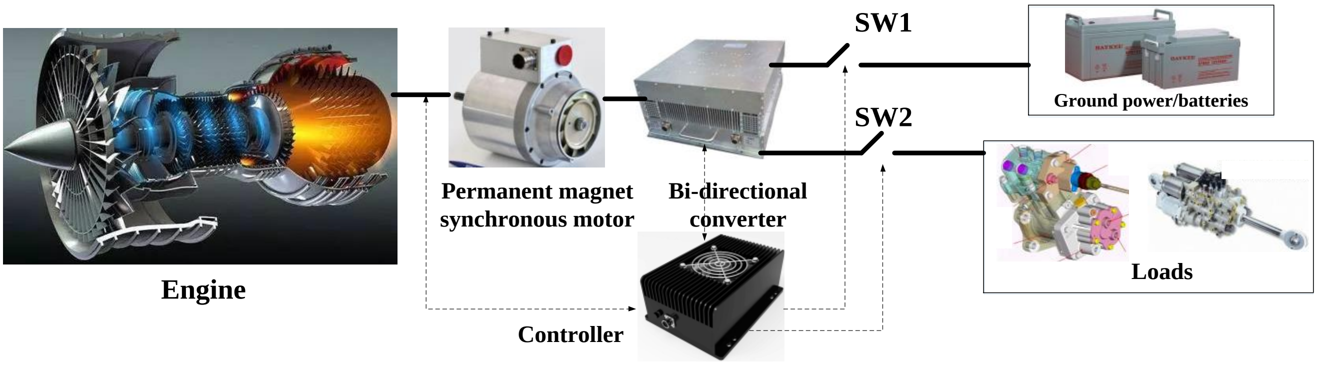

Figure 1–Typical structure of a starter/generator system.

3. An integrated control scheme for starter/generator system

As shown in Fig.2, an integrated improved control scheme of ISGS is proposed in this paper. In starting mode, ISGS operates as a motor where the primary engine is behaving as a mechanical load. The engine is accelerated to the self-sustaining speed. In generating mode, the variable speed (VS) engine sustains itself, and the ISGS supplies the electric power for onboard loads. The motor speed is regulated in starting mode and the output DC voltage is regulated in generating mode. In order to ensure the safety of electrical equipment, an integrated control scheme in transition mode is proposed and the output DC voltage of ISGS can be regulated to 270V and then the generator contactor can be automatically connected to provide electric power for aircraft loads.

