An Open-End Winding IG-Based AC/DC Hybrid In APU For Electric Power Generation System for More Electric Aircraft

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ABSTRACT

In more electric air ship (MEA) framework, both air conditioning and dc electric power with numerous voltage levels are required for different air ship loads. This paper exhibits an acceptance generator-based air conditioning/dc cross breed electric power age framework for MEA. In the proposed framework design, a rapid enlistment starter/generator and a low-speed acceptance generator are introduced on the high weight (HP) and low weight (LP) spools of the motor, individually. In producing method of task, the majority of the steady voltage variable recurrence air conditioning power is created by the HP generator while the dc control request is shared by both HP and LP generators. A control conspire is created to direct the air conditioner stack voltage and facilitate dc control age between the two generators. The proposed enlistment generator based air conditioning/dc crossover age framework brings about diminished equipment prerequisite contrasted and both air conditioning and dc essential age frameworks.

Keyword : - *Aircraft, distributed power generation, generators, induction motors, power generation control.*

1. INTRODUCTION

THE EMERGING pattern toward more electric design for planes is planned to supplant mechanical, pressure driven, and pneumatic frameworks with electrical frameworks however much as could reasonably be expected. It is for the most part thought about that the more electric air ship (MEA) would prompt lower fuel utilization and emanations, lessened upkeep, and perhaps bring down expenses [1]– [4]. Progressions of on-board charge have expanded the electric power request of the air ship. A huge raise of age limit is required to supply the extra loads. As is appeared in Fig. 1, in display MEA frameworks (e.g., Boeing 787, Airbus A380), the injury field synchronous generator (SG)-based air conditioning essential age framework [5], [6] can encourage the recurrence uncaring burdens straightforwardly from the SG terminals. The steady voltage variable recurrence (CVVF) air conditioning load voltage is managed by controlling the field current of the SG through an

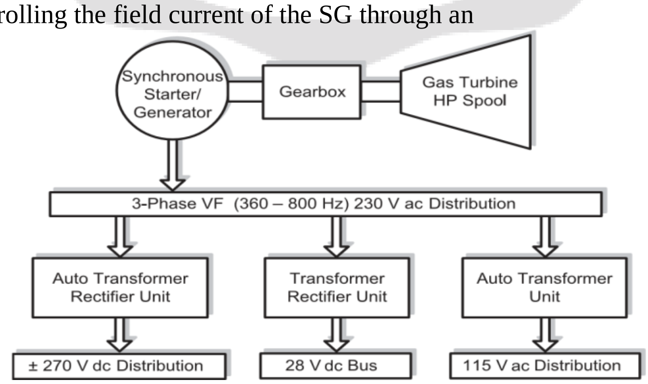

Fig. 1. System configuration of the SG-based ac primary generation system [6].

outer brushless exciter. This exciter comprises of a perpetual magnet (PM) machine and a diode rectifier mounted on the generator shaft. By changing the excitation of the field winding, the air conditioner source voltage can be directed with variable shaft speed. Be that as it may, in the SG-based air conditioning essential age framework, the unpredictable rotor structure makes the torque to latency proportion of SG lower than other sort of electric machines [1]. Also, the turning diode connect structure constrains the best speed of the generator shaft. On the off chance that the synchronous machine is utilized as a starter/generator, isolate field and armature voltage controls are required amid its motoring task.

In MEA frameworks, the impact of electrical power offtake can once in a while have noteworthy effect on the progression and control of the air ship engine[7].For occurrence, amid the change from journey to plunge stage, the air ship motor power is momentarily decreased while keeping up high electrical power request. This progress makes a plausibility of motor flimsiness and may require significant electric load shedding. This issue can be settled by introducing an additional generator on the low pressure(LP) spool of the motor and sharing the electrical power extraction between the high weight (HP) and LP spools [4]– [7].

Keeping in mind the end goal to parallel the two generators worked at various frequencies, a dc essential age framework with control electronic converters is favored as a propelled more electric engineering [8], [9]. PM generator is favored in this twinspool twin-generator design because of its powerful thickness and self-energized ability [8]– [10]. As appeared in Fig

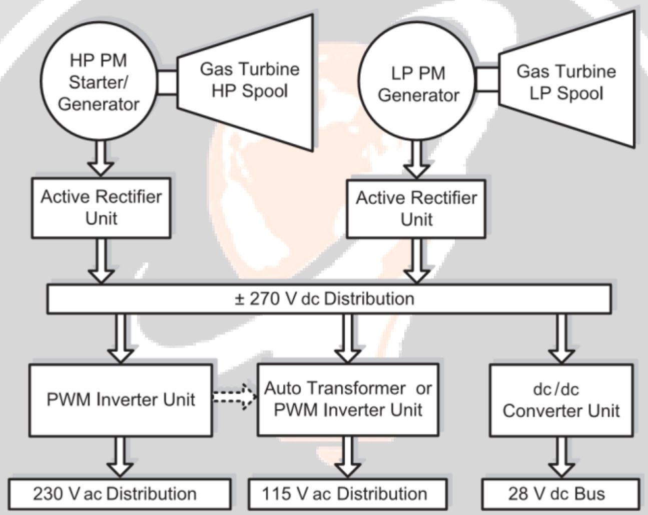

Fig.2. System configuration of the PM generator-based dc primary generation system

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. During the flight mission, the power generated from the two generators are rectified and transmitted to a ±270-V dc power bus. This type of system presents high power factor and high efficiency, but suffers from excessive current flow during fault condition because of the use of PM generators]. Albeit multiphase blame tolerant PM generators have been explored to restrict the short out blame current [11]–[13], utilizing PM generator to satisfy the over-burden current necessity of principle motor generator in aviation application is as yet risky. Moreover, introducing the PM generator near the gas turbine motor may significantly influence the framework dependability since most PM materials are defenseless against demagnetization under high temperature. At long last, contrasted with the SG based air conditioning essential age framework engineering, the CVVF control requested by recurrence coldhearted burdens (e.g., wing de-icing framework, galleys, and so forth.) in dc essential age framework is first changed over to dc control by the dynamic rectifier of the generator, and reversed back to air conditioning power through committed inverters. This two-arrange ac– dc– air conditioning transformation includes additional misfortunes and extra equipment to the framework. In Boeing 787, under reviling condition, the power devoured by the recurrence inhumane air conditioning loads is near half of the aggregate electrical power utilization [8].

Utilizing enlistment machine as fundamental motor generator in flying machine application is infrequently revealed in writing [14]– [16]. In medium power applications (50– 150 kW), the power thickness of enlistment generator (IG) is moderately higher than wound-field SG, however lower than PM generator [17]. In any case, the worry of unreasonable blame current because of the PM excitation for airborne applications can be effortlessly tended to by utilizing IGs. What's more, the inside impedance of IG is the most minimal among all kind of generators.

From the age framework design perspective, since neither air conditioning nor dc essential age framework can meet all the power prerequisites with upgraded execution regarding volume, weight, proficiency, dependability, and cost. Thus, in this paper, an IG-based air conditioning/dc half and half age framework is proposed to join the points of interest and address the deficiencies of the two frameworks. In this paper, the setup of the proposed IG-based air conditioning/dc half and half age framework for MEA is introduced. A relentless state investigation is done to clarify the proposed twin-spool twin-generator air conditioning/dc cross breed age technique. A shut circle control conspire for air conditioning and dc voltage direction of the proposed framework is created in view of field situated control (FOC) hypothesis. As an expansion of the work in [18], the attainability of activity of the proposed framework is shown by equipment on the up and up ongoing copying.

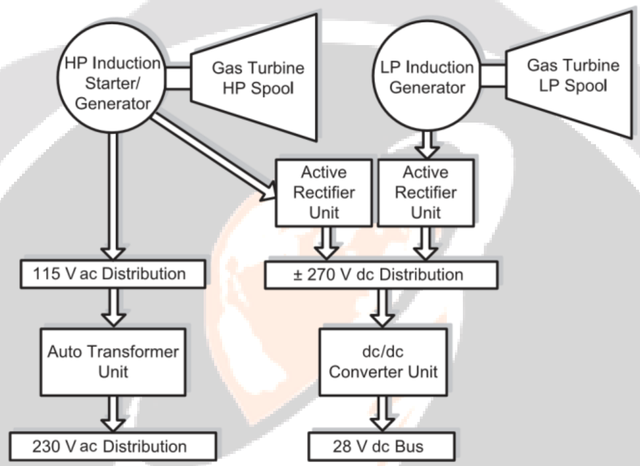

Fig. 3. System configuration of the IG-based ac/dc hybrid generation system.

2. SYSTEM CONFIGURATION

The proposed IG-based air conditioning/dc mixture age framework is appeared in Fig. 3. In the proposed framework, a fast open-end winding squirrel-confine acceptance starter/generator and a low speed tradition alwye-associated squir rel-confine IGareattached to the HP and LP spools of the motor ,separately .Ingenerating method of task, the HP generator is responsible for creating the greater part of the CVVF control, while the dc control request is shared by both HP and LP generators. The proposed air conditioning/dc cross breed age design can supply CVVF control specifically from one side of the generator twisting terminals without outside exciter, and create dc control on the opposite side of the generator twisting terminals through an inverter/rectifier unit. From the age framework design perspective, contrasted with dc essential age framework in Fig. 2, the undesired ac– dc– air conditioning transformation is evaded by applying air conditioning/dc half and half age on HP spool in the proposed framework, while the benefits of the twin-spool twin-generator dc essential age design have been saved.

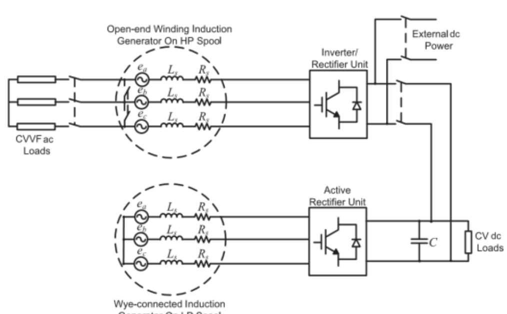

Fig. 4. Electrical system diagram of the IG-based ac/dc hybrid generation system.

