An Enhanced Power Generation Centre for More Electric Aircraft Applications

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Abstract — The more-electric aircraft (MEA) concept has become a major trend due to its multiple advantages. Many functions which are conventionally driven by pneumatic, hydraulic and mechanical power systems are replaced by electrical ones onboard MEA. This results in increased electrical power demand for MEA. Due to power off-take limit from high-pressure (HP) spool of an engine, extra power needs to be extracted from the low-pressure (LP) spool. Besides, recent studies have revealed that transferring power between LP and HP shafts in certain flight missions, like taxiing and descending will not only decrease fuel consumption but also increase compressor surge margins. This paper introduces an enhanced power generation centre for the MEA applications. It extracts power from both HP and LP spools, with each shaft is driving one electrical generator. These generators supply electrical power to a common DC bus through active AC/DC converters. Using the droop-control concept, the power sharing between LP and HP shafts can be smoothly controlled. Control method when power transferred from LP spool to HP spool is also presented. This architecture is built and simulated in the Matlab/Simulink environment. Simulations results including performances of electrical machines, power converters and engine under different scenarios are presented in this paper.

Keywords — Modeling, power transfer, more electric aircraft (MEA), engine operating mode, starter/generator control.

I. INTRODUCTION

During the past decades, great progress has been made towards more electric aircraft (MEA) due to advantages like reduced CO$_2$ and NO$_x$ emission, decreased fuel consumption, low maintenance cost and etc. [1-3]. Due to the increased electrical equipment onboard MEA, it is essential to extract more electrical power from aircraft engines. This leads to significant challenges to design an efficient and reliable electrical power system (EPS) [4]. Different EPS structures are studied and compared in [5]. It reveals that compared with AC system generally adopted in modern aircrafts, the HVDC system is superior due to its high efficiency, convenience of paralleling DC multiple buses, no need for reactive power compensation [6-7]. Therefore, HVDC serves as a better choice for EPS structure.

Besides the challenge in EPS design, the increased electrical power demand also requires a suitable power extraction system in the engine. Conventionally, electrical power is extracted from the HP spool only [1]. However, extracting power only from HP spool could have a negative impact on the performance of engine, like compressor surge [15]. In [8-9], it has been proved that there is a limit on the amount of power off-take from HP shaft. If the power extracted is over the limit, the engine will surge and stall. This issue can be addressed either by increasing the speed of HP shaft or bypass excess air to fan discharge duct, whereas those measurements will increase the fuel consumption and lead to fuel waste [10]. Another way to extract more power is to take power from LP shaft, and this will lead to a multi-source power generation system within the engine.

A promising EPS with multi-source supplying a main DC bus is shown in Fig.1, and it will be referred as enhanced power generation centre (EPGC) in this paper. The engine fan, the LP compressor (LPC), and the LP turbine are connected through LP shaft. The HP compressor (HPC) and the HP turbine are connected via HP shaft. A starter/generator (SG) is attached to HP spool and a generator is linked to LP spool. The two electric machines are regulated by two bidirectional converters and supply a common main DC bus, of which the nominal voltage is 270V according to standard MIL-STD-704F. Here two permanent magnet machines (PMMs) are adopted. Details about why choosing PMMs can be found in [11]. The typical loads in MEA are constant impedance load (CIL), like resistive loads; And constant power load (CPL), like inductive loads; And constant power load (CPL), like motor drives regulated by power converters. It also worth to note that such parallel generation system is able to provide “no-break” power even one of the generator shutdown.

In addition to the aforementioned advantages, the EPGC can also achieve power transfer between LP and HP shafts, which would be beneficial for engine performance. For example, when engine operates at low speed settings, like...
taxiing and descent, the speed of HPC decreases which means HPC accepts less airflow. Thereby the bleeding is implemented between LPC and HPC to bypass excess air to fan discharge duct, preventing the risk of LPC surge. However, this action creates the waste of thrust. While by adding a bleed air to the fan discharge duct, preventing the risk of LPC surge. Implemented between LPC and HPC to bypass excess air to LP power generation channel. Thereby the bleeding is incorporated. Since HP machine works in a very high speed (e.g. from 10,000r/min to 20,000r/min [1]), flux weakening is needed to guarantee the HP machine to operate within the voltage limit circle. The command of $d$ axis current can be shown:

$$i_d^{ref} = \frac{k_{FW}}{s}(u_{e,max} - u_d)$$

where $k_{FW}$ is the integration gain of flux weakening controller; $u_{e,max} = \sqrt{3}v_e$, $u_d = \sqrt{u_{d,e}^2 + u_{d,q}^2}$. $C. LP Channel Voltage Controller Design$

First consider the design process for LP power generation channel. The overall control diagram of LP power generation channel is shown in Fig.3. The LP power generation is with the same control structure. The HP and LP power generation channels are in parallel and supplying a common DC bus. Power sharing between two channels are achieved by droop control. A current-mode droop method presented in [14] is adopted in this paper due to its advantages, including the absence of communication, high modularity, and immunity from the impact of cable impedance. The power sharing is achieved by supplying the total load current $i_L$ with currents $i_{dc,LP}$ and $i_{dc,HP}$, and $i_L = i_{dc,LP} + i_{dc,HP}$. Using droop control characteristic, the references for $i_{dc,LP}$ and $i_{dc,HP}$ can be given:

$$i_{dc,LP}^{ref} = \frac{V_{e,ref}}{g_{LP}} - \frac{V_{e,ref}}{g_{HP}}$$

where $g_{LP}$ and $g_{HP}$ are the droop gains and the current-mode droop characteristic is demonstrated in Fig.3.

In the following section the modeling process for LP power generation channel will be presented. According to the electrical dynamics shown in (1), the $q$-axis voltage in Laplace form can be expressed as:

$$u_q = -(R + L_S)\omega_S + \alpha_S\omega_S L_S$$

Since the generator is driven by an engine shaft which is normally with big inertia, the time constant of mechanical system will be bigger than that of electrical system. For small signal analysis, the electrical angular speed $\omega_S$, which is proportionate to the engine shaft speed can be viewed as a constant value. The small signal model of (5) thus can be given as:

$$\Delta u_q = -(R + L_S)\Delta \omega_S + \alpha_S L_S \Delta \omega_S$$

Considering the active power delivered by the LP generator as $P_{LP}$:

$$P_{LP} = \frac{3}{2}(u_d i_d + u_q i_q)$$
Equation (7) can be linearized at operating point (indicated with the subscript “o”) as:
\[
\Delta P_{LP} = \frac{3}{2} \left( \Delta u_{q_o} - (R + L_s) i_{q_o} \right) \Delta i_q
\]  
(8)

Considering the situation that LP generator operates in a region that no flux weakening is required, i.e. \(i_{d_{LP}} = 0\) and \(\Delta \sigma = 0\). Then (8) can be rewritten as:
\[
\Delta P_{LP} = \frac{3}{2} \left( \Delta u_{q_o} - (R + L_s) i_{q_o} \right) \Delta i_q
\]  
(9)

Combining (9) and (6), the active power of LP generator in small signal manner can be written as:
\[
\Delta P_{LP} = \frac{3}{2} \left( \Delta u_{q_o} - (R + L_s) i_{q_o} \right) \Delta i_q
\]  
(10)

The active power delivered from the AC side to the DC side can also be calculated as:
\[
P_{LP} = V_{dc} i_{d_{LP}}
\]

Applying small signal analysis to (11) gives:
\[
\Delta P_{LP} = V_{dc} \Delta i_{d_{LP}} + i_{d_{LP}} \Delta V_{dc}
\]

Combining (12) and (10) gives the relation between \(\Delta i_{d_{LP}}\) and \(\Delta i_q\):
\[
\frac{\Delta i_{d_{LP}}}{\Delta i_q} = \left( \frac{1.5}{V_{dc}} \right) \left( \frac{u_{q_o} - (R + L_s) i_{q_o}}{i_{d_{LP}} \Delta V_{dc}} \right) - \Delta i_q
\]  
(13)

