An Induction Generator based AC/DC Hybrid Electric Power Generation System for More Electric Aircraft

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***Abstract* - In more electric aircraft (MEA) system, both AC and DC electric power with multiple voltage levels are required for various aircraft loads. This paper presents an induction generator based AC/DC hybrid electric power generation system for MEA. In the proposed system, a high speed induction starter/generator and a low speed induction generator are installed on the high pressure (HP) and low pressure (LP) spools of the engine, respectively. In generating mode of operation, all of the constant voltage variable frequency AC power is generated by the HP generator while the DC power demand is shared by both HP and LP generators. A control scheme is developed to regulate the AC load voltage and coordinate DC power generation between the two generators. The proposed induction generator based AC/DC hybrid generation system presents reduced hardware installment compared to existing AC and DC primary generation systems.**

Index Terms--*induction motors, genrators, distributed power generation, aircraft, power generation control*

I. INTRODUCTION

The emerging trend towards more electric architecture for airplanes is intended to replace mechanical, hydraulic and pneumatic systems with electrical systems as much as possible. It is generally considered that the more electric aircraft (MEA) would lead to lower fuel consumption and emissions, reduced maintenance, and possibly lower costs [1]-[4]. Advancements of electrification on board have increased the electric power demand of the aircraft. A significant raise of generation capacity is required to supply the additional loads.

In present MEA systems (e.g. Boeing 787, Airbus A380), the wound-field synchronous generator (SG) based AC primary generation system can feed the frequency insensitive loads directly from the synchronous generator terminals. The constant voltage variable frequency (CVVF) AC voltage is regulated by controlling the field current of the SG through an external brushless exciter. This exciter is consisted of a permanent magnet (PM) machine and a diode rectifier mounted on the generator shaft. The complex rotor structure makes the torque to inertia ratio of SG lower than other type of electric machines [1]. Moreover, the rotating diode bridge structure has limited the top speed of the generator shaft. If the synchronous machine is used as a starter/generator, separate field and armature voltage controls are required during its motoring operation.

In [5]-[6], a high voltage (+/-270 V) DC primary generation system using embedded PM generators is presented as a potential solution for more electric architecture. This type of system presents high power factor and high efficiency, but suffers from excessive current flow in fault condition [7], [8]. Although multi-phase fault-tolerant PM generators have been investigated to limit the short-circuit fault current [9]-[11], using PM generator to fulfill the overload current requirement of main engine generator in aerospace application is still problematic. Furthermore, in PM generator based DC primary generation system, the CVVF AC power demanded by frequency insensitive loads (e.g. wing de-icing system, galleys, etc.) is first converted to DC power by the active rectifier of the generator, and inverted back to AC power through dedicated inverters. This two-stage AC-DC-AC conversion adds extra losses and additional hardware to the system.

Since neither AC nor DC primary generation system is able to meet all the power requirements with optimized performance in terms of volume, weight, efficiency, reliability and cost, an induction generator based AC/DC hybrid generation system is proposed to combine the advantages and address the shortcomings of both systems. In the proposed system, a high speed induction starter/generator and a low speed induction generator are attached to the high pressure (HP) and low pressure (LP) spools of the engine, respectively. In generating mode of operation, the HP generator is in charge of generating all of the CVVF AC power, while the DC power demand is shared by both HP and LP generators. Using induction machine as main engine generator in aircraft application is rarely reported in literature [12]-[14]. In this paper, an open-end winding squirrel-cage induction generator and a conventional wye-connected squirrel-cage induction generator are used as the HP and LP generators, respectively. The concern of excessive fault current due to the PM excitation is addressed. In addition, thanks to the self-excited capability of induction generator, the proposed AC/DC hybrid generation architecture can supply CVVF

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AC power directly from generator terminals without external exciter. As a result, the overall hardware installment of the proposed system is reduced compared to both AC and DC primary generation systems.

In this paper, the configuration of the induction generator based AC/DC hybrid generation system for MEA is presented. A steady-state analysis is carried out to explain the proposed twin-spool twin-generator AC/DC hybrid generation method. A closed-loop control scheme for AC and DC voltage regulation of the proposed system is developed based on field oriented control theory. The feasibility of operation of the proposed system is demonstrated by means of software simulation.

II. SYSTEM CONFIGURATION

The system configuration of a synchronous generator based AC primary generation system [6], [7] is shown in Fig. 1. A wound field synchronous starter/generator is connected to the HP spool of the gas turbine engine through a mechanical gearbox. While the engine is starting, the synchronous machine can operate as a motor to start the gas turbine using ground power supply. During the flight mission, the same machine serves as the main electrical power source at a constant AC voltage (230 V) and variable frequency (360 to 800 Hz). The field current of the synchronous generator is controlled by a smaller PM machine with a diode bridge rectifier installed on the generator shaft. By adjusting the excitation of the field winding, the AC source voltage can be regulated with variable shaft speed.

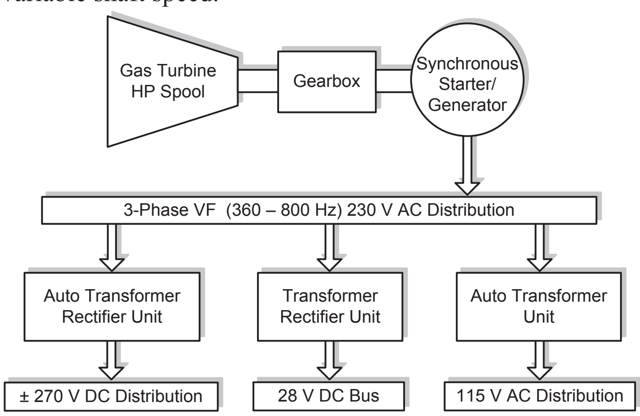

Fig. 1. System configuration of the synchronous generator based AC primary generation system

In aircraft systems, the effect of electrical power offtake can sometimes have significant impact on the dynamics and control of the aircraft engine. For instance, during the transition from cruise to descent phase, the aircraft engine power is transiently reduced while maintaining high electrical power demand. This transition creates a possibility of engine instability and may require substantial electric load shedding. Furthermore, with the increasing electric power consumption in MEA, the above effect will be more severe if the electric power is solely extracted from the HP spool of the gas turbine engine [15]. This issue can be resolved by installing an extra generator on the LP spool of the engine and sharing the power extraction between the HP and LP spools [4]-[6]. In this way, the power generated from the LP spool could compensate for the decreased power from the HP spool so that the electrical power demand is not compromised.

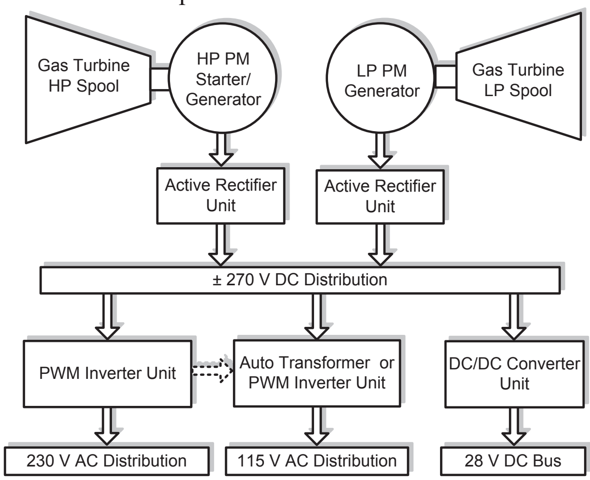

Fig. 2. System configuration of the permanent magnet generator based DC primary generation system

