Battery Energy Storage System Control and Integration Strategy for the More Electric Aircraft DC grid Application

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***Abstract*—In this paper, a strategy for the control and integration of battery energy storage system (BESS) for the more electric aircraft (MEA) electrical power system (EPS) application is proposed. This will help in meeting the increasing power demand of the loads onboard the aircraft without the need to install additional generators (which are heavier) and ensure a continuous power supply. The MEA DC EPS considering a single source and a battery storage system in the MEA is studied in this paper. The BESS is integrated into the MEA EPS distribution network DC bus (270 V) using the bidirectional DC-DC converter. The battery and the PMSG are linked to the same DC bus through a DC-DC converter and an AC/DC converter, respectively. The main source of power to feed the load demand is a permanent magnet synchronous generator (PMSG). The battery serves as an auxiliary source of power to the MEA EPS. The BESS can be used to power some onboard loads during an emergency, and to provide or absorb power when there is load variation. Also, the battery could be used to provide peak power in an overload condition which could help in reducing the ratings of the generators. Therefore, the control of the BDC with a fast dynamic response is required. In this paper, a strategy for the fast response control of the inductor current for the integration of the BESS to the MEA EPS distribution network is proposed. The proposed strategy will make the MEA EPS robust, meet the increasing power demand of the loads onboard the aircraft, have better fuel economy and possibly reduce the weight of the aircraft. The proposed strategy is validated using simulations.**

***Index Terms*—Battery energy storage, bidirectional converter, control strategy, DC grid, integration, more electric aircraft.**

I. Introduction

The recent trend of migration toward more electric aircraft (MEA) is necessitated by the need to realize an environmentally friendly and more efficient aircraft [1]. The advancement in power electronics technology, advanced control technologies and electric machines has made it possible to replace many functions which are hitherto driven by mechanical, pneumatic and hydraulic power in conventional aircraft with electrical power in the MEA. This is believed will bring about a reduction in the cost of operation and maintenance of the aircraft, improve the fuel economy, increase reliability and reduce the weight and gas emission of the aircraft. As a result, there is a huge increase in the onboard installed electrical loads, and this leads to significant demand for electrical power by the loads [1]. Hence, it is paramount to extract electric power

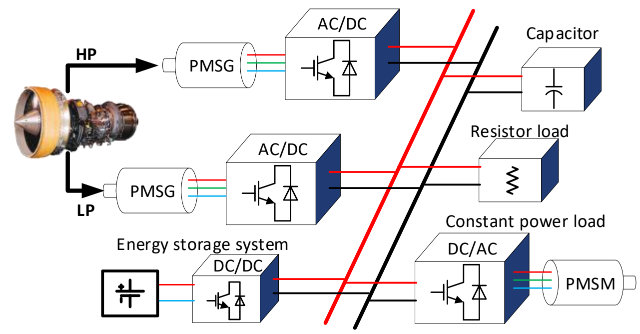

Fig. 1. Typical DC-grid in More Electric Aircraft.

from both the high-pressure (HP) and low-pressure (LP) engine shafts as shown in Fig.1. The HP and LP shafts within an aircraft engine are each driving a generator and feeding power to a single HVDC bus through an active front end rectifier [1, 2].

A typical DC grid for the MEA EPS is shown in Fig. 1. Due to the several advantages of the high voltage DC (HVDC) system when compared to the AC system, the DC system is the preferable choice for the MEA EPS architecture. The DC system has higher efficiency, is easy to control and has no requirement for frequency and reactive power regulations. Therefore, it will improve the system's stability, controllability, reliability and power quality [1]. As shown in Fig. 1, the grid comprises a power generation system, an energy storage system (ESS), a DC link and loads. The electrical power is usually supplied by at least two permanent magnet synchronous generators (PMSGs) operated in parallel. The PMSGs extract power from the engine shafts. The system can be operated with multiple sources or one active source, depending on the flight scenario. In either case, the power is fed to the single DC bus. Also, to realize a flexible power exchange and support the high electrical power need in the MEA EPS, an ESS can be integrated with the aid of a bi-direction DC-DC converter. This way, the charge and discharge mode of the battery can be controlled with ease. The power load is made up of both resistive and constant power loads.

Researchers are finding ways to make the electrical power grid resilient, with the ability to continue to provide power supply and restore normal operation within the shortest possible time in the event of natural disasters, human errors and cyber-attacks. Hence, the need for a smart and robust grid that incorporates the use of energy storage systems (ESS) [3, 4, 5]. The energy storage system is required to assist in adjusting the power flow to meet the load demand and possibly reduce the generator ratings. Furthermore, due to the increase in the electrical power demand in the MEA EPS, the integration of the battery energy storage system (BESS) could assist in meeting such demand. Hence, there may be no need for the installation of additional generators which are much heavier in size. This will be of high importance concerning the more electric aircraft ambition of weight reduction, fuel economy and reduction in gas emission [6].

The DC bus is a critical component in the proposed single bus-based multi-generator based EPS for the MEA as shown in Fig. 1. It serves as a platform for the transmission of power between the sources, loads and batteries onboard the aircraft. In this paper, a battery is interfaced with the DC bus via a bidirectional DC to DC converter (BDC). The energy storage device and the DC-DC power converter make up the DC bus voltage controller. The converter is controlled to regulate the DC bus voltage under certain conditions. The need to regulate the DC bus voltage cannot be overemphasized, it is required to protect the loads, sources and power converters from unsafe unregulated DC bus voltage [7].

Many technologies are now integrating energy storage systems into their system architecture. Some of these technologies include hybrid electric vehicles, all-electric hybrid vessels, all-electric aircraft, and electrochemical and pneumatic technologies [8, 9, 10]. The most common energy storage devices used in electrochemical technologies are lithium-ion batteries, lead-acid batteries and ultracapacitors, [8, 9, 10]. Among these energy storage devices, the battery has the advantage of ease of installation, better charge efficiency, cheaper, and fast response compared to the other ESS. Quantitatively, the charge efficiency of the lithium-ion batteries is around 99% and the energy efficiency is between 86-99% depending on the charge and discharge C-rate. The C-rate is a measure of the rate at which the battery is discharged relative to its maximum charge [11]. Conversely, the fuel cell has only 66% efficiency [12], which is quite low compared to the battery. Furthermore, the batteries can deliver power within a short period. On the other hand, it may take some time for the fuel cell to supply its power. For systems that require remote power generation, such as the more electric aircraft electrical power system, the battery can be employed in setting up a standalone renewable power system. The battery can store and give out energy based on the generator and load profiles [13, 14, 10].

The bidirectional DC-to-DC power converter is used to realize power transfer between two DC power sources in either direction. The presence of diodes in the basic DC-DC converters (Buck and Boost converters) makes them incapable of bidirectional power flow. Switches are used in the BDCs to achieve bidirectional power flow. The switches are usually semiconductor switches such as power MOSFET and IGBT/diode. The BDC finds application in renewable energy sources, hybrid electric vehicles, energy storage systems (ESS), fuel cell vehicles and switch power supply. Hence, it can be utilized in the MEA EPS. When the BDC is used to interface energy storage systems (ESS) to DC microgrid, it helps in regulating DC bus voltage, damping grid harmonics and resonance, balance the shortfall between loads and power sources.

The BDC is divided into two topologies: isolated and non-isolated BDC, to achieve different application needs [15, 16]. The isolated topologies make use of transformers to provide galvanic isolation between the source and the load and assist in voltage matching. However, the use of the transformer makes the system bulky, increases cost and losses, has poor dynamic performance and is unattractive to use in high power applications [17]. Therefore, in high power applications such as the more electric aircraft where weight and size reduction, high efficiency, good dynamic performance and reduced cost are required, the non-isolated (transformer-less) type of BDC is employed. There are several studies presented on the regulation of the DC bus through BDC, some of the researchers employed linear control [18, 19, 20, 21], others made use of intelligent control [22, 23, 24, 25, 26], and the third category of researchers used non-linear control approach [27, 28, 29, 30, 31]. The BDC works in boost and buck mode depending on the power flow direction. Hence, controllers with good dynamic performance are essential to make sure of appropriate power flow while keeping the DC bus voltage at the desired reference value in either direction of power flow.

A strategy for the control and integration of battery energy storage systems is proposed in this paper for more electric aircraft applications. In this paper, the seamless integration of the BESS to the MEA EPS distribution network using a bidirectional DC-DC converter with a fast response to changes in the inductor current is proposed. The proposed strategy will improve the MEA EPS performance and reliability. The proposed strategy is studied considering one source and a battery energy storage system operated in parallel and linked to the DC bus. The cascaded control technique which is a non-linear control approach is used due to the non-linear nature of the bidirectional dc-dc converter. The cascaded control scheme utilizes two proportional-integral (PI) controllers. As a result, this control scheme is reliable and could improve the system control performance.

II. System Under Study Description

In this paper, a PMSG is the main source of power for the electrical loads onboard the aircraft. The PMSG is controlled by a space vector pulse-width modulated (SVPWM) active front end (AFE) rectifier to provide power to the DC bus. According to the MIL-STD-704 standard, the DC bus nominal voltage is 270 V in a steady-state, although a range between 250 V and 280 V is also acceptable [32]. Therefore, the regulation of the DC bus voltage within the acceptable range can be realized with the aid of a BESS integrated into the MEA EPS distribution network DC bus. This is because the BESS has the capability of injecting or absorbing power when controlled appropriately.

The ESS is made up of a 200 VDC battery and is usually located in the aft area of the aircraft. A bidirectional DC-DC converter helps to regulate the exchange of electrical power

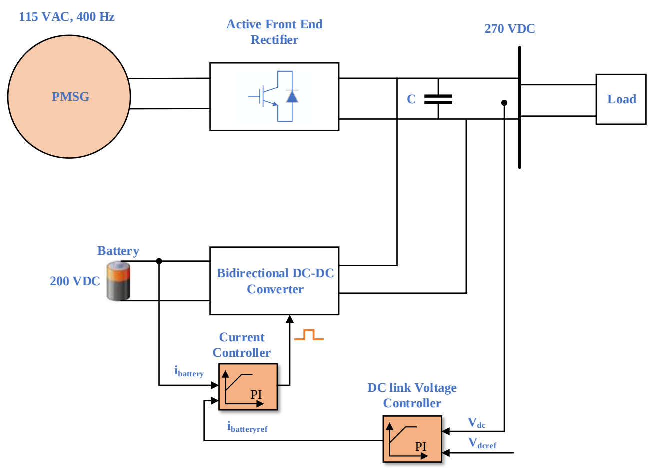

Fig. 2. The Studied Battery Energy Storage System Control and Integration Architecture.

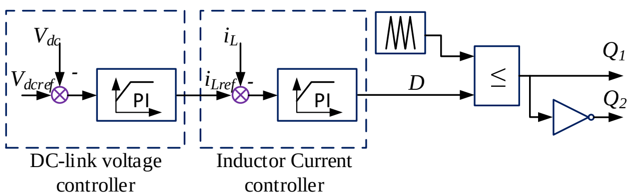

Fig. 3. BESS Controller.

between the battery and the 270 V DC bus. The energy storage device (battery) has the capability of storing (charging mode) the excess energy produced by the PMSG and giving out the stored energy (discharging mode) when it is required. This can potentially reduce the size and weight of the MEA EPS distribution network. The DC microgrid architecture of the electrical power system proposed for the more electric aircraft is shown in Fig. 1. The proposed battery energy storage system control and integration strategy for the MEA EPS application are studied using a single source as shown in Fig. 2, before moving to the complex system with two or more generators shown in Fig. 1.

When the main DC bus voltage is 270 V, the battery will be in “offline mode”. In this case, there is no flow of power from or to the battery and the generator could solely provide power to the DC bus which will, in turn, feed the loads connected to it. When the main DC bus voltage exceeds 270 V, the battery will go into charging mode to utilize the excess power from the DC bus. In a situation whereby more loads are linked to the main DC bus, the bus voltage will reduce. If the DC bus voltage is less than 270 V, the battery will discharge its power to restore the DC bus voltage to 270 V.

III. BESS System Modelling and Control Operation

The controller of the bi-directional DC-DC converters is as shown in Fig. 3. To obtain the duty cycle, two cascaded PI controllers are used as shown in Fig. 3.

A. System Modelling

The system modelling starts with the inner current control loop under steady-state operating conditions. The transfer function for the inner current controller is as expressed in equation (1). To realize a continuous average transfer function, the design process is carried out using small signals.

$$\frac{\partial i_L}{\partial D} = \frac{V_{s0}Cs + i_{L0}(1-D_0)^2}{(1-D_0)^3\left(1+\frac{LCs^2}{(1-D_0)^2}\right)} \tag{1}$$

where the ∂ terms signify the small-signal variables and the $_0$ notation shows quantities in steady-state operating conditions, D_0, i_{L0}, and V_{s0} represent the value of the duty cycle, inductor current and source voltage respectively in steady states. L and C are the inductance of the inductor and capacitance of the capacitor respectively. Usually, high bandwidth is selected for the inner current control loop and as a result, equation (1) can be simplified to a first-order transfer function as expressed in (2) to obtain the transfer function between the inductor current and the duty cycle.

$$\frac{\partial i_L}{\partial D} = \frac{V_{s0}}{(1-D_0)Ls} \tag{2}$$

Therefore, the inner current loop closed-loop transfer function is determined as expressed in (3.3). This will help in the derivation of the outer voltage loop transfer function.

$$\frac{\partial i_L}{\partial i_{Lref}} = \frac{\frac{V_{s0}}{(1-D_0)L}(k_{pc}s+k_{ic})}{s^2+\frac{V_{s0}k_{pc}s}{(1-D_0)L}+\frac{V_{s0}k_{ic}}{(1-D_0)L}} \tag{3}$$

where k_{pc} and k_{ic} represent the proportional and integral gains of the inner current loop controller respectively. The inner current controller is designed to achieve a control bandwidth of 2 kHz, while the outer voltage controller has a 400 Hz bandwidth and the controller's gain parameters are as shown in TABLE 1. Furthermore, equation (4) expresses the relationship between the current passing through the DC-link (i_{dc}) and the current at the battery side (i_L) [33].

$$\partial i_{dc} = (1-D_0)\partial i_L - i_{L0}\partial D \tag{4}$$

When integrating the BESS to the MA EPS distribution network 270 V DC bus using the BDC, the value of the duty cycle will change based on the battery’s state of charge (SOC). The relationship between the duty cycle, the battery voltage and the DC link voltage are shown in Fig. 4. The direction of flow of the inductor current depends on the relationship between these variables. The value of the duty cycle is as expressed in equation (5) when the inductor conductor is zero. The duty cycle (D) is greater than D_0 in the buck mode and the inductor current i_L is positive. In boost mode, the duty cycle (D) is less than D_0 and therefore, the inductor current is negative [34].

To ensure that the inductor current operates under a CCM, the minimum inductance (L_{min}) value of the BDC can be obtained as expressed in (6) [35, 3].

$$L_{min} = \frac{D(1-D)^2{V_0}^2}{2P_cf} \tag{5}$$

where D is the duty cycle, V_0 is the high-voltage side, f is the switching frequency, and P_c is the critical light load power. On the other hand, the capacitance (C_{min}) design is carried out based on the expression in (6) [29, 1].

$$C_{min} = \frac{D}{2fR_L} \tag{6}$$

$$D_0 = \frac{V_{s0}}{V_0} \tag{7}$$

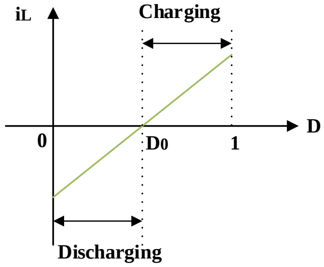

Fig. 4. Relationship Between Inductor Current and Duty Cycle

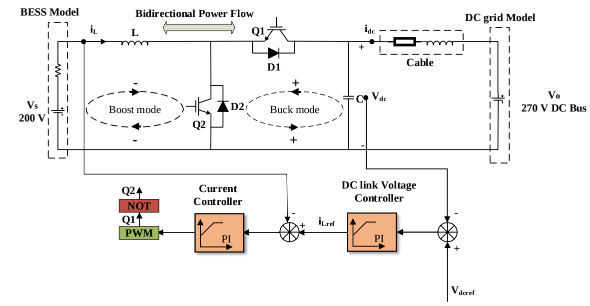

Fig. 5. Cascaded Control of the Half-bridge Non-isolated Bidirectional DC-DC Converter Interfaced with a Battery Energy Storage System.

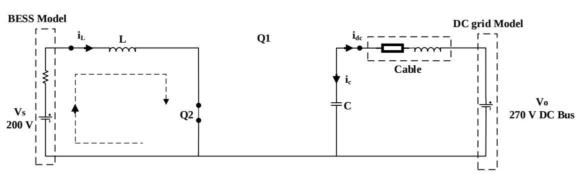

Fig. 6 (a). Boost Operation On state: Q2 is ON and D1 is OFF

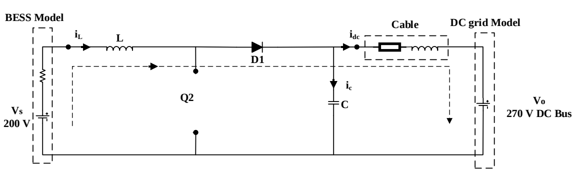

Fig. 6 (b). Boost Operation Off state: Q2 is OFF and D1 is ON

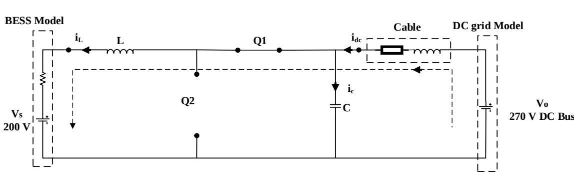

Fig. 7 (a). Buck Operation On state: Q1 is ON and D2 is OFF

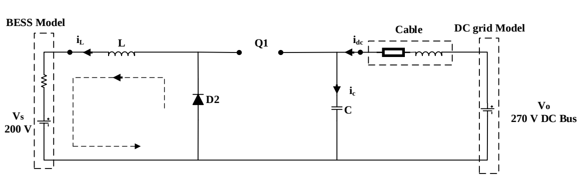

Fig. 7 (b). Buck Operation Off state: Q1 is OFF and D2 is ON

B. *Control and Integration Scheme*

The control topology of the BESS is as shown in Fig. 5. The battery is modelled using a simple voltage source, V_s connected in series with a resistor, connected to the DC bus through a bidirectional DC-DC converter. The BDC converter is made up of series inductance-resistance (LR), capacitance (C), and two switches (Q_1 and Q_2). The current flowing from the battery is depicted as i_L. The local DC link voltage and current after the converter are represented by V_{dc} and i_{dc} respectively. The switches (Q_1 and Q_2) are always in the opposite state of each other. A series inductance-resistance (LR) cable is also connected to the main DC bus. The bidirectional DC-DC converter is designed to operate in the continuous conduction mode (CCM) (a situation whereby the inductor current flows continuously) and the switches are assumed to be ideal. The inductor current and the local DC bus voltage are used as feedback signals to the inner and outer PI controllers respectively. The current i_L is controlled by the inner current controller. The duty cycle reference, D, for the switches is produced by the inner current controller. The outer PI controller regulates the local DC link voltage and provides the reference current for the battery i_{Lref}. The inner loop PI controller helps to control the inductor current while the outer loop PI controller helps in regulating the DC bus voltage. Furthermore, the use of the cascaded control scheme helps to decouple the inductor current from the main DC bus voltage provided the inner current control loop is designed to be faster than the outer voltage control loop. The PWM technique is employed to generate a control pulse used to control the two switches of the bidirectional DC-DC converter.

C. *Circuit Principle of Operation*

The half-bridge non-isolated bidirectional DC-DC Converter operates in two modes and this is defined based on the direction of current flow in the inductor as shown in Fig. 6. When the direction of current flow is from the battery to the main DC bus, it is referred to as "boost" or discharging mode. In the boost mode, the IGBT/diode switch (Q_2) serves as the main switch and the IGBT/diode switch (Q_1) serves as the auxiliary switch with a diode (D_1) acting as a freewheel diode. Fig. 6 (a) and (b) show the operation of the power converter in boost mode during the ON and OFF states of the switches.

As shown in Fig. 6 (a), the switch Q_2 is turned ON while Q_1 is turned OFF and the diodes D_1 and D_2 are reverse biased. Therefore, the power converter works in boost mode and the inductor is charged and the current passing through it increases. Conversely, as shown in Fig. 6 (b), both switches (Q_1 and Q_2) are OFF and diode D_1 is conducting. In this case, the converter output voltage is applied across the DC bus.

Conversely, when the direction of current flow is from the main DC bus to the battery, it is referred to as the "buck" or charging mode. In the buck mode, the IGBT/diode switch (Q_1) serves as the main switch and the IGBT/diode switch (Q_2) serves as the auxiliary switch with a diode (D_2) acting as a freewheel diode. Fig. 7 (a) and (b) show the operation of the power converter in buck mode during the ON and OFF states of the switches.

As shown in Fig. 7 (a), the switch Q_1 is turned ON while Q_2 is turned OFF and the diodes D_1 and D_2 are reverse biased. Therefore, the power converter works in buck mode. Conversely, as shown in Fig. 7 (b), both switches (Q_1 and Q_2)

are OFF and diode D_2 is conducting.

D. System Working Mode

When the power generated by the PMSG is in excess, the battery enters charging mode to utilize the excess power. In this case, i_L will be positive and flow towards the battery direction (buck mode). Conversely, the battery will enter the discharging mode in a situation whereby the PMSG cannot supply adequate power to feed the load. In this situation, the i_L magnitude becomes negative and flows towards the DC bus direction (boost mode). The main target for the control is to regulate the main DC bus voltage to 270 V. The control method involves processing the error between the measured DC link voltage (V_{dc}) and its referenced value (V_{dcref}) to obtain the battery charge/discharge current reference value (i_{Lref}) to be processed by the current controller. Finally, the current controller detects the battery charge and discharge current (i_L) to follow its reference value to realize DC link voltage regulation. The control system employs the proportional-integral (PI) controllers to implement the control scheme.

IV. Simulation Studies

The dynamic performance of the cascaded control scheme used is tested and validated in MATLAB Simulink by controlling the inductor current in both directions. Step testing is carried out by varying the reference DC bus voltage. The controllers are designed in such a way that they can easily detect the required mode of operation (either buck or boost), based on the direction of the inductor current.

When the DC bus reference voltage is varied from 270 V to 271 V at 0.2 sec as shown in Fig. 8, it is observed that the average inductor current is zero with a 270 V reference DC bus voltage and a current of about 5A flows from the DC bus to the battery (charging mode) when the reference DC bus voltage is 271 V at 0.2 sec as shown in Fig. 9.

Also, when the DC bus reference voltage is varied from 271 V to 269 V at 0.2 sec as shown in Fig. 10, it is observed that a 271 V reference DC bus voltage and a current of about 5 A flow from the DC bus to the battery (charging mode) as shown in Fig. 11. However, when the reference DC bus voltage is 269 V at 0.2 sec, a current of 5A flows from the battery to the DC bus (discharging mode) as shown in Fig. 11.

Based on the results obtained, it is observed that the dynamic response of the control system is good and fast, and the DC link voltage can maintain its desired reference value. It is also observed that the response has a slight overshoot and short rise time.

V. Conclusion

The control and integration of a battery energy storage system have been proposed in this paper. The BESS was integrated into the MEA EPS distribution network 270 V DC bus using a BDC with a fast response. The suitability of the proposed control strategy and its fast response have been presented.

The proposed strategy can enhance the performance and reliability of the MEA EPS, increase the system efficiency, help meet the ever-increasing electrical power demand of the loads onboard the aircraft, reduce the generator ratings and may help

TABLE I
System and Controller Parameters [33, 34]

Category	Parameter	Symbol	Value
Bidirectional DC-DC Converter	Inductance	L	100 µH
	Capacitance	C	25 µC
	Battery Voltage	V_s	200 V
	Battery resistance	R_b	10 mΩ
	Switching frequency	f	10 kHz
	DC Bus Voltage	V_0	270 V
Cable	Cable resistor	R_c	260 mΩ
	Cable inductor	L_c	36.5 µH
Inner current controller gains	Proportional	k_{pc}	0.0050
	integral	k_{ic}	7.49
Outer voltage controller gains	Proportional	k_{pv}	0
	integral	k_{iv}	-7500

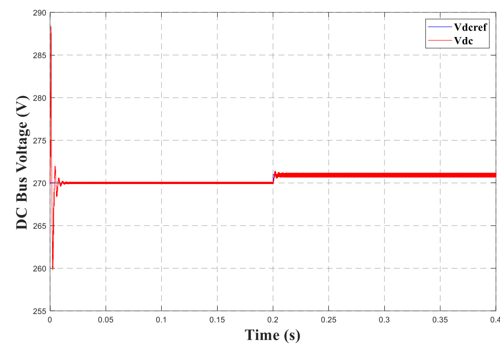

Fig. 8. DC bus voltage response to step change of the DC bus reference voltage.

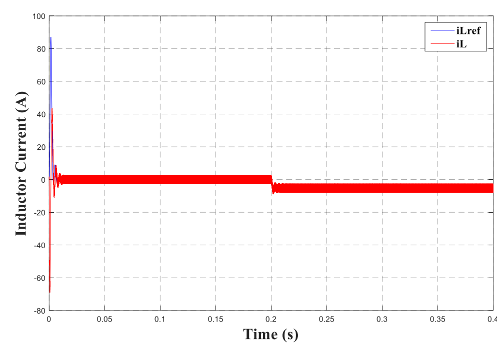

Fig. 9. Bidirectional Converter Response During Battery Charging

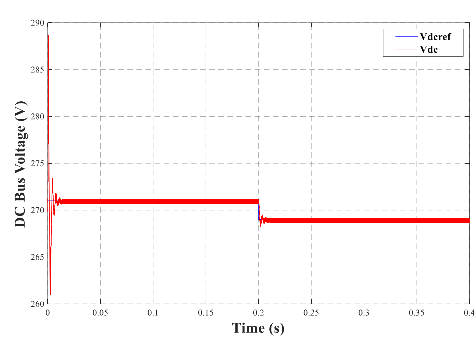

Fig. 10. DC bus voltage response to step change of the DC bus reference voltage.

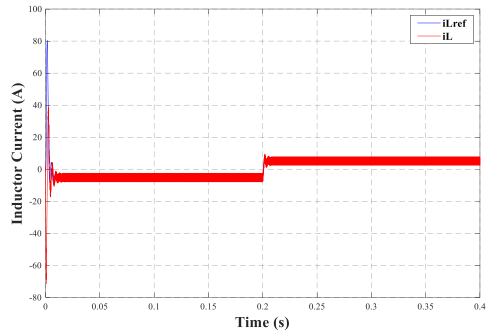

Fig. 11. Bidirectional converter response during charging and discharging

in achieving a reduction in the weight of the aircraft. The battery energy storage system can be a very useful and alternative source of power for more electric aircraft.

When the DC bus voltage is maintained at 270 V, the average inductor current is 0 A, hence, the battery is in offline mode. Conversely, when there is a fluctuation in the DC bus voltage away from 270 V, the average inductor current is no longer 0 A.

The proposed control scheme ensures that the bi-directional DC-DC converter operates with fast response in either boost or buck mode depending on the status of the PMSG and battery so that the battery can be discharged or charged as required by the MEA EPS. The buck and boost mode of the BDC are analysed in detail and simulation results are provided to validate the proposed strategy.

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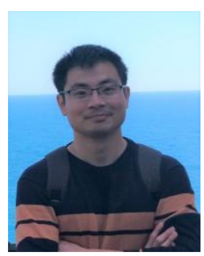

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