An Induction Generator Based Auxiliary Power Unit for Power Generation and Management System for More Electric Aircraft

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Abstract- *In more electric aircraft (MEA) systems, the adoption of electro-hydraulic actuators (EHAs) and electromechanical actuators (EMAs) requires a power-on-demand electrical power system with regenerative power management capability. This paper proposes an auxiliary power unit (APU) for power generation and management system to supply/absorb the highly dynamic power demand/regeneration from the EHA/EMAs. The proposed system utilizes an open-end winding induction starter/generator (OEWIS/G) to create a separate DC bus for the actuators without adding significant hardware installment to the system. During the entire flight mission, the regenerative power is recovered by one side of the OEWIG terminals; meanwhile, the power delivery to the main DC network of the aircraft electrical power system can be independently controlled by using the same generator through the other side of the terminals. A closed-loop control scheme based on field oriented control and instantaneous power theory is developed to regulate both the main DC bus voltage and the electric actuation DC bus voltage simultaneously in aircraft emergency power mode.*

Keywords- induction motors, generators, aircraft, power generation control, regenerative power management

I. INTRODUCTION

In the trend towards more electric aircraft (MEA), the traditional hydraulic flight control actuators with central hydraulic system are being replaced by electro-hydraulic actuators (EHAs) or electro-mechanical actuators (EMAs). Compared to the traditional actuators, EHAs and EMAs have lower weight and volume, increased reliability and reduced maintenance [1-3]. However, these actuators have highly dynamic power profile, which includes high peak power demand and power regeneration [4-5]. The most widely used regenerative power management method for EHA/EMAs on aircraft is to employ resistor banks paralleled with the actuators, dissipating the regenerated energy with associated cooling devices. This solution renders the weight, volume, and efficiency of the overall system far from optimized [6]. Instead of dissipating the regenerative energy as heat, several researchers have proposed to use electrical energy storage elements (ESEs) such as ultra-capacitors and batteries to enable energy recovery [7-9]. Separate electric actuator bus can also be created with ESEs to protect the main electrical power network from disturbance and risks [8].. It is clear that returning the regenerative energy to the power source(s) demands minimum hardware installment [9]. However, without a separate electric actuation bus, securing the operation of the main aircraft electrical power grid within the limits of the specified standards [10-11] is quite a challenging task. This paper proposes an auxiliary power unit (APU) for power generation and management system that allows the regenerative power from the actuators to be absorbed by the turbine shaft of the APU. The open-end winding topology [12-14] is adopted to provide direct power flow path from the EHA/EMAs to the power source, and to create a separate electric actuation bus without significant additional hardware requirement. Since induction generators present higher power density compared to wound-field synchronous generators and better robustness and fault-tolerant capability compared to permanent magnet (PM) generators in MEA systems [15-16], an open-end winding induction starter/generator (OEWIS/G) is used as the APU starter/generator.

The separate actuation DC bus is located on one side of the OEWIG terminals, while the main DC bus of the aircraft electrical power system is connected to the other side of the terminals. In this way, the operation of aircraft main DC power network is prevented from perturbation and disturbance caused by the actuators. In this paper, the configuration and modeling of the proposed induction generator based APU for power generation and management system are presented. System operation for all operating conditions of the aircraft is analyzed. A closed-loop control scheme for regulating both main DC bus and actuation DC bus voltages in aircraft emergency power mode is developed based on field oriented control and instantaneous power theory. The feasibility of operation of the proposed system is demonstrated by simulation in Matlab/Simulink.

II. OPEN-END WINDING INDUCTION GENERATOR AND INVERTER/RECTIFIER UNITS MODEL

The configuration of the proposed induction generator based APU for power generation and management system for MEA is shown in Fig. 1. An open-end winding induction starter/generator is installed on the turbine shaft of an APU. The generator terminals are connected to two.inverter/rectifier units (IRUs). The main DC bus is connected to the left side of the generator terminals through IRU 1, while the electric actuation DC bus is located at the right side of the generator terminals through IRU 2. The common mode voltage and current between the two DC buses are inherently eliminated [17]. Consequently, all the space vector PWM switching combinations of the IRUs can be utilized.