In a twin-spool aircraft engine, the generators on HP and LP spool need to operate at different frequencies. In order to parallel the two generators with enhanced efficiency and reduced size and weight, a DC primary generation system with power electronic converters is preferred as an advanced more electric architecture [6], [16]. PM generator is preferred in this twin-spool twin-generator architecture due to its high power density and self-excited capability [5], [6]. As shown in Fig. 2, a high speed starter/generator and a low speed generator are placed directly on the HP and LP spool of the engine, respectively. In the engine starting process, the PM starter/generator on HP spool can operate as a motor to start the engine using ground power supply. In the flight mission, the power generated from the two generators are rectified and transmitted to a ±270 V DC power bus. In Boeing 787, power consumption of frequency insensitive AC loads under cursing condition is close to 50% [16]. This amount of AC power is supplied through a two-stage AC-DC-AC conversion. Such arrangement adds extra losses and additional hardware to the system.

The proposed induction generator based AC/DC hybrid generation system is shown in Fig. 3. Similar to the DC primary generation system, the ±270 V DC power demand is shared by two generators on HP and LP spool of the engine. In contrast, the frequency insensitive AC loads are supplied directly from the HP spool generator terminal like the AC primary generation system. Compared to DC primary generation system in Fig. 2, the undesired AC-DC-AC conversion is avoided by applying AC/DC hybrid generation on HP spool in the proposed system, while the merits of the twin-spool twin-generator DC primary generation architecture have also been reserved. As compared to the AC primary generation system in Fig. 1, the application of induction generator removes the external exciter, while the twin-spool twin-generator architecture improves the overall generation performance.

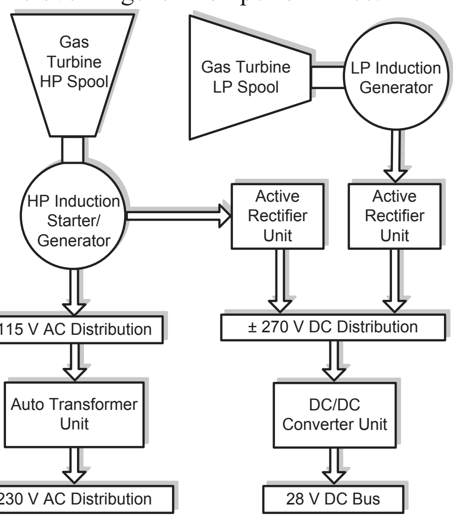

Fig. 3. System configuration of the induction generator based AC/DC hybrid generation system

A more detailed electrical system configuration is shown in Fig. 4. An inverter/rectifier unit and frequency insensitive AC loads are connected to each end of the HP spool open-end winding induction generator terminals. An active rectifier unit is connected to the LP spool wye-connected induction generator. The DC output end of the inverter/rectifier unit and the active rectifier unit are paralleled to the DC bus.

In the engine starting mode of operation, the AC loads are disconnected from the HP generator, and the AC load terminals are shorted to transform the open-end induction generator on HP spool into a wye-connected induction motor. Using a ground DC power supply, the transformed induction motor can be driven by the inverter/rectifier unit to start the aircraft engine. Once the engine shaft reaches its idle speed, induction machine will be connected back to form the configuration as shown in Fig. 4, and the DC capacitor will be fully charged. Additional circuit breakers are required to implement this transformation. Because only a small portion of power is needed to start the aircraft engine, the size and power rating of the extra circuit breakers are relatively small.

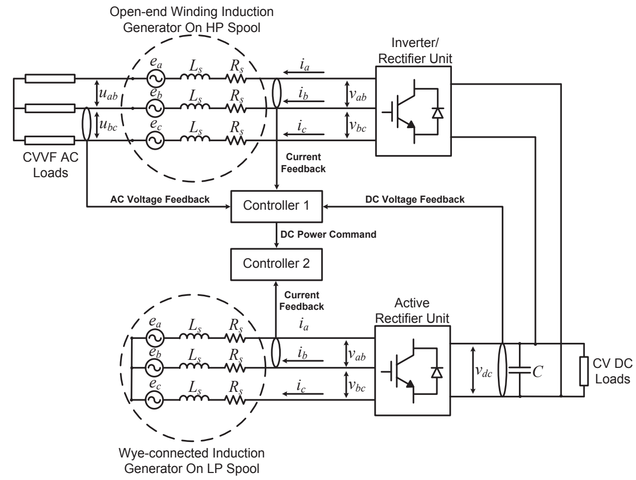

Fig. 4. Electrical system diagram of the induction generator based AC/DC hybrid generation system

