Optimised low voltage loads allocation for MEA electrical power systems

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***Abstract*—this paper proposes a smart controller design for an automated power load allocation for the more electric aircraft application. As the aircraft manufacturers are moving towards more electrified solutions, power management and optimization are becoming more important design considerations. With the evolution of control techniques, and newly available intelligent tools and powerful hardware, it is now possible to find smart solutions to the distribution and load allocation problem. In this paper a mathematical solution is proposed to reconfigure the connected loads on each single bus based on the value of the available power and the level of priority of each load with the aim to optimize the allocation of the loads. Simulations performed within Simulink environment are used to verify the results.**

***Index Terms*—More Electric Aircraft, Load allocation problem, Optimization**

I. Nomenclature

MEA	More electric aircraft
AEA	All electric aircraft
EPS	Electrical power system
PEC	Power electronics converter
HV270DC	High voltage 270 Vdc

II. Introduction

Electrification has been a key trend amongst aircraft manufacturers in recent years. The level of electrification on board is growing quite rapidly [1, 2]. The final result of this electrical expansion aims at hybrid or all electric aircraft [3]. The advantages of the electrical system over hydraulic and pneumatic equivalents, in terms of reliability and availability of the electrical components, as well as, the redundancy of these systems, are well known from literature [4, 5]. In the market, examples of MEA are represented by the Airbus A380, the Boeing 787 Dreamliner, with almost 1 MW of electrical power installed, and the more recent Airbus A350. As the installed electric power is rising, the complexity of the electrical network is also growing, due to the introduction of more electric system on board. In order to cope with the power demand of the electrical loads, it is important to manage the electrical grid of the aircraft as efficiently (and safely) as possible. From the main generators to the low voltage side loads, the electrical grid of the aircraft is composed of electrical buses, which connect the electrical sources with the loads, PECs used to adapt the voltage levels on each bus and, batteries as an emergency power source for critical scenarios. According to current technologies, the electric grid can be composed of AC systems, DC systems or a combination of the both. The high voltage side of the bus is conventionally in AC (i.e. 115 Vac), whilst the low voltage bus is in DC (i.e. 28 Vdc). The former (i.e. AC) supplies high power loads (e.g. ice-protection systems, galley ovens, etc.), while low power loads are fed by the DC bus (e.g. avionics, entertainment, etc.). In order to manage the aircraft grid there are some suitable solutions, ranging from the first controllers designed in C programming language, to the more complex techniques based on e.g. linear temporal logic, fuzzy logic and finite state machine [6]. Increased computational capabilities facilitate more powerful and faster controllers, which are able to manage multiple-aspects of the network. By relating the problem of the electrical grids with the aircraft networks, there are two main priority tasks that the control system must accomplish in order to guarantee some vital operations of the EPS.

- *Reconfiguration strategy*: it is used by the control system according to the management system rules. It can regards safety and power quality rules, and consist in the distribution of the power paths along the EPS. Thus, changing the electrical configuration of the system through the use of electrical switches and the available source power, the network can be reconfigured as well.
- *Load allocation problem*: it consists in finding the best solution to accommodate loads on the buses, respecting the available power and the priority levels of each load.

This paper proposes how it is possible to optimize the "*Load allocation*" on the bus by using of a smart controller in analytical way. In the next Section (III) the problem of load allocation on the EPS is explained. Section IV presents the mathematical theory beyond the optimization method and how the method is applied on the described problem. Section V explains the tool used to run and simulate the computational code, and in the VI section will be presented the simulation results.

III. Buses and Load Allocation Management

Based on the MEA concept previously introduced, Fig. 1 shows the single line diagram of a theoretical model of an EPS for MEA system. Since the authors want to demonstrate the capabilities of the controller used to supervise the EPS, the passive components in the diagram are depicted as devices that require power without focusing on the type of load (i.e. motors, actuators, lights, emergency systems).

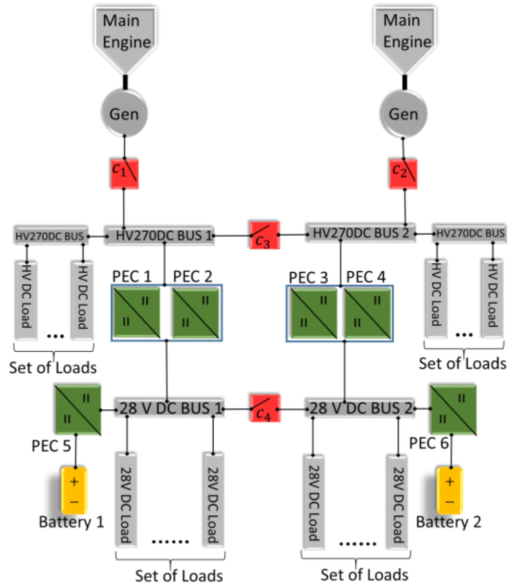


Fig. 1, theoretical model of MEA EPS concept.

The system in Fig. 1, which represents a HV270DC system, is composed of two main generators connected to the main engines of the aircraft. The electrical power is delivered from the AC generator to the high voltage bus, through a rectifier, supplying the loads and the DC/DC PECs. The PECs are used to adapt the voltage level from the 270 V buses to the 28 V buses. The switches, highlighted in red, are used to connect each device, loads, and buses. On the low voltage side there are 2 batteries used in case of emergency (i.e. fault of a component), and to keep the bus voltage level fixed. Moreover, a controller is used to manage the EPS, in order to optimise the performances, and improving the reliability and availability overall the system. As mentioned in the previous section, the aim of this paper is to solve the "*load allocation problem*", i.e. allocation of each load to the bus while respecting the available power of the system compared with the level of priority. where, the level of priority of a load can indicate if that load can be disconnected (Low level of priority) or must be supplied under every scenario that could affect the EPS (High level of priority); this value can also vary according with the flight phases. A prime example is the electro-mechanical actuators, considered as a high priority loads.

IV. Knapsack Method and How to Fit the Code in the Load Allocation Problem

This section introduces a mathematical theory of the knapsack problem that will be applied to the EPS for the power allocation. In previous studies, several techniques have been investigated in order to determine the best solution for allocating power on the EPS, from the heuristic approaches, meta-heuristic to mathematical formulations [7, 8]. The proposed method approaches the problem with pure mathematical formulations, optimizing the value of the distributed power along the buses.

The knapsack problem is an example of a mathematic combinatorial optimization problem. This is a problem that has been studied for more than a century, when, there is a need of finite and optimized solution, where an exhaustive search is not possible [9]. The problem can be found in real-world scenarios as resource allocation in financial constraints or even in selecting investments and portfolios [10]. It also can be found in fields such as applied mathematics, complexity theory, cryptography, combinatorial and computer science [11]. In the knapsack problem, the given items have two attributes at minimum: 1) an item's value, which affects its importance and 2) an item's weight or volume, which is its limitation aspect, due to the fact that could limit the maximum value. Based on Knapsack problem, given a set of items, each with a weight and a value, it has to be determined the number of each item to include in a collection so that the total weight is less than or equal to a given limit and the total value is as large as possible. The Fig. 2 represents a synthesis of the proposed problem, with a pre-defined capacity knapsack and objects with weight and value.

Fig. 2, Example of knapsack problem, having a maximum capacity, the value has to be maximized without exceeding in the weight

The following equations are used to describe the problem in a mathematical way.

Given two n −tuples of positive numbers "v_i" as given in (1) which are representing the value of each item, and "w_i" as given in (2) which are representing the weight of each items, it is possible to represent the total capacity of the knapsack define by the equation (3).

$$\langle v_1, v_{2,} \dots, v_n \rangle \quad (1)$$

$$\langle w_1, w_{2,} \dots, w_n \rangle \quad (2)$$

$$W > 0 \quad (3)$$

The task is to determine the subset

$$T \subseteq \{1, 2, \dots, n\} \text{ that}$$

$$maximizes \sum_{i \in T} v_i$$

$$subject\ to \sum_{i \in T} w_i < W$$

It is possible to find a solution by the use of '*dynamic programming*', a computer programming method that consist in breaking a complex problem into a smaller one by obtaining a smaller set of simple problems[12], by following the steps below:

- Decomposing the problem into smaller problems → from the Fig. 3a a table is created, dividing the problem in column on index *i* and rows *w*
- Finding a relationship between the structure of the optimal solution of the original problem, and the solution of the smaller problems → scrolling each row a sub-solution is found that will be compared with other ones.
- Recursively defining the value of an optimal solution → by comparing the solutions of each rows with each other
- Bottom-up computation → compute the value of the optimal solution in a bottom-up fashion by using a table structure.
- Construction of the optimal solution from the computed information.

The source code used to fill the table I is shown in the Fig. 3a:

```
Knapsack(v, w, n, W)
{
  for(w=0 to W) V[0,w]=0;   // Set the first row to 0
  for(i=1 to n)
    for(w=0 to W)
      if(w[i]<=w)            // Scroll the elements of the table
        V[i,w]=max{V[i-1,w], v[i] + V[i-1,w-w[i]]};
      else                   // Set the value of
        V[i,w]=V[i-1,w];     // the element V[i,w]
  return V[n,W];             // at the maximum value
}
```

Fig. 3a. Knapsack source code

Table I, table representing the operation of dynamic programming approach

V[i,w]	w=0	1	2	3	...	...	W
i= 0	0	0	0	0	...	...	0
1	→	→	→	→	→	→	→
2	→	→	→	→	→	→	→
:	→	→	→	→	→	→	→
n	→	→	→	→	→	→	→

bottom ↓ up

Table I shows how the first part of the code fill-up the table (Bottom-up computing). However, the method is not giving the optimal solution but it only defines what the sub-sets are. The final part of the code, displayed in Fig. 3b, give back the value of the sub-set T that contains the solution:

```
K=W;
for(i=n downto 1)      // Scroll the elements backwards
   if(keep[i,K]==1)    // if keep[i,k]==1 n belongs to T
   {                   // if keep[i,k]==0 n doesn't belong to T
      output i;
      k = k-w[i];
   }
```

Fig. 3b, Source code used to extract the solution from the table I

Through the use of the source code above, it is possible to scroll each element backward and find the solution that solve the problem. Referring to the Knapsack problem, it is possible to relate the optimization with the problem of the "*Load allocation*". In the case under study it is possible to adopt the following relationships:

$\langle v_1, v_{2,} \dots, v_n \rangle$ → *Level of priority for each load*
$\langle w_1, w_{2,} \dots, w_n \rangle$ → *Power of each load in Watt*
$W > 0$ → *Available power*

Thus, solving the Knapsack with the variables above, it is possible to obtain a vector of solution that activate the switches based on the available power of the system and the power required from the loads. In the next section will be presented the tool used to develop the control system.

V. FSM TOOL

In order to compute the algorithm presented in the previous section, it has been adopted a finite state machine tool (FSM). A finite state machine is a computation model that can be implemented with hardware or software and can be used to simulate sequential logic. FSMs are also used to model problems in many fields including mathematics and artificial intelligence (i.e. robotic and autonomous drive car). The principal advantages in using a FSMs are 1) easy to use and implement and 2) powerful and intuitive algorithms compared with the common coding techniques (i.e. standard programming languages such as '*C*' and '*python*').

In this paper a FSM controller has been developed within the Simulink environment of Matlab. In a FSM the behavior of the system can be modelled as a set of states and transitions between states. Hence, the FSM can be expressed as (4)

$$f(\sum, S, s_0, \delta, s_n) \quad (4)$$

where, $\sum$ represents a finite set of symbols (variables of the system), S is a finite set of sates, s_0 is the initial state, so that $s_0 \in S$, δ is a state transition function as defined in (5) and F is finite set of final states.

$$\delta: S \times \sum \rightarrow S \quad (5)$$

An example of the formulation of a FSM is depicted in Fig. 4.

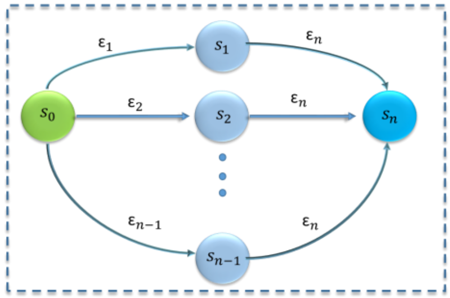


Fig. 4: Example of reactive system

The following equations describe the system in Fig. 4

$$\sum = [\varepsilon] \tag{6}$$

$$S = [s_0,\ s_1, \dots\ s_n] \tag{7}$$

$$\delta = \left[{}^{s_0}/_{\varepsilon} \rightarrow s_1,\ {}^{s_1}/_{\varepsilon} \rightarrow s_2, \dots ,\ {}^{s_{n-1}}/_{\varepsilon} \rightarrow s_n\right] \tag{8}$$

$$F = s_n \tag{9}$$

The EPS can also be seen as a reactive system; where, the states define the behaviour of the controlled system, and the controller will pass from one state to another as a feedback reaction for a transition condition. Thus, it is possible to use the FSM to control the EPS, as reported in [13], treating it as a reactive system. In the next section the model used for the simulation will be showed and discussed with the results.

VI. Model and Simulation Results

This section presents the model used for the simulation. Fig. 5 shows a low voltage bus1 of the EPS model presented in figure 1, in which the loads are highlighted and labeled with a priority level, and the source represents the power that can be sent to the considered bus from the high voltage bus1 through power converters PEC 1 and PEC2 and the battery 1. Each of the loads can be turned on or off using switches labelled as C_1 to C_n in Figure 5.

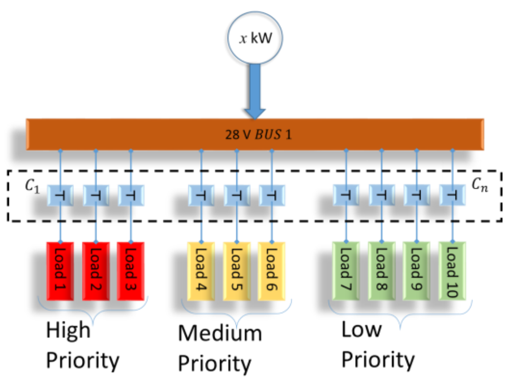


Fig. 5, The electrical subsystem model used for simulation

Three case scenarios will be considered in this section to optimise the power allocation given the priority level (v) for each load and the power (w) required by each load in Table II. It is to be noted that the total power required by all the ten loads is 20 kW.

Table II: Priority level and power required by each load

	Loads									
	1	2	3	4	5	6	7	8	9	10
Priority (v)	1000	900	800	70	60	50	4	3	2	1
Power (w)	3 kW	3 kW	2 kW	2 kW	2 kW	2 kW	2 kW	2 kW	1 kW	1 kW

In case 1 at the start of the simulation the system has to supply 20 kW loads with 20 kW of available power. In case 2, which occurs after 10 s the available power is reduced to 17 kW, and therefore, the control system has to recalculate a new solution. After a further 20 s the available power is reduced from 17 kW to 13 kW forcing the system to change configuration again.
The controller, built in the Simulink State-chart tool, is shown in Fig. 6, has the task to reconfigure the switches based on the power allocation optimisation. The knapsack algorithm is given in the *"State_k"* in Fig. 6.

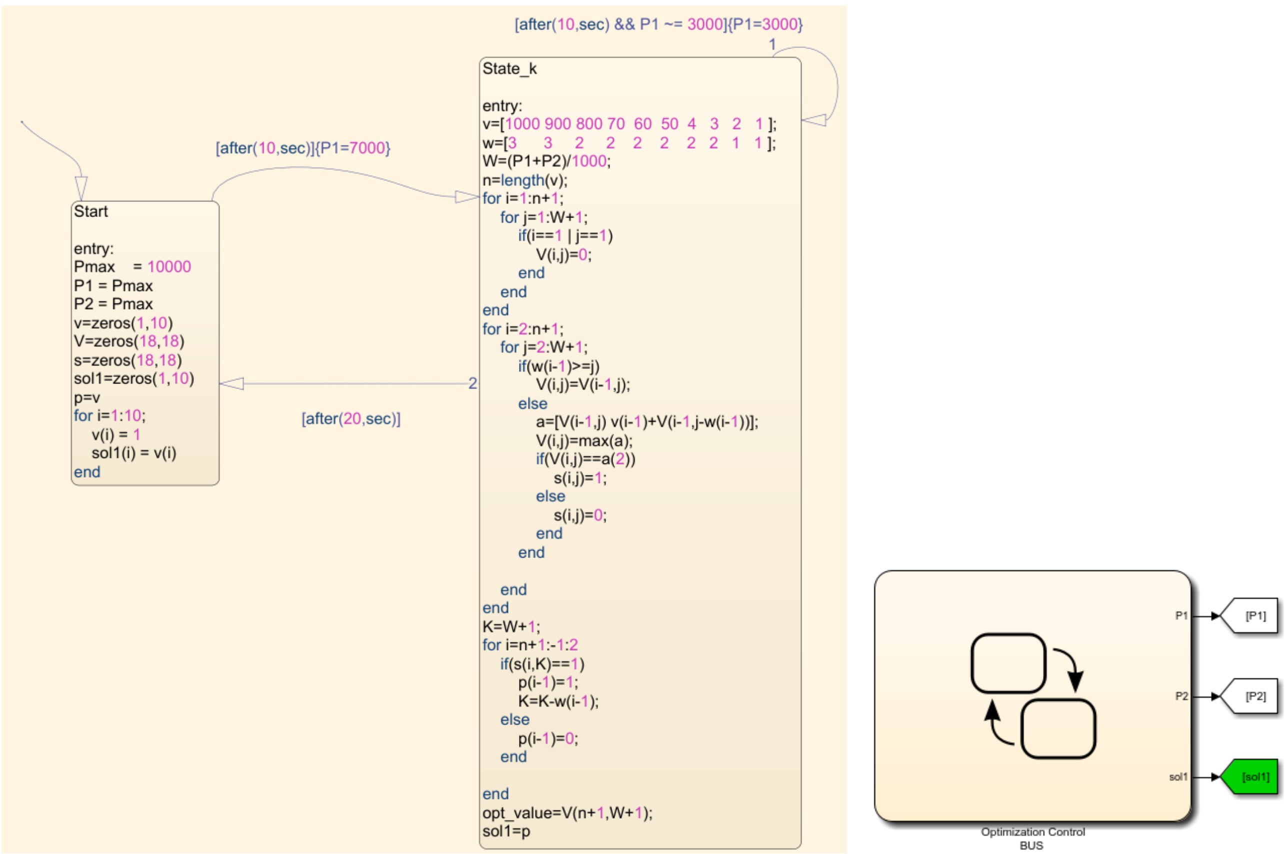


Fig. 6, model of the controller used to optimize the power flow to loads

In Figure 6, P_{max} is the maximum power delivered from either PEC1 or PEC2; P_1 and P_2 represent the instantaneous power delivered from PEC1 and PEC2 respectively.
Of note is that in order to guarantee that the loads with the highest priority will not be disconnected before the ones with medium and low priority, equation (10) was introduced. The equation (10) imposes that the sum of the high priority loads must be greater that the sum of the medium priority loads, and the sum of the medium priority loads must be greater than the sum of the low priority loads.

$$\sum_{i=1}^{n} HP_{load_i} > \sum_{j=1}^{m} MP_{load_j} > \sum_{k=1}^{z} LP_{load_k} \qquad (10)$$

The state models were run for the three cases and the resulting vector of solutions that configure the status of the switches are given in Table III. The contactor status is "1" when closed and "0" when open. As shown in Table III and in simulation charts in Figure 8(a) to 8(j), for case 1 which occurs from time 0 to time 10s, all the contactors are closed; For case 2 where the power available is reduced to 17 kW, contactors 8 and 10 are switched off and for case 3 contactors 6, 7, 8 and 10 are open.

Table III: Simulation results for cases 1, 2 and 3 (1=closed switch, 0=open switch)

Case	Available power (W)	State of switches									
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Sol1_case1	20 kW	1	1	1	1	1	1	1	1	1	1
Sol1_case2	17 kW	1	1	1	1	1	1	1	0	1	0
Sol1_case3	13 kW	1	1	1	1	1	0	0	0	1	0

The next Figs. show the behavior of the switches status during the simulation time.

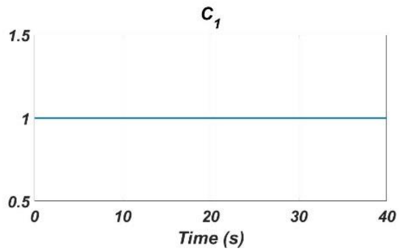


Fig. 8 a

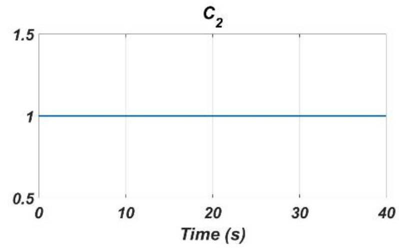


Fig. 8 b

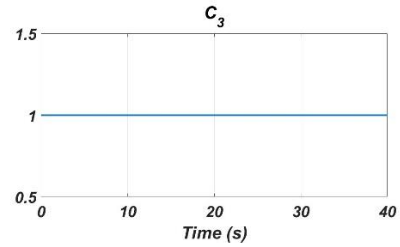
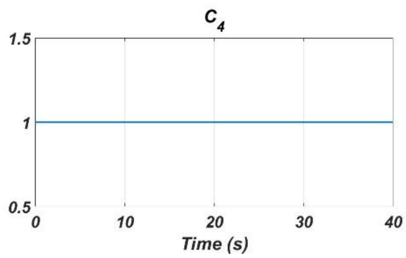


Fig. 8 c



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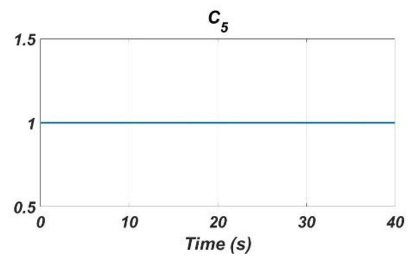
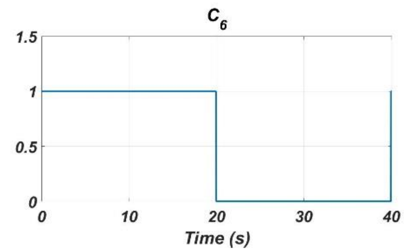


Fig. 8 e



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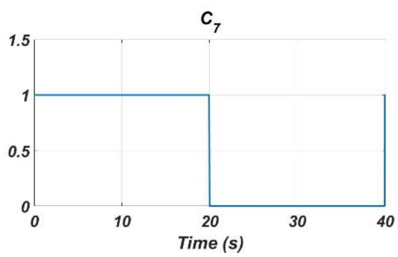

Fig. 8 g

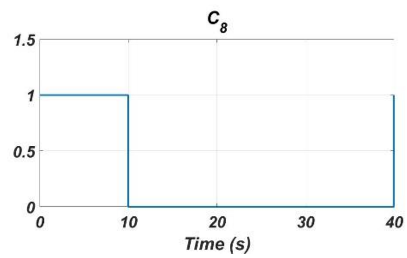

Fig. 8 h

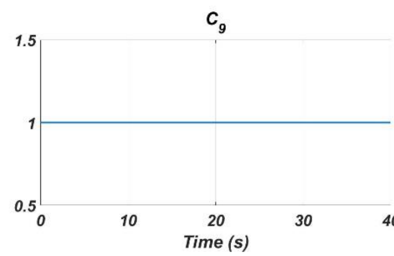

Fig. 8 i

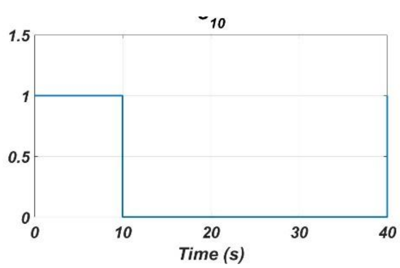

Fig. 8 j

Fig. 8(a-j), plot of the switches behavior during the simulation

Fig. 9 shows the measured power on the LV bus at different times of the simulation. It can be noted that from time 0s to 10 s, the power allocated on the bus is 20 kW which matches the available power. From time 10s to 20s, the power allocated on the bus is 17 kW, and finally from time 20s to 40s, the power on the LV bus is 13 kW. These simulation results validate the knapsack algorithm applied for the load allocation problem.

