IEEE PEDS 2015, Sydney, Australia
9 – 12 June 2015

Intelligent Power Allocation and Load Management of More Electric Aircraft

Alireza Barzegar*, Rong Su, Changyun Wen,
Leila Rajabpour, Yicheng Zhang
School of Electrical and Electronic Engineering
Nanayang Technological University, Singapore
*Alireza001@e.ntu.edu.sg

Amit Gupta**, Chadnana Gajanayake,
Meng Yeong Lee
Rolls-Royce Corporate, Singapore
** Amit.Gupta@Rolls-Royce.com

***Abstract*—Intelligent power allocation and load management systems have been playing an increasingly important role in aircrafts whose electrical network systems are getting more and more complex. Load shedding used to be the main means of aircraft power management. But the increasing number of electrical components and the emphasis of safety and human comfort call for more resilient power management. In this paper we present a novel power allocation and scheduling formulation which aims for minimum load shedding and optimal generator operational profiles. The problem is formulated as a mixed integer quadratic programming (MIQP) problem and solved by CPLEX optimization tool.**

I. Introduction

Power system of aircraft has been one research focus for the last three decades, which aims to increase efficiency by replacing hydraulic and pneumatic devices with electrical motors and actuators the latter have significantly higher efficiency than nonelectric devices. This revolution of employing more electrical devices leads to more electric aircraft which has improved efficiency, reliability [1-2], survivability, and reduced weight, fuel consumption and cost [3]. Nowadays, one major challenge of more electric aircraft research is to develop efficient and more reliable ways of electric power generation, conversion and distribution. Description of the recent progress of more electric aircraft electrical power system can be found in [4-5]. In response to this challenge electrical power management system (EPMS) has been under development which supervises and controls different subsection control units of generators, buses, converters and loads. For example EPMS manages load connection switches to prevent overloading and power peaks on generators which might be caused by fault occurrence at each of the main generators. Some of the available power management methods can be found in [6-7], which are mostly based on the load shedding idea that detects overloading, disconnects and connects relevant load(s) according to their priority and sufficiency of power supply. These algorithms have some weaknesses e.g., non-optimality of decisions, and instability during disconnecting and reconnecting of the loads which have been described in [6]. In response to these weaknesses, recent research works in this field have focused on providing more accurate, reliable and optimal electric power management formulations [8-9].

This work was conducted within the Rolls-Royce@NTU Corporate Lab with support from the National Research Foundation (NRF) Singapore under the Corp Lab@University Scheme.

Next generation aircraft usually requires electric power more than 1 MW, so platform efficiency becomes one of the main goals of aircraft electric management which aims to optimize power allocation and load shedding to prevent power peaks on generators in different phases of flight. Although the electrical energy usage of an aircraft is a very small portion of the total energy produced in engines, optimizing the electrical power system can lead to reduced fuel consumption and aircraft weight.

In this paper we consider generators, loads and batteries and provide an MIQP problem formulation for management in which the decision variables are the generator power supply magnitudes and schedules, load connections (under possible shedding) and batteries charging schedules. The global objectives are to minimize the load shedding, which may follow some priorities, and ensure the generators to operate within their optimal ranges as long as possible.

Comparing our proposed management strategy and formulation with previous works, the main difference and novelty is the aim of confining generators to work within their optimal ranges by intelligently using batteries as the temporary sources to cope with anticipated demand spikes. This idea is more technical and optimal than minimizing number of working generators [8], which cannot be an efficient decision since in some periods one of the generators may not be used. On the other hand, in our formulation there is no concern of instability during shedding and reconnecting the loads in contrast to the situation described in [6-9], due to our centralized MIQP based scheduling strategy, which considers all possible constraints related to demands and supplies when rendering a power management decision. For a large scale system, we may need to develop advanced computation architecture such as distributed architecture to cope with complexity.

The paper is organized as follows: in section 2 an electrical power management system of MEA is described, and then the problem formulation is provided in section 3. Simulation results are summarized in section 4. Finally, in section 5 conclusions are drawn.

978-1-4799-4402-6/15/$31.00 ©2015 IEEE

II. Electrical Power Management System of MEA

An aircraft electrical power management system (EPMS) consists of three main subsections: generator control unit (GCU), bus power control unit (BPCU) and solid state power controller (SSPC), whose job is to implement the EPMS decisions to the network. These decisions are related to the aircraft flight phases, operational conditions and prioritization rules. The conventional implementation of EPMS depends on load shedding in case of overloading of generators capacities which may be caused by failure of one or more main sources. By moving toward more electric aircraft, the number of loads and their required power has increased significantly. Therefore, the electrical system and power sources size need to be increased. The conventional way is to consider the maximum required power of loads at every flight phase and choose the proper dimension of aircraft generators which is not an optimal choice and may raise the cost and weight of aircraft. By employing an intelligent EPMS that prevents overloading on generators, it is feasible to optimize the generator size and the fuel consumption.

An aircraft electrical system may work in three operational conditions: normal, abnormal and emergency. In a normal condition power sources and the power network perform ideally. An abnormal condition happens if one of the main generators stops working. Failure of all main sources leads to an emergency condition. In the latter case only emergency loads are permitted to connect and all other loads are disconnected.

Here, our EPMS main task is to undertake load shedding at the demand side in abnormal and even normal conditions to prevent overloading on the main sources. At the same time we want to confine the generators to work within their optimal working ranges as long as possible. As mentioned in [10] the link between electrical and mechanical power could be

$$\eta = \frac{P_{elec}}{P_{mech}} \approx 0.85.$$

Since the energy consumption of the electrical system of an aircraft is only a small portion of whole produced power by engines, reducing the electrical power does not have any significant effect on the size of engine. But it is possible to reduce the negative effect of load spikes on the engine side and consequently reduce the fuel consumption which could be a considerable amount for long distance flights. Thus, by considering an optimal working range for a generator and by bringing storage devices into play within normal conditions, to support the loads during peak times, it will be possible to provide an optimal working schedule for generators and reduce related engine fuel consumption.

Since timely decision making in an aircraft power management system is critical for aircraft operations, providing an EPMS formulation which involves all the constraints and requirements in a compact and simple form is expected to play an important role in developing an effective power management strategy. Next, we provide such a problem formulation.

III. Problem Formulation

In this paper we consider typical architecture of an electrical distribution system for the most recent more electric aircraft, Boeing 787 and Airbus 380, which is presented in Fig. 1. In this structure there are two generators as main power sources of the aircraft. There is also one emergency generator which would be used if both of the main generators failed. Each of the generators operation is controlled by the GCU. The main generators feed two main AC buses in order to distribute power to electrical network. It should be taken into consideration that based on technical issues, every bus can only be fed by one generator at each time, so it is not possible to connect one bus to more than one generator at the same time due to frequency and phase difference of different sources which may cause catastrophic consequences.

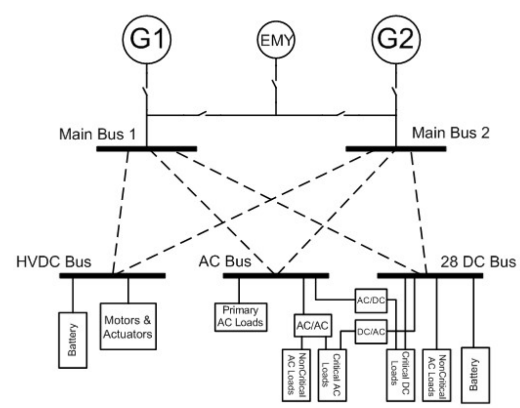


Fig. 1. Electrical distribution system of most recent MEA

Based on this rule, a priority should be considered for each of the buses in order to support the main buses in normal and faulty situations. The prioritization table I defines that main bus 1 and 2 should be fed with a generator at normal conditions or in case of failure in one or both of the main generators. The main AC buses power the secondary buses including 270 HVDC bus, 115 volt AC bus and 28 volt DC bus. By using Auto-Transformer Rectifier Unit (ATRU), Auto-Transformer Unit (ATU) and Transformer Rectifier Unit (TRU), supporting of the secondary buses is provided in the same way as that for main buses, a predefined priority of feeding secondary buses should be taken into consideration, table I.