Generally, the dynamic response of outer voltage loop is slower than that of inner current loop. Hence, the term \(\frac{i_{d_{LP}} \Delta V_{dc}}{V_{dc} \Delta i_q}\) can be treated as disturbance. Considering \(i_{d_{LP}} = P/V_{dc}\), where \(P\) is the total power required from the load, the following relationship in small signal manner can be derived according to the DC side configuration shown in Fig.3:
\[
C \frac{d \Delta V_{dc}}{dt} = \Delta i_d - \Delta i_q = \left( \frac{\Delta P}{V_{dc}} - \frac{P}{V_{dc}} \frac{d \Delta V_{dc}}{dt} \right) - \Delta i_q
\]  
(14)

In the Laplace domain, (14) can be rewritten as:
\[
\Delta V_{dc} = \frac{1}{Cs + \frac{P}{V_{dc}}^2} (\Delta i_d - \Delta i_q)
\]  
(15)

Assuming the power sharing ratio between LP converter and HP converter is \(k:1\), the ratio of corresponding droop gains should be \(1:k\) according to (4). Then the following relationship can be obtained:
\[
i_{d_{LP}} = i_{d_{HP}} \Rightarrow i_d = \left( 1 + \frac{1}{k} \right) i_{d_{LP}} = \sigma i_{d_{LP}}
\]  
(16)

where \(\sigma = (k+1)/k\).

Using equations (13), (15) and (16), the control block diagram of voltage-loop can be obtained in Fig.4. It worth to note that in the generation mode, the active power flow is towards the DC link, which indicates that \(i_{d_{LP}}\) is negative for redirecting the power flow to the DC link [11]. This is the reason why \(\Delta i_{d_{LP}}\) is negative in Fig.4.

In this paper, the bandwidth for voltage-loop is designed as 200Hz. Therefore, the current-loop can be simplified as a unit module since the bandwidth of current-loop is set to 1.5kHz, i.e. \(G(s) = 1\). Considering \(\Delta \sigma\) as a disturbance, and moving the feedback junction from \(\Delta i_{d_{LP}}\) to \(\Delta V_{dc}\), the diagram can be converted into Fig.5. Using the zero of PI controller to eliminate the pole of forward path, the PI controller can be designed using:
\[
k_{sp} + k_{si} = \gamma_L \left( C + \frac{P}{V_{dc}^2} \right)
\]

where \(k_{sp}\) and \(k_{si}\) are the proportion and integration gains of PI controller, \(\gamma_L\) is a factor related to closed-loop bandwidth. (17) reveals that \(k_{sp}\) and \(k_{si}\) are adaptive according to specific operation conditions, like output power \(P\) and DC voltage \(V_{dc}\). This will guarantee the desired transient and steady performance of DC voltage loop.

The machine parameter is shown in Table I, where \(R = 0.02\Omega, L_s = 99\mu H\). And \(V_{dc} = 270V, C = 1.5mF\). Assuming the speed of LP generator is 4,000rpm at full thrust setting, \(u_{q_o} = 0.45V\). The selection of droop gain \(g_{LP}\) is 1/5. In this paper, HP converter and LP converter are assumed to be with the same topology and switching devices, thereby assume they account for same power, i.e. \(\sigma = 2\). The \(V_{dc}\) closed-loop bode diagram when total power \(P\) changes from 20kW to 60kW is shown as Fig.6 when \(\gamma_L\) is tuned to 600.