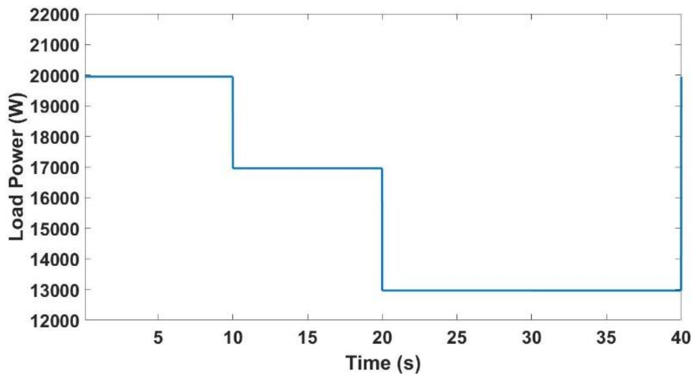

Fig. 9, The measure power on the LV buses match the available power for cases 1, 2 and 3.

As seen from the simulation results, the system changes the status of the switches automatically, hence optimizing the bus power, based on the mathematical criteria. Moreover, it should be noted that the voltage level of the bus is kept constant at 28 V during throughout the simulation. Fig. 10 (a), 10 (b) and (c) represent the power supply to the different loads for cases 1, 2 and 3 respectively based on the application of load allocation knapsack algorithm. The loads which are not supplied are “white” in color in Fig. 10.

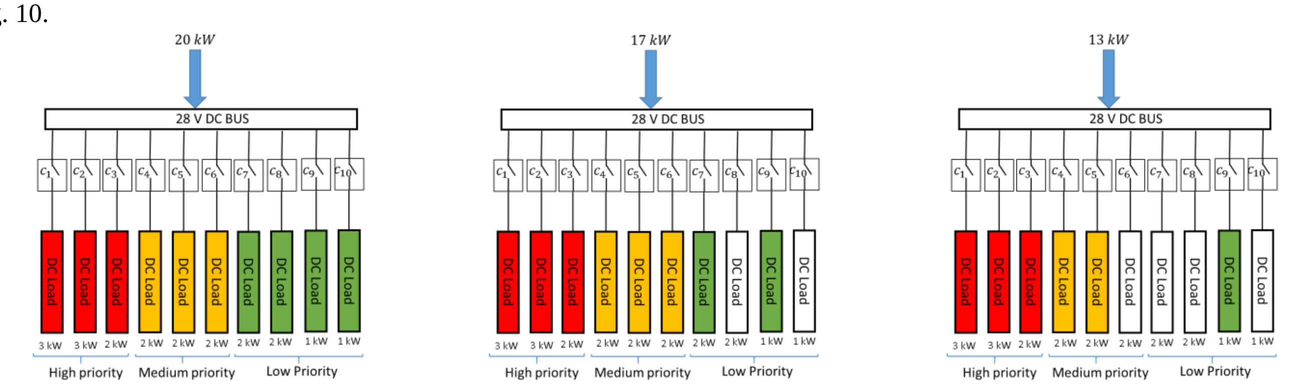

Fig. 10 a *Fig. 10 b* *Fig. 10 c*

Fig. 10(a-c), Load distribution based on the available power

VII. Conclusion

This paper applied the mathematical method based on Knapsack problem and the FSM control technique to optimise the load allocation of a representative subsystem of an aircraft electrical power system. Through a set of case studies and simulations in the Simulink environment, the paper demonstrates how the proposed algorithm successfully allocates a fixed amount of available power to a set of loads which have varying levels of priorities and power requirements. The method proposed in this paper can be further extended and exploited for the energy management of the electrical power system for more electrical aircraft application.

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