A Dual-Channel-Enhanced Power Generation Architecture With Back-to-Back Converter for MEA Application

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Abstract—This article proposes an improved power generation architecture (PGA) for future more electric aircraft applications. In the proposed architecture, a starter/generator is connected to the high-pressure (HP) shaft, and a generator is connected to the low-pressure (LP) shaft. Their outputs supply a common dc bus via active power converters. A back-to-back (B2B) converter is deployed to link the ac terminals of the two generators. The proposed topology embraces three main advantages. First, with the B2B converter, the HP generator can operate at a high speed without flux weakening; thus, the magnitude of stator current will be decreased when output same active power. This will lead to the reduction of power losses on the generators and the active rectifiers. Second, the proposed PGA allows power transfer from the LP and to the HP shafts. This can potentially reduce the fuel consumption and increase aircraft engine compressor surge margins when the engine is at low-speed setting. Third, the B2B converter provides an additional power flow path to the generators under converter fault scenarios, hence improving the postfault operation ability. For the proposed PGA, engine benefits, modeling, control design, and efficiency improvements are illustrated in detail. The control performances of the proposed PGA, engine performance improvement by transferring power from the LP to HP shaft, and power loss reduction are verified via simulations and experimental results collected from a twin-shaft aircraft power generation test rig.

Index Terms—Back-to-back (B2B) converter, modeling, more electric aircraft (MEA), power generation control, power transfer.

I. INTRODUCTION

The more electric aircraft (MEA) concept is one of the major trends toward the modern aerospace industry for gas emission reduction, decreased fuel consumption, low maintenance cost, etc. [1]. Existing pneumatic, hydraulic, and mechanical actuators are substituted by their electrical counterparts on MEA. Consequently, the onboard installed electrical power increases significantly and this results in high electrical power demand. For a twin-shaft engine, the LPT drives the fan and LPC via the LP shaft, and the HPT drives the axial and radial HPCs via HP shaft. Traditionally, electrical generator is driven by a gearbox linked to the HP shaft of the engine. This is due to the desirable HP shaft characteristics, such as high and relatively constant speed, which enables engines to decrease the size and weight of HPG. Nevertheless, extracting the high amount of power from the HP shaft could have a negative impact on the performance of the engine system. In [2] and [3], it has been proved that there is a limit on the amount of power off take from HP shaft, where if exceeded will cause compressor surge a critical threat to the engine. This can be addressed by oversizing the HPT or excessive bleedings, whereas those actions will either increase the fuel consumption or lead to undesirable thrust [4].

An alternative way is to use the LP shaft as an additional power source, i.e., using the LP shaft to drive another electrical generator. Because of the wide speed range of the two shaft drives, the easiest way concerning power electronic devices is to supply the electric power to one common dc bus, as dc bus configuration can reduce weight and does not need reactive power compensation component compared with ac bus. This gives a two-generator single-dc-bus structure. So far, several publications have dedicated on designing proper power generation architectures (PGAs) with different types of electrical machines.
To resolve the aforementioned issues of the PGA in Fig. 1, a new PGA containing a back-to-back (B2B) converter is proposed, as shown in Fig. 2. The additional B2B converter will bring various benefits including the following.

1) Enabling the HPG to operate without FW at high speed.
2) Better fault tolerance performance as an additional power flow channel is provided when the converters associated with HPG or LPG are shutdown.
3) Enabling power transfer between LPG and HPG. This will increase the compressor margin and its overall efficiency.

The rest of the article is organized as follows. Details of the proposed PGA and the basics of the engine will be described in Section II. Section III illustrates the modeling and controller design of the whole system, including a voltage controller, power-sharing method, inductor selection, power-transfer control, etc. Section IV compares the power loss of the proposed PGA and the existing PGA in Fig. 1. In Section V, control performances of the proposed PGA and benefits to engine performance when transferring power from the LP to HP shaft as well as power loss reduction using the proposed PGA are validated. Section VI makes a conclusion of the whole article.

II. PROPOSED PGA AND THE BASICS OF TURBOFAN ENGINE

A. Proposed PGA With a B2B Converter

The diagram of the proposed PGA is shown in Fig. 2. Two electrical generators (HPG and LPG) are supplying a common dc bus (270 V) through its own dedicated converter. A B2B converter is used to connect the HPG and LPG. When the modern engine is moving toward more electric and with high-bypass ratio, the electrical power that can be extracted from the HP shaft will become further limited. Thus, it is considered that LPG generally outputs more power than HPG [3], [10]. In this case, the B2B converter is mainly used to transfer power from the LP side to the HP side. Therefore, the converter connected to the LPG within the B2B converter is denoted as \( B2B_{\text{Rectifier}} \) and the other is denoted as \( B2B_{\text{Inverter}} \). Besides, it is worth to note that the intermediate voltage \( V_{\text{mid}} \) in the B2B converter can be set to a value much higher than 270 V, as it does not supply onboard loads directly. Two groups of inductors, denoted as \( L_1 \) and \( L_2 \), respectively, are deployed to separate voltage sources, i.e., LP converter and \( B2B_{\text{Rectifier}} \), and HP converter and \( B2B_{\text{Inverter}} \). To the best knowledge of authors, this is the first time to present this kind of PGA. The main contributions of the proposed PGA are highlighted as follows.

1) HPG could operate at a high speed without FW due to high \( V_{\text{mid}} \) in the B2B converter. Hence, the magnitude of the stator current will decrease. This will help to reduce the power losses in HPG and power converters.
2) The proposed PGA has the postfault operation ability when any of the HP or LP converters shut down under fault scenarios since the B2B converter provides an additional power flow path to both LPG and HPG.
3) The power of LP shaft can be transferred to HP shaft electrically via the B2B converter by controlling HP machine in motoring mode. This will not only improve the fuel efficiency but also increase the compressor surge margin.
B. Basics of Turbofan Engine

In this part, the basics of turbofan engine will be introduced and the reason why power transfer from the LP to HP shaft is beneficial to engine performance will also be explained.

High-bypass ratio turbofan is considered as the dominant source of propulsion for most of the civil aircraft. The schematic diagram of a two-spool high-bypass turbofan engine with an unmixed exhaust is shown in Fig. 2. The major engine components of a turbofan can be named as fan, booster (LPC), HPC, combustion chamber, HPT, LPT, and discharge nozzles. The HPT drives the HPC on the HP shaft and the LPT drives the fan and LPC on the LP shaft.

In order to study the effect of the proposed power-transfer method on engine performance, an aircraft engine model has been developed with the article presented in [2] and [3] by our group. The model contains the nonlinear thermodynamic behavior of a multispool engine for the whole range of operation. In this article, it is proved that by transferring power from the LP to HP shaft, the fuel consumption will be reduced and compressor SM will be expended. To make the advantages more understandable, the basics of compressor surge and the relationship between fuel consumption and power transfer are given as follows.

1) SM Enlargement by Power Transfer: The surge effect is a critical threat to the engine. If the downstream pressure of the compressor keeps increasing, at some point, the pressurized air will act as a blockage, causing total breakdown of the airflow and stall all over the compressor blades, accompanied with the reversal of the airflow. This phenomenon is referred to as surge. Surge can lead to mechanical damage to the compressor blades and the thrust bearings due to the large fluctuations of airflow and direction of the forces on the rotor. Until now, multispool and variable geometry compressors have been the main solutions to overcome the surge phenomenon [14].

By electric power transfer from the LP to HP shaft at low-speed settings, the swallowing capacity of the engine, the swallowing capacity of HPC increases. This widens the SM of LPC and HPC. SM is referred to as the margin between the operating line and surge line on the compressor map (see Fig. 3).

2) Fuel Consumption Reduction by Power Transfer: The engine efficiency is higher at a higher core pressure ratio. In this case, power transfer from LP to HP shaft can move the operating line to higher pressure ratios at low-speed settings of the engine. With a higher pressure ratio, the fuel consumption is reduced. Hence, with the proposed PGA, the desirable amount of power can be transferred from LP to the HP shaft via the B2B converter by controlling the HPG as a motor. This will increase compressor SM and efficiency.

III. MODELING AND CONTROLLERS DESIGN

Since the proposed PGA contains two ARs, one B2B converter, two PMGs with distinct speeds, and two groups of inductors, the modeling and controller design is complex and challenging. In this article, different controllers are tailored for controlling the LP, HP, and B2B converters to achieve power and voltage control. The controller gains are adaptive to keep a constant closed-loop bandwidth. Droop control is utilized for power sharing between the sources. The criteria of inductor $L_1$ selection are derived from the phase diagram analysis and gradient descent method.

In Fig. 2, there are four power converters: LP converter, HP converter, B2B Rectifier, and B2B Inverter. They can be further classified according to their positions: LP converter and B2B Rectifier are the LP-side converters, and HP converter and B2B Inverter belong to the HP-side converters. The control methods design of the LP- and HP-side power converters, the selection of inductors, and how to control the system in the converter fault scenario are illustrated as follows.

A. Modeling and Controller Design for LP-Side Converters

1) Voltage Control for LP Converter: The overall control diagram of the LP converter is shown in Fig. 4. It can be seen from Fig. 2 that the HP converter and LP converter are parallel connected to supply a common dc bus; therefore, measures
should be taken to realize the output power sharing between two converters. Here, the current-mode droop method presented in [9] is adopted to fulfill power sharing. Its aim is to control individual dc current to follow the reference computed from the droop characteristic, which is shown as

\[
i_{\text{ref}}^\text{dc} = \frac{(V_{\text{ref}}^\text{dc} - V_{\text{dc}})}{g_{\text{LP}}}
\]  
(1)

where \(g_{\text{LP}}\) is the droop gain of the LP converter.

The dynamic equations for PMG in generator mode in \(dq\) frame are given as follows:

\[
\frac{di_d}{dt} = \frac{1}{L_d} (-u_d - R_s i_d + \omega_c L_d i_q)
\]
\[
\frac{di_q}{dt} = \frac{1}{L_q} (-u_q - R_s i_q - \omega_c L_d i_d + \omega_c \psi_f)
\]

where \(u_d\) and \(u_q\) are the \(dq\) axes stator voltages for LPG; \(i_d\) and \(i_q\) are the \(dq\) axes stator currents for LPG; \(L_d\) and \(L_q\) are the \(dq\) axes stator inductance of LPG; \(R_s\) is the stator resistance; \(\psi_f\) is the flux linkage of permanent magnet; and \(\omega_c\) is the electrical rotor speed. For the surface-mounted PMG used in this article, \(L_d = L_q = L_s\).

Since LPG is connected to the LP shaft, which has a large moment of inertia, the mechanical constant can be treated as much slower than the electrical constant. Then, the linearized \(q\)-axis voltage can be derived as

\[
\Delta u_q = -(R + L_s s) \Delta i_q - \omega_c L_s \Delta i_d.
\]  
(3)

The linearized active power of the LP converter can be expressed at operating point (indicated with “o”) as follows:

\[
\Delta P_{\text{LP}} = 1.5 \left( \Delta u_d i_{\text{ds}} + u_{\text{do}} \Delta i_{\text{ds}} + \Delta u_q i_{\text{qs}} + u_{\text{qo}} \Delta i_{\text{qs}} \right)
\]  
(4)

where \(i_{\text{ds}}\) and \(i_{\text{qs}}\) are obtained from LP-side main branch currents \(i_{\text{LS}}, i_{\text{bLS}},\) and \(i_{\text{cLS}}\) in Fig. 5; and \(P_{\text{LP}}\) is the output power of the LP converter.

Assume that the ratio between the power generated by LPG and the power transferred to B2B\(_{\text{Rectifier}}\) is \(n:1\); hence, \(i_{\text{qo}}\) is \(n:1\). Consider the situation that LPG operates with \(i_{\text{d}} = 0\), the linearized active power of the LP converter in a small-signal manner can be written as

\[
\Delta P_{\text{LP}} = 1.5 \left( \Delta u_q i_{\text{qso}} + u_{\text{qo}} \Delta i_{\text{qs}} \right)
\]
\[
= 1.5 \left[ \rho u_{\text{qo}} - (R + L_s s) i_{\text{qso}} \right] \Delta i_{\text{q}}
\]  
(5)

where \(\rho = (n-1):n\). Since the active power in a small-signal manner can also be represented as \(\Delta P_{\text{LP}} = V_{\text{dc}} \Delta i_{\text{dcLP}}\), the transfer function between \(\Delta i_{\text{dcLP}}\) and \(\Delta i_{\text{q}}\) can be obtained as

\[
\frac{\Delta i_{\text{dcLP}}}{\Delta i_{\text{q}}} = \frac{1.5 \left[ \rho u_{\text{qo}} - (R + L_s s) i_{\text{qso}} \right]}{V_{\text{dc}}}.
\]  
(6)

Considering \(i_{\text{dc}} = P/V_{\text{dc}},\) the following relationship in a small-signal manner can be derived as:

\[
C \frac{dV_{\text{dc}}}{dt} = \Delta i_{\text{dc}} - \Delta i_L = \left( \frac{\Delta P}{V_{\text{dc}}} - \frac{P_o}{V_{\text{dc}}^2} \right) V_{\text{dc}} - \Delta i_L.
\]  
(7)

In the Laplace domain, (7) can be rewritten as

\[
\Delta V_{\text{dc}} = \frac{1}{C s + \frac{P_o}{V_{\text{dc}}^2}} (\Delta i_{\text{dc}} - \Delta i_L).
\]  
(8)

Assume that the power-sharing ratio between the LP converter and HP converter is \(k:1\), then the ratio of corresponding droop gains is \(1:k\). Then, the following relationship can be derived as:

\[
i_{\text{dcLP}} = ki_{\text{dcHP}} \Rightarrow i_{\text{dc}} = (1 + 1/k) i_{\text{dcLP}} = \sigma i_{\text{dcLP}}
\]  
(9)

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

Using (6)–(9), the control block diagram of the LP converter can be constructed in Fig. 6. Using the zero of voltage-loop proportion-integration (PI) controller to eliminate the pole of forward path, the expression of PI controller can be given as

\[
k_{\text{vp}} + k_{\text{vi}} = \frac{\omega_c (C s + P_o/V_{\text{dc}}^2)}{s}
\]  
(10)

where \(k_{\text{vp}}\) and \(k_{\text{vi}}\) are the proportion and integration gains of PI controller, \(\omega_c\) is a factor related to the closed-loop bandwidth. Equation (10) reveals that \(k_{\text{vp}}\) and \(k_{\text{vi}}\) should be adaptive according to different operation conditions, such as \(P_o\) and \(V_{\text{dc}}\).

By tuning factor \(\omega_c\) instead of \(k_{\text{vp}}\) and \(k_{\text{vi}}\), desirable transient and steady performance of dc voltage loop can be obtained.

From Fig. 6, the closed-loop transfer function of voltage loop can be derived as eq. (11) shown at the bottom of this page. Where \(g_{\text{LP}}\) is the droop gain, \(a_1 = -1.5 \omega_c L_q i_{\text{qso}}, a_0 = 1.5 \omega_c (u_{\text{qo}} - R_{\text{qso}}), b_1 = V_{\text{dc}}, m_1 = V_{\text{dc}} C, m_0 = P,\) and \(n_0 = V_{\text{dc}}^2 \sigma\).

System parameters are given in Table 1. In this article, the HP and LP converters account for the same power, i.e., \(\sigma = 2\). By comparing the characteristic equation in (11) with the desired second-order system, \(\omega_c\) can be obtained by the pole placement technique [15]. In this article, the desired poles are placed at

\[
G_{\text{cc}}(s) = \frac{a_1 m_0 + a_0 n_0}{g_{\text{LP}} a_1 m_1 s^2 + [g_{\text{LP}} (a_1 m_0 + a_0 m_1 - n_0 b_1) + a_1 n_0] s + (g_{\text{LP}} a_0 m_0 + a_0 n_0)}
\]  
(11)
−300 ± j 810, which guarantee the stability and closed-loop bandwidth at 200 Hz simultaneously.

The closed-loop bode diagram when total power $P$ changes from 20 to 60 kW is shown in Fig. 7. As can be seen from Fig. 7, 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 droop characteristic. Moreover, at around 200 Hz, the magnitude damps −3 dB compared with the initial value in the low-frequency region. This proves that the bandwidth of the designed voltage loop is set to around 200 Hz, no matter how $P$ changes by choosing the factor $\omega_c$ using the pole placement idea.

2) Selection of Inductor $L_1$: From Fig. 5, the LP-side circuit is derived as Fig. 8(a), where $U_{a\text{Con}}$ represents a phase voltage generated by the LP converter, $U_{a\text{Rec}}$ is the voltage generated

![Fig. 8. Equivalent circuit and phase diagram of the LP-side circuit. (a) Equivalent circuit of a phase. (b) Phase diagram of LP-side voltage vectors.](image)

by B2B_{Rectifier}, $N$ is the reference point of B2B_{Rectifier}, and $N'$ is the reference point of the LP converter. The inductor $L_1$ is important because of two main reasons: First, it separates $U_{a\text{Con}}$ and $U_{a\text{Rec}}$, and adjust $U_{a\text{Rec}}$ according to load profiles; Second, it filters high-frequency pulsewidth modulation (PWM) harmonics. Therefore, the optimal value of $L_1$ should be carefully selected. If the value is too large, the weight and size of the core of $L_1$ will increase. If the value is too small, it cannot fulfill the function to filter the high-frequency PWM harmonics.

The following voltage equation can be obtained from Fig. 8(a) using Kirchhoff voltage law:

$$u_{a\text{Con}} = R_i a_{\text{Rec}} + L_1 \frac{d i_{a\text{Rec}}}{dt} + u_{a\text{Rec}} + u_{NN'}.$$  

(12)

Since $|V_{L1}| = j\omega L_1 |I_{\text{Rec}}| \cos \theta = \sin \varphi$, (14) can be rewritten as

$$|U_{\text{Rec}}|^2 = |U_{\text{Con}}|^2 + \omega^2 L_1 |I_{\text{Rec}}|^2 - 2 \omega L_1 |U_{\text{Con}}| |I_{\text{Rec}}| \sin \varphi.$$  

(15)
Choose $L_1$ as the variable, then $L_1$ can be obtained as

$$L_1 = \left[ \frac{\bar{U}_{Con}}{\sin \varphi + \sqrt{\bar{U}_{Con}^2 \sin^2 \varphi + \bar{U}_{Rec}^2 - \bar{U}_{Con}^2}} \cdot \frac{1}{\omega} \right] \mid \bar{I}_{Rec} \mid \ . \tag{16}$$

The phase diagram of LPG is demonstrated in Fig. 9, considering that LPG operates in $i_q = 0$ mode. The expressions of LP-side variables can be given as follows:

$$\left| \frac{\bar{U}_{Con}}{\sin \varphi + \sqrt{\bar{U}_{Con}^2 \sin^2 \varphi + \bar{U}_{Rec}^2 - \bar{U}_{Con}^2}} \cdot \frac{1}{\omega} \right| \mid \bar{I}_{Rec} \mid \ . \tag{17}$$

where $\omega_{eLP}$, $i_{qLP}$, and $P_{LP}$ are the speed, $q$-axis current, and output power of LPG, respectively. The ratio between the power generated by LPG and the power transferred to B2B is assumed to be $n:1$.

The phase diagram of LPG is shown in Fig. 9.

$$\varphi = \gamma = -\arctan \left( \frac{\omega_e L_i q_{Lq}}{\omega_e f - R_s i_{Lq}} \right) . \tag{18}$$

Considering the modulation technique applied to the B2B, the largest modulation index (MI) is $3\sqrt{3}/3$; hence, the following expression regarding $\bar{U}_{Rec}$ can be derived considering both largest MI and phase diagram in Fig. 8(b):

$$\left| \bar{U}_{Con} \sin \theta \right| \leq \left| \bar{U}_{Rec} \right| \leq \frac{\sqrt{3}}{3} V_{mid} . \tag{19}$$

Substituting (17)–(19) into (16), the value of $L_1$ can be expressed as the function of $\omega_{eLP}$, $P_{LP}$, and $n$ as follows:

$$J(\Theta)_{\min} \leq L_1 = J(\Theta) \leq J(\Theta)_{\max} \tag{20}$$

where

$$J(\Theta)_{\min} = n L_q$$

$$J(\Theta)_{\max} = n L_q + \frac{1.5 n T \sqrt{V_{mid}^2 / 3 - (\omega_{eLP} f R_s i_{Lq})^2}}{P_{LP}}$$

and $\Theta = [\omega_{eLP}, P_{LP}, n]^T$.

The operation region for LPG is speed: 2000–10 000 r/min, $P_{LP}$: 10–60 kW, and $n$: 5–7. Hence, the maximum value of $J(\Theta)_{\min}$ should be $n_{\max} = 0.7$ mH. And $\min(\Theta, \max)$ can be obtained by solving the iterative equation in (21). The result within the given operation region is 1.5 mH.

For further validating this result, the relationships of $J(\Theta)_{\max}$ and $\omega_{eLP}$, $P_{LP}$, and $n$ are also plotted in Fig. 10. Here, two main findings can be summarized.

1. From Fig. 10(a), it can be seen that $\min(\Theta, \max)$ is almost independent of the LPG speed $\omega_{eLP}$. This means that the selection of $L_1$ does not rely on $\omega_{eLP}$.

2. From Fig. 10(b), it shows that $\min(\Theta, \max)$ locates on the point of the maximum power of $P_{LP}$ and minimum power ratio $n$. This indicates that the value of $L_1$ is very sensitive to $P_{LP}$ and $n$.

The result in Fig. 10(b) matches with that from the iterative equation, both with 1.5 mH. Hence, the value of $L_1$ should be chosen between 0.7 and 1.5 mH. In the latter validations, the value of $L_1$ is set as 1.0 mH.

3. Controller Design of B2B, branches: Since the phase terminals of LPG and B2B branches share the same junctions, as shown in Fig. 5, an effective way to control the transferred power to B2B is to control the phase currents of LPG ($i_{xL}$) and B2B ($i_{xRec}, x = a, b, c$) [see Fig. 11] in phase. Hence, the ratio of the phase current magnitude is proportional to the ratio of power.

Apart from regulating currents in phase, the B2B controller is also responsible to control the intermediate dc voltage $V_{mid}$. However, if adopting the conventional control structures in applications, such as active front-end [18] or flywheel energy storage system [19], the output of outer voltage controller, which is the reference of active power or active current, will not be able to control $i_{xRec}$ and $i_{xL}$ in phase. To cope with this problem, a new method is proposed aiming to realize the following two major functions:

1. dc voltage $V_{mid}$ regulation;
2) controlling currents \(i_{x \text{Rec}}\) and \(i_{xL}\) in phase, \(x = a, b, c\).

The block diagram of B2BRectifier controller is shown in Fig. 11. Compared with the conventional control structure in [18] and [19], where active current reference equals to the output of voltage controller, in the proposed control structure, current references come from the product of the LPG dq axes currents and a gain \(m\). Obviously, in this way, the phase currents \(i_{x \text{Rec}}\) and \(i_{xL}\) can be controlled in phase if \(i_{x \text{Rec}}\) and \(i_{xL}\) conduct abc/dq transformation using same frame. And the value of \(m\) should increase so that more current can be pumped into dc link and \(V_{\text{mid}}\) will increase, and vice versa. Therefore, with such control method, \(V_{\text{mid}}\) can be stabilized and \(i_{x \text{Rec}}\) can be controlled in phase with \(i_{xL}\).

B. Modeling and Control Design for HP-Side Converters

1) Controller Design of B2BInverter. As can be seen in Fig. 2, terminals of HPG are directly connected to the B2BInverter. Therefore, the operation of HPG is controlled by the B2BInverter. The rotary speed of HPG is imposed by the HP shaft of the engine and is denoted as \(\omega_{m \text{HP}}\). Hence, for properly controlling the power of HPG, the core is to control the torque for a surface-mounted permanent magnet (PM) machine is to control the \(q\)-axis current. Hence, the \(q\)-axis current reference can be obtained as follows:

\[
i_{q \text{ref}} = \frac{P_{\text{HP}}}{1.5 pe \omega_{m \text{HP}}} \tag{22}
\]

where \(P_{\text{HP}}\) and \(p\) are the power and pole pairs of HPG.

Since the dc voltage \(V_{\text{mid}}\) is set high enough, the HPG is able to operate at high generation speed without FW. Hence, \(i_{d \text{Ref}}\) is set as 0 to maximize efficiency.

2) Control Design for HP Converter: The equivalent circuit of a phase at HP side is presented in Fig. 12. The electrical dynamics in \(dq\) axes can be derived as

\[
\begin{align*}
    u_{d \text{Inv}} &= R i_{dHs} + L_2 \frac{d i_{dHs}}{dt} + u_{d \text{Con}} - \omega L_2 i_{qHs} \\
    u_{q \text{Inv}} &= R i_{qHs} + L_2 \frac{d i_{qHs}}{dt} + u_{q \text{Con}} + \omega L_2 i_{dHs} \\
    P_{\text{HP,Con}} &= 1.5 (u_{d \text{Con}} i_{dHs} + u_{q \text{Con}} i_{qHs})
\end{align*}
\tag{23}
\]

where the direction of the voltage vector \(U_{\text{Inv}}\) generated by the B2BInverter is selected as \(d\)-axis, which means \(u_{d \text{Inv}} = U_{\text{Inv}}\) and \(u_{q \text{Inv}} = 0\). The position of \(U_{\text{Inv}}\) is obtained by implementing a phase-locked loop to voltages \(U_{a \text{Inv}}, U_{b \text{Inv}},\) and \(U_{c \text{Inv}}\). Besides, \(u_{d \text{Con}}\) and \(u_{q \text{Con}}\) are the \(dq\) axes’ voltages generated by the HP converter, \(i_{dHs}\) and \(i_{qHs}\) are the \(dq\) axes currents of HP-side main branches; and \(P_{\text{HP,Con}}\) is the active power of HP converter.

Next we discuss how to acquire \(dq\) current reference. As aforementioned, the power sharing of LP and HP converters is fulfilled by droop control. Therefore, the active current reference comes from the droop controller. It should be noted that the magnitude of \(U_{\text{Con}}\) is smaller than \(U_{\text{Inv}}\); hence, the reactive current cannot be 0 as what usually do to control the grid-connected AR [13]. Here, the reactive current command is obtained from the required power of HP converter. Assume that the power sharing ratio between LP and HP converter is \(k:1\). Based on (23), the reactive current reference can be derived as

\[
i_{qHs} = \left[ \frac{P}{1.5 (k + 1)} - u_{d \text{Con}} i_{dHs} \right] / u_{q \text{Con}} \tag{24}
\]

where \(P\) is the total power demand.

The overall control diagram of the HP converter is shown in Fig. 13. In Fig. 13, \(g_{\text{HP}}\) is the droop gain; the decoupling terms in the current loop are obtained from (23).

C. Postfault Operation When HP Converter Shuts Down

One of the main advantages of the proposed PGA over the existing one in Fig. 1 is the postfault operation ability. For
example, when using the PGA in Fig. 1, if HP converter fails, such as the open-circuit fault, the HP converter should be shut down; hence, the HPG cannot provide power to the loads if there is no redundant converter. While with the proposed PGA, the B2B converter provides an additional power flow path for the HPG when the HP converter fails. The power flow, when the HP converter fails, is shown in Fig. 14.

In this case, there are three converters left in the system, B2BInverter, B2BRectifier, and LP converter. The structures of their controllers are discussed in the following text but the details are not given since this is not the main focus of this article.

1) For the controller of B2BInverter, there should be two cascaded loops, the outer loop is responsible for stabilizing the voltage \( V_{\text{mid}} \), and the inner loop should be the current loop to control the \( dq \) axes currents of the HPG.

2) For the controller of B2BRectifier, there should be two major functions. The first one is to make sure the phase current of LPG and the phase current of \( L_1 \) in phase. The second is to manipulate the magnitude ratio of the phase currents of LPG and the phase current of \( L_1 \) to transfer a given amount of power via the B2B converter.

3) For the controller of the LP converter, an outer voltage loop is required for controlling the main dc bus voltage to 270 V. And the inner loop is supposed to control the \( dq \) axes currents of LPG.

D. Power Control of the System

Here, the power control method for HP and LPs, HP and LP converters, and B2B converter is summarized. The power of HPG is independently controlled by B2BInverter, and power sharing between the LP and HP converter is realized by a droop method. Hence, the power transferring via the B2B channel is self-tuned by the difference between the powers of HPG and HP converter.

IV. EFFICIENCY IMPROVEMENTS

In this section, the power losses of generators and power converters of the existing PGA (denoted as PGA\(_1\)) and the proposed PGA (denoted as PGA\(_2\)) are discussed. As a starting point, the expressions of generator losses are given.

The copper loss of the PMG is given as follows:

\[
P_{\text{copper}} = \frac{3}{2} R_s I^2
\]  

(25)

where \( R_s \) is the stator resistance and \( I \) is the peak value of the phase current.

The iron loss density \( P_{\text{iron}} \) is modeled approximately as

\[
P_{\text{iron}} = P_h + P_e = k_h B^2 \omega_c + k_e B^2 \omega_e^2 \quad \text{W/m}^3
\]  

(26)

where \( P_h \) and \( P_e \) are the hysteresis and the eddy current loss, respectively, \( k_h \) is the hysteresis constant, \( k_e \) is the eddy current constant, \( B \) is the magnetic flux density, and \( \beta \) is the Steinmetz constant.

Here, the operating trajectories of HPG under different speeds are presented in Fig. 15. As can be seen in Fig. 15 that with a 270 V dc bus voltage, the HPG has to work in the FW region in most of the time of the generation mode at high speed. While with an increased dc bus voltage 400 V, the \( d \)-axis current can be allowed to be 0 at high speed, hence greatly decreasing the current magnitude when generating the same active power. Based on (25) and (26), some conclusions regarding the generator loss can be derived.

1) From (25), it can be concluded that compared with PGA\(_2\), the existing PGA\(_1\) will lead to large copper loss due to large FW current, or \( d \)-axis current.

2) The FW effect caused by large \( d \)-axis current in PGA\(_1\) will help to diminish the flux density \( B \) in the stator core, as a consequence from (26), the iron loss would be a bit smaller than that of PGA\(_2\) at the same speed.

Here, HPG losses are studied with a finite-element analysis (FEA) tool MagNet and validated by experiments. The details of the main findings are given in Section V-C. Apart from the machine loss, attention is also paid to the converter loss. The conduction loss of one IGBT and diode is given as

\[
\begin{align*}
P_{\text{IGBT}} &= \frac{1}{2} IV_t \left( \frac{1}{\pi} + \frac{M}{3} \cos \phi \right) + I^2 R_{ce} \left( \frac{1}{3} + \frac{2M}{3\pi} \cos \phi \right) \\
P_{\text{diode}} &= \frac{1}{2} IV_j \left( \frac{1}{\pi} - \frac{M}{2\pi} \cos \phi \right) + I^2 R_{ak} \left( \frac{1}{4} - \frac{2M}{3\pi} \cos \phi \right)
\end{align*}
\]  

(27)

where \( V_t \) and \( V_j \) are the built-in voltages of the IGBT and diode, while \( R_{ce} \) and \( R_{ak} \) are the differential resistances of the IGBT.
and diode, respectively. $M$ is the MI, $\varphi$ is the displacement angle between the fundamental of the voltage and the current.

Since the proposed PGA$_2$ helps to reduce the magnitude of phase current $I$ compared with PGA$_1$; thus, from (27), it can be expected that the conduction loss of HP converter can be significantly reduced when using PGA$_2$ than PGA$_1$.

V. VALIDATIONS

An overall control block diagram of the proposed PGA is demonstrated in Fig. 16, where the connections of various components and control structures of LP, HP, and B2B converters are presented. A test rig for mimicking the LP and HP shafts of a twin-shaft engine is constructed, as shown in Fig. 2. It is composed of two PMGs and two induction machines as prime movers. Two bidirectional three-level neutral point clamped (NPC) converters are used as the interfaces between the LP and HP generators and dc bus. Experiments of power transfer from the LP to HP shaft and power loss analysis are done on this rig, which verifies the improvements in engine performance and power loss reduction using the proposed PGA. Simulations of the control performance of the proposed PGA are also conducted.

A. Proposed PGA in Dual-Generator and Power-Transfer Modes

In the dual-generator mode, HP and LP machines both perform as generators. The results are shown in Fig. 17(a)–(e). In the power-transfer mode, the HP machine performs as a motor providing power to the HP shaft. The results are shown in Fig. 17(f). In the dual-generator mode, there are three different
stages. Stage 1: 0–0.1 s, the power-sharing ratio between the LP and HP machines is 2:1. Total power demand is 10.6 kW; Stage 2: 0.1–0.2 s, the power-sharing ratio between the LP and HP machines is changed to 3:1; Stage 3: 0.2–0.3 s, the total power demand increases to 17.5 kW.

The currents of LPG and HPG are shown in Fig. 17(a) and (b). In Fig. 17(b), $i_{dH}$ is controlled to 0 due to high dc voltage $V_{mid}$. This confirms that the proposed PGA allows HPG to operate without FW even at high speed of 20 000 r/min. However, with the existing PGA in Fig. 1, in this case $i_{dH}$ will be over 100 A [11]. As will be shown in Section V-C, this benefits to improve the efficiency.

The dc voltages of main bus $V_{dc}$ and $V_{mid}$ inside the B2B converter are demonstrated in Fig. 17(c). $V_{dc}$ remains stable throughout the whole process. This confirms the effectiveness of the voltage controller and droop method in Section III-A. $V_{mid}$ also remains stable with a slight deviation from reference, since only proportional (P) control is adopted in Fig. 11. As it does not supply power to the onboard load directly, it is acceptable that $V_{mid}$ slightly declines. And P control is useful enough as well as easy tuning. If the system requires a stable $V_{mid}$, a PI controller can be applied.

The output powers in dual-generator mode are exhibited in Fig. 17(d). At stages 1 and 2, LP power is twice and thrice of HP power, respectively. This confirms the effectiveness of the proposed PGA to realize precise power control between sources with the proposed control methods.

The currents of $i_{aL}$, $i_{aRec}$, and $i_{aLs}$ are shown in Fig. 17(e), where $i_{aL}$, $i_{aRec}$, and $i_{aLs}$ are tightly kept in phase, which confirms the effectiveness of B2B Rectifier controller in Fig. 11. And the ratio of their current magnitudes is proportional to the ratio of the powers at different stages.

The output powers in the power-transfer mode are presented in Fig. 17(f). HP machine performs as a motor, which output 10 kW power to the HP shaft. While LPG on the one hand supplies power to the loads on main dc bus, whereas on the other hand, it supplies power to the HP machine. This confirms the feasibility of transferring power from the LP to HP shaft using the proposed PGA and controllers.

B. Engine Performance Improvement With Power Transfer

To transfer some power from the LP to HP shaft, the LPG should output a certain amount of power and HPG should work in motoring mode to absorb power generated from LPG. The experimental results when LPG generating 11.3 kW power and HPG absorbing 11.2 kW power are shown in Fig. 18.

As can be seen in Fig. 18(a), the speeds of LPG and HPG are controlled to 10 000 and 13 000 r/min by two induction machines, which perform as prime movers. The $dq$ axes currents of LPG and HPG are exhibited in Fig. 18(b), where a negative $i_q$ of LPG indicates that it is working in generator mode and a positive $i_q$ of HPG indicates motoring mode. $i_d$ of HPG is negative for the purpose of FW. The dc bus voltage is shown in Fig. 18(c), which is 270 V as required in the standard [12].

The powers of LPG and HPG are shown in Fig. 18(d) and (e), respectively. LPG generates 11.3 kW power to the dc bus and HPG absorbs 11.2 kW power from the dc bus. No other loads are connected to the dc bus. It means 11.3 kW mechanical power of the LP shaft is converted into electric power by LPG and this amount of power is transferred to the HP shaft by controlling the HP machine in motoring mode. The line-to-line voltage and phase current of HPG are also shown in Fig. 18(f), where five voltage levels can be observed due to the nature of the NPC converter. The peak value of the phase current is around 50 A, which is consistent with the $dq$ axes currents in Fig. 18(b). And the frequency of phase currents is 650 Hz, which is consistent with the speed of HPG, 13 000 r/min.

The data in this power-transfer experiment are used to feed the engine’s model, as mentioned in Section II-B. Here, the flight idle mode is selected as an example of the low-speed setting of the engine. Results for flight idle mode at 20 000 ft are presented in Table II. They reflect that in flight idle mode, as some amount of the power is transferred from the LP to HP shaft, the reduction

Fig. 18. Experimental results when 11.3 kW power is transferred from LP shaft to HP shaft. (a) Speeds of LPG and HPG. (b) $dq$ currents of LPG and HPG. (c) Main dc voltage. (d) Power of LPG in generator mode. (e) Power of HPG in motoring mode. (f) Line-to-line voltage and phase current of HPG at 13 000 r/min and 11.2 kW.
TABLE II
ENGINE PERFORMANCE IMPROVEMENT WHEN 11.3 kW POWER IS TRANSFERRED FROM THE LP TO HP SHAFT

| Fuel consumption | reduces 1.8% |
|------------------|-------------|
| LPC surge margin | increases 0.7% |
| Axial HPC surge margin | increases 0.5% |
| Radial HPC surge margin | increases 0.8% |

C. Comparison of Power Losses of Different PGAs

In this section, the existing PGA in Fig. 1 is denoted as PGA1, and the proposed PGA is denoted as PGA2. The results of dc bus voltage, HPG phase currents, and line-to-line voltages with different PGAs at 13 000 r/min are exhibited in Fig. 19(a) and (b). As can be seen in Fig. 19(a) that with PGA1, the magnitude of phase current is 65 A. While Fig. 19(b) shows that the magnitude of the phase current with PGA2 is reduced compared with that in Fig. 19(a). The operating point moves from $E_1$ to $E_2$, as shown in Fig. 15. Hence, the great reduction of copper loss can be achieved, as analyzed in Section IV. The data of phase currents are imported into the FEA model of HPG. Corresponding magnetic fields and losses are given in Fig. 19(c) and (d). The copper loss is reduced from 103.3 to 52.3 W. In Fig. 19(c), the flux density of the stator core with PGA1 is 0.85T due to the FW effect. While the flux density with PGA2 increases to 1.1T as no FW action is applied with high $V_{mid}$. Hence, the iron loss with PGA2 (169.1 W) is higher than that with PGA1 (130.8 W). The total loss of HPG with PGA2 is smaller than with PGA1.

The power loss of PGA1 and PGA2 is further compared considering the entire HP channel, including HPG and HP converter. The results are given in Fig. 20. The generated active power is fixed to 4.2 kW for both PGAs. The speed of prime mover is controlled to be 13 000 r/min. With PGA1, the torque of prime mover is 3.607 N·m, while that of PGA2 is 3.507 N·m, which means when outputting the same active power, less power of prime mover is consumed when using the proposed PGA2. Hence, it can be concluded that compared with PGA1, the proposed PGA2 is able to reduce the power loss of HPG and HP converter, hence improving efficiency by eliminating the FW operation of HPG due to an increased dc bus voltage from 270 to 400 V.

To further compare the efficiency with the two PGAs, performances at high-speed high-load condition (15 000 r/min, 10.3 kW, indicating the cruise mode), and low-speed light-load condition (9500 r/min, 2.2 kW, indicating the taxiing mode) are demonstrated in Figs. 21 and 22, respectively.

In Fig. 21, the generated power is 10.3 kW for both PGAs. The speed is fixed to be 15 000 r/min to emulate the high-speed
Fig. 21. Performance of HP channel in cruise mode at 15,000 r/min, 10.3 kW active power, with PGA₁ and PGA₂, respectively. (a) Voltages and phase current with PGA₁. (b) Voltages and phase currents with PGA₂. (c) Generated active power with PGA₁. (d) Speed and torque of prime mover with PGA₁. (e) Generated active power with the proposed PGA₂. (f) Speed and torque of prime mover with the proposed PGA₂.

condition at cruise mode. With PGA₁, the torque of prime mover is 7.592 N·m, while that of PGA₂ is 7.199 N·m. This means that when generating the same active power, prime mover needs to provide relatively less power with the proposed PGA₂. As discussed above, this improvement comes from the elimination of the FW operation of HPG. As can be seen from Fig. 21(a), with PGA₁, the magnitude of phase current is around 100 A because of a high defluxing current component. In Fig. 21(b), the magnitude of phase current is only 50 A since there is no defluxing component when using PGA₂.

In Fig. 22, the generated power is 2.2 kW for both PGAs and the speed is 9500 r/min to emulate the low-speed light-load condition when the aircraft is taxiing on the ground. From the prime mover side, the torque with PGA₁ is 2.669 N·m and that with PGA₂ is 2.700 N·m. In this case, the efficiency with PGA₂ is slightly lower than with PGA₁. This can be explained by the characteristics of HPG. HPG is designed for high-speed operation, hence with low inductance and low back EMF coefficient as can be seen from Table I. Therefore, at a low speed 9500 r/min, the MI is low, leading to undesirable current harmonics. Current harmonics can be further degraded as dc voltage increase from 270 to 400 V. Therefore, the current waveform in Fig. 22(b) with PGA₂ is worse than Fig. 22(a) with PGA₁. Large current harmonics will cause power loss in both generator and power converter.

However, in the main operation modes, such as cruise, the proposed PGA₂ is advantageous in terms of efficiency.

VI. CONCLUSION

In this article, a new PGA for the MEA application is proposed. Two PMGs are attached to the LP and HP shafts feeding a 270 V main dc bus. A B2B converter is used to transfer power between the LP side and HP side. Modeling, controller design for each individual converter, and the criterion for inductor selection are given. Power sharing between the LPG and HPG, as well as the output power sharing between the LP and HP converters, could be effectively controlled. The main contributions that have been experimentally validated can be highlighted as follows.
1) Fuel consumption can be reduced and compressor SM can be expanded by transferring power from the LP to HP shaft at low-speed settings.

2) The HPG could operate at a high speed without FW, reducing the magnitude of stator current of HPG. This will help to reduce the overall power losses.

Furthermore, the proposed PGA also has the postfault operation ability when any of the HP or LP converters shut down under fault scenarios since the B2B converter provides an additional power flow path for the generators. Details of this characteristic will be investigated in the future study.

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