Optimal and stable electric power system for more electric aircraft: parallel operation of generators and weight reduction

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More electric aircraft has become an interesting topic in recent studies. In this paper, an optimal electric power generation mechanism is proposed for aircraft. Inverter-interfaced engine-driven induction generators are considered as distributed generators in the aircraft microgrid. Droop controller is applied to enable the parallel operation of generators and eliminate using of conventional constant speed drives. A new method is proposed to determine optimal droop gain for active power sharing. The method is applied to minimize the frequency deviation of the AC aircraft network. In the following, the reactive power sharing is considered as a challenge in case of asymmetrical load distribution. By proposing a new algorithm, optimal reactive power droop gain is determined with regard to the small signal stability of the system. Proposed power sharing methods are evaluated by simulation of a sample aircraft grid. The optimization results for assigned power and droop gain are given. Simulation results show that the frequency regulation of aircraft electric grid is properly achieved. Also it is shown that the reactive power sharing is enhanced and the system stability is maintained.

keywords: *Aircraft, Constant Speed Drive, Optimal Droop Gain, Power Sharing.*

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NOMENCLATURE

Nomenclature

n Index of generator number
k Index of time interval
$m_{n,k}$ Droop gain
f_{Nom} Nominal frequency
$f_{n,k}$ Output frequency of generator
$P_{n,k}$ Active power of generator
f_k^M Frequency of the microgrid
D_k Frequency elasticity
i Index of optimization iteration number
$m_{k,i}^{ref}$ Reference droop gain
$\eta_{k,i}$ Weighting coefficient
$f_{k,i}^{ref}$ Reference frequency
MSFE Mean square frequency error
μ Convergence factor
L_c Coupling inductance
r_{Lc} Internal resistance of coupling inductance
L_f Output filter inductance
r_{Lf} Internal resistance of output filter inductance
C_f Output filter capacitance
ω Inverter output frequency
ω_f Cut-out frequency
P Average value of active power
Q Average value of reactive power
ω_n Nominal value for frequency of the aircraft grid
V_n Nominal value for voltage of the aircraft grid
k_1 Active power droop gain
k_2 Reactive power droop gain
k_{pv} Proportional coefficient of PI controller for voltage controller
k_{iv} Integral coefficient of PI controller for voltage controller
k_{pc} Proportional coefficient of PI controller for current controller

k_{ic} Integral coefficient of PI controller for current controller
f_s Switching frequency of inverter
F Feed forward gain

1. INTRODUCTION

In modern aircrafts, utilization of electric power has been more increased [1]. Electrical systems are more efficient in comparison with mechanical, hydraulic and pneumatic systems. Therefore, recent aircraft energy management systems have moved toward more electric aircraft (MEA). Due to the sensitive characteristic of aircraft, optimal power generation has great importance in electric system availability [2].

Electrical utility in aircrafts often consists of two 400 Hz AC generators with a voltage amplitude of 115 volts, which are driven by turbojet engines. DC load demand is supplied by transformer rectifier units. DC aircraft has also been studied in aircraft electric system studies [3, 4]. With regard to the protection challenges of DC networks, reliability of DC aircraft grids is not completely guaranteed.

For generating AC power, constant speed drives are used in combination with synchronous generators. They provide nearly constant output frequency for the output voltage. Constant speed drive comprises a mechanical system that is connected to the engine. Nevertheless, constant speed drives increase the total weight of the aircraft due to gearbox and other mechanical structures. Also, the system price is high and its maintenance is too complex [5].

In conventional aircraft power grids, two synchronous generators in the right and left side separated by a tie switch, supply the loads. In case of failure, one generator is isolated and load demand is supplied by the other generator while the normally open tie switch is closed. Thus, the lack of control mechanism for the parallel operation of generators has reduced the overall system reliability [6].

Electrical loads in the aircraft comprise lighting services, motors and actuators, heating, avionics systems and controllers. The reactive power demand is noteworthy due to the wide range of electric motor applications in the aircraft [7, 8]. Hence, generators should be properly controlled to produce load reactive power.

At present, distributed generation (DG) has become an interesting type of power source in modern utilities. DGs give decentralized power management potential to power grids and are more flexible due to the using of power electronic converters. Many researches have been developed to improve the controller of these converters for industrial applications like aircrafts [9].

Hybrid energy systems have also been considered to enhance the efficiency and reliability of modern aircrafts. In [10], a hybrid energy storage system with supercapacitor and battery is considered to supply the power. Discrete wavelet transform is used as a frequency method for power generation. In [11], an adaptive online power management algorithm is proposed for a hybrid battery-supercapacitor energy storage system of the aircraft to minimize the power fluctuation of the generators. In [12], hybrid fuel cell and fossil fuel based generators are considered as the power sources of the aircraft and optimal fossil fuel and hydrogen consumption and polluted gas emission are determined by Karush–Kuhn–Tucker optimality condition. Increasing the total aircraft weight and cost and low battery life due to the high cycling, are the main drawbacks of hybrid systems.

Aircraft electric system can be considered as an islanding microgrid. In microgrids due to the limitation of power capacity, energy management has great importance. The microgrid stability and sustainability depend on power quality of electric system [13, 14].

Many researches have been developed in optimal power management and improving frequency stability in islanded AC microgrids. In these studies optimization approach is provided for active power sharing to enhance the frequency regulation [15, 16].

Load balance is another important factor in the power distribution of aircraft electric grid [17, 18]. Asymmetrical load distribution concerns the reactive power sharing among the generators [19]. The respect of generators reactive power is not compatible with the respect of their active power generation which has been scheduled. In microgrids, one of the most important issues is to supply high quality powers in the presence of load unbalance. This problem is commonly solved by using energy storage systems [20], which is not practical solution in economic and reliable point of view for aircrafts.

The stability of the aircraft power system is critical along with the power availability to completely supply the load demand. In [21], the aircraft power system is modeled for eigenvalue analysis and the impact of system parameters on the small signal stability is investigated. In [22], an aircraft system with recharging batteries is considered and an adaptive sliding manifold design is proposed to enhance system robustness against uncertainties. The effect of stability analysis on power management along with reactive power sharing control is not considered in these studies.

In recent studies, in order to have reliable and stable aircraft power system, generators normally supply their own network loads while the networks are electrically isolated. Conventional generators have high weight due to the utilization of constant speed drives. On the other hand, modern hybrid power supplies use battery, supercapacitor and other energy storage systems which are more costly and less reliable. In these studies, there is the lack of control method to share the load active and reactive powers among the generators using power electronic converters.

This paper proposes an optimal power management framework for the aircraft electric grid. Aircraft electric system is considered as a microgrid. An optimal droop control mechanism is presented to minimize the frequency deviation of the AC network. A new control method is proposed for reactive power sharing improvement in presence of asymmetrical load distribution. Also, voltage and frequency of the equipment in aircraft network is properly maintained in standard rating. The paper innovations can be summarized as follows.

- Using power electronic converter instead of constant speed drive to reduce the aircraft total weight.
- Parallel operation of generators using droop control method to enhance power supply system reliability.
- Proposing an optimization method in active power sharing to maintain the frequency of AC network in standard rating.
- Improving the reactive power sharing by modified droop control method with regard to small signal stability of the aircraft electric network.

The remainder of the paper is organized as follows. In section 2 power generation characteristic and power sharing strategy in microgrids are discussed. The proposed methodology for optimal power management of aircraft power system is presented in section 3. Section 4 evaluates the proposed method on a sample aircraft electric grid and gives the simulation results. Finally, section 5 consists of the conclusion remarks.

2. POWER SHARING CONTROL IN AIRCRAFT MICROGRID

In this section, the principle of power sharing between generators in a microgrid is explained. Droop control is a method to control the power flow of inverter-based DGs in islanded microgrids. Inspired from conventional systems, it facilitates the power sharing among the power sources and operates like governor and exciter of synchronous generators [23].

Droop control mechanism does not use communication links among the grid generators and it operates by measuring local voltage and current values. Droop control studies commonly consider the power flow, voltage and frequency regulation and line and generation capacity constraints [24, 25].

The output characteristic of fuel-based DGs depends on the mechanical structure of their primary energy source (PES) [26, 27]. In aircrafts, as the output of the PES has a variable frequency voltage, the output voltage is rectified to produce a DC voltage. This DC voltage source is connected to the grid with voltage source inverter to produce an AC voltage source with the desired frequency as it is shown in Fig 1.

The energy delivered to the grid is determined by the droop control method as it is shown in Fig. 1. By means of this method the demand power is autonomously shared among the generators. Back to back voltage and current controllers are used to enhance the power quality. Subsequently, the switching pulses are determined with the inverter pulse width modulation (PWM) technic [28].

For a microgrid with n generators, droop characteristic for n-th generator in time interval k is formulated as (1), where $m_{n,k}$ and f_{Nom} denote droop gain and nominal frequency respectively. $f_{n,k}$ and $P_{n,k}$ are the output frequency and active power for each generator.

$$f_{n,k} = f_{Nom} - m_{n,k}.P_{n,k} \tag{1}$$

It should be noted that the power deviations due to the load variation will cause the frequency to be violated from its nominal value which is 400 Hz in aircrafts. The frequency of all generators should be the same in the microgrid (f_k^M). Therefore the equality condition of (2) is always imposed. In this way, the assigned power of each generator is determined.

$$f_k^M = f_{Nom} - m_{1,k}.P_{1,k} = f_{Nom} - m_{2,k}.P_{2,k} \tag{2}$$

Change in the load or generation in time interval k results in frequency deviation which is mathematically formulated as (3). Frequency elasticity of load during time interval k is shown by D_k. As can be seen in this equation, the amount of droop gain can affect the frequency of the microgrid.

$$\Delta f_k^M = \frac{\sum_n P_{n,k} - P_k^{load}}{D_k + \sum_n \frac{1}{m_{n,k}}} \tag{3}$$

Similar to (1), the v-Q droop equation is also applied in microgrids, relating the output voltage of each generator to its output reactive power.

Considering the aircraft electric system as an islanding microgrid, droop control can be applied for parallel operation of generators. In this paper it is aimed to determine the optimal droop gains for the aircraft generators. As it is declared in the next section, state-of-the-art is to exploit an optimization technic to assign power to each generator which results in the minimum frequency deviation for the electric grid. Also, a methodology is proposed for enhancing reactive power sharing. The new method improves the reactive power sharing in presence of asymmetrical load distribution.

3. PROPOSED POWER SHARING METHODOLOGY

A. Active power sharing

In this paper, a new control method is proposed for the aircraft electric system to provide 115-volt AC voltage, with a frequency of 400 Hz. Constant speed drive is eliminated while the induction generator is directly coupled to the prime mover and considered as PES.

A DC voltage is provided by rectifying the output voltage of the generator. This structure has less mass and higher efficiency in comparison with conventional mechanical-based systems. Faults and degradation can be easily monitored by the sensors. Monitoring signals are electronic and can be transmitted to the pilot in real time. The Schematic diagram of aircraft network is shown in Fig. 2

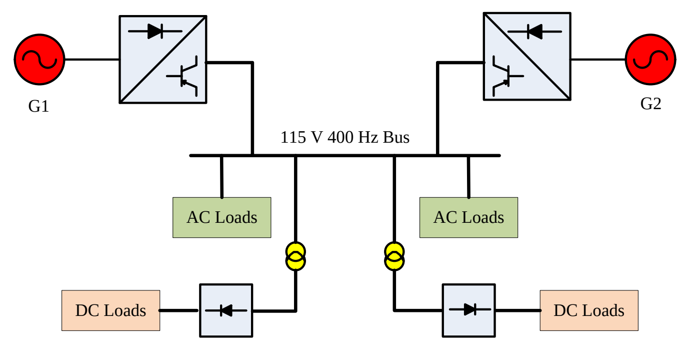

Fig. 2. Schematic diagram of the aircraft network.

In the proposed structure for the MEA, voltage source inverters with an optimized droop control method supply the power demand of AC loads. Also, DC loads are supplied by transformer rectifier units. This method enables the parallel operation of generators and enhances the system reliability. The main goal of the optimization is to have proper frequency regulation for the MEA.

In interval k and for the first iteration of optimization ($i = 1$), the reference droop gain is initially set equal to its previous interval value ($m_{k,1}^{ref} = m_{k-1}^{ref}$). According to (4), the weighting coefficient ($\eta_{k,i}$) is determined in each iteration.

$$m_{k,i}^{ref} = \eta_{k,i}.f_{Nom} \tag{4}$$

Reference frequency ($f_{k,i}^{ref}$) is calculated by (5).

$$f_{k,i}^{ref} = f_{Nom} - m_{k,i}^{ref}.P_{n,k} \tag{5}$$

The maximum frequency deviation for the MEA is equal to one percent of the nominal frequency ($\Delta f_{\max} = 4$Hz) [29]. Eq. (6) is used to check the frequency deviation.

$$\left| f_{k,i}^{ref} - f_{Nom} \right| < \Delta f_{\max} \tag{6}$$

If (6) is satisfied, active power droop gain is calculated by (7). Otherwise, the weighting coefficient is updated in the next iteration.

$$m_{k,i} = \eta_{k,i}.f_{k,i}^{ref} \tag{7}$$

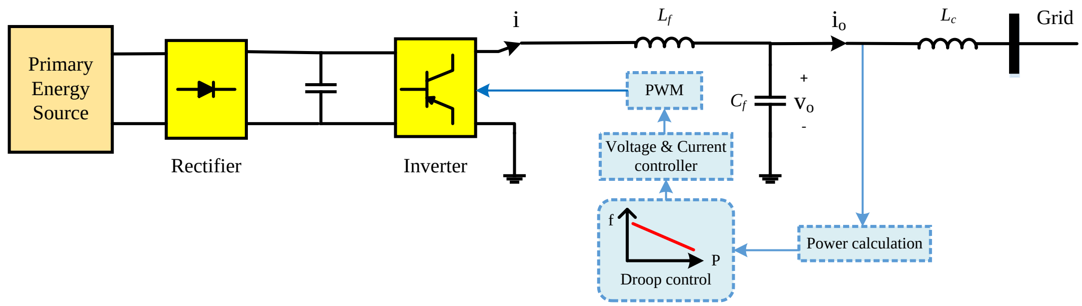

Fig. 1. Droop Control mechanism of a distributed generator.

In order to determine the optimal value of the weighting coefficient, mean square frequency error (MSFE) is used which is defined as (8).

$$MSFE = E\left[(m_{k,i}^{ref})^2\right] - 2.E\left[m_{k,i}^{ref}.f_{k,i}^{ref}\right].\eta_{k,i} + \eta_{k,i}^2.E\left[(f_{k,i}^{ref})^2\right] \quad (8)$$

Equations (9) and (10) can be assumed as follows.

$$E\left[\left|m_{k,i}^{ref} - m_{k,i}\right|^2\right] \approx \overline{\left|m_{k,i}^{ref} - m_{k,i}\right|}^2 \quad (9)$$

$$\nabla\left[\left|m_{k,i}^{ref} - m_{k,i}\right|^2\right] = 2.\left|m_{k,i}^{ref} - m_{k,i}\right| .\nabla\left[\left|m_{k,i}^{ref} - m_{k,i}\right|\right] \quad (10)$$

By considering $MSFE$ as a function of $\eta_{k,i}$, the gradient function (with respect to $\eta_{k,i}$) is calculated as (11).

$$\nabla_{MSFE} = -2.E\left[m_{k,i}^{ref}.f_{k,i}^{ref}\right] + 2.E\left[(f_{k,i}^{ref})^2\right].\eta_{k,i} \quad (11)$$

Consequently Eq. (12) can be concluded.

$$\nabla_{MSFE} = -2.\left|m_{k,i}^{ref} - m_{k,i}\right|.f_{k,i}^{ref} \quad (12)$$

According to the steepest descent methodology [30], the weighting coefficient is updated by (13) in each iteration. μ is the convergence factor and can be chosen according to (14).

$$\eta_{k,i+1} = \eta_{k,i} - 2.\left|m_{k,i}^{ref} - m_{k,i}\right|.f_{k,i}^{ref}.\mu \quad (13)$$

$$|\mu| < \frac{1}{f_{Nom}} \quad (14)$$

The flow chart which is shown in Fig. 3 summarizes the proposed optimization method. By applying this methodology, the minimum frequency deviation can be achieved for parallel operation of generators in the aircraft electric grid.

B. Reactive power sharing

For parallel operation of generators in the aircraft electric grid, it should be noted that load reactive power is not properly shared among the generators in the conventional methods like droop control mechanism. In this section, a new method is proposed to improve reactive power sharing. This method is based on small signal stability analysis of the network.

In power generation, according to droop methodology, it is assumed that the generator output frequency is affected by the produced active power. Also, the voltage magnitude is affected by the generated reactive power. This assumption is acceptable for a network with inductive transmission lines. But for the aircraft, transmission lines are semi-resistive. Therefore, the generator output frequency and voltage magnitude are both affected by the produced active and reactive powers.

For mathematical analysis of the droop control method, equations are usually represented in the *dq0* coordinate frame with the Clarke transformation of voltage and current variables shown in Fig. 1.

In order to demonstrate the proposed method, first the formula of generators output power are presented as (15) and (16) in which the instantaneous value of active and reactive powers are calculated. These equations are obtained from the Clarke transformation of voltage and current quantities.

$$p = v_{od}i_{od} + v_{oq}i_{oq} \quad (15)$$

$$q = v_{od}i_{oq} - v_{oq}i_{od} \quad (16)$$

To obtain the average value of active and reactive powers (P and Q)), a filter with a cut-out frequency of ω_f is applied to p and q values. For each generator, output frequency and voltage can be calculated as (17) and (18) which are realized as droop equations.

$$\omega = \omega_n - k_1 P \quad (17)$$

$$v_{od}^* = V_n - k_2 Q \quad (18)$$

In frequency and voltage droop equations, ω_n and V_n are the nominal value for frequency and voltage of the aircraft grid. Active and reactive power droop gains (k_1 and k_2) are commonly determined from allowable frequency and voltage deviation based on the construction of each individual generator as shown in (19) and (20).

$$k_1 = \frac{\omega_{\max} - \omega_{\min}}{P_{\max}} \quad (19)$$

$$k_2 = \frac{v_{od\max} - v_{od\min}}{Q_{\max}} \quad (20)$$

Frequency is a general value for all the generators in the microgrid and the voltage is a local variable. It means that generators should have equal output frequencies but their output voltage can be different according to the symmetry of load distribution. Therefore according to (17) and (18), asymmetrical load distribution can affect the reactive power sharing while it has no impact on active power sharing.

In order to improve reactive power sharing, the value of k_2 should be optimally selected. Increasing the reactive power droop gain from k_2 to k_2' reduces the amount of reactive power generation for a reference output voltage as it can be seen in Fig.

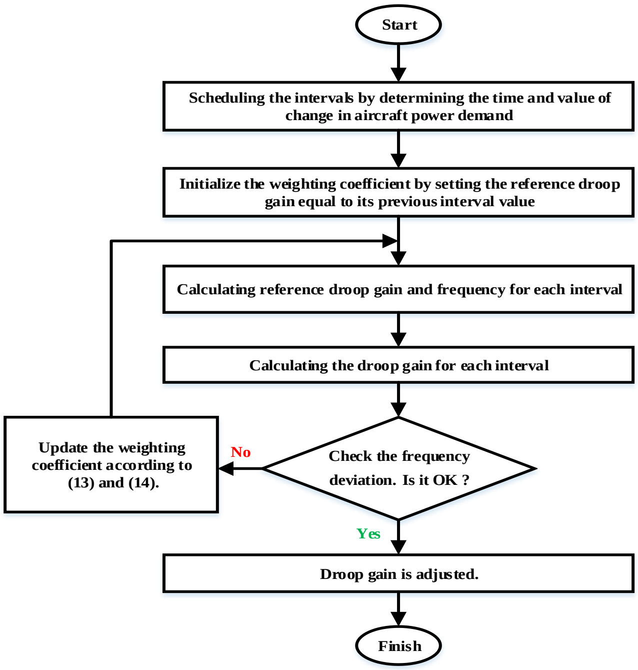

Fig. 3. The flowchart for determining the optimal active power droop gain.

4. In this figure, k_2 and k_2' are the slope of v-Q charachtristic. It shows that the high reactive power droop gain results is lower required reactive power generation for a specific terminal voltage. The aircraft electric grid stability is affected by increasing

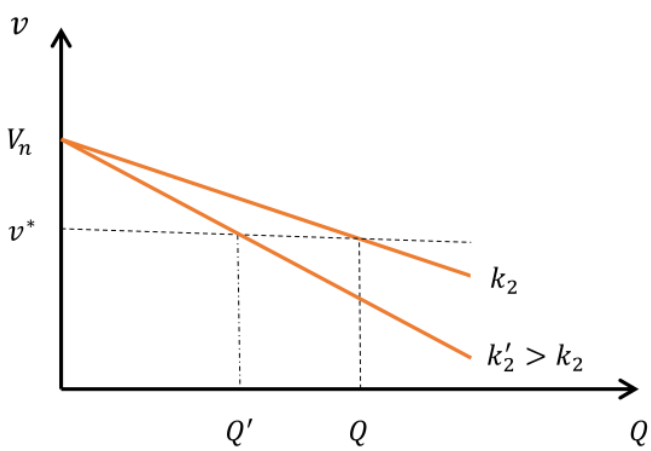

Fig. 4. Effect of increasing droop gain on the generator reactive power generation.

the reactive power droop gain. In order to study this impact on the system stability, an eigenvalue analysis is provided in the following. By linearizing droop equations given in (21) and (22), the system eigenvalues can be obtained as a function of reactive power droop gain which is shown in Fig. 5.

$$\delta = \int (\omega - \omega_n) \quad \mathbf{(21)}$$

$$\begin{bmatrix} \Delta\omega \\ \Delta v^*{}_{odq} \end{bmatrix} = \begin{bmatrix} C_{P\omega} \\ C_{Pv} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta P \\ \Delta Q \end{bmatrix} + \begin{bmatrix} 0 \\ B_{Pv} \end{bmatrix} [\Delta v_n] \quad \mathbf{(22)}$$

$$C_{P\omega} = \begin{bmatrix} 0 & -k_1 & 0 \end{bmatrix}, C_{Pv} = \begin{bmatrix} 0 & 0 & -k_2 \\ 0 & 0 & 0 \end{bmatrix}, B_{Pv} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad \mathbf{(23)}$$

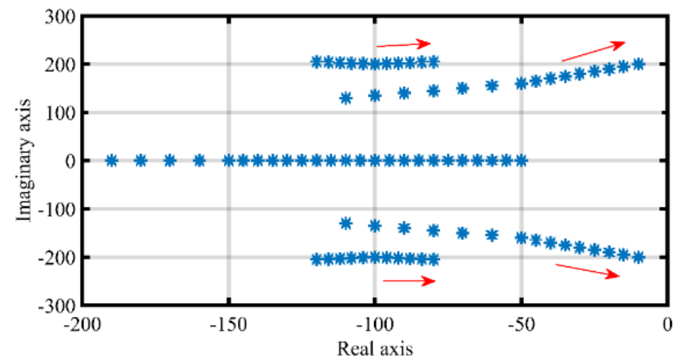

Fig. 5. The impact of increasing droop gain on the aircraft network eigenvalues.

Fig. 5 shows that higher values of k_2, results moving eigenvalues to instability region (positive side of horizontal frame). This will cause the instability of the aircraft electric grid. In the proposed control structure, reactive power droop gain is increased and it is marginally selected according to the stable region. In other words, the upper limit for the reactive power droop gain is selected when eigenvalues move beyond the stable region according to small signal stability analysis of the aircraft electric system.

In addition to using of the proposed method for determining the optimal reactive power droop gain, the voltage and current controllers are applied as shown in Fig. 6. It can be seen in this figure that the controller consists of two voltage and current parts. The inputs of the controller are v^*_{od} and ω which are determined by droop controller. Also, v^*_{oq} equals zero to eliminate the negative sequence of output voltage for the generator. Other variables are measured from the utility according to Fig. 1.

Voltage and current controllers with inner PI controllers, damp high-frequency oscillations and improve the aircraft network stability. Also, inner feed-forward loops improve the system sustainability against load disturbances. PI gains can be determined by Ziegler-Nichols rule to ensure the system stability. The positive proportional control gain (k_c) is selected when a step up in the input, results a moved up in the steady state value of the process output when the controller is in the P-only mode. By applying step increments in k_c and observing the steady state output, when a sustained periodic oscillation happened, this critical value of k_c is considered as the ultimate gain (G_u). Also, the period of oscillation is referred to as the ultimate period (P_u). Therefore, proportional coefficient of PI controller is equal to $\frac{G_u}{2.2}$ and the integral coefficient is equal to $\frac{6G_u}{11P_u}$. Proportional gain will decrease the output response rise time while the integral gain will eliminate the steady state error.

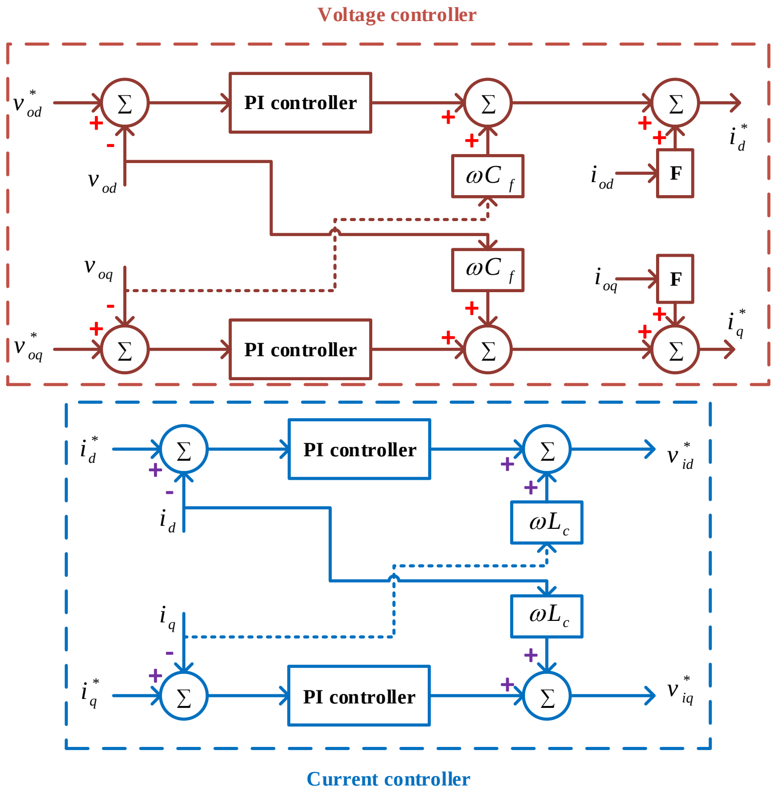

Fig. 6. Voltage and current controllers.

4. RESULTS AND DISCUSSION

In this section, the proposed power sharing method is evaluated. A sample aircraft electric grid is considered as a microgrid and the simulation results are shown. Aircraft electric loads include pumps, fans, heater, avionics systems, valve operation and lighting services. Two generators, one (G1) in the left and other (G2) in the right side of the aircraft are planned to have equal droop gain in order to generate the same active power.

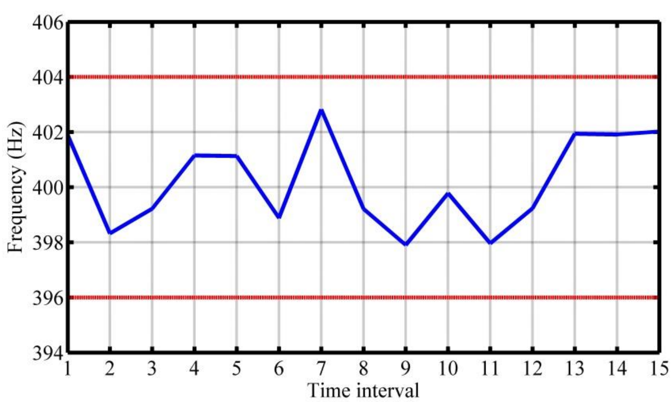

Fig. 7. Operating frequency of the aircraft grid for all time intervals of a sample flight.

Operating frequency of aircraft grid for all time intervals of a sample flight is given in Fig. 7. It can be seen that the aircraft frequency is maintained between upper and lower limits according to standard rating [29]. Optimization results of droop gains for different time intervals of aircraft operation are given in Table 1. It can be seen that the microgrid frequency regulation is properly

Table 1. Optimization results of active power droop gains.

Mode	Time interval	Total Load (kw)	Droop gain (mHz/kw)	Frequency (Hz)
Ground	1	128	160.75	**401.89**
	2	149	159.32	**398.32**
	3	159	159.69	**399.22**
Climb	4	144	160.46	**401.15**
	5	130	160.45	**401.13**
	6	144	159.55	**398.88**
Cruise	7	109	161.12	**402.82**
	8	120	159.68	**399.21**
	9	150	159.16	**397.9**
Descend	10	148	159.91	**399.78**
	11	174	159.18	**397.96**
	12	183	159.69	**399.23**
Ground	13	159	160.77	**401.94**
	14	136	160.76	**401.91**
	15	110	160.81	**402.02**

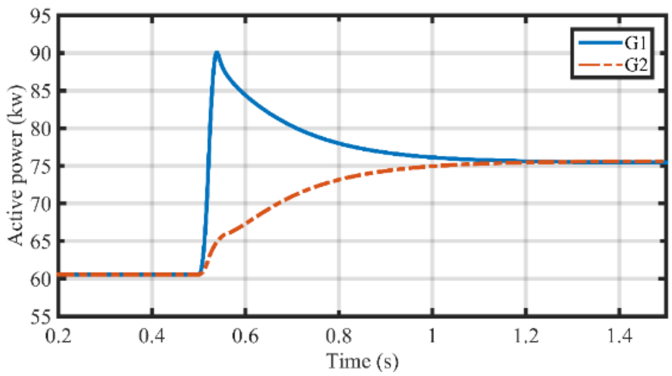

Fig. 8. Active power sharing between generators in the aircraft network.

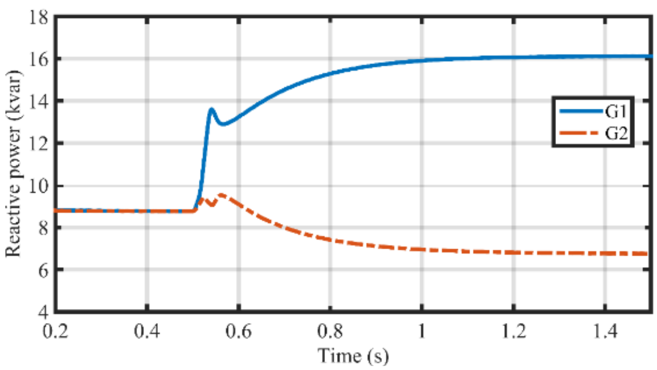

Fig. 9. Reactive power sharing results in the conventional method.

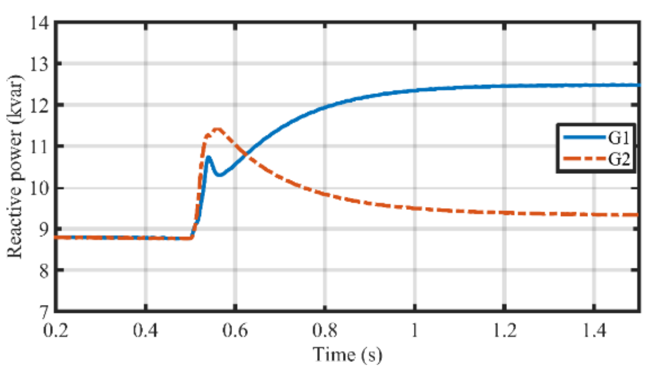

Fig. 10. Reactive power sharing results in the proposed method.

achieved.

The simulation results for active power sharing in one interval is shown in Fig. 8. As it is expected, two generators generate equal active power in the steady state time. It is due to the equal active power droop gain which has been set. The transient time is very short and does not concern the power quality of the aircraft electric system. In order to show the performance of proposed reactive power sharing algorithm in the aircraft, first, the simulation results of reactive power sharing are given for conventional droop method in Fig. 9 [31]. In the test system, the load is balanced between the left and right side of the aircraft before $t = 0.5s$.In this time an asymmetrical step-up load change occurs in the left side of the network. It can be seen that two generators have equal reactive power generation in case of balanced load distribution between the left and right side of the aircraft. Unlikely, after an increment in the load level of the left side, generated reactive power of G1 is dominantly higher than G2. Simulation results are given in Fig. 10 for the aircraft with the proposed methodology. The controller and network parameters are given in Table 2. Proportional and integral coefficients of the inner PI controller are given. For the voltage controller they are k_{pv} and k_{iv} and for the current controller are k_{pc} and k_{ic}. Switching frequency is given as f_s for the inverter. By comparing Figs. 9 and 10, it can be concluded that reactive power sharing is enhanced in the proposed method. In other words, the difference between generated reactive power of generators in the proposed method is less than the conventional method. This has been achieved by choosing an optimal reactive power droop coefficient considering small signal stability of aircraft electric grid.

Table 2. The grid and controller parameters for the proposed control method.

L_f	1.35 mH	f_s	8 kHz
r_{Lf}	0.1 Ω	C_f	50 μ F
r_{Lc}	0.03 Ω	L_c	0.35 mH
F	0.75	ω_f	31.41 rad/s
k_{ic}	390	k_{pv}	0.05
r_{iv}	16000	k_{pc}	10.5

Applying the optimal reactive power droop gain has no impact on active power sharing and the electric system of aircraft is stable. Fig. 11 shows the output voltage of generators in the proposed method. It can be seen that the terminal voltage is in the standard range (± 10%) for the equipment of the aircraft [29].

In the droop control method, frequency of each generator changes by variations in generated active power. When a change in the load demand occurs, the frequency of microgrid reaches the steady state point after the transient time. Generators may have different frequencies during the transient time. It should be pointed out that only one operating frequency is possible for generators in the microgrid. Therefore, active power is shared among the generators with respect to their droop gain ratios. In the aircraft, generators produce equal active power because they have equal active power droop gain.

Active power sharing does not depend on the symmetry of load distribution in the aircraft network. But in case the load consumption is not equally distributed between the left and right side, the reactive power sharing is not equal among the generators with equal reactive power droop gain. By applying the proposed method, the optimal reactive power droop gain is determined which results in a minimum difference between reactive power generations of two generators.

It should be noted that having equal reactive power is not possible for generators in the aircraft according to the relation between output reactive power and the output voltage for each generator. Unlike the frequency which is a general quantity in the network, the output voltage of each generator is a local value.

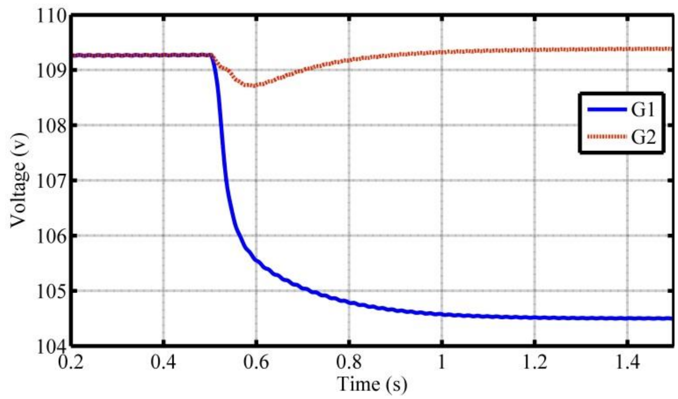

Fig. 11. Output voltage of generators in the proposed method.

Bus voltages are mainly dominated by grid structure. The state of the art in this paper is to minimize the reactive power sharing difference between generators in the presence of asymmetrical load distribution.

In the proposed method, active power droop gains are determined based on load variations. In the aircraft, load variations are scheduled according to five operating modes including ground, climb, cruise, descend and ground which are given in Table 1. In each mode, the aircraft has an specific power demand which is consumed in a specific time in the flight. Therefore the rate of change of frequency (ROCOF) is limited and determined based on prescheduled operating modes.

On the other hand, the installed capacity of generators can completely supply the load demand in each mode because the load demand is deterministic. The frequency deviation is also limited according to (6) in the proposed method to be maintained in IEEE standard order. In the methodology of determining the reactive power droop gain, droop coefficient is marginally selected according to stable system region as it is mentioned in Fig. 5. Therefore the aircraft system stability is ensured when both the active and reactive power droop gains vary.

The proposed method for active and reactive power sharing can be applied in all small microgrids as like as the electric network of the aircraft. The important limitation of this method is the amount of load reactive power. For high reactive loads such as welding applications, the proposed method may face stability issues. Also for large networks the application of poroposed optimization method will be more complex.

5. CONCLUSIONS

A comprehensive electric power management algorithm was proposed for an aircraft in this paper. Engine-driven induction generator was considered as a primary power source creating an ideal DC link for an inverter to produce AC power. In this way, constant speed drive which is a mechanical structure is eliminated and the aircraft weight is reduced. A droop control method is applied to enable the parallel operation of generators in the aircraft. By using MSFE and gradient descent algorithms, optimal droop gain was obtained. Also, a methodology is proposed to improve the reactive power sharing in asymmetrical load distribution. It is showed that choosing the optimal reactive power droop gain according to the stability analysis of the system improves the reactive power sharing. Hence, considering eigenvalue analysis of the aircraft electric grid, optimal droop gains were determined. The proposed method was applied to a sample aircraft electric network and simulation results were given. Results proved the effectiveness of the proposed algorithm in minimizing the grid frequency regulation as well as proper active power sharing. Also, simulation results show that the reactive power sharing is enhanced and the aircraft system stability is maintained.

REFERENCES

1. C. E. D. Riboldi, "An optimal approach to the preliminary design of small hybrid-electric aircraft," Aerospace Science and Technology, vol. 81, pp. 14-31, 2018.
2. Z. Zhang, J. Li, Y. Liu, Y. Xu, and Y. Yan, "Overview and development of variable frequency AC generators for more electric aircraft generation system," Chinese Journal of Electrical Engineering, vol. 3, no. 2, pp. 32-40, 2017.
3. S. Yousefizadeh, J. D. Bendtsen, N. Vafamand, M. H. Khooban, F. Blaabjerg, and T. Dragičević, "Tracking Control for a DC Microgrid Feeding Uncertain Loads in More Electric Aircraft: Adaptive Backstepping Approach," IEEE Transactions on Industrial Electronics, vol. 66, no. 7, pp. 5644-5652, 2019.
4. D. Riu, M. Sautreuil, N. Retière, and O. Sename, "Control and design of DC grids for robust integration of electrical devices. Application to aircraft power systems," International Journal of Electrical Power & Energy Systems, vol. 58, pp. 181-189, 2014.
5. S. Sathyamoorthi and S. Selvaperumal, "Study the performance about the implementation of variable speed constant frequency Aircraft Electrical Power System," Materials Today: Proceedings, 2020.
6. I. Moir and A. Seabridge, Aircraft systems: mechanical, electrical, and avionics subsystems integration. John Wiley & Sons, 2011.
7. C. Jie and W. Anhua, "New VF-power system architecture and evaluation for future aircraft," IEEE Transactions on Aerospace and Electronic Systems, vol. 42, no. 2, pp. 527-539, 2006.
8. I. Bolvashenkov et al., "Fault Tolerant Multi-phase Permanent Magnet Synchronous Motor for the More Electric Aircraft," in Fault-Tolerant Traction Electric Drives: Reliability, Topologies and Components Design, I. Bolvashenkov et al., Eds. Singapore: Springer Singapore, 2020, pp. 73-92.
9. H. N. Jazi, A. Goudarzian, R. Pourbagher, and S. Y. Derakhshandeh, "PI and PWM Sliding Mode Control of POESLL Converter," IEEE Transactions on Aerospace and Electronic Systems, vol. 53, no. 5, pp. 2167-2177, 2017.
10. L. Cheng, F. Zhang, S. Liu, and Z. Zhang, "Configuration method of hybrid energy storage system for high power density in More Electric Aircraft," Journal of Power Sources, vol. 445, p. 227322, 2020.
11. Y. Wang, F. Xu, S. Mao, S. Yang, and Y. Shen, "Adaptive Online Power Management for More Electric Aircraft with Hybrid Energy Storage Systems," IEEE Transactions on Transportation Electrification, pp. 1-1, 2020.
12. M. J. Salehpour, O. Zarenia, S. M. Hosseini Rostami, J. Wang, and S. J. Lim, "Convex multi-objective optimization for a hybrid fuel cell power system of more electric aircraft," International Transactions on Electrical Energy Systems, p. e12427.
13. T. H. M. Al-Mhana, V. Pickert, B. Zahawi, and D. J. Atkinson, "Performance Analysis of Forced Commutated Controlled Series Capacitor Rectifier for More Electric Aircraft," IEEE Transactions on Industrial Electronics, vol. 66, no. 7, pp. 5759-5768, 2019.
14. H. El-Kishky and H. Ebrahimi, "On modeling and control of advanced aircraft electric power systems: System stability and bifurcation analysis," International Journal of Electrical Power & Energy Systems, vol. 63, pp. 246-259, 2014.
15. M. Afrasiabi and E. Rokrok, "A New Decentralized Control Scheme for Improving Frequency Stability in Islanded Micro-grids," Journal of Energy Management and Technology, vol. 3, no. 1, pp. 8-16, 2019.
16. A. Khaledian and M. A. Golkar, "A new power sharing control method for stability enhancement of islanding microgrids," in 2016 IEEE 16th

International Conference on Environment and Electrical Engineering (EEEIC), 2016, pp. 1-5.
17. M. Terorde and D. Schulz, "New real-time heuristics for electrical load rebalancing in aircraft," IEEE Transactions on Aerospace and Electronic Systems, vol. 52, no. 3, pp. 1120-1131, 2016.
18. M. Terorde, H. Wattar, and D. Schulz, "Phase balancing for aircraft electrical distribution systems," IEEE Transactions on Aerospace and Electronic Systems, vol. 51, no. 3, pp. 1781-1792, 2015.
19. A. Khaledian and M. Aliakbar Golkar, "A new power sharing control method for an autonomous microgrid with regard to the system stability," Automatika, vol. 59, no. 1, pp. 87-93, 2018.
20. S. Hajiaghasi, A. Salemnia, and M. Hamzeh, "Hybrid Energy Storage For Microgrid Performance Improvement Under unbalanced load Conditions," Journal of Energy Management and Technology, vol. 2, no. 1, pp. 30-39, 2018.
21. J. Liu, J. Cai, J. Huang, and Z. Yang, "Eigenvalue Sensitivity Analysis of Aircraft Power System," in Proceedings of the 11th International Conference on Modelling, Identification and Control (ICMIC2019), Singapore, 2020, pp. 165-172: Springer Singapore.
22. A. Cavallo, G. Canciello, and A. Russo, "Integrated supervised adaptive control for the more Electric Aircraft," Automatica, vol. 117, p. 108956, 2020.
23. S. Golestan, M. Joorabian, H. Rastegar, A. Roshan, and J. M. Guerrero, "Droop based control of parallel-connected single-phase inverters in D-Q rotating frame," in 2009 IEEE International Conference on Industrial Technology, 2009, pp. 1-6.
24. M. Mehrasa, E. Pouresmaeil, H. Mehrjerdi, B. N. Jørgensen, and J. P. S. Catalão, "Control technique for enhancing the stable operation of distributed generation units within a microgrid," Energy Conversion and Management, vol. 97, pp. 362-373, 2015.
25. R. He, R. Qiu, Z. Jin, and W. Yu, "Control Strategies of Hybrid Power Supply System Based on Droop Control," in Proceedings of the 2015 International Conference on Electrical and Information Technologies for Rail Transportation, Berlin, Heidelberg, 2016, pp. 441-450: Springer Berlin Heidelberg.
26. S. Kang and K.-Y. Ahn, "Dynamic modeling of solid oxide fuel cell and engine hybrid system for distributed power generation," Applied Energy, vol. 195, pp. 1086-1099, 2017.
27. X. Xu, K. Li, H. Jia, X. Yu, J. Deng, and Y. Mu, "Data-Driven Dynamic Modeling of Coupled Thermal and Electric Outputs of Microturbines," IEEE Transactions on Smart Grid, vol. 9, no. 2, pp. 1387-1396, 2018.
28. M. N. Marwali and A. Keyhani, "Control of distributed generation systems-Part I: Voltages and currents control," IEEE Transactions on Power Electronics, vol. 19, no. 6, pp. 1541-1550, 2004.
29. "IEEE Standard for Aerospace Equipment Voltage and Frequency Ratings," IEEE Std No.127, pp. 1-111, 1963.
30. Y.-x. Yuan, "Step-sizes for the gradient method," AMS IP Studies in Advanced Mathematics, vol. 42, no. 2, p. 785, 2008.
31. A. Khaledian, A. Ahmadian, and M. Aliakbar-Golkar, "Optimal droop gains assignment for real-time energy management in an islanding microgrid: a two-layer techno-economic approach," IET Generation, Transmission & Distribution, vol. 11, no. 9, pp. 2292-2304, 2017.