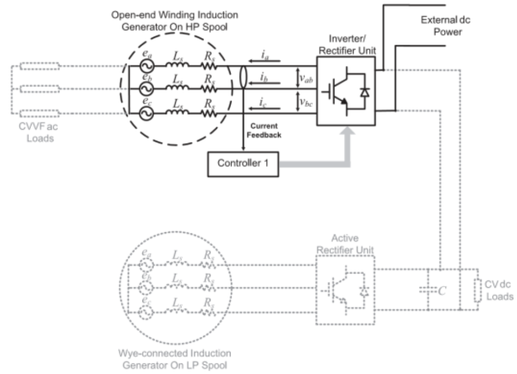

Fig. 5. Starter mode of operation of the IG-based ac/dc hybrid generation system.

the general age execution. Subsequently, the general equipment prerequisite of the proposed framework is lessened contrasted with both air conditioning and dc essential age frameworks. A more point by point electrical framework design is appeared in Fig. 4. An inverter/rectifier unit and recurrence heartless air conditioning loads are associated with each finish of the HP spool open-end winding IG terminals. A dynamic rectifier unit is associated with the LP spool wye-associated IG. The dc yield end of the inverter/rectifier unit and the dynamic rectifier unit are paralleled to the dc transport. In the vast majority of the MEA applications, other than producing electric power, the principle motor generator is additionally utilized as a starter for beginning the airplane motor. A dc control supply from the APU age framework or ground control supply is generally accessible forward is process.As is showninFig.5,in the motor beginning method of task, the whole LP spool age subsystem is deactivated. The air conditioner loads are detached from the HP generator, and the air conditioner stack side generator terminals are shorted to change the open-end IG on HP spool into a wye-associated enlistment engine. Extra circuit breakers are required to execute this change. Utilizing the dc control supply, the CHANGED

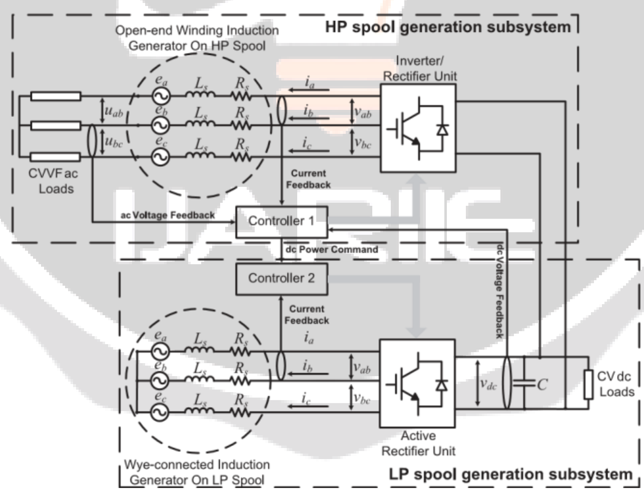

Fig. 6. Generator mode of operation of the IG-based ac/dc hybrid generation system.

enlistment engine can be driven by the inverter/rectifier unit to begin the airplane motor. Once the motor shaft achieves its sit without moving rate, the proposed framework starts to work in generator mode. As is appeared in Fig. 6, in this method of task, the air conditioner stack side terminals of the HP generator are associated with the CVVF loads, and the we associated IG on LP spool is actuated. All the CVVF control is created just by the HP generator, while the power request of the dc loads is shared between both the HP and LP generators. The dc-transport capacitor will be completely charged toward the start of the generator method of activity. In the proposed air conditioning/dc half breed age framework, rather than utilizing a regular wye-associated IG and interfacing the CVVF stacks in parallel with the inverter/rectifier unit [19], the CVVF loads, the HP shaft open-end winding IG, and the inverter/rectifier unit are associated in arrangement. Contrasted with the traditional shunt associated design

[19], the arrangement associated inverter/rectifier unit requires higher current appraisals. Be that as it may, the open-end winding generator design can build the yield voltage of the generator [20], [21], from which the present rating of the generator can be decreased for a similar measure of energy age request. Accordingly, the size and weight of the generator can be extraordinarily lessened contrasted with the shunt associated setup.

3. Framework MODELING AND OPERATION PRINCIPLE

As is appeared in Fig. 6, in the proposed age framework, all the CVVF control is just produced by the HP generator, while the power request of the dc loads is shared between both the HP and LP generators. The age subsystem on HP spool incorporates a fast generator, an inverter/rectifier unit, a CVVF appropriation transport, and a mutual CV dc dissemination transport. The age subsystem on LP spool comprises of a low speed generator, a dynamic rectifier unit, and the mutual CV dc dissemination transport. The framework model and activity rule of the age subsystems on HP and LP spools are examined in detail in the accompanying segments. A. HP Spool Generation Subsystem and AC Load Voltage Regulation In the HP spool age subsystem, the recurrence heartless loads in MEA (e.g., wing de-icing framework and cookroom loads), which are for the most part resistive warmers, are symmetrically disseminated at the generator terminals. Hence, the open-end twisting IG on HP spool can be demonstrated as a wye-associated IG with an expanded stator protection. In the rotor motion arranged reference outline, ignoring the immersion impacts, the steadystate voltage and torque conditions for the HP spool IG can be communicated as [17]

$$
\begin{aligned}
V_{qs1} &= (R_{s1} + R_{\mathrm{ac}L})\, I_{qs1} + \omega_{e1}\lambda_{ds1} \\
V_{ds1} &= (R_{s1} + R_{\mathrm{ac}L})\, I_{ds1} - \omega_{e1}\lambda_{qs1} \\
T_{e1} &= \frac{3}{2}\frac{P1}{2}\frac{{L_{m1}}^2}{L_{r1}} I_{qs1} I_{ds1} \\
\lambda_{qs1} &= L_{s\sigma 1} I_{qs1} \\
\lambda_{ds1} &= L_{s1} I_{ds1} \\
L_{s\sigma 1} &= L_{s1} - \frac{L_{m1}^2}{L_{r1}}.
\end{aligned}
$$

the above equations, Vqs1, Vds1, Iqs1, Ids1, λqs1, and λds1 are the q- and d-axis stator voltages, currents, and flux linkages, respectively. Rs1 is the stator winding resistance and RacL is the ac load resistance. Lsσ1 stands for the stator transient inductance (stator short-circuit inductance). Ls1, Lr1, Lm1, and P1, are the stator, rotor, magnetizing inductance, and pole pairs of the induction machine 1, respectively. ωe1 is the electrical frequency of the induction machine 1. In the proposed system, the ac loads (resistive heaters) are modeled as three-phase balanced resistors connecting in series with HP generator windings. In order to regulate the ac RMS loadvoltage,theacloadcurrent(statorcurrentmagnitude)needs to be controlled according to the load resistance variation. The ac line-to-line RMS load voltage can be expressed as

$$v_{\mathrm{ac}} = \sqrt{v_{a1}^2 + v_{b1}^2 + v_{c1}^2}$$

The ac load current reference can be expressed as

$$I^* = \sqrt{{I_{qs1}^*}^2 + {I_{ds1}^*}^2}$$

Limited by the current rating of the generation system, the power generated for frequency insensitive ac loads can be modeled as the heat generated by the three-phase balanced resistors connected in series with the HP generator. Thus, the power transmitted to the dc bus can be written as

$$P_{\mathrm{dc}1} = -\omega_{e1}\frac{T_{e1}^*}{P1} - (R_{s1} + R_{\mathrm{ac}L})\, I^{*2}$$

where Te∗1 is the torque reference of the HP generator.

According to (9), the torque reference can be determined by the ac load current reference and dc power output command. The theoretical equilibrium points of the HP spool generation subsystem for a given ac and dc power demand are illustrated in Fig. 7.

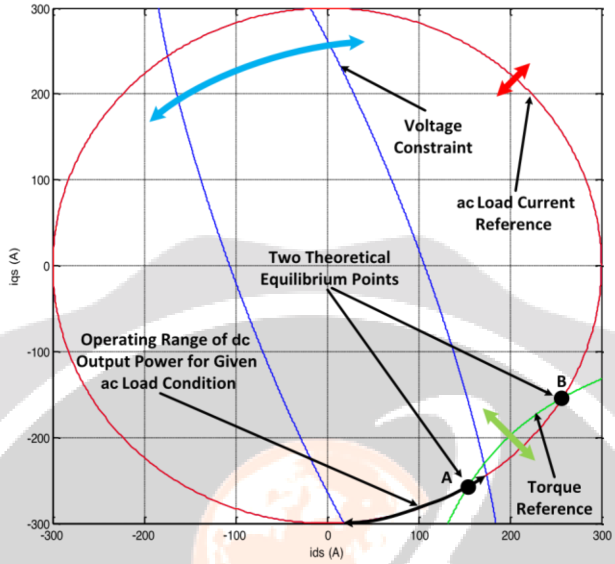

Fig. 7. Operating constraints of the HP spool generation subsystem.

In Fig. 7, 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 IG is limited by the voltage rating of the system. This voltage limitation can be expressed as follows:

$$V_{s21,\max} \geq V_{qs21} + V_{ds2\,1} \qquad (10)$$

Substituting (1), (2), (4), (5) into (10), the voltage constraint equation becomes

$$\left[\frac{(R_{s1}+R_{\mathrm{ac}L})\,I_{qs1}}{\omega_{e1}}+L_s I_{ds1}\right]^2 + \left[\frac{(R_{s1}+R_{\mathrm{ac}L})\,I_{ds1}}{\omega_{e1}}-L_{s\sigma 1} I_{qs1}\right]^2 \leq \frac{V_{s1,\max}^2}{\omega_{e1}^2}.$$

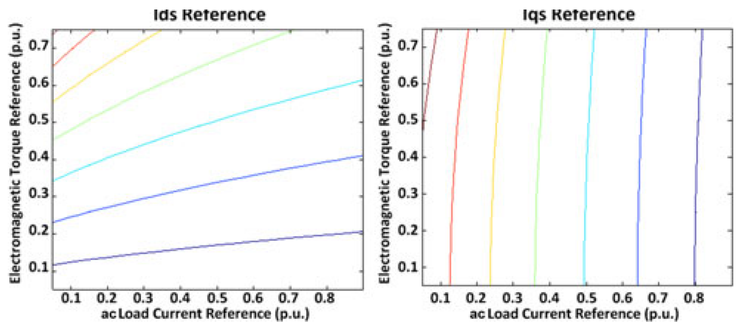

Fig. 8. Contour maps of *d-q* axis current commands for ac load current

Equation (11) forms a voltage limit ellipse in Fig. 7. This ellipse is similar to the analysis of flux weakening operation for induction motor [22], 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 clockwise rotation of the voltage limit ellipse and vice versa. Therefore, equilibrium point B in Fig. 7 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. The flux current command and torque current command Iqs∗ 1 can be calculated as the simultaneo us solution of (3) and (8). For a given ac load current reference and HP generator torque reference, the d and q-axis current references can be expressed as follows:

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

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

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 twodimensional sweep test of ac load current and generator torque reference is performed using MATLAB. Theresultsofthetestareshownascontourmapsin Fig.8.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 spool generation subsystem greatly depends on the flux variation of HP generator, resulting in a very slow system response. In contrast, 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 spool generation subsystem.

B. LP Spool Generation Subsystem and DC-Bus 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 the dc power demand. The dc power output of the LP generator is determined as

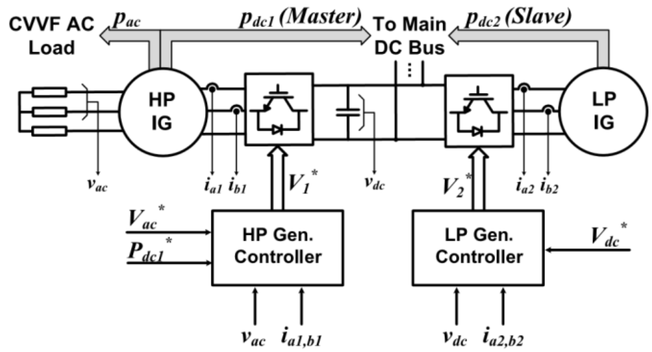

Fig. 9. Overall closed-loop control scheme for the proposed ac/dc hybrid generation system

$$P_{dc2} = v_{dc} C \frac{dv_{dc}}{dt} + v_{dc} i_{dcL} - P_{dc1} \quad (14)$$

where idcL is the dc-bus load current, Pdc1 and Pdc2 are the dc power output of the HP and LP generator, respectively. Other than the dc power extraction from the HP spool 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.

4. CONTROL SCHEME

The over all closed-loop control scheme for the proposed ac/dc hybrid generation system is shown in Fig. 9. The ac load voltage is solely controlled by the HP generator controller. The dc-bus voltage is regulated by a master-slave control strategy, which involves both the HP and LP generator controllers.The dc power output command Pdc1∗ from HP generator controller (master controller) is designed as a control input commanded by the engine control unit in order to prevent instability issue of the engine caused by high off-take of power extraction on HP spool. An additional control freedom is provided to the engine control unit to balance the power extraction from the HP and LP spools. The operating range of Pdc1∗ can be calculated and fed back to the engine control unit using (8), (9), and (11). The LP generator controller (slave controller) is commanded to fulfill the rest of the dc power demand from the main dc bus. 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 the generator current feedbacks. Neither the rotational speed of rotor nor the rotor position feedback is essential to control the proposed generation system. The control scheme of both the HP and LP spool generation subsystems are discussed in detail in the following sections.

A. Control Scheme for HP Spool Generation Subsystem

The proposed control scheme for HP shaft generation subsystem is shown in Fig. 10. In the HP spool generation subsystem, ac and dc power are generated from the two sides of the HP

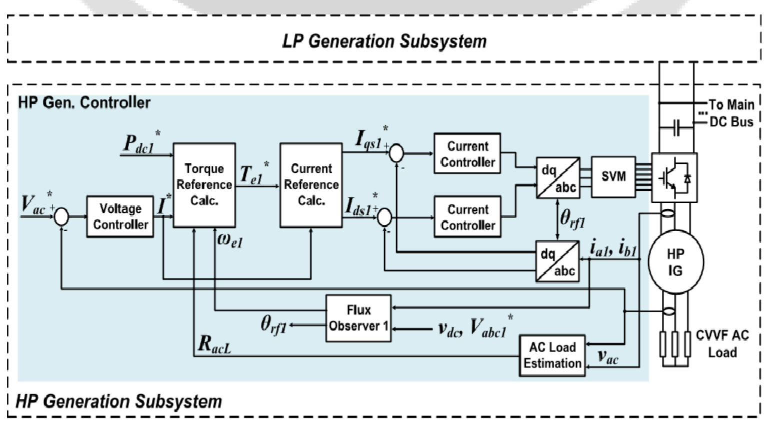

Fig. 10. Proposed closed-loop control scheme for HP spool generation subsystem.

related your research work Conclusion related your research work Conclusion related your research work Conclusion related your research work Conclusion related your research work Conclusion related your research work Conclusion related your research work Conclusion related your research work Conclusion related your research work Conclusion related your research work Conclusion related your research work generator winding, respectively. In order to decouple the ac and dc power supply of the HP spool generation subsystem, the two subsystem control inputs, ac load voltage reference Vac∗ and dc output power reference , are converted into d- and q-axis current commands of the HP generator.

This conversion can be implemented in four steps as follows.

1) Given the reference ac line-to-line RMS load voltage Vac∗ , a PI controller is used to provide the required ac load current command I∗ for regulating the voltage across the three phase balanced resistor (ac loads).

2) The ac load resistance RacL is estimated as the ac load voltage vac divided by the stator current magnitude I.

3) Given dc power output command Pdc1∗ , ac load current command I∗, ac load resistance RacL, and generator electrical frequency ωe1, the torque reference of the HP spool generator Te∗1 is calculated using (9).

4) Given the torque reference of the HP spool generator Te∗1 and the ac load current command I∗, the d- and q-axis current commands Ids∗ 1 and Iqs∗ 1 are obtained from (12) and (13).