TABLE I
Main and Secondary Buses Feeder Priority for the Sample Architecture of Fig.1

Bus \ Priority	1^{st}	2^{nd}	3^{rd}
Main Bus 1	Gen1	Gen2	EMY
Main Bus 2	Gen2	Gen1	EMY
HVDC Bus	Main Bus 1	Main Bus 2	-
Sec. AC Bus	Main Bus 2	Main Bus 1	-
28VDC Bus	Main Bus 2	Main Bus 1	-

At the secondary bus level, there are three different groups of load feed buses: AC load bus, HVDC load bus and 28 volt DC bus. HVDC bus supplies power to high voltage motors and actuators. AC bus supports AC loads like galley loads and environmental control system (ECS) loads, and 28 volt DC load bus provide electrical power to low voltage avionic loads.

A. Load Classification

The main task of intelligent load management is to shed loads based on predefined priorities, which requires a well defined classification of the loads. The MEA loads could be classified into critical and noncritical loads. *Critical loads* include those linked with flight safety status and avionics systems that should be supplied during the flight without any shedding even in case of emergency situations and failure of any or both of the main generators, to provide a reliable flight. *Noncritical loads* are the other classes of loads, which provide a comfortable environment for passengers. *Emergency loads* are those critical loads which must be supported in case of an emergency condition, e.g., failure of all main generators.

According to our architecture depicted in Fig.1, there are two categories of loads, critical and noncritical. On each bus, for high reliability the critical loads of AC bus and 28 volt DC bus can be powered from other buses through proper converters in case of failures in main linked buses.

B. Power Distribution Requirements and constraints

In normal and abnormal operating conditions two sets of loads can be considered in order to have an intelligent load shedding; *critical and non-sheddable loads*, *noncritical and sheddable loads*. By this definition, the required power on each bus would be

$$P_i^{req} = \sum_{j \in S_i^C} y_{ij} p_{ij}^C + \sum_{j \in S_i^{NC}} y_{ij} p_{ij}^{NC} + \sum_{j \in S_{i'}^C} x_{i'j}^i p_{i'j}^C \tag{1}$$

in which P_i^{req} is the required power at bus i, p_{ij}^C (p_{ij}^{NC}) refers to required power of critical (noncritical) load j at bus i, y_{ij} describes the connection of load j to bus i and $x_{i'j}$ describes the redundant connection of critical load j, which its main feeding path from bus i' is not possible. S_i^C and S_i^NC show the set of critical and noncritical loads at bus i. Load connections should satisfy the following constraints

$$y_{ij} \in \{0,1\}, \forall i, \forall j \in S_i^{NC} \tag{2a}$$

$$y_{ij} \in \{1\}, \forall i, \forall j \in S_i^C \tag{2b}$$

In case of a failure in the main supplier bus of critical load j, another feeding way has been considered for this load, so in a situation that $y_ij = 1$ is not technically possible, the following constraints should be satisfied:

$$y_{i'j} + x_{i'j}^i = 1, \forall j \in S_{i'}^C \tag{3}$$

Based on previous discussions, in case of an overloaded situation the power network may not be able to feed all the loads, thus some of the loads should be disconnected or shedded according to the prescribed priority rules.

According to the presented architecture, storage devices like batteries have been considered at DC buses, aiming to serve power peak demands in normal and abnormal operating situations and allow the generators to work within their optimum ranges, meanwhile having the least load shedding. So the battery dynamic model which can provide the state of change (SoC) of battery is needed. As a simple state space modelling we have:

$$SoC_i(t+1) = SoC_i(t) + \rho_i \cdot \gamma_i(t) \tag{4}$$

in which ρ_i is a constant coefficient related to the battery structure, $\gamma_i(t) \in \{-1, 0, 1\}$ shows the battery charging or discharging mode. If $\gamma_i(t) = 1$, battery is in the charging mode, and it is in the discharging mode if $\gamma_i(t) = -1$.

The batteries modes are described by the following constraints:

$$\text{"If } P_i^{Bus} > P_i^{req} \rightarrow \rho_i = 1.\text{"} \tag{5a}$$

$$\text{"If } P_i^{Bus} < P_i^{req} \rightarrow \rho_i = -1.\text{"} \tag{5b}$$

Rule (5a) (5b) shows that if the provided power to the secondary DC bus is greater than the required power at this bus, then the storage device may start charging to store this excess amount of power for future use. On the other hand, the safe maximum and minimum permitted level of SoC should be applied to the formulation:

$$\underline{SoC_i} \leq SoC(t) \leq \overline{SoC_i} \tag{6}$$

The required power, storage devices power capacity and actual power supply at each secondary bus i can be described as follows:

$$P_i^{req} + \gamma_i P_i^{Bat} \leq P_i^{Bus} \tag{7a}$$

$$P_i^{Bus} \leq P_{i,max}^{Bus} \tag{7b}$$

in which P_i^{Bus} and P_i^{Bat} are the available power and battery power at secondary bus i respectively. Inequality (7b) shows the maximum limit of available power at bus i.

Power to each of the secondary buses is supplied from one of the main buses, q, at any time possibly with a connection to another main bus as a backup. Thus, we have

$$\sum_q \lambda_{qi} p_{qi} = P_i^{Bus}, \forall i \in S_{Sec.Bus} \tag{8a}$$

$$\sum_i \lambda_{qi} p_{qi} = P_q^{MainBus}, \forall q \in S_{MainBus} \tag{8b}$$

$$\sum_q \lambda_{qi} = 1, \forall i \in S_{Sec.Bus} \tag{8c}$$

$$P_q^{MainBus} \leq P_{q,max}^{MainBus}, \forall q \in S_{MainBus} \tag{8d}$$

where $P_q^{MainBus}$ is the available power at main bus q with the maximum level of $P_{q,max}^{MainBus}$, p_{qi} is the transferred power from main bus q to secondary bus i and $\lambda_{qi} \in \{0, 1\}$ indicates the connection or disconnection between them. $S_{Sec.Bus}$ and $S_{MainBus}$ are the sets of secondary and main buses, respectively. Constraint (8c) indicates that it is not permitted to connect secondary bus i to more than one primary bus q at any time.

Required power to the main buses may only be provided by one of the main generators, k. Similar to secondary buses power allocation, redundancy should be considered in case of failure of the first allocated generator. Thus, we have

$$\sum_k \alpha_{kq} p_{kq} = P_q^{MainBus}, \forall q \in S_{MainBus} \tag{9a}$$

$$\sum_q \alpha_{kq} p_{kq} = P_k^G, \forall k \in S_{Gen} \tag{9b}$$

$$\sum_k \alpha_{kq} = 1, \forall q \in S_{MainBus} \tag{9c}$$

where p_{kq} is transferred power from generator k to the main bus q and $\alpha_{kq} \in \{0, 1\}$ shows their connection status. S_{Gen} indicates the set of generators. Constraint (9c) states that only one of the generators can feed the main bus q at each moment.

Since one of the most important goals of our management strategy is keeping the main generators working within their preferred and optimal range, the last constraint is to capture this goal,

$$\underline{\tilde{P}_k^G} \leq \tilde{P}_k^G(t) \leq \overline{\tilde{P}_k^G}, \forall k \in S_{Gen} \tag{10}$$

It should be mentioned that the generators are allowed to go out of these bounds in case of emergency. But operating within this range leads to reduced fuel consumption.

C. Objective Function

Our goal is to minimize load shedding in case of overloading, enforce the main buses supplier priority rules, and confine the generators to work within their optimal ranges. The following goal function captures our goal:

$$\min \Big(\sum_k (P_k^G - \tilde{P}_k^G)^2 + \sum_i \sum_j w_{ij}(1 - y_{ij}) + \sum_k \sum_q w'_{kq} \alpha_{kq} + \sum_q \sum_i w''_{qi} \lambda_{qi} \Big)$$

Here, w_{ij} is related penalty of disconnecting or shedding of load j from bus i, which is based on the load priority list, the lower the priority the lower the penalty. The coefficients w'_{kq} and w''_{qi} are penalties of connecting secondary bus i and main bus q to the main bus i and power supply k, respectively. The quadratic, least square, term of the cost function penalizes the generator k for work outside its optimal range, i.e. , $\left[\underline{\tilde{P}_k^G}, \overline{\tilde{P}_k^G}\right]$

D. Transformations

The aforementioned formulation contains logic constraints; we use the following transform to convert them into mixed integer linear constraints. For battery constraints, (5a) and (5b), we introduce

$$\delta_i = \frac{\gamma_i + 1}{2} \tag{11}$$

By employing the transformation techniques proposed in [11] we can transform constraints (5a) and (5b) into

$$1 - f_i(t) \geq \epsilon + (m_i - \epsilon)\delta_i \tag{12a}$$

$$1 - f_i(t) \geq \epsilon + (m_i + \epsilon)(1 + \delta_i) \tag{12b}$$

respectively, where $f_i(t) = P_i^{Bus} - P_i^{req}$, $m_i = \min(f_i(t))$ and ϵ is a small positive value. Inequalities (12a) and (12b) involves boolean variable δ_i and continues variable $f_i(t)$ in a mixed integer linear form.

Besides the above transformation, another technique is required to convert mixed integer quadratic constraints, (8a) and (8b), into mixed integer linear ones. So by considering $z_{qi}(t) = \lambda_{qi}(t)p_{qi}(t)$ we can replace the quadratic term by $z_{qi}(t)$ if the following inequalities are satisfied

$$\underline{p_{qi}}\lambda_{qi}(t) - z_{qi}(t) \leq 0 \tag{13a}$$

$$z_{qi}(t) - \overline{p_{qi}}\lambda_{qi}(t) \leq 0 \tag{13b}$$

$$p_{qi}(t) + \overline{p_{qi}}\lambda_{qi}(t) - z_{qi}(t) \leq \overline{p_{qi}} \tag{13c}$$

$$z_{qi}(t) - p_{qi}(t) + \underline{p_{qi}}\lambda_{qi}(t) \leq -\underline{p_{qi}} \tag{13d}$$

where $\underline{p_{qi}} = \min(p_{qi}(t))$ and $\overline{p_{qi}} = \max(p_{qi}(t))$. So we can rewrite constraints (8a) and (8b) as mixed integer linear constraints

$$\sum_{q=1}^{2} z_{qi}(t) = P_i^{Bus}, \forall i \in S_{Sec.Bus} \tag{14a}$$

$$\sum_{i=1}^{3} \lambda_{qi} p_{qi} = P_q^{MainBus}, \forall q \in S_{MainBus} \tag{14b}$$

$$\sum_{q=1}^{2} \lambda_{qi} = 1, \forall i \in S_{Sec.Bus} \tag{14c}$$

$$\underline{p_{qi}}\lambda_{qi}(t) - z_{qi}(t) \leq 0 \tag{14d}$$

$$z_{qi}(t) - \overline{p_{qi}}\lambda_{qi}(t) \leq 0 \tag{14e}$$

$$p_{qi}(t) + \overline{p_{qi}}\lambda_{qi}(t) - z_{qi}(t) \leq \overline{p_{qi}} \tag{14f}$$

$$z_{qi}(t) - p_{qi}(t) + \underline{p_{qi}}\lambda_{qi}(t) \leq -\underline{p_{qi}} \tag{14g}$$

The same transformation can be applied to constraints (9a) and (9b).

By applying the described transformations to our problem, we have a mixed integer quadratic programming with linear constraints, and standard optimization tools such as CPLEX can be directly applied.

IV. Simulation Results

In this section the predicted power management strategy, which has been formulated in a mixed integer quadratic programming form, is applied to the latest MEA electrical system architecture depicted in Fig.1. The problem is simulated and solved by CPLEX [12]. The prediction horizon for simulation is set as $t_h = 5s$, i.e., the MIQP problem is solved once per every $5s$. For testing the optimization formulation we consider an electrical platform with two main generators and one emergency generator, two main AC buses, three secondary buses including two DC bus and one AC bus, 10 loads at each bus. Two batteries are also installed in secondary DC buses. The average solution time for this system is about $0.11s$. The simulation is carried out for three different cases to evaluate performance of the algorithm:

Case 1: we suppose that all the electrical components and generators are in normal operating condition.

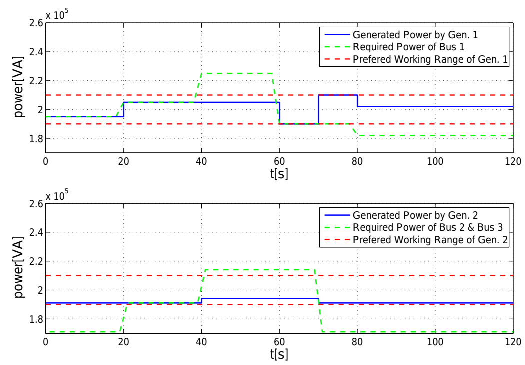


Fig. 2. Generated power by each of main sources

As illustrated in Fig. 2, during the interval $[0, 20)s$ the required power from Gen. 2 is below its optimal working range, so the connected battery to secondary bus 3 goes in the charging mode, as shown in Fig. 3, which leads to an increased power demand for Gen. 2 that keeps it working within its preferred range. At $t = 20s$ a load spike happens which increases the power demand for Gen. 2, so Battery 3 stops charging. Since the power demand is within the optimal range, battery is not needed and load shedding is unnecessary. Thus, battery is disconnected as shown in Fig. 3, and all the loads are powered.

The previous condition continues till $t = 40s$, then a large increase of power demand happens which is supposed to force two main generators to go out of their preferred working ranges. But it turns out that this additional power demand can be met by batteries, which start discharging as depicted in Fig. 3 and provide additional power to loads connected to their buses. From Fig. 2 we can see that during the whole simulation interval both generators operate within their reference working ranges, while all the loads are supported without any shedding. It should be stated that each of the generator working conditions without the proposed method would be equal to the total required power of the loads supported by that generator, green dashed line in Fig. 2.

Case 2: we consider an abnormal situation, in which Gen. 1 fails at $t = 50s$. Since main bus 1 has been powered by Gen. 1, after the failure of Gen. 1, other sources need to feed this bus.

According to Table I, the next choice for supporting bus 1 is Gen. 2. But since the load on Gen. 2 from bus 2 is high and connecting Gen. 2 to both main buses may lead to a larger number of load sheddings, the optimal power management decision is to supply main bus 1 by emergency Gen. as depicted in Fig. 4. It is visible from Fig. 5(a) that only two