III. SYSTEM MODELING AND OPERATION PRINCIPLE

As shown in Fig. 4, in the proposed generation system, all the CVVF AC power is generated by the HP generator only, while the power demand of the DC loads is shared between both the HP and LP generators. The generation subsystem on HP spool includes a high speed generator, an inverter/rectifier unit, a CVVF AC distribution bus and a shared CV DC distribution bus, whereas the generation subsystem on LP spool is consisted of a low speed generator, an active rectifier unit and the shared CV DC distribution bus. The system model and operation principle of the generation subsystems on HP and LP spools will be discussed in detail in the following sections.

A. HP Spool Generation Subsystem and AC Voltage Regulation

In the HP spool generation subsystem, the frequency insensitive loads in MEA such as wing de-icing system and galleys are generally resistive heaters symmetrically distributed at the generator terminals. Therefore, the open-end winding induction generator on HP spool can be modeled as a wye-connected induction generator with an increased stator resistance. In the rotor flux oriented reference frame, neglecting the saturation effects, the steady-state voltage and torque equations for the HP spool induction generator can be expressed as [17], [18]:

$$V_{qs1} = (R_{s1} + R_{acL})I_{qs1} + \omega_{e1}\lambda_{ds1} \tag{1}$$

$$V_{ds1} = (R_{s1} + R_{acL})I_{ds1} - \omega_{e1}\lambda_{qs1} \tag{2}$$

$$T_{e1} = \frac{3}{2}\frac{P1}{2}\frac{{L_{m1}}^2}{L_{r1}}I_{qs1}I_{ds1} \tag{3}$$

where

$$\lambda_{qs1} = L_{s\sigma1}I_{qs1} \tag{4}$$

$$\lambda_{ds1} = L_{s1} I_{ds1} \quad (5)$$

$$L_{s\sigma 1} = L_{s1} - \frac{{L_{m1}}^2}{L_{r1}} \quad (6)$$

In the above equations, V_{qs1}, V_{ds1}, I_{qs1}, I_{ds1}, λ_{qs1}, λ_{ds1} are the q and d axis stator voltages, currents, flux linkages, respectively. R_{s1} is the stator winding resistance and R_{acL} is the AC load resistance. $L_{s\sigma 1}$ stands for the stator transient inductance. L_{s1}, L_{r1}, L_{m1}, P1, are the stator, rotor magnetizing inductance and pole pairs of the induction machine 1, respectively. In order to regulate the AC load voltage, the AC load current (stator current magnitude) needs to be controlled according to the load resistance variation. The AC load current reference can be expressed as:

$$I^* = \sqrt{{I_{qs1}}^2 + {I_{ds1}}^2} \quad (7)$$

Limited by the current rating of the generation system, the power generated for frequency insensitive AC loads can be modeled as the ohmic loss of the increased stator resistance of the HP generator. Thus, the power transmitted to the DC bus can be written as:

$$P_{dc1} = -\omega_{e1} \frac{T_{e1}^*}{P1} - (R_{s1} + R_{acL}) {I^*}^2 \quad (8)$$

where T_{e1}^* is the torque reference of the HP generator.

According to (8), the torque reference can be determined by the AC load current reference and DC power output command. The theoretical equilibrium points of the HP generation subsystem for a given AC and DC power demand are illustrated in Fig. 5. The intersections A and B indicate two theoretical equilibrium points for corresponding AC load current and HP generator torque references. For a given AC load condition, the torque reference of the HP generator varies with different DC output power command of the system. When the DC power output increases, the torque reference curve will move away from the AC load current reference circle. Therefore, the DC power output needs to be limited to ensure that there exists at least one intersection point of the torque reference curve and the load current reference circle.

Furthermore, the maximum torque of an induction generator is limited by the voltage rating of the system. This voltage limitation can be expressed as follows:

$${V_{s1,max}}^2 \geq {V_{qs1}}^2 + {V_{ds1}}^2 \quad (9)$$

Substituting (1), (2), (4), (5) into (9), the voltage constraint equation becomes:

$$\left[\frac{(R_{s1}+R_{acL}) I_{qs1}}{\omega_{e1}} + L_s I_{ds}\right]^2 + \left[\frac{(R_{s1}+R_{acL}) I_{ds1}}{\omega_{e1}} - L_{s\sigma 1} I_{qs1}\right]^2 \leq \frac{{V_{s1,max}}^2}{{\omega_{e1}}^2} \quad (10)$$

Equation (10) forms a voltage limit ellipse in Fig. 5. This ellipse is similar to the analysis of flux weakening operation for induction motor [18], yet the load resistance makes the ellipse rotation varies from different load condition in the proposed system. An increased AC load power demand will result in a clock-wise rotation of the voltage limit ellipse and vice versa. Therefore, equilibrium point B in Fig. 5 is not a valid operating point of the system. Besides the constraint to guarantee the existence of equilibrium point, the DC output power from HP spool is hereby further bounded by the voltage limit of the system. This bounded operating range can be demonstrated as the segment of the AC current reference circle inside of the voltage limit ellipse.

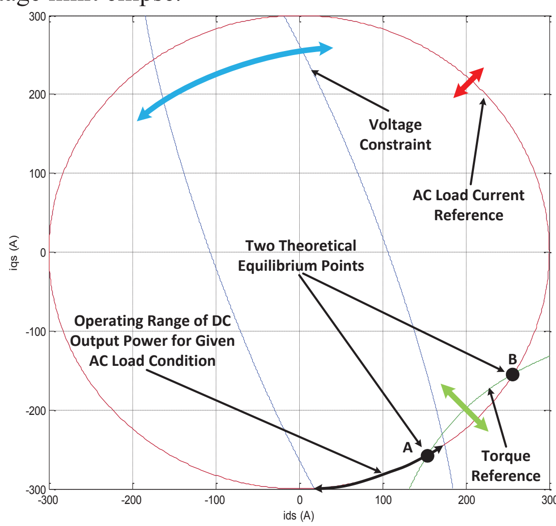

Fig. 5. Operating constraints of the high pressure spool generation subsystem

The flux current command $I_{ds,ref}$ and torque current command $I_{qs,ref}$ can be calculated from given AC load current and generator torque reference as follows:

$$I_{ds1}^* = \frac{\sqrt{{I^*}^2 - \frac{2T_{e1}^*}{k_1}} - \sqrt{{I^*}^2 + \frac{2T_{e1}^*}{k_1}}}{2} \quad (11)$$

$$I_{qs1}^* = \frac{-\sqrt{{I^*}^2 - \frac{2T_{e1}^*}{k_1}} - \sqrt{{I^*}^2 + \frac{2T_{e1}^*}{k_1}}}{2} \quad (12)$$

where $k_1 = \frac{3}{2} \frac{P1}{2} \frac{{L_{m1}}^2}{L_{r1}}$ is the torque coefficient.

In order to illustrate the disposition of d, q axis current commands with AC and DC power demand variations, a two-dimensional sweep test of AC load current and generator torque reference is performed using Matlab.

The results of the test are shown as contour maps in Fig. 6. Evidently, the q-axis (torque) current command and AC load current reference variations are almost proportional, while changing q-axis current command has little impact to the generator torque with a fixed AC load current command. The d-axis (flux) current command changes greatly with generator torque variation, but it is relatively insensitive to AC load current changes. It can be inferred from the sweep test results that changing DC power output of the HP generation subsystem greatly depends on the flux variation of HP generator, resulting in a very slow system response. On the other side, regulating AC load voltage with a constant (or slowly varied) DC output power can be achieved by controlling q-axis current with small variation of generator flux. The DC bus voltage can be regulated with a master-slave control strategy with cooperation of the LP generation subsystem.

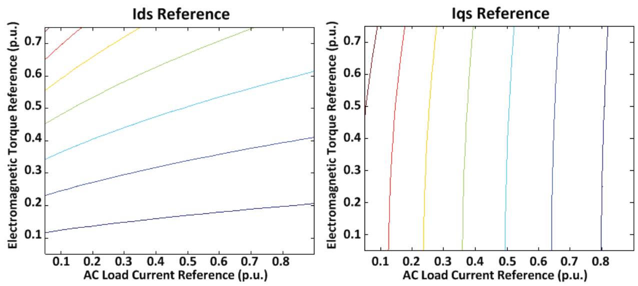

Fig. 6. Contour maps of d-q axis current commands for AC load current and generator torque reference sweep test

B. LP Spool Generation Subsystem and DC Voltage Regulation

The DC voltage regulation of the proposed hybrid AC/DC generation system is implemented by a master-slave control strategy. The HP generator, while regulating AC load voltage, operates as the master in DC power generation and offers a constant power output to the DC bus. In contrast, the LP generator operates as the slave and supplies the rest of DC power demand. The DC power output of the LP generator is determined as:

$$P_{dc2} = v_{dc} C \frac{dv_{dc}}{dt} + v_{dc} i_{dcL} - P_{dc1} \tag{13}$$

where i_{dcL} is the DC bus load current, P_{dc1} and P_{dc2} are the DC power output of the HP and LP generator, respectively.

Other than the DC power extraction from the HP generation subsystem, the LP spool generation subsystem operates as a conventional front end DC generation system. The control scheme of the overall generation system will be discussed in greater detail in the next section.

IV. CONTROL SCHEME

The closed-loop control scheme for the proposed AC/DC hybrid generation system is shown in Fig. 7. Two voltage sensors are used at the AC load terminals of the generator to monitor the AC load voltages. An additional voltage sensor is installed to measure the DC bus voltage. Four current sensors are used to provide generator current feedbacks. Neither rotational speed of rotor nor rotor position feedback is essential to control the proposed generation system.

To prevent instability issue of the engine caused by high off-take of power extraction on HP spool, the DC power output command $P_{dc1}{}^*$ is designed as a control input commanded by the engine control unit. An additional control freedom is provided to the engine control unit to balance the power extraction from the HP and LP spools. The adjustable range of $P_{dc1}{}^*$ can be calculated and fed back to the engine control unit using (7), (8) and (10).

The AC load voltage is controlled by controller 1 in the HP generation subsystem. Assuming purely resistive load condition, the AC load resistance R_{acL} can be estimated as the AC load voltage v_{ac} divided by the stator current magnitude I. The AC load current command I^* can then be calculated using the estimated load resistance. The current reference calculation can be implemented in two steps: i) Given DC power output command $P_{dc1}{}^*$, AC load current command I^*, AC load resistance R_{acL} and generator electrical frequency ω_{e1}, the torque reference of the HP generator T_{e1}^* is calculated through (8); ii) Given the torque reference of the HP generator T_{e1}^* and AC load current command I^*, the d and q-axis current commands I_{ds1}^* and I_{qs1}^* are obtained from (11) and (12). Using rotor-flux orientation, two PI controllers are applied to regulate i_{ds1} and i_{qs1}.

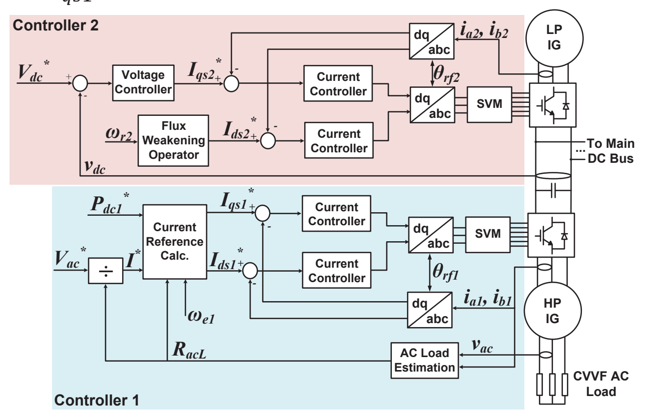

Fig. 7. Closed-loop control scheme for the proposed AC/DC hybrid generation system

The DC bus voltage is regulated by controller 2 in the LP generation subsystem. In the DC bus voltage control loop, a PI controller is used to generate LP generator q-axis (torque) current command I_{qs2}^*. The d-axis (flux) current of the LP generator is commanded to be inverse proportional to the generator shaft speed to obtain a wide speed operation range. Using rotor-flux orientation, two PI controllers are applied to regulate i_{ds2} and i_{qs2}.

Controller 1 and 2 in Fig. 7 are field oriented by the direct flux observer in [19] using inverter terminal voltage and generator stator current feedbacks. The inverter terminal voltages are re-constructed using DC bus voltage feedback and inverter gating signals. The speed estimator in [19] is also used in the LP generation subsystem to provide shaft speed feedback to the flux weakening operator.

V. SIMULATION RESULTS

A closed-loop simulation for the proposed induction generator based AC/DC hybrid generation system is simulated in Matlab/Simulink. In the simulation, a 150 kW, 12000 rpm induction generator and a 60 kW, 3150 rpm induction generator are used on the HP and LP spool, respectively. The generators are controlled to supply 75 kW three phase 230 V AC balanced resistive load and 60 kW 540 V DC load at their rated speed. The AC load is changed from 75 kW to 60 kW at 1.3s, and the DC load is changed from 60 kW to 50 kW at 1.45s.

The DC bus and AC load voltages of the system are shown in Fig. 8 and Fig. 9, respectively. The dynamic performance for both DC bus voltage and AC load voltage regulation is satisfactory.

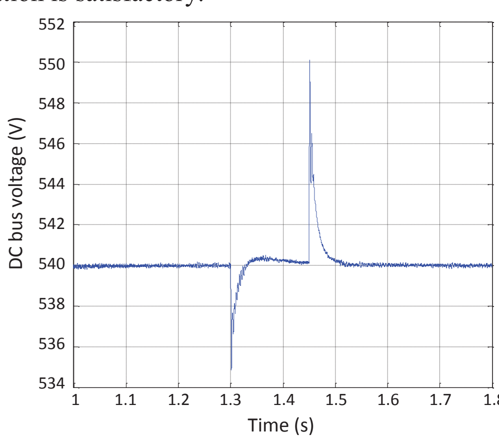

Fig. 8. The DC bus voltage regulation characteristics of the proposed AC/DC hybrid generation system

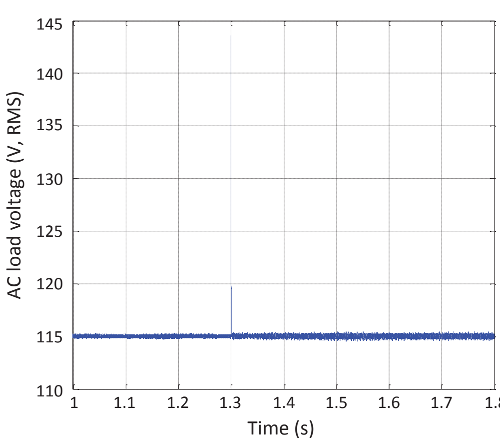

Fig. 9. The AC load voltage regulation characteristics of the proposed AC/DC hybrid generation system

The electromagnetic torque characteristics of the HP and LP generators are illustrated in Fig. 10. Clearly, the slow torque response of HP generator is compensated by the fast responded LP generator. At 1.45s, the HP generator operates as the master and does not react as the DC load changes, while the LP generator decreases its torque to accommodate the DC load change.

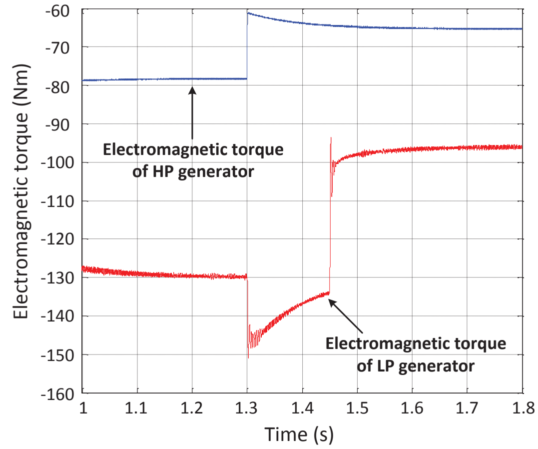

Fig. 10. The electromagnetic torque characteristics of HP and LP generators in the proposed AC/DC hybrid generation system

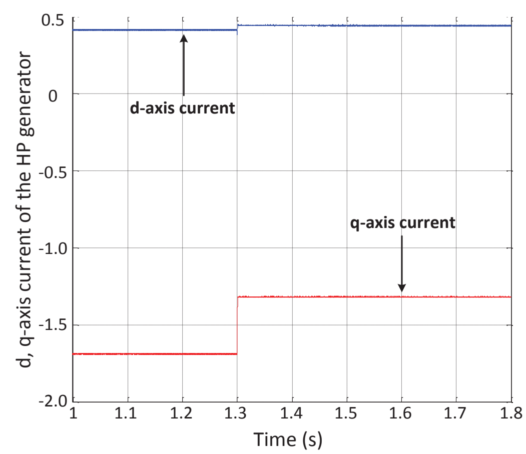

Fig. 11. The d, q-axis current characteristics of the HP generator in the proposed AC/DC hybrid generation system

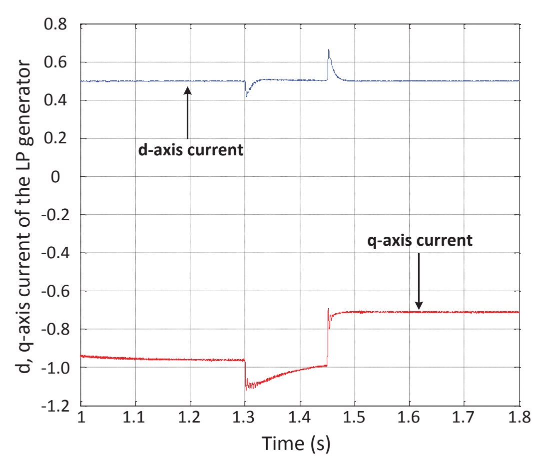

Fig. 12. The d, q-axis current characteristics of the LP generator in the proposed AC/DC hybrid generation system

The *d* and *q* axis currents of the HP and LP generators in the proposed system are shown in Fig. 11 and Fig. 12. As it is mentioned in Section III, regulating AC load voltage with a constant (or slowly varied) DC output power can be achieved by controlling q-axis current with small variation of generator flux.

VI. CONCLUSION

In this paper, an induction generator based AC/DC hybrid generation system for MEA is presented. The application of induction generator addresses the concern of excessive fault current due to the PM excitation in PM generator based generation system. The proposed AC/DC hybrid generation architecture supplies CVVF AC power directly from generator terminals without external exciter. As a result, the hardware installment is reduced compared to both AC and DC primary generation systems. Both AC and DC output voltages of the system can be well-regulated with load variation. The feasibility of operation of the proposed system is demonstrated in Matlab/Simulink.

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