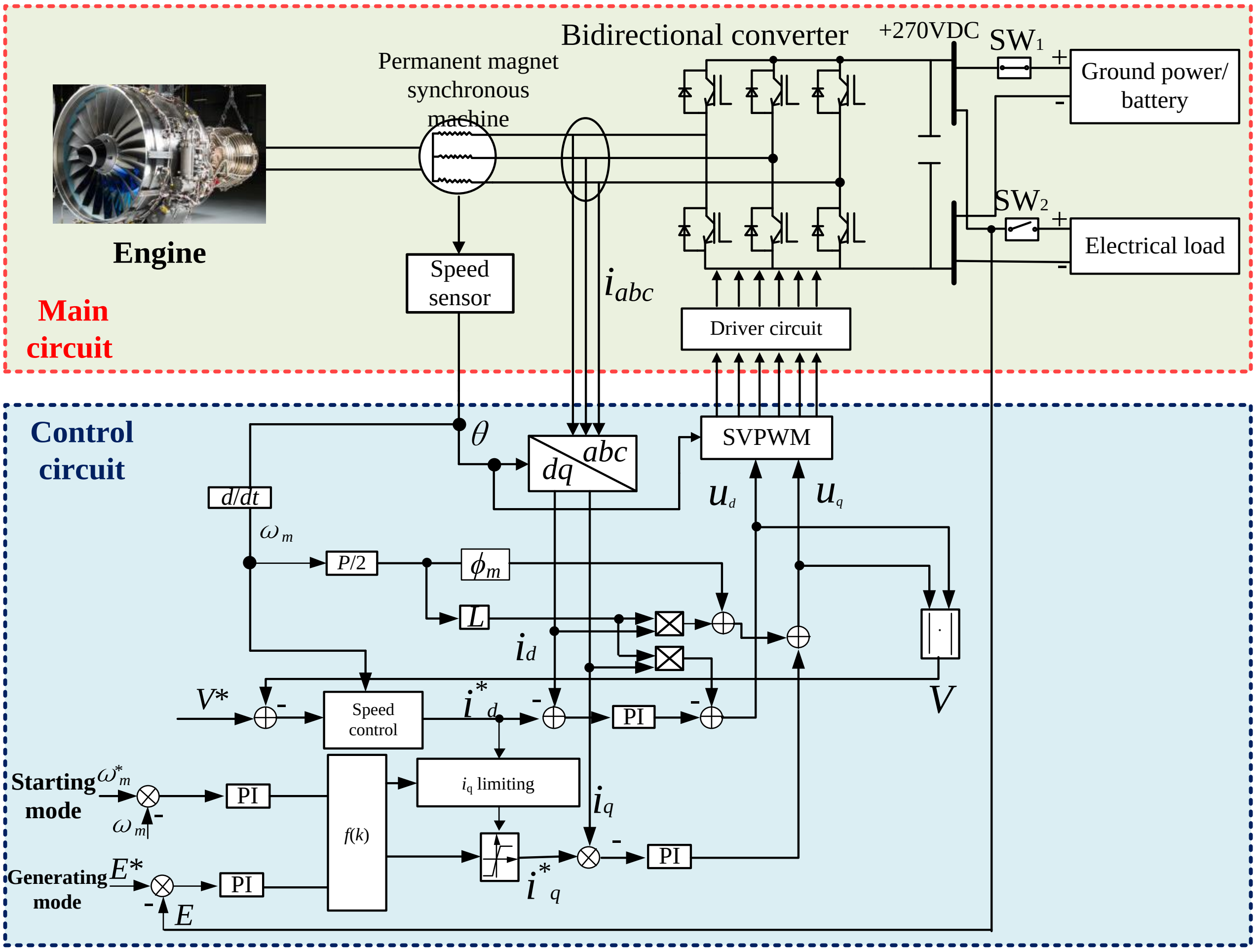

Figure 2–The block diagram of proposed integrated control scheme of starting/power generation system.

3.1 Coordinate transformation algorithm

The ISGS requires a three-phase bi-directional converter to regulate current and voltage in starting mode or in generating mode. The behavior of three-phase machines is usually described by their voltage and current equations. The coefficients of the differential equations that describe their behavior are time varying (except when the rotor is stationary). The mathematical modeling of such a system tends to be complex since the flux linkages, induced voltages, and currents change continuously as the electric circuit is in relative motion. For such a complex electrical machine analysis, mathematical transformations are often used to decouple variables and to solve equations involving time varying quantities by referring all variables to a common frame of reference.

Clarke Transformation can convert balanced three-phase quantities into balanced two-phase quadrature quantities. And then Park Transformation can convert vectors in balanced two-phase orthogonal stationary system into orthogonal rotating reference frame, as shown in Fig.3.

$$[x_{abc}] = \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \frac{3}{2}\begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \frac{3}{2}\begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta-120) & -\sin(\theta-120) \\ \cos(\theta+120) & -\sin(\theta+120) \end{bmatrix}[x_{dq}] \quad (1)$$

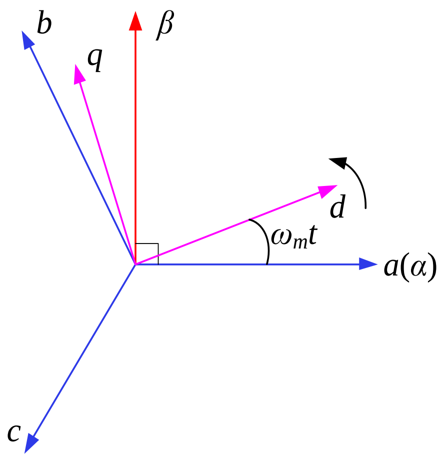

Figure 3–Schematic diagram of the relationship between static abc coordinate system and static αβ coordinate system and dq coordinate system

where $[x_{abc}]$ and $[x_{dq}]$ are variables in *abc* coordinate system and the *dq* coordinate system, respectively. And angular velocity θ is equal to $\omega_m t$.
Accordingly, inverse Park and Clarke transformation can be obtained as follows:

$$\left[x_{dq}\right]=\begin{bmatrix}x_d\\x_q\end{bmatrix}=\frac{2}{3}\begin{bmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix}\begin{bmatrix}1 & -1/2 & -1/2\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2\end{bmatrix}\begin{bmatrix}x_a\\x_b\\x_c\end{bmatrix}=\frac{2}{3}\begin{bmatrix}\cos\theta & \cos(\theta-120) & \cos(\theta+120)\\ -\sin\theta & -\sin(\theta-120) & -\sin(\theta+120)\end{bmatrix}\left[x_{abc}\right] \tag{2}$$