The voltage equations of the dual inverter/rectifier system are [17-18]:

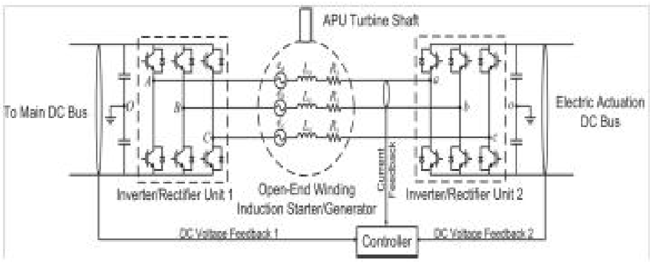

Fig. 1. System configuration of the proposed induction generator based APU for power generation and management system

$$v_{Aa} = R_s i_{as} + \frac{d\lambda_{as}}{dt}$$
$$v_{Bb} = R_s i_{bs} + \frac{d\lambda_{bs}}{dt}$$

$$v_{Cc} = R_s i_{cs} + \frac{d\lambda_{cs}}{dt}$$

$$v_{Aa} = v_{AO} - v_{ao} + v_{Oo}$$

$$v_{Bb} = v_{BO} - v_{bo} + v_{Oo}$$
$$v_{Cc} = v_{CO} - v_{co} + v_{Oo}$$

In the above equations, vAa, vBb, vCc are the stator phase voltages of the generator vAa, vBb, vCcare the pole voltages of IRU 1; vAa, vBb, vCc are the pole voltages of IRU 2; ia,ib,ic is the voltage difference between the mid-point of the two separated DC bus. are the generator stator currents and flux linkages, respectively. this is the stator winding resistance of each phase. Assuming the three phase windings of the induction generator are symmetric, it can be concluded that the mid-points of the two DC bus O and o are virtually equipotential In rotor flux oriented reference frame, the steady-state generator terminal voltage and electromagnetic torque can be written as [19]

According to Equations it can be concluded that the mid-points of the two DC bus O and o are virtually equipotential (i.e., vOo = 0). In rotor ux oriented reference frame, the steady-state generator terminal voltage and electromagnetic torque can be written as [82]

$$v_{qg} = v_{qs1} - v_{qs2} = R_s i_{qs} + \omega_e L_s i_{ds}$$
$$v_{dg} = v_{ds1} - v_{ds2} = R_s i_{ds} - \omega_e L_{sc} i_{qs}$$
$$T_e = \frac{3}{2} PP\,(L_s - L_{sc})\, i_{qs} i_{ds}$$

where vqg, vdg, iqs, ids are the q and d axis generator voltages and currents, respectively; vqs1, vds1, vqs2, vds1 are the q and d axis voltages of IRU-1 and IRU-2, respectively. Te is the electromagnetic torque of the generator, while PP is the number of generator pole pairs. Ls, is the generator stator inductance, Lsc is the generator short-circuit inductance. The instantaneous active power delivered to the main DC bus and electric actuation DC bus can be expressed as

$$p_{dc1} = \frac{3}{2}\left(v_{qs1} i_{qs} + v_{ds1} i_{ds}\right)$$

$$p_{dc2} = -\frac{3}{2}\left(v_{qs2} i_{qs} + v_{ds2} i_{ds}\right)$$

$$p_g = p_{dc1} + p_{dc2} = \frac{3}{2}\left[(v_{qs1} - v_{qs2}) i_{qs} + (v_{ds1} - v_{ds2}) i_{ds}\right] = T_e \omega_e \triangleq T_e \omega_r = \frac{3}{2}\omega_r PP(L_s - L_{sc}) i_{qs} i_{ds} \quad (12)$$

III. SYSTEM OPERATING PRINCIPLE

The major functionalities of a conventional APU are: i) to start itself using aircraft battery or ground electric power supply (self-start mode); ii) to start the main engine while the aircraft is on the ground (main engine start mode); iii) to provide emergency electrical power (and other types of auxiliary power) during main engine failure (emergency power mode). In addition, a more advanced integrated APU can also act as environmental control system (ECS) and thermal management system (TMS) during the flight mission (cooling mode) [20]. The four major operating modes of the proposed integrated APU for power generation and management system are explained as follow:

A. Self-start mode of operation

As shown in Fig. 2 (a), in self-start mode, the electric actuation DC bus is disconnected from the system. The right side terminals of the induction machine are shorted through IRU 2. The open-end winding induction generator is thereby transformed into a wye-connected induction motor. IRU 1 is operated as an inverter, driving the induction machine as starter to accelerate the APU turbine shaft using the electrical power from the aircraft battery or ground power supply. Once the APU shaft speed exceeds its self-sustaining speed, the self-start mode is complete.

B. Main engine start mode of operation

In main engine start mode, the APU engine produces mechanical power to the turbine shaft through combustion of fuel, and drives the induction machines as a generator. As it is illustrated in Fig. 2 (b), the electric actuation DC

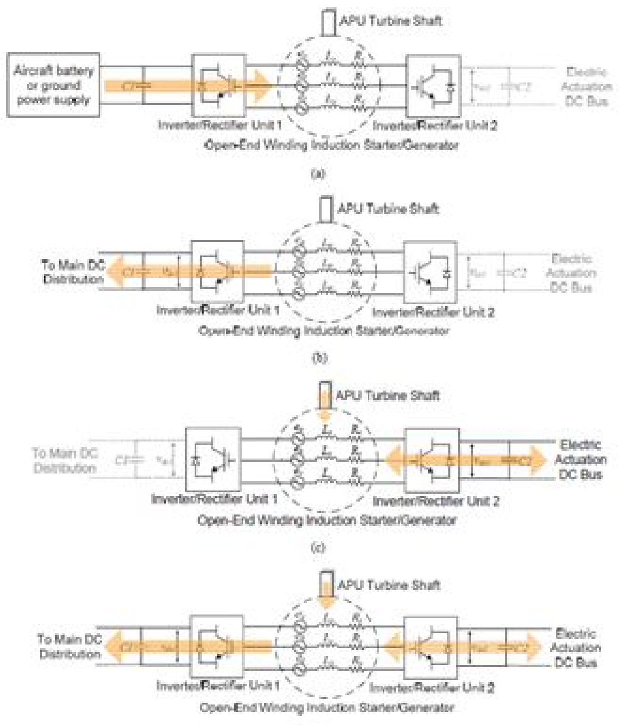

Fig. 2. Operation principles for the propose integrated APU for power generation and management system in (a) self-start mode, (b) main engine start mode of operation, (c) cooling mode and (d) emergency power mode

bus is still disconnected from the system. The transformed we-connected induction machine now operating as a generator provides electrical power through IRU 1 to the main DC bus. The transmitted power is used by the main engine starter/generator to spin up the high pressure (HP) spool turbine of the main engine. After the main engine is started, the system transits into cooling mode.

C. Cooling mode of operation

In the cooling mode of operation, the combustor of APU is no longer used. The high stage bleed air from the main engines is first cooled down by the APU turbine, and then sends to supply cabin pressurization and air conditioning. Part of the cooled air is also circulated to provide forced air cooling for avionics, flight critical electronics and other liquid cooled heat loads [20]. During a normal flight mission, most of the electrical loads on board are supplied by main engine generation system. Hence, as it shown in Fig. 2 (c), the main DC bus is disconnected from the APU power management system in the cooling mode. The left side terminals of the open-end winding induction machine are shorted through IRU 1. The APU turbine shaft, powered by the high stage bleed air from main engines, is responsible to supply/absorb the high peak power demand/regeneration from the EHA/EMAs using IRU 2.

D. Emergency power mode of operation

The emergency mode operation of the proposed system is shown in Fig. 2 (d). When an in-flight main engine failure occurs, the APU is commanded to operate in full power and produce electricity to support main DC network and potential main engine re-start. In case of dual (all) engine failure, the APU generator is responsible for regulating the main DC bus voltage. As one of the most critical electrical loads on board, the power of EHA/EMAs must be secured at all time during the flight mission. Therefore, in emergency power mode of operation, both sides of the open-end winding induction generator are activated. IRU 2 is responsible for supplying the highly dynamic actuator loads, while IRU 1 is used to provide disturbance-free DC power supply or voltage regulation for the main DC bus.

IV. SYSTEM DESIGN CONSIDERATIONS

In self-start mode, main engine start mode, and in cooling mode of operation, the main DC bus and electric actuation DC bus are isolated because only one side of the open-end winding induction generator is activated. In these modes of operation, the amount of power generation and managed by the proposed system is only a portion of the full system power rating. In the emergency power mode, both sides of the open-end winding induction generator are activated. The proposed power management system is responsible for supplying disturbance-free DC power to the main DC network and regulating the electric actuation DC bus voltage simultaneously. The main DC network has a relatively large but stable load power requirement, whereas the load profile of the actuators, although has smaller peak value, is bidirectional and highly dynamic. The continuous duty of the APU generator can be rated as the sum of nominal main DC load power requirement and average actuator bus load demand. While the actuators are drawing power from the system in the emergency power mode, the open-end winding induction generator is providing electrical power to both ends. In this scenario, the electromagnetic torque command of the generator is increased, but limited by the generator's current rating. Since the two IRUs and the generator are connected in series, the current ratings of these units are identical. In other words, the current rating of the proposed system should be designed to fulfill the total maximum power demands from both the main DC bus and the actuator DC bus. The maximum current requirement can be expressed as a function of the APU generator speed and flux current command

$$I_{smax} \approx \sqrt{\left[\frac{4(P_{dc1,max}+P_{dc2,max})}{3PP(L_s-L_{sc})\omega_r i_{ds}^*}\right]^2 + {i_{ds}^*}^2}$$

As an APU generator, the OEWIG in the proposed system is operated in the flux weakening region for a wide speed range. In most flux weakening algorithms, the flux current command is calculated as a function of the generator speed. Therefore, the current rating of the proposed system can be eventually determined by the APU generator speed range and the maximum power requirement from the main DC bus and actuation DC bus.

While the actuators are sending regenerative power back in the emergency operation mode, the power demanded by the main DC network is partially contributed by the regenerative power from the actuators, and the remaining power demand is supplied from the APU shaft power. Since the generator power command is the sum of the power demand of the two DC buses, for the same main DC bus power demand and APU shaft speed, increasing regenerative power from the actuator bus leads to a decreased generator torque command. As the torque command of the generator decreases, the current magnitude falls down. To supply the same amount of active power to the main DC bus with reduced current magnitude, the voltage magnitude of IRU 1 needs to be increased. The larger the regenerative power is absorbed by the generator, the higher output voltage is needed on IRU 1 side. As it shown in Fig. 3, in order to deliver maximum active power to the main DC network with limited output voltage, IRU 1 should be commended to operate under unity power factor.

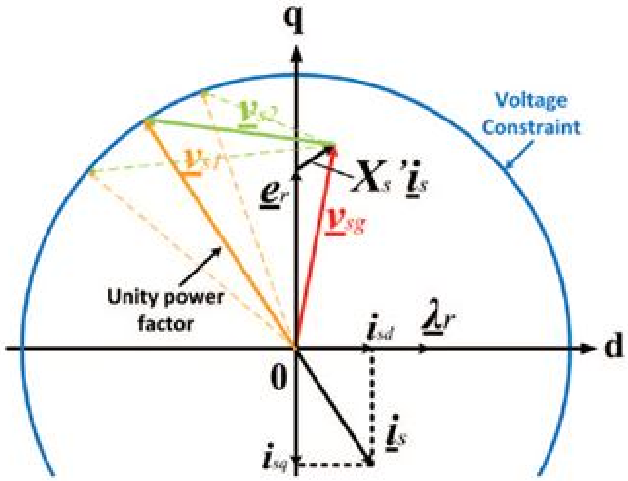

Fig. 3. Unity power factor operation on main DC network side inverter/rectifier unit

In unity power factor operation, assuming space vector modulation method is used and neglecting the power losses, the active power transmitted through IRU 1 and delivered to the main DC network can be written as:

$$p_{dc1} = \frac{3}{2} m \frac{v_{dc1}}{\sqrt{3}} |i_s|$$

where m is the modulation index of IRU 1, and is the current magnitude of the induction generator. According to (14), the modulation index of IRU 1 would eventually reach its limit with the increasing regenerative power. In this manner, for a given shaft speed, the regenerative power absorption capacity of the proposed power management system can be expressed as:

$$P_{dc2\,\max\,regen.} \triangleq \frac{3}{2}\omega_r PP(L_s - L_{sc}) i_{ds}^* \sqrt{\frac{4}{3}\frac{{p_{dc1}^*}^2}{{v_{dc1}^*}^2} - {i_{ds}^*}^2}$$

V. CONTROL SCHEME IN EMERGENCY POWER MODE

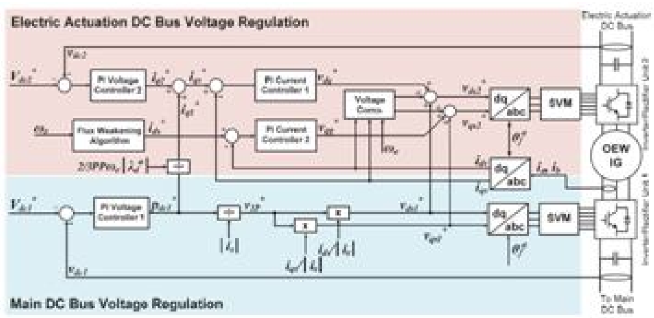

Fig. 4. Closed-loop control scheme for the proposed APU for power generation and management system in emergency power mode

The closed-loop control scheme for the proposed APU for power generation and management system in emergency power mode is shown in Fig. 4. Two voltage sensors are used to monitor the voltages of two separated DC buses. Two current sensors are used to provide stator current feedbacks. Neither rotational speed of rotor nor rotor position feedback is essential to control the proposed generation system. The proposed control scheme is developed based on field oriented control and instantaneous power theory [19], [21]. The field orientation of the proposed control scheme is implemented by an active flux based direct flux observer using inverter terminal voltage and generator stator current feedbacks [22]. The inverter terminal voltages are reconstructed using DC bus voltage feedback and inverter gating signals.

If all of the engines of the aircraft have failed during flight mission, the main DC bus voltage is regulated by the proposed system through PI voltage controller 1. The output of this controller is the main DC side power command . In case of single engine failure, the main DC bus voltage control loop is disabled, and can be provided by main DC bus voltage regulator from the main engine system. To ensure unity power factor operation, the output voltage vector of IRU 1 is always kept aligned with generator current vector and can be calculated as

DC power output of IRU 1 from generator current magnitude variation. PI voltage controller 2 is used to regulate the electric actuation DC bus voltage. The generator q-axis (torque) current command is determined by the adding the q-axis (torque) current needed for the actuation DC bus with the q-axis (torque) current demanded by the main DC bus . Using rotor-flux orientation, two PI current controllers are applied to regulate and .