The current control loop of the proposed control scheme is based on the field oriented control theory. A direct flux observer from [23] is used to provide the rotor flux speed ωe1 and angle θrf1 information. This flux observer inverter requires terminal voltage and generator stator current feedbacks. Since the inverter terminal voltages can be reconstructed using dc-bus voltage feedback and inverter gating signals, only stator current sensor and dc-bus voltage sensor are needed for field orientation. Using rotor flux orientation, two PI controllers are applied in the current control loop to regulate the d-axis current ids1 and q-axis current iqs1 of the HP generator. Space vector pulse width modulation (SVPWM) is used to generate gating signals for the active rectifier unit.

B. Control Scheme for LP Spool Generation Subsystem

The closed-loop control scheme for LP shaft generation subsystem is shown in Fig. 11. In the dc-bus voltage control loop, a PI controller is used to generate LP generator q-axis (torque) current command Iqs∗ 2. Since LP shaft generator has a wide speed operating range, flux weakening operation is required in the LP spool generation subsystem. The d-axis (flux) current of the LP generator is commanded to be inversely proportional to the generator shaft speed to obtain a wide speed operation range. The direct flux observer from [23] is used in the LP spool generation subsystem to provide the rotor flux speed ωe2 and angle θrf2 information.

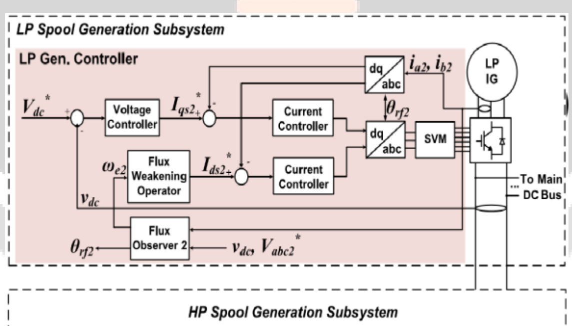

Fig. 11. Closed-loop control scheme for the LP spool generation subsystem.

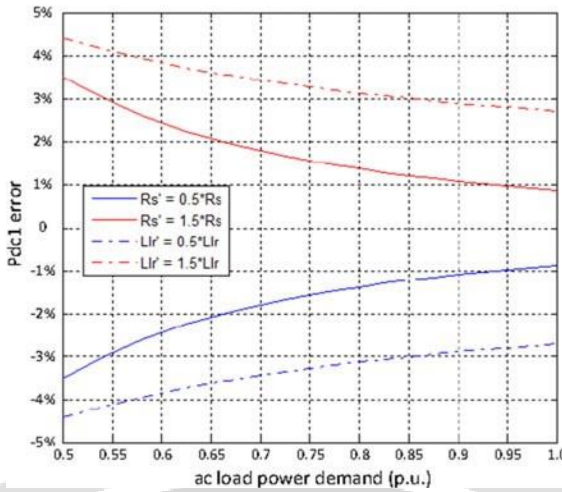

Fig. 12. DC power output error from HP generator stator resistance and rotor leakage inductance estimation inaccuracy

C. Robustness Assessment of the Proposed Control Scheme

The overall control scheme robustness toward generator parameter variations greatly depends on the flux orientation in both HP and LP generator controller. The robustness study and parameter sensitivity evaluation of the full-order flux observer [23] used in the proposed control scheme is well documented in [24] and [25]. In the proposed HP spool generation subsystem, the d- and q-axis current reference calculation requires the estimated values of the stator resistance Rs1, rotor leakage inductance Llr1, and magnetizing inductance Lm1 of the HP generator. As a result, the accuracy of the d- and q-axis current reference calculation results can be affected by the discrepancy between the actual and estimated values of the above HP generator parameters.

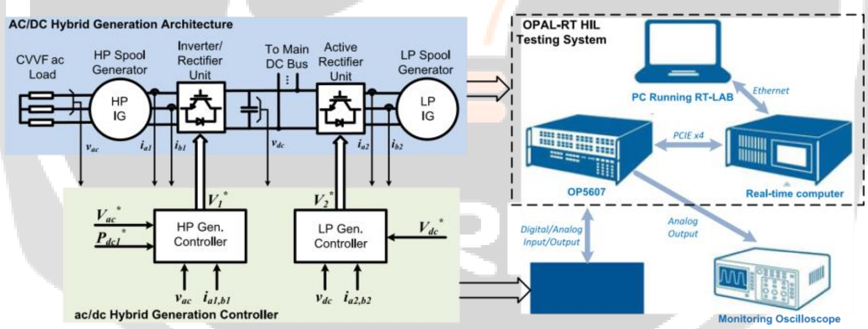

Fig. 13. Hardware-in-the-loop emulation implementation for the proposed ac/dc hybrid generation system.

q-axis current reference calculation errors caused by incorrect HP generator parameter estimation. Therefore, the robustness of ac load voltage control loop toward the generator parameter variation is superior. However, the inaccurate d- and q-axis current references can result in dc power output error in HP spool generation subsystem. Among the three generator parameters which have impact to the dc power output regulation precision of the HP spool generation subsystem, the stator resistance Rs1 and rotor leakage inductance Llr1 are relatively small, and contribute minor effect to the regulation robustness degradation. A parameter sensitivity test for dc power output in terms of HP generator stator resistance and rotor leakage inductance is performed using MATLAB. The results of the test are shown in Fig. 12. In this test, the dc power output is commanded to be kept as 1.0 (p.u.), while the ac load power demand varies from 0.5 to 1.0 (p.u.). For ±50% estimation inaccuracy in stator resistance and rotor leakage inductance, the resultant dc power output error is less than 5% throughout the ac load power variation. The dc power output regulation precision of the HP spool generation subsystem depends greatly on the estimation accuracy of the magnetizing inductance Lm1 of HP generator. Since the dc-bus voltage regulated in a master-slave strategy, as the master control output, the dc power output error from the HP spool generation subsystem can be compensated by the slave dc voltage controller in LP spool generation subsystem in normal operation. If the HP generator is operated in deep saturation region, saturated magnetizing inductance estimation methods [26]–[28] can be used to improve the dc power output regulation precision of the HP spool generation subsystem.

5. REAL-TIME EMULATION

In order to demonstrate the feasibility of operation of the proposed IG-based ac/dc hybrid generation system, a real-time emulation platform is built using OPAL-RT hardware-in-theloop (HIL) testing system. The emulated generation system is controlled by a Texas Instrument TMS320F28335 digital signal processor (DSP). A. Real-Time Emulation Setup As is shown in Fig. 13, the proposed ac/dc hybrid generation architecture is emulated using the OPAL-RT HIL testing system. The proposed architecture includes the HP generator, the

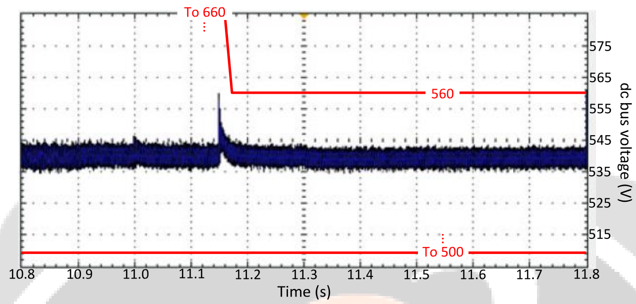

Fig. 14. DC-bus voltage regulation characteristics of the proposed ac/dc hybrid generation system.

inverter/rectifier unit, and 115-V balanced resistive ac load; as well as the LP generator, the active rectifier unit, and 540-V dc loads on the main dc bus. The OPAL-RT HIL testing platform is consisted of a Virtex 7 FPGA processor and I/O expansion unit (OP5607),are al-time target computer running Redhat operating system (OS), and a PC running the real-time simulation software (RT-LAB). Prior to the real-time emulation, the proposed system model is built and encrypted into FPGA codes in the PC running RT-LAB. The encrypted codes can then be loaded through the target computer running Redhat OS and executed in real time using the OP5607. The proposed control scheme is implemented in the DSP. The carrier frequencies of the HP and LP generator controllers are set tobe20and10kHz,respectively.TheFPGAunitcanreadthe10 and 20 kHz gating signal through the time-stamped digital input channels of OP5607 and execute the real-time emulation with time steps on nanosecond level. However, the feedback analog signals sent from the OP5607 can only update in every 40 us due to the limited computation power of the target computer. The analog outputs are read by the DSP analog-to-digital converter in every switching period. These feedbacks can also be monitored using an oscilloscope through the same analog output channels
B. Real-Time Emulation Case Study and Results
A real-time emulation case study is conducted under the HIL platform shown in Fig. 13. In the case study, a 85-kW 11 060-r/min IG and a 60-kW 3150-r/min IG are used on the HP and LP spool, respectively. In the beginning of the emulation, the generators are controlled to supply 60-kW three-phase 115-V ac balanced resistive load and 60-kW 540-V dc load at their rated speed. Step changes are applied to the ac load from 60 to 65 kW at 11.0 s, and to the dc load from 60 to 50 kW at 11.15 s. From 10.9 to 11.2 s, the HP and LP generator speed ramp to 110% and 120% of their rated speed, respectively. The dc power output command of the HP spool generation subsystem changes from 20to10 kW at 11.3 s. Currently, airborne electrical power system does not have an official voltage regulation standard for 540-Vdcbus.Theclosest available standard (MIL-STD-704F [29]) is for 270-V dc bus and limits the voltage variation so as not to exceed +10/ − 20V in steady state. Assuming the voltage variation limitation in MIL-STD-704F is doubled for the 540-V dc bus, the voltage variation allowed for the dc voltage regulation for the proposed system would be +20/ − 40V. The transient voltage limitation of the proposed system is assumed to be doubled for the same reason.

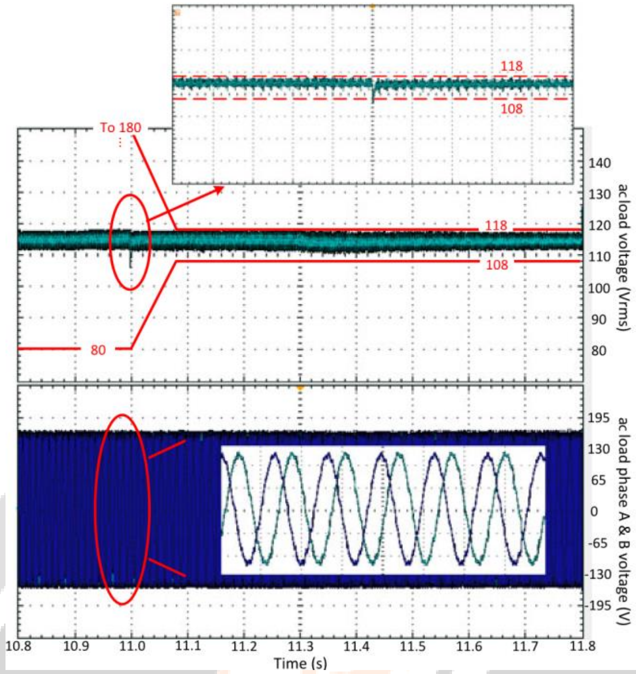

Fig. 15. AC load voltage regulation characteristics of the proposed ac/dc hybrid generation system.

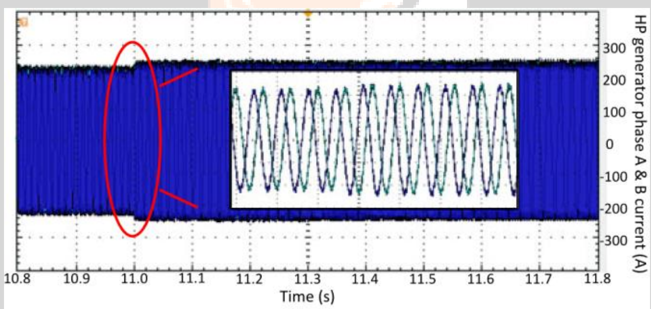

Fig. 16. Phase A and B current characteristics of the HP generator in the proposed ac/dc hybrid generation system.

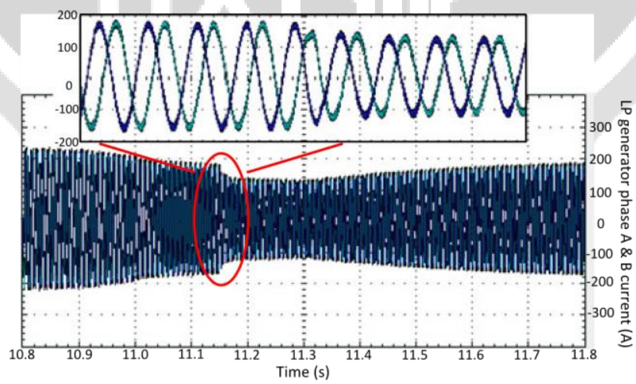

Fig. 17. Phase A and B current characteristics of the LP generator in the proposed ac/dc hybrid generation system.

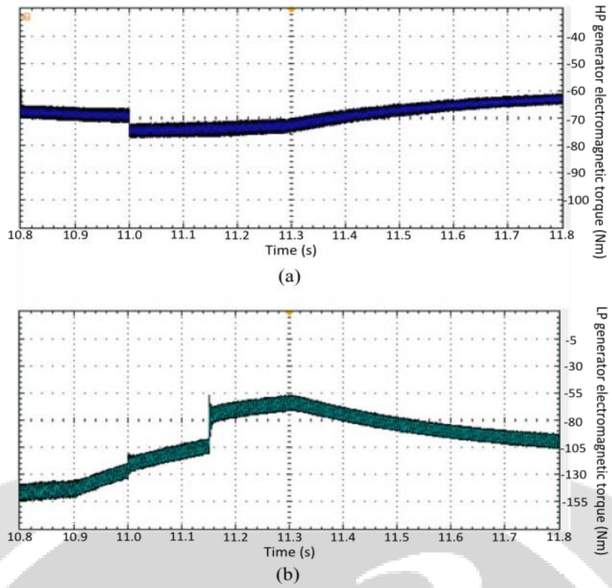

Fig. 18. Electromagnetic torque characteristics of (a) HP and (b) LP generators in the proposed ac/dc hybrid generation system

Thedc-busvoltagewaveformisshowninFig.14,theassumed voltage limit of the 540-V dc bus is illustrated as red lines. The ac load voltage waveform of the proposed system is shown in Fig. 15, the steady-state and transient voltage limit for a variable frequency 115-V ac distribution in MIL-STD-704F [29] is shown as red lines. The third phase ac voltage is absent because only two voltage sensors are installed to monitor the ac load voltage. The current waveforms of the HP and LP generators in the proposed system are shown in Figs. 16 and 17. The third phase current is absent because only two current sensors are installed for each generator. The electromagnetic torque characteristics of the HP and LP generators are illustrated in Fig. 18. When the dc load decreased from 60 to 50 kW at 11.15 s, 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 this load variation. At 11.3 s, the dc power output command changed from 20 to 10 kW. Since the dc power output of the HP spool generation subsystem greatly depends on the flux variation of HP generator, the torque response of HP generator is much slower compared to its immediate reaction to the ac load change at 11.0 s. Clearly, the slow torque response of HP generator is compensated by the fast responded LP generator. Both HP and LP generator respond to the speed variation from 10.9 to 11.2 s. The dc and ac voltage are not affected by the speed variation. The torque characteristics are monitored only for demonstration purposes, no torque transducer is needed for the proposed control scheme.

6. CONCLUSION

In this paper, an IG-based ac/dc hybrid generation system for MEA is presented. The application of IG addresses the problem of excessive fault current due to the PM excitation in PM generator-based generation system. The proposed ac/dc hybrid generation architecture supplies CVVF power directly from generator terminals without external exciter. As a result, the hardware requirement 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 generator speed, ac and dc side load, and dc power output command variation. The feasibility of operation of the proposed system is demonstrated by HIL real-time emulation.

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