It can be seen from Fig.6 that in the low-frequency region the magnitude is smaller than 0. This can be explained by the feature of droop control: the actual DC link voltage is smaller than the reference in heavy load condition due to the
Voltage limit circle: using the following equation, which is also the expression of closed-loop bode diagram can be obtained and given in Section B (Fig.5). Therefore the DC voltage of HP power generation channel is the same as that of LP channel, it is slightly different from the above process. Since HP machine works at a high speed, \( i_d < 0 \) to guarantee the torque weakening operation. In this case, \( i_d \) can be expressed using the following equation, which is also the expression of voltage limit circle:

\[
i_d = -\frac{\omega_f}{\omega_L} + \frac{V_{max}^2 - \left( \omega_f L_i \right)^2}{\omega_f L_i}
\]

(18)

where \( \omega_e \) is the electrical speed of HP SG; \( V_{max} \) is \( V_s/\sqrt{3} \).

Then the relationship between \( \Delta i_d \) and \( \Delta i_q \) can be derived:

\[
\Delta i_d = \frac{\partial f}{\partial i_q} \Delta i_q = \frac{\omega_f L_i}{\sqrt{V_{max}^2 - \left( \omega_f L_i \right)^2}} \Delta i_q
\]

(19)

Using equation (8) and (19), the transfer function between \( \Delta i_{d,HP} \) and \( \Delta i_q \) can be obtained:

\[
\frac{\Delta i_{d,HP}}{\Delta i_q} = \frac{-L_i s + \left( \omega_f L_i + u_{de} \right)}{V_{dc}} - R_i s
\]

(20)

The structure of DC voltage loop control block diagram of HP power generation channel is the same as that of LP channel which is shown in Fig.5. Therefore the DC voltage closed-loop bode diagram can be obtained and given in Fig.6.

For power transfer control design, the power transfer from LP to HP side is studied. The EPGC shown in Fig.1 is able to achieve power transfer between these two shafts by manipulating one of the converters as inverter and the machine in motoring mode. The control method is proposed in the following.

Assuming the rotary speed of HP machine as \( \omega_m \), the mechanical power is \( P_m = \omega_m T_m \), where \( T_m \) is the torque of HP machine. \( \omega_m \) is imposed by the engine shaft, therefore only torque, or current can be controlled when outputting certain power. The HP machine in this paper is also assumed to be a surface-mounted PMM of which the parameters are shown in Table I. The torque \( T_e \) can be expressed as:

\[
T_e = 1.5 \frac{P_{HP}}{\omega_m} \quad (21)
\]

where \( i_{q,HP} \) is the \( q \)-axis current of HP SG.

From (21), the \( i_{q,HP} \) reference can be obtained:

\[
i_{q,ref} = P_{HP} - 1.5 \frac{P_{HP}}{\omega_m} \quad (22)
\]

where \( P_{HP} \) is the power transferred from LP to HP side.

From (22), the \( i_{q,ref} \) can be obtained if \( P_{HP} \) is fixed. And \( i_{q,ref} \) comes from flux weakening controller shown in part B. The current control structure of HP SG has already been presented in Fig.2. Therefore the power transfer from LP to HP shaft is realized by controlling \( i_{d,LP} \) and \( i_{q,LP} \).

However, it needs to note that during the power transfer process, the LP machine performs as the unique power source. On the one hand it provides power to HP machine, on the other hand feeds the main DC bus. Therefore, the droop control should be revised since there is no need for power sharing between multi-sources. Here a compensation term is used to compensate the voltage deviation caused by the droop control, and the new voltage reference is:

\[
V_{ref} = V_{rated} + \gamma P_{rated} - \frac{1}{5} P_{rated}
\]

where \( P_{rated} \) is set as 1/5. The total power \( P \) changes from 20kW to 60kW. The factor \( \gamma \) which is related to bandwidth is tuned to 100. From Fig.7 it can be concluded that the closed-loop bandwidth for HP voltage loop is around 200Hz when choosing \( \gamma \) to 100.

### Power Transfer Control Design

The LP and HP spools of an engine are not mechanically connected, and they independently rotate [1]. In [15] it has been proved that transfer certain amount of power between two shafts could improve the engine performance at certain Engine Operating Mode. In this paper, power transfer from LP shaft to HP shaft is studied. The EPGC shown in Fig.1 is able to achieve power transfer between these two shafts by manipulating one of the converters as inverter and the machine in motoring mode. The control method is proposed in the following.