VI. RESULTS

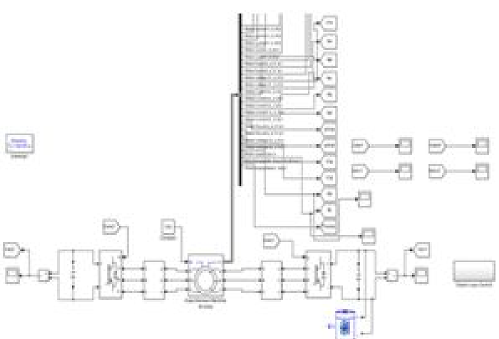

Fig 6.1 Simulation diagram for an induction generator based auxiliary power unit for power generation and management system for more electrical aircraft

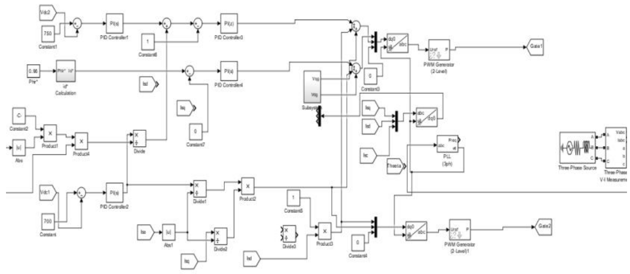

Fig 6.2 Close loop scheme for the processed APU

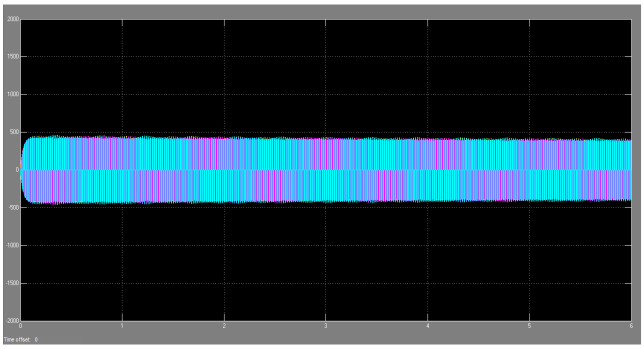

Fig 6.3 Input voltage Vabc1 at right side of the generator

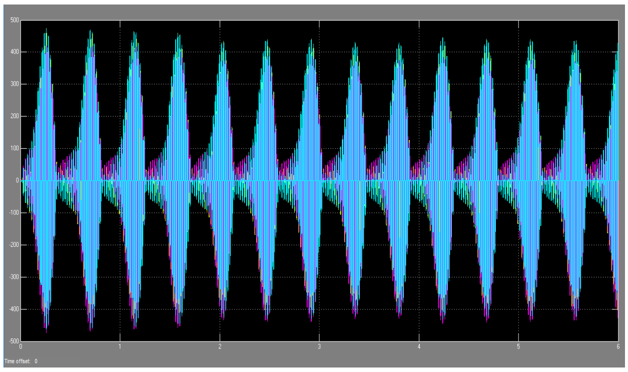

Fig 6.4Input voltage Vabc2 at left side of the generator

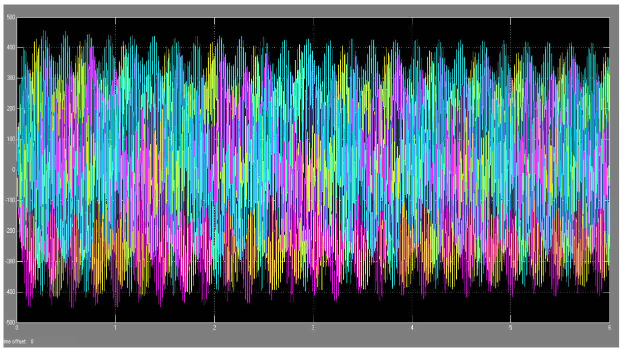

Fig 6.5 Input current Iabc1 at right side of the generator

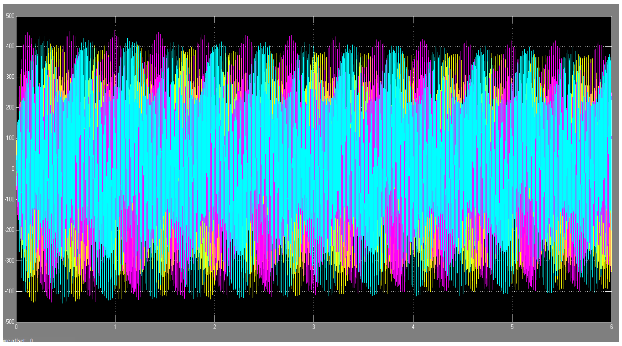
Fig 6.6 Input current Iabc2 at left side of the generator