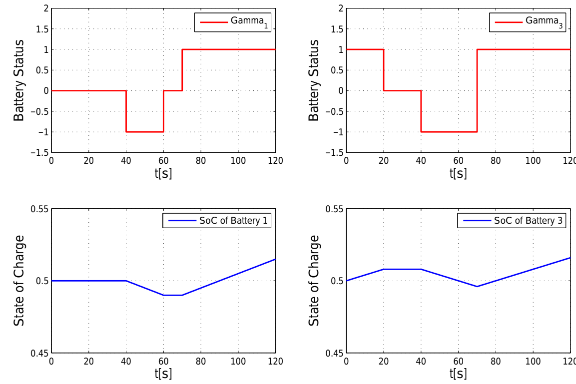


Fig. 3. Batteries connections status (Charging, Discharging, Disconnected) and their State of Charge

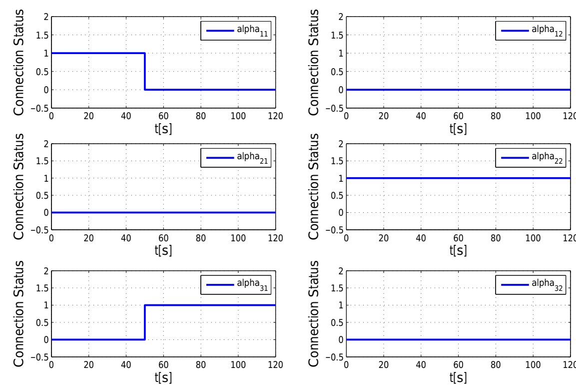


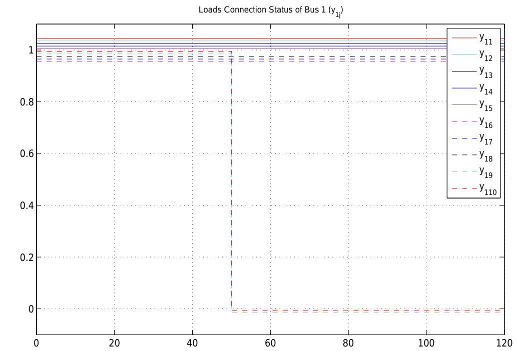
Fig. 4. Allocated Generator to each main bus

loads with the lowest level of importance are disconnected due to load shedding to cope with low capacity of the emergency generator.

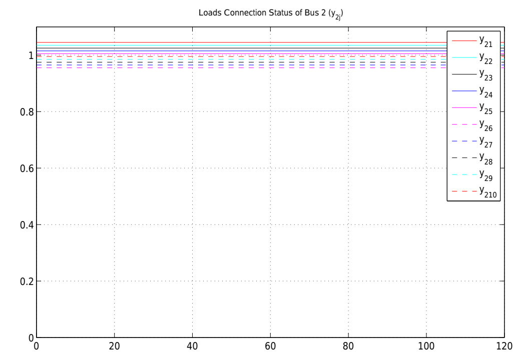
Case 3: We consider a failure in one of the secondary buses. We assume that the secondary bus 2 encounters a problem and stops supplying power to its connected loads. Since a redundancy feeding path that powers critical loads of secondary bus 2 from secondary bus 3 has been considered, the power management system sends signals to establish these redundancy connections to feed three critical loads of the failed bus as depicted in Fig. 6. We can see that the critical loads are powered and other non-critical loads are shedded till the problem in their feed bus is resolved.

V. CONCLUSIONS

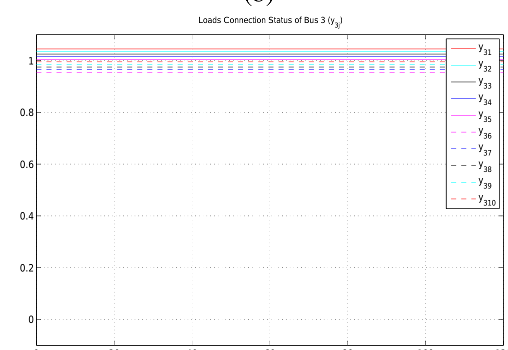
So far we have developed an electrical power management strategy, which, by solving in mixed integer quadratic programming problem, aims for the least load shedding, proper power allocation to each load and bus, and confinement of the generators operations within their preferred and optimal ranges. Storage devices such as batteries are used as temporary sources which can cope with load spikes, and result in a decreasing peak power supply from generators. The suggested