Therefore, the voltage and current in the natural coordinate system can be converted to the synchronous rotation axis, and the three-phase AC variables can be converted to the DC variables in *dq* coordinate system. And DC variables can be further regulated to the reference values by Proportional Integral (PI) controllers.

3.2 An integrated control scheme in starting mode

As shown in Fig. 2, the controller consists of a PI controller, and the frequency and voltage can regulated as:

$$i_q^* = k_{sqp}\left(\omega_m^* - \omega_m\right) + \frac{k_{sqi}}{s}\left(\omega_m^* - \omega_m\right),\quad i_d^* = k_{sdp}\left(V^* - V\right) + \frac{k_{sdi}}{s}\left(V^* - V\right) \tag{3}$$

where ω_m and V are the speed and voltage, respectively.
The current is controlled as follows:

$$u_D = k_{ip}\left(i_d^* - i_d\right) + \frac{k_{ii}}{s}\left(i_d^* - i_d\right),\quad u_Q = k_{ip}\left(i_q^* - i_q\right) + \frac{k_{ii}}{s}\left(i_q^* - i_q\right) \tag{4}$$

where k_{sqp} and k_{sdp} are proportional coefficients, respectively. k_{sqi} and k_{sdi} are integral coefficients, respectively. ω^*_m and V^* are rated speed and rated voltage, respectively. k_{ip} and k_{ii} are proportional and integral coefficients respectively. u_D and u_Q are the output voltage of the current loop, respectively.
Considering the voltage characteristics of permanent magnet synchronous motor, the voltage needs to

be regulated using space vector pulse width modulation (SVPWM), which can be written as follows:

$$u_d = u_D - \frac{P}{2} L i_q \frac{d\theta}{dt}, \quad u_q = u_Q + \frac{P}{2} \varphi_m i_q + \frac{P}{2} L i_d \frac{d\theta}{dt} \tag{5}$$

where φ_m, L, P and θ are generator flux, inductance, polar logarithm and motor speed, respectively. u_d and u_q are the voltage variables regulated by SVPWM, and then the three phase bi-directional converter is used to realize the closed loop control of system.

3.3 An integrated control scheme in transition mode

There is a transition state when starter-generator system changes from starting mode to generating mode. An improved smooth switching control strategy is proposed to realize smooth transition between the two states, as shown in Fig.2. The dynamic performance of SGS can be improved significantly, and the detailed algorithm of *f*(*k*) is shown in Fig. 4.

After the ground power and batteries are connected to the system, the ISGS controller can send a signal to aircraft electric power system to cut off the ground power and batteries power supply when high pressure compressor rotor of the engine (n_2) is equal or greater than 60% of rated rotor, namely $n_2 \geq 60\%\ n_{rated}$, and the speed of ISGS is equal or greater than ω_{cutoff}. ω_{cutoff} and ω_{min} are the speed limit value of ISGS in starting mode or generating mode, respectively. After the controller receives the disconnect signal and the speed of ISGS is equal or greater than (0.9~1.0) ω_{min}, aircraft electric power system will send a signal to ISGS to change starting mode to generating mode.

After SG operates in generator mode stably, the output voltage can be collected by hall sensor and further regulated to the rated voltage 270V. To above, the improved smooth switching control strategy can improve the dynamic performance and reliability of SGS and guaranteed SG change to generator state safely. The specific voltage control strategy is described in next Section.

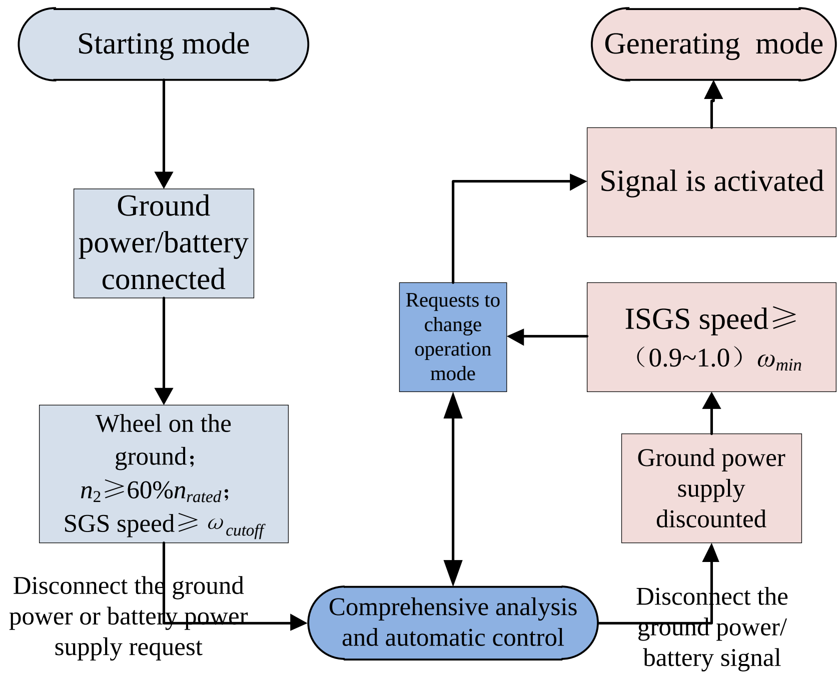

Figure 4–Diagram of transition control logic *f(k).*

3.4 An integrated control scheme in generating mode

In generating mode, the maximum output voltage of the ISGS is limited by the bus voltage. When the speed of the ISGS is from ω_{DCmin} to ω_{DCmax}, the voltage can be adjusted to 270V to meet the requirements of aircraft. ω_{DCmin} and ω_{DCmax} are the minimum and maximum limit speed of the ISGS when the engine operates normally, respectively.

When the speed of the ISGS is less than ω_{DCmin}（n_2<60% n_{rated}）, the output voltage is limited and the transition controller $f(k)$ can disconnect switches for powering loads. And batteries can provide power for important loads of aircraft. When the engine is abnormal and the speed of ISGS is larger than ω_{DCmax}, and the bus voltage may be out of control. In this situation, the excitation current needs to be limited to ensure the reliability of power supply for aircraft. A variable speed power-based optimized control strategy in generation mode is proposed to guarantee the quality of power supply voltage when the speed of ISGS exceeds the limit, and the detailed control strategy is shown in Fig. 5.

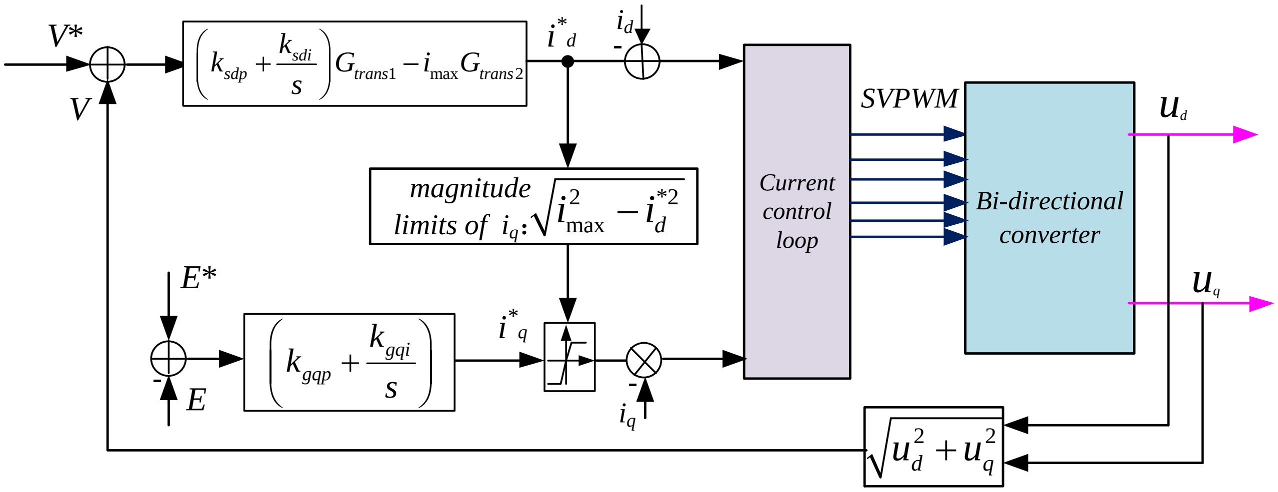

Figure 5–Diagram of variable speed-based control scheme in generating mode.

In generating mode, an improved voltage and current duel closed-loop controller is proposed:

$$i_q^* = k_{gqp}\left(V^*-V\right)+\frac{k_{gqi}}{s}\left(V^*-V\right),\quad i_d^* = \left(k_{sdp}+\frac{k_{sdi}}{s}\right)\left(V^*-V\right)G_{trans1}-i_{max}G_{trans2} \qquad (6)$$

The proportional-integral coefficients of PI controller are k_{gqp} and k_{gqi}, respectively. E^* and E are rated voltage amplitude and main DC bus voltage, respectively.

In addition, the reference values i_d^* and i_q^* of the inner current loop are obtained. Furthermore, the proposed closed-loop voltage controller is adopted to regulate the output voltage to 270V, which further improves quality of DC bus voltage of aircraft.

4. Simulation Results

To verify the effectiveness of the proposed control scheme, a starting/generator system is implemented in Matlab/Simulink. The rated power of PMSM is 64kVA, and the polar logarithm P is 4. In starting mode, the proportional integration coefficients k_{sqp} and k_{sqi} of q-axis PI controller are 1 and 10, respectively. The proportional integration coefficients k_{sdp} and k_{sdi} of d-axis PI controller are 1 and 10, respectively. The proportional integration coefficients k_{ip} and k_{ii} of current inner loop controller are 1.4 and 100, respectively. The minimum speed ω_{DCmin} and maximum speed ω_{DCmax} are 2000rpm and

12000rpm, respectively. In generating mode, the coefficients k_{gqp} and k_{gqi} of *q*-axis voltage PI controller are 0.03 and 0.6, respectively. The proportional-integral coefficients k_{gdp} and k_{gdi} of *d*-axis voltage PI controller are 0.03 and 0.6, respectively. Fig. 6 shows the dynamic response of the throttle of aircraft. When *t*=0.5s, the throttle is pushed forward from “shut-down” position to “idel” position, and ISGS operates in starting mode.

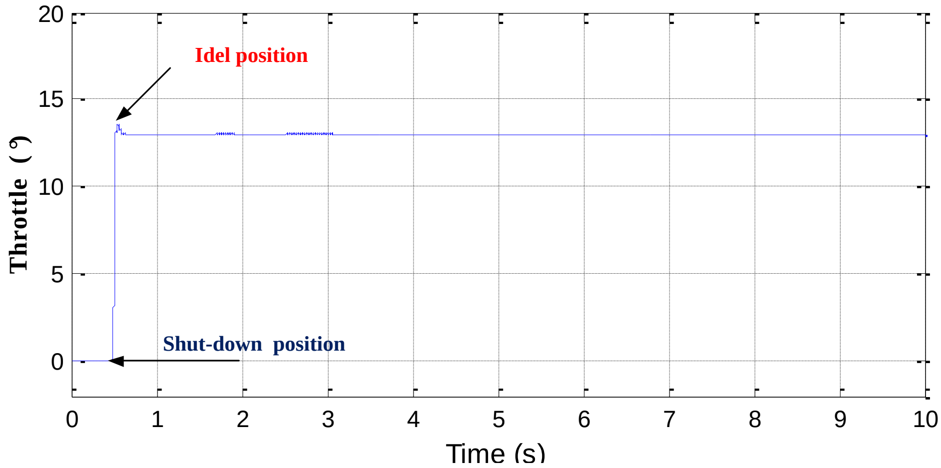

Figure 6-Dynamic response of the throttle of aircraft.

Fig.7 shows the high pressure compressor rotor n_2 of the engine. When *t*=0.5s, SG drives the engine and operates in starting mode before n_2=45% of the rated rotational speed. In addition, SG operates in transition mode during *t*=2.8~4.8 s. At *t*=6.75s, n_2 is 70% of the rated rotational speed and then the engine drives the SG. It can be observed that the SG provides DC bus voltage for aircraft in generator mode.

Fig.8 shows the dynamic response of main DC bus voltage of aircraft. During *t*=0~6.8s, the ground power provides 270V DC voltage for aircraft. When *t*=0.5s, SG accelerates the engine HP compressor rotor in starting mode and partial loads of aircraft are connected to the system. It can be observed that the main DC bus voltage drops slightly. When *t*=6.8s, SG provides electric power for aircraft. And the main DC bus voltage can be regulated to 270±3V to meet requirements of aircraft when all loads connected to the system.

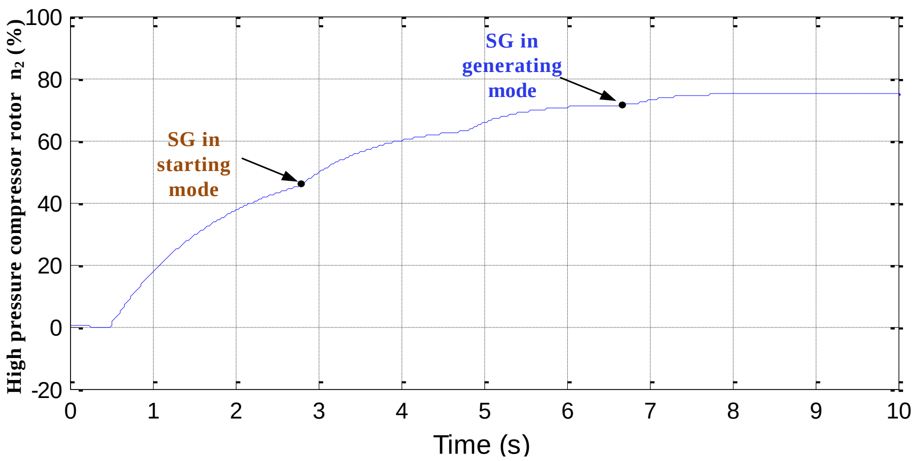

Figure 7-Dynamic response of the high pressure compressor rotor of aircraft.

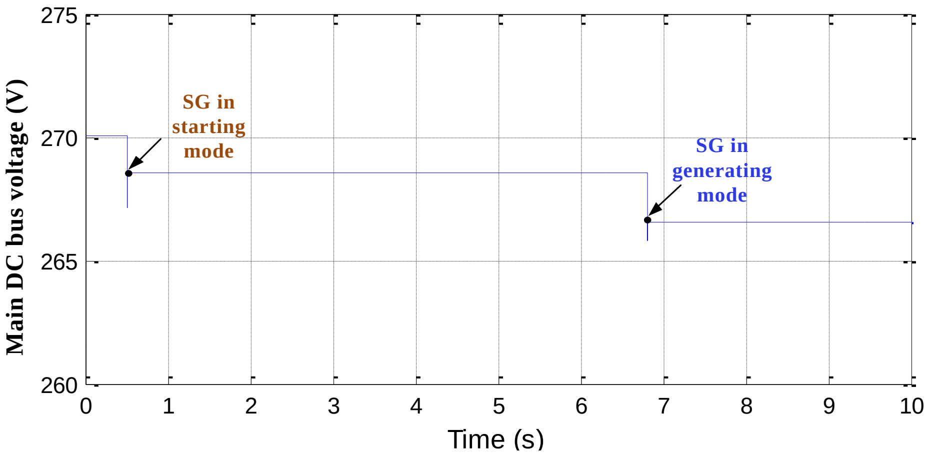

Figure 8-Dynamic response of the main DC bus of aircraft.

To conclude, the simulation results of the dynamic response of the high pressure compressor rotor and main DC bus voltage verify the effectiveness of the proposed control scheme and safety of the aircraft can be further ensured.

5. Conclusion

This paper introduces architecture of an integrated starting/generating system of aircraft, and proposes a control strategy to regulate the engine and output voltage of aircraft when SG operates in starting mode, transition mode and power generator mode. In starting mode, PI controller of voltage, current and frequency are considered to accelerate the engine high pressure compressor rotor to reference values. In transition mode, improved smooth switching control strategy is provided to improve the dynamic performance and reliability of SGS and guaranteed SG change to generator state safely. In generator mode, duel voltage and current closed loop controller are considered, which can regulate the main DC bus voltage to the rated value and meet requirements of aircraft when all loads connected to the system. In order to verify the correctness of the proposed control strategy, an integrated starting/power generator system is simulated in Matlab/Simulink environment. And the feasibility and effectiveness of the proposed control strategy can be validates and safety of the aircraft can be further ensured.

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7. Copyright Statement

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