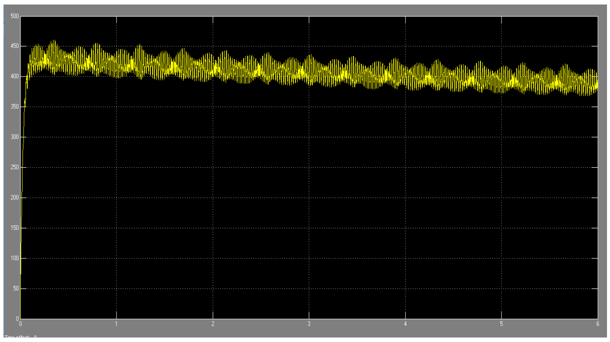
Fig 6.7 Output voltage at actuator side Vdc1

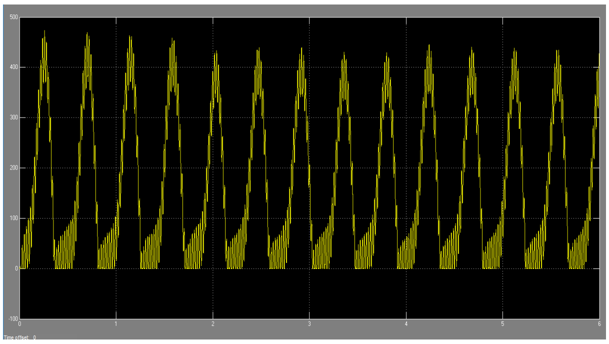
Fig 6.8 Output voltage at main D.C bus side Vdc2

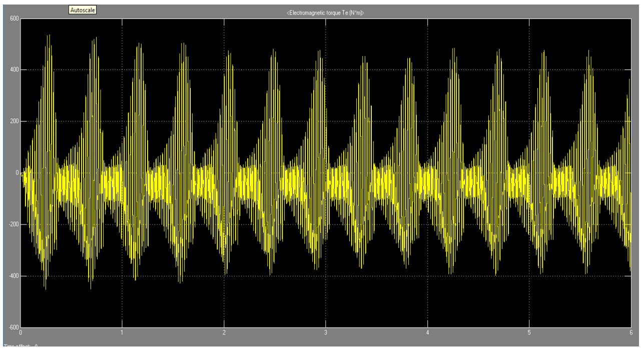
Fig 6.9 Electromagnetic torque (Te)

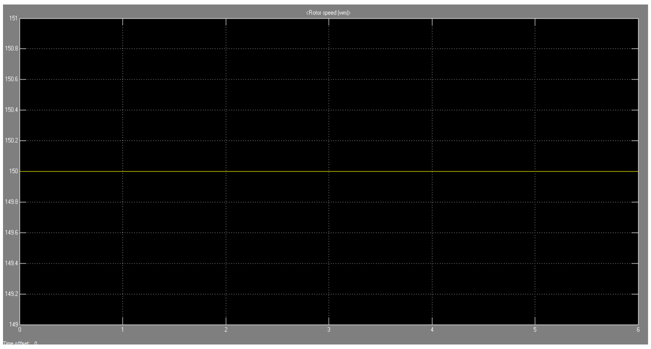
Fig 6.10 Rotor speed (Wr)

VII. CONCLUSION

In this paper, an induction generator based auxiliary power unit for power generation and management system for MEA is presented. The proposed APU power generation and management system provides direct power flow path from the EHA/EMAs to the power source, but prevents the main DC network from perturbation and disturbance caused by the actuators. A separate DC bus is created for the EHA/EMAs without adding significant hardware installment. Both main and electric actuation DC bus voltages of the system can be well-regulated simultaneously. The feasibility of operation of the proposed system is verified in Matlab/Simulink and the results are presented.

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