(a)



(b)



(c)

Fig. 5. Loads switches status (ON/OFF) of (a) Secondary bus 1, (b) Secondary bus 2 and (c) Secondary bus 3, in abnormal condition (Failure of Generator 1 at $t = 50s$).

strategy has been applied to the latest electrical system architecture of more electric aircraft. Experimental results under different operational conditions and fault scenarios have shown its effectiveness. In the future we will consider to adopting a distributed strategy to cope with the scalability issue due to the involvement of possibly a large number of integer variables in our MIQP formulation proposed in this paper.

REFERENCES

[1] R. Quigley, "More Electric Aircraft," in Proceedings of Eighth Annual Applied Power Electronics Conference and Exposition, APEC, pp. 906-911, 1993.

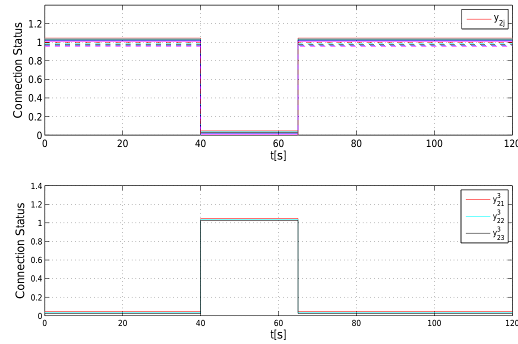


Fig. 6. Critical Loads feeding in case of failure of their main supporting bus (Failure of Secondary bus 2 at $t = 40s$)

[2] S. Cutts, "A collaborative approach to the More Electric Aircraft," in Proceedings of International Conference on Power Electronics, Machines and Drives,PEMD, pp. 223-228, 2002.

[3] A. A. AbdElhafez, A. J. Forsyth, "A review of More Electric Aircraft," 13th International Conference on Aerospace Sciences Aviation Technology, pp. 1-13, May 2009.

[4] I. Moir, A. Seabridge, " Aircraft Systems: Mechanical, electrical, and avoinics subsystems integration," Third Edition ed., John Wiley and Sons, 2008.

[5] R. Abdel-Fadil, A. Eid, M. Abdel-Salam, "Electrical distribution power systems of modern civil aircrafts," 2nd International conference on Energy Systems and Technology, pp. 201-210, Feb. 2013.

[6] D. Schlabe, J. Lienig,, "Energy management of aircraft electrical systems - state of the art and further directions," Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS), pp. 1-6, 2012.

[7] T. Schroeter, D. Schulz, "Aircraft power management - Algorithm and Interactions," International Symposium on Power Electronics, Electrical Drives, Automation and Motion, pp. 432 - 439, June 2012.

[8] M. Maasoumy, F. Iandola, M. Kamgarpour, "Optimal load management system for Aircraft Electric Power distribution," IEEE 52nd Annual Conference on Decision and Control (CDC), pp. 2939 - 2945, Dec. 2013.

[9] D. Schlabe, and D. Zimmer, "Model-Based Energy Management Functions for Aircraft Electrical Systems," SAE 2012 Power System Conference, 2012.

[10] T. Schroeter, B.H. Nya and D. Schulz, "Potential analysis for the optimization of the electrical network of large modern civil and future single aisle aircraft and examples of the network capacity utilisation," Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS), pp. 1-7, Oct. 2010.

[11] A. Bemporad and M. Morari, "Control of systems integrating logic, dynamics, and constraints," Automatica, vol. 35, no. 3, pp. 407-429, 1999.

[12] "IBM CPLEX Optimizer," [Online]. Available: www-01.ibm.com/software/commerce/optimization/cplex-optimizer/. [Accessed Nov. 2014].