Assuming the rotary speed of HP machine as \( \omega_m \), mechanical power is \( P_m = \omega_m T_e \), where \( T_e \) is the torque of HP machine. \( \omega_m \) is imposed by the engine shaft, therefore only torque, or current can be controlled when outputting certain power. The HP machine in this paper is also assumed to be a surface-mounted PMM of which the parameters are shown in Table I. The torque \( T_e \) can be expressed as:

\[
T_e = 1.5 \frac{P_{HP}}{\omega_m} \quad (21)
\]

where \( i_{q,HP} \) is the \( q \)-axis current of HP SG.

From (21), the \( i_{q,HP} \) reference can be obtained:

\[
i_{q,ref} = P_{HP} - 1.5 \frac{P_{HP}}{\omega_m} \quad (22)
\]

where \( P_{HP} \) is the power transferred from LP to HP side.

From (22), the \( i_{q,ref} \) can be obtained if \( P_{HP} \) is fixed. And \( i_{q,ref} \) comes from flux weakening controller shown in part B. The current control structure of HP SG has already been presented in Fig.2. Therefore the power transfer from LP to HP shaft is realized by controlling \( i_{d,LP} \) and \( i_{q,LP} \).

### Table I. Parameters of PMM

| Parameter                  | Rated value |
|----------------------------|-------------|
| Motor Power                | 45 kW       |
| Poles                      | 6           |
| Phases                     | 3           |
| Stator Inductance (in dq axes) | 99 μH      |
| Flux Linkage of Magnet     | 0.03644 Wb  |

Fig.7. In Fig.7, assuming the speed of HP generator is 25,000r/min at full thrust settings. The droop gain \( g_{m} \) is set as 20 Hz. The total power \( P \) changes from 20kW to 60kW. The factor \( \gamma \) which is related to bandwidth is tuned to 100. From Fig.7 it can be concluded that the closed-loop bandwidth for HP voltage loop is around 200Hz when choosing \( \gamma \) to 100.
As aforementioned, transferring power from LP spool to HP spool at low speed settings could benefit both fuel efficiency and compressor surge margin. More detailed analysis could refer to [15]. In order to prove the benefits, maps from GASTURB (GasTurb 11, 2010) has been used to establish a two-spool high bypass ratio (BPR=8) unmixed flow 140 kN turbofan engine, where LPT drives the fan and the LPC via LP shaft, HPT drives axial HPC and radial HPC.
In the process of descending, the engine is normally on an idle mode. Under this condition, the HP speed should not be lower than the minimum limitation otherwise the engine cannot sustain its speed anymore. Results for flight idle at 20,000ft are presented in Fig. 11. The results reflect that as the increase of power transferred from LP to HP shaft, the speed of LP shaft will slight decrease and that of HP shaft will increase. This will reduce the fuel consumption and increase available compressors surge margin.

IV. CONCLUSION

In this paper, a multi-source single DC bus enhanced power generation centre (EPGC) is studied for MEA application. The EPGC system can work in two modes: dual-generator and power-transfer modes. Generally, the two electrical machines both work as generators to supply a common DC bus. While at certain engine operation mode, like flight idle mode, some amount of power can be transferred from LP shaft to HP shaft by controlling HP machine to work as a motor to speed up the HP shaft. This will benefit the fuel efficiency and compressor surge margin. Control method design are presented for both dual-generator and power-transfer modes.

Simulation results show that in dual-generator mode, the two generators can supply power to DC bus, and the power sharing ratio is set by droop control gains. The DC bus voltage will slightly reduce as the increase of load power due to droop effect. While in power-transfer mode, the LP machine serves as the only generator to supply power for both HP machine and load connected to the DC bus. And the DC bus voltage can be kept to its nominal value in steady state. In addition, the simulation results of engine performances confirm the improvement of fuel efficiency and compressor surge margin in flight idle mode if power transfer is carried out from LP to HP shaft. The results highlight the promising future for applying such EPGC system in future MEA applications.

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