



Automatic Optimal Synthesis of Aircraft Electric Power Distribution System

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Abstract: Reliability is one of the most critical design features in Aircraft Electric Power Distribution system (EPDS). In an EPDS, the power is distributed from generators to loads, sensors and actuators through AC and DC distribution buses using control switches. Because of the increasing demands of loads and their power requirements, EPDS design must be optimized in order to have maximum efficiency. In this paper, we propose a synthesis tool based on a need-based design method to obtain the optimal topology of EPDS considering maximum reliability, continuous connectivity, power requirements, and minimum cost. We treat the EPDS as an optimization problem by using Integer Linear Programming (ILP) to achieve minimum cost and maximum reliability while satisfying a set of constraints.

Keywords: Fault Tree Analysis (FTA), Linear Solver, Integer Linear Programming (ILP), Recursive Algorithm.

1. INTRODUCTION

With the concurrent technological advances in the aircraft design, Electric Power Distribution Systems (EPDS) need to be able to manage the huge amount of power which is due to the increasing number of loads required. As several hydraulic, pneumatic and mechanical components are replaced by electrical components, modern aircraft EPDS becomes more complex, because of the larger number of hardware subsystems as well as their interactions with the embedded control software [8]. Furthermore, there can be unforeseeable problems in these systems including sudden node failure, reliability issues, poor performance, and safety issues. Not considering these potential complications during initial design stage, can cause extra cost later in regards to redesigns and maintenance.

There are several limitations with current common design practice. System requirements are predominantly written in text-based languages that are not suitable for mathematical analysis and verification. Not being able to interact between heterogeneous components and between the physical and cyber side of the system create potential problems. Therefore, traditional heuristic design process based on text-based method leads to implementations that are inefficient [1]. As a result, it

will delay the design process and waste unnecessary time and money on redesigning the entire system.

Previously, we started our goal to design a synthesis tool that automatically designs the EPDS which fulfills user's need-based requirements [5]. The synthesis tool first synthesizes the EPDS considering the specific requirements. Then, it continues synthesizing until all the constraints are satisfied. After the synthesizing stage is finished, the tool outputs the optimal topology of EPDS automated flow that fulfills user's defined criteria. Following the idea, the author in [6] discusses the viability and implementation of the resulted topology on typical large aircraft specifications. We will discuss finding the best topology for an aircraft EPDS with a focus on DC loads in this paper. Moreover, we have added extra design constraints for improving the connectivity in the topology. The proposed synthesis tool uses modular approach considering particular components in different layers while the power flows down from the top layers to the lower layers. The power can flow in the directed loops or the bi-directional edges between the nodes. At the end of the synthesis, the algorithm will give optimal topology with the number of generators needed to optimally supply the input loads.

The outline of this paper is as follows; a brief overview of the typical aircraft electric power system is discussed in Section II. Then, the background and related works are discussed in Section III. Afterward, we introduce proposed need-based method in Section IV. In Section V, we provide details of the design topology and define associated terminologies, equations and formulas. We then summarize the simulation results and provide detailed analysis in Section VI. Finally, the overall conclusion of the paper is represented in Section VII. components, incorporating the applicable criteria that follow.

2. AIRCRAFT ELECTRIC POWER DISTRIBUTION SYSTEM

A typical EPDS of a passenger aircraft represented in single line diagram (SLD) form can be seen in Fig. 1 which is adapted from a Honeywell patent. Mainly, the first elements in the architecture are generators (GEN) which supply power to a set of loads through high voltage AC buses (HVAC). Typically, each HVAC bus delivers power to high voltage DC bus (HVDC) through rectifier unit (RU). Rectifier unit converts AC to DC power in order to supply power to the loads. Moreover, Transformer rectifier unit (TRU) steps down the voltage from high to low AC voltage and then converts it from AC to DC form. Furthermore, AC transformer (ACT) steps down AC voltage from high to low AC power. In addition, Auxiliary power unit (APU) is connected to high voltage AC buses. In fact, the APU is used during engine starting time when aircraft is on the ground or is used in an emergency situation when one of generators malfunctions. Contactors, which are high-power switches, control the power flow by configuring the topology of the EPDS and establishes connection between different components. The EPDS topology can be reconfigured by opening or closing the contactors [9]. Then, we can mention the buses in the architecture which can be essential or non-essential. Essential buses must power the essential loads at all time. Essential loads are also called non-sheddable loads. For instance, Avionic components, fuel boost pump, hydraulic and window heating are considered as non-sheddable loads, but it can potentially handle as many loads as needed while achieving an optimal EPDS topology.

In Fig. 1, starting from the top layer, the power comes from four generators and two APUs. L1 and R1 are high voltage AC generators; L2 and R2 are low voltage AC generators.

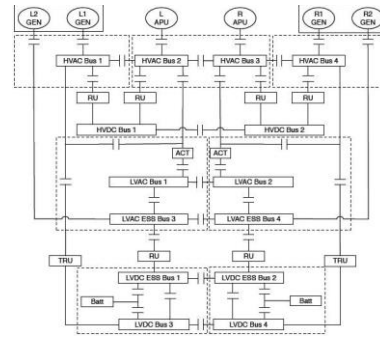


Figure 1. Single line diagram of an electric power system adapted from a Honeywell, Inc, patent [9]

Three distribution panels indicated by the dotted lines consist of HVAC buses, which are selectively connected to HVAC generators, APU and to one another with contactors. HVAC buses connect to either HVDC buses through RU while AC power converts to DC power or they connect to LVDC buses through TRU while the power voltage steps down and converts from AC to DC. Then, HVDC bus 1 and 2 connects to the high-power loads, which is not shown in the Fig. 1. The two panels in the middle consist of LVAC subsystem. A set of ACTs convert HVAC power to LVAC power and are connected to the two LVAC buses. LVAC Bus 3 and 4 are essential and are selectively connected to low voltage AC generators (L2 gen and R2 gen). The LVAC essential buses are also connected to the LVDC essential Buses through RU. Then, two batteries are connected to LVDC subsystem to supply power to essential buses in case of emergency or nodes failure. Moreover, power can be selectively routed from HVAC bus 1 and 4 to LVDC bus 3 and 4 through TRUs. Finally, LVDC buses supply power to low voltage loads [1].

3. RELATED WORKS

There are numerous studies in the area of electric power distribution systems. In [2], the authors explain design methodologies and examples for DC power distribution in an aircraft. In [3], S. Günter discusses challenges in peak power demand, overload conditions, increasing weight and total cost of operation in electric power distribution systems of aircrafts. Moreover, V. Madonna in [4] gives a thorough review about the evolution of electric power generation and power distribution systems in aircrafts. In [10], A. Rauzy presents a new method for fault tree management based on binary decision diagrams which allows efficient computation of the probability of the fault tree root events.

A compositional extension of the FTA technique was discussed in [15], where each component is represented by an extended fault tree. However, these works do not use

both directional and bi-directional loops in the architecture of an EPDS. A. Metzner explains a SAT-based approach in [25] to the task and message allocation problem of distributed real-time systems which can be also effectively applied into real-time aircraft power distribution systems. On the other hand, C. L. Jun-Mo focuses on hybrid electric vehicles in [24] and presents a procedure for improving the energy management strategy on the basis of dynamic optimization over a given time.

N. Ozay focuses on designing distributed control protocols for aircraft vehicle management systems in [17] and explains a method to cooperatively allocate electric power while meeting certain higher level goals and requirements, and dynamically reacting to the changes in the internal system state and external environment. In [16], H Xu demonstrates how text-based specifications can be translated into a temporal logic specification language and how it is used to automatically synthesize a control protocol for an EPDS of an aircraft. P. Krus demonstrates in [21] how the actuation system control surfaces can be simulated using a flight dynamics model of the aircraft coupled to a model of the actuation system. Furthermore, A. Benveniste dives into more details and advantages of contract-based design methodology in [22] and explains how contracts can be precisely defined and characterized so that they can be used in design methodologies. In [1], P. Nuzzo presents a platform-based methodology for designing the aircraft EPDS. The topology synthesis, control synthesis and simulation-based design space exploration are discussed in that paper. In [8], M. Maasoumy deliberates about the optimal load management system for aircraft EPDS. He divided the whole system to high level and low-level load management system. Then, the high-level system handles load shedding, source allocation and battery utilization where as low level system actuates EPDS contactors. Furthermore, design constraints are fundamental pieces of solving power distribution problem which C. Hang covered in [18]; he provides a meta-architectural specification language that allows designers to specify what properties their cyber-physical architectural models should have.

There are various avionics architectures that designers have suggested for the purpose of scalability and reducing integration activities. In [20], C. B. Watkins explains a guidance for developing the methodology and tools to efficiently manage the set of shared intersystem resources in an aircraft. Moreover, K. Sampigethaya introduces a novel cyber-physical system (CPS) framework in [23] to understand the cyber layer and cyber-physical interactions in aviation and their impacts. Moreover, T. Kurtoglu in [19] comes up a simulation-based framework that enables

designer to systematically explore architectural design decisions during the early stage of system development prior to the selection of specific components.

We concentrate on improving the reliability of the loads while considering other important features in this paper. This paper is based on the work done in [1], to make further improvement on the reliability of the essential loads which require power at all times. By considering node failures and safety requirements of the system [11], we introduce critical safety feature by adding battery power source to the system. In addition, our algorithm is not limited to small number of loads, but it can potentially handle as many loads as needed while achieving an optimal EPDS topology

4. NEED-BASED DESIGN

Based on Honeywell electric power system, we propose a simplified topology design. The block diagram of the proposed design is shown in Fig. 2. Given the required loads, the goal is to determine the systems architecture that satisfy loads power requirements while achieving maximum reliability and continuous connectivity without sacrificing the system costs.

In the EPDS, the power flows from generators to loads through buses, transformers and rectifiers. We synthesize the topology using a modular approach considering each specific group of components in each layer; then the power flows from one layer to another layer. Each component is represented as a node while the connection between each pair of nodes can be directional (directed loops) or bi-directional (bi-directional edge). Directed loop means that the power can only flow in one direction while in bi-directional edge, the power can flow in both directions. Since aircraft power system is symmetric; there are identical numbers of left hand side (LHS) and right hand side (RHS) components. In Fig. 2, generators, APU, rectifiers, battery and loads are denoted by circular shaped nodes. AC and DC buses are indicated by rectangular shaped nodes. The switches are used between all nodes. Moreover, the direction of the arrow lines indicates the power flow direction between different nodes.

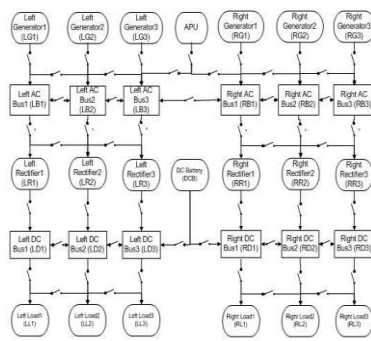


Figure 2. Proposed need-based design topology of electric power system

In Fig. 2, at the top layer, the power comes from three generators located on LHS; three generators located on RHS and one APU at the center. The power flows down to the rectifiers through AC buses. Rectifiers convert AC power to DC power and then supply DC power to the loads using DC buses. Furthermore, DC buses are also connected to the battery (DCB) to manage emergency cases. In the event that a rectifier fails, the battery will supply power to the essential loads to ensure continuous power. Contactors, which are switches, are used between all of the nodes to allow the system to control the path of the power flow by opening and closing the switches. AC and DC buses are connected via bi-directional edge to allow the power to flow between LHS and RHS of the system.

5. DESIGN SPECIFICATION

EPDS synthesis can be treated as an optimization problem by setting all of the requirements as constraints and solving the problem until objective function is satisfied. In this synthesis problem, we treat the connectivity and power requirements as the constraints of an integer linear program (ILP) and we solve the problem by using an ILP solver to get the EPDS topology with minimum cost. We then calculate the reliability of the resulting architecture to ensure whether it satisfies the reliability objectives or not. Then, we repeat this process by adjusting the constraints and adding more safety constraints into the system until the maximum reliability can be achieved without sacrificing extra cost in the system.

The overall design logic flow is shown in Fig. 3. The only input required is the number of loads and their power requirements. Based on the loads input, the

synthesis tool first checks whether the total generators power satisfies the total loads requirement. If power requirement is not met, the tool will ask the user to increase generator power or decrease load requirements. Then the tool will construct the initial topology using connectivity

matrix. By adding safety feature, the APU will be connected to essential AC bus to deal with the situation in which all of the generators fail. As a result, the DC battery will be connected to the essential loads to deal with the situation in which all of the rectifiers fail. After adding the constraints, the synthesis tool will run the first iteration to output the topology. Then, the reliability of the resulting topology is calculated; if the reliability value is not satisfied, the tool will continue running multiple iterations while adjusting the constraints until maximum reliability can be achieved.

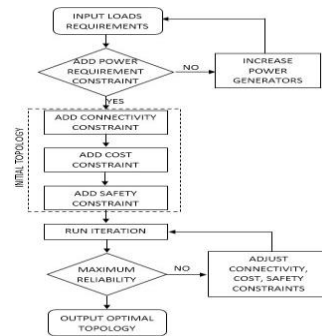


Figure 3. Design logic flow

A. Connectivity Constraints

Connectivity ensures that the specific nodes are connected to each other utilizing minimum number connections in order for power to flow from the generators to the loads. Consequently, we need to list all the possible connections between different types of components. Connectivity matrices in Table I, shows the interconnections between different components in the system topology. Then, the connectivity constraints can be defined using these matrices as the following rules and equations.

TABLE I. CONNECTIVITY MATRIX

Variable	In-Between Connection	Matrix Dimension
GB	Generators - AC Buses	n gen X n acbus
BB	AC Buses - AC buses	n acbus X n acbus
BR	AC Buses - Rectifiers	n acbus X n rec
RD	Rectifiers - DC Buses	n rec X n dcbus
DD	DC Buses - DC Buses	n dcbus X n dcbus
DL	DC Buses - DC Loads	n dcbus X n load
APUB	APU - AC Buses	n apu X n acbus
DCBD	DC Battery - DC Buses	n dcba X n dcbus

Rule 1: Any DC load must be connected to only one DC bus. This prevents using extra unnecessary buses.

$$\sum_{i=1}^{n_{loads}} DL(i, :) = Ones(1, n_{loads}) \quad (1)$$

Rule 2: The DC bus connected to a load or another DC bus must be connected to a rectifier. This ensures that when a DC bus plays an important role in the topology, it must be connected to a rectifier.

$$\max[BR(:, i)] = \max[RD(i, :)] \quad (2)$$

$$\max[RD(:, i)] = \max[RD(i, :)] \quad (3)$$

Rule 3: The rectifier connected to a DC bus must be connected to an AC bus to ensure the power flow.

$$\max[BR(:, i)] = \max[RD(i, :)] \quad (4)$$

Rule 4: The AC bus connected to a rectifier or another AC bus must be connected to a generator. This ensures that when an AC bus plays an important role in the topology, it must be connected to a generator.

$$\max[GB(:, i)] \geq \max[BR(i, :)] \quad (5)$$

$$\max[GB(:, i)] \geq \max[BB(i, :)] \quad (6)$$

Rule 5: The rectifier cannot be connected to more than one AC bus. This saves AC bus operation cost.

$$\sum_{i=1}^{n_{ACbus}} BR(i, :) \leq Ones(1, n_{rect}) \quad (7)$$

Rule 6: The rectifier cannot be connected to more than one DC bus. This will save DC bus operation cost.

$$\sum_{i=1}^{n_{DCbus}} RD(:, i) \leq Ones(n_{rect}, 1) \quad (8)$$

Rule 7: Each generator can be connected to only one AC bus. This will save AC bus operation cost.

$$\sum_{i=1}^{n_{ACbus}} GB(:, i) \leq Ones(n_{Gen}, 1) \quad (9)$$

Rule 8: No AC bus on each side can be connected to itself.

$$\sum_{i=1}^{n_{ACbus}} BB(i, i) == 0 \quad (10)$$

Rule 9: No DC bus on each side can be connected to itself.

$$\sum_{i=1}^{n_{DCbus}} DD(i, i) == 0 \quad (11)$$

Rule 10: The APU cannot be connected to more than one AC bus on each side to save connection cost.

$$\sum_{i=1}^{n_{ACbus}} APUB(:, i) == Ones(n_{APU}, 1) \quad (12)$$

Rule 11: The AC bus which is not connected to another AC bus or rectifier must not be connected to the APU. This ensures that only the operating AC buses are connected to the APU.

$$\max[BR(i, :)] \geq \max[APUB(:, i)] \quad (13)$$

$$\max[BB(i, :)] \geq \max[APUB(:, i)] \quad (14)$$

Rule 12: The DC battery cannot be connected to more than one DC bus on each side to save operational cost.

$$\sum_{i=1}^{n_{DCbus}} DCBD(:, i) == Ones(n_{DCB}, 1) \quad (15)$$

Rule 13: The DC bus which is not connected to another DC bus or load must not be connected to the DC battery. This ensures that only the operating DC buses are connected to Battery.

$$\max[DD(i, :)] = \max[DCBD(:, i)] \quad (16)$$

$$\max[DL(i, :)] = \max[DCBD(:, i)] \quad (17)$$

B. Power Requirement Constraints

The total power capacity of the generators must satisfy the total power requirements of the loads. The APU needs to be connected to the AC bus and be capable of powering non-sheddable loads on each side when generators fail. In addition, the DC battery should be capable of powering non-sheddable loads on each side in the event that a rectifier fails.

$$\sum_{i=1}^{n_{AC}} GENP(i, :) \geq \sum_{i=1}^{n_{loads}} LoadsP(i, :) \quad (18)$$

$$\sum_{i=1}^{n_{APU}} APUP(i, :) \geq \sum_{i=1}^{n_{ESSloads}} ESSLoadsP(i, :) \quad (19)$$

$$\sum_{i=1}^{n_{DCB}} DCBP(i, :) \geq \sum_{i=1}^{n_{ESSloads}} ESSLoadsP(i, :) \quad (20)$$

C. Cost Objective

In this optimization problem we define the cost objective using connectivity matrices and specific cost values which have been defined for all of the components in this topology such as the generator, APU, rectifier and etc. These cost values are defined in meaningful manner. For example, using an extra component is more expensive than adding an extra switch (contactor). As well as using an AC bus is more expensive than using a DC bus. The goal is to minimize the total cost by using a minimum number of components and choosing inexpensive components over expensive ones.

$$\begin{aligned} LHS_{cost} = & cost_{perGenL} * \max(GB_{left}) + \\ & Cost_{perRL} * \sum(RD_{left}) + cost_{perACbusL} + \\ & \max(BR_{left}, BB_{left}) + cost_{perDCbusL} * \\ & \max(DL_{left}, DD_{left}) \end{aligned} \quad (21)$$

$$\begin{aligned}
 RHS_{cost} = & cost_{perGenl} * \max(GB_{right}) + \\
 & Cost_{perRR} * \sum(RD_{right}) + cost_{perACbusR} + \\
 & \max(BR_{right}, BB_{right}) + cost_{perDCbusR} * \\
 & \max(DL_{right}, DD_{right}) \quad (22)
 \end{aligned}$$

In equation 21, left-hand side (LHS) costs include the total cost of generators, rectifiers, AC and DC buses on the left hand side. The same principal applies for right-hand side (RHS) cost shown in equation 22.

For calculating the cost of switches used on LHS (equation 23) and RHS (equation 24), we multiply the cost of the switch by the number of connections on each side.

$$SW_{Lcost} = cost_{PerSW} * Con_{NL} \quad (23)$$

$$SW_{Rcost} = cost_{PerSW} * Con_{NR} \quad (24)$$

The total cost (equation. 25) includes the cost of LHS and RHS components, APU, DC battery and switches that are being used.

$$\begin{aligned}
 Total_{cost} = & LHS_{cost} + RHS_{cost} + SW_{Lcost} + \\
 & SW_{Rcost} + APU_{cost} + DCB_{cost} \quad (25)
 \end{aligned}$$

D. Reliability and Safety

In an EPDS, every type of component has a specific failure rate. A failure rate of λ for a component means a failure can occur every $1/\lambda$ hours for that component. The failure rates can be translated into the failure probabilities. As a result, those system reliability specifications can be expressed in terms of the failure probabilities of the components [1].

The probability of a component failure in a time interval T can be expressed as below.

$$P_{fail} = 1 - e^{-\lambda T} \quad (26)$$

Where λ is the component failure rate and T is the exposure time.

In order to determine reliability of the system, we need to compute the probability of loads failures by using fault tree analysis (FTA) [12]. A simple fault tree can be seen in Fig. 4. The fault tree is the logical model of the relationship of the undesired event to the more basic events.

The top level node (a) is known as the top undesired event. The middle nodes (b1, b2) are called immediate events and the bottom nodes (c1, c2, and c3) are called basic events. Node (a) is connected to b1 and b2 by using OR gate, which represents the logical union of inputs: the output will occur if any of the inputs occur. Node (b1) is

connected to c1 and c2 by an AND gate, which represents the logical intersection: if all inputs occur then the output occur.

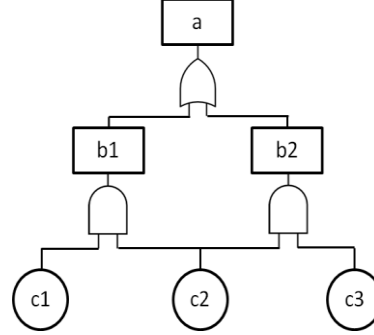


Figure 4. A fault tree [10]

The logic shown in Fig. 4 is defined by three equations.

$$a = b1 \cup b2 \text{ (} b1 \text{ or } b2 \text{)} \quad (27)$$

$$b1 = c1 \cap c2 \text{ (} c1 \text{ and } c2 \text{)} \quad (28)$$

$$b2 = c2 \cap c3 \text{ (} c2 \text{ and } c3 \text{)} \quad (29)$$

The fault tree encodes the following Boolean function:

$$F(c1, c2, c3) = (c1 \cap c2) \cup (c2 \cap c3) \quad (30)$$

The probability of a component to fail is caused by two attributes. A component may fail by its own failure (self-failure) or by failure of all other components powering that component (induced failure). Considering the load "a" in Fig. 4, if the load "a" itself fails, then there will be no power. If load "a" survives, then the power can either come from node b1 or b2. If both b1 and b2 survive, then the probability of node "a" failure depends on c1, c2 and c3 and so on. We use this concept to develop recursive algorithm to calculate probability of failure for all of the components in the EPDS topology. Finally, we can calculate the probability of failure of the loads. The probability of failure at load x can be expressed by the following equation.

$$P(F_x) = p_x + \bar{p}_x * \prod_{i=1}^{n_{comp}} p_x^{a_{xi}} \quad (31)$$

$$a_{xi} = \begin{cases} 1, & \text{if } i \text{ can power } x \\ 0, & \text{if } i \text{ cannot power } x \end{cases} \quad (32)$$

x = a component (load)

n_{comp} = number of components that powers component x.

p_x = probability of failure of component x (self failure)



\bar{p}_x = probability of failure of component x (induced failure)

Consider a simple example of an EPDS shown in Fig. 5. The fault tree of load1 (L1) is shown in Fig. 6. If load 1 (L1) fails, then there will be no power. If L1 survives, the power will depend on D1. If both L1 and D1 survive, the power can come from either R1 or D2. If R1 fails, the power can route through D2. If B1 fails, there will be no power coming from generator G1. However, the power can still come from generator G2 and so on. We will derive the Boolean equation by using recursive algorithm to calculate the probability of failure of the load 1 (L1).

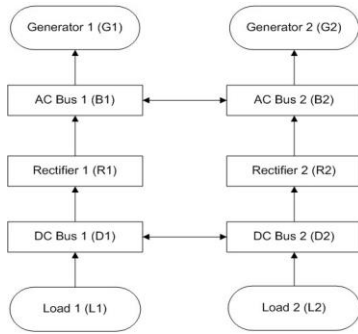


Figure 5. Simplest EPDS flow

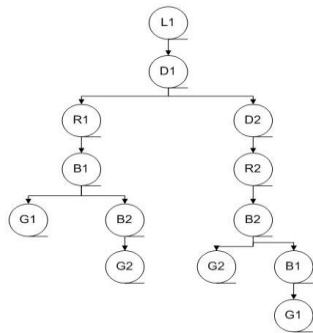


Figure 6. Fault tree of load 1 (L1)

The following equations are derivations of event of Induced failure at load 1(L1). The notation \cup is called union and \cap is called intersection. For any event E, the self-failure is shown with E and the induced failure is shown with Et. (’’ ’’ is not a complement sign).

$$L1' = (D1 \cup D1') \tag{32}$$

$$L1' = (D1 \cup R1 \cup R1') \cap (D1 \cup D2 \cup D2') \tag{33}$$

$$L1' = (D1 \cup R1 \cup B1 \cup B1') \cap (D1 \cup D2 \cup R2 \cup R2') \tag{34}$$

$$L1' = [D1 \cup R1 \cup B1 \cup (G1 \cap (B2 \cup B2'))] \cap [D1 \cup D2 \cup R2 \cup B2 \cup (G2 \cap (B1 \cup B1'))] \tag{35}$$

$$L1' = [D1 \cup R1 \cup B1 \cup (G1 \cap (B2 \cup G2))] \cap [D1 \cup D2 \cup R2 \cup B2 \cup (G2 \cap (B1 \cup G1))] \tag{36}$$

$$L1' = (R1 \cap D2) \cup (R1 \cap R2) \cup (R1 \cap D2) \cup (R1 \cap B2) \cup (R1 \cap G2 \cap (B1 \cup G1)) \cup (B1 \cap D2) \cup (B1 \cap R2) \cup (B1 \cap B2) \cup (B1 \cap G2 \cap (B1 \cap G1)) \cup (G1 \cap (B2 \cup G2) \cap D2) \cup (G1 \cap (B2 \cup G2) \cap R2) \cup (G1 \cap (B2 \cup G2) \cap B2) \cup (G1 \cap B2 \cup G2) \cap G2 \cap (B1 \cup G1) \tag{37}$$

$$L1' = R1 \cap D2) \cup (R1 \cap R2) \cup (R1 \cap D2) \cup (R1 \cap B2) \cup (B1 \cap D2) \cup (B1 \cap R2) \cup (B1 \cap B2) \cup (B1 \cap G2) \cup (G1 \cap B2) \cup (G2 \cap G2) \tag{38}$$

6. SYNTHESIS RESULTS AND ANALYSIS

The proposed algorithm for synthesizing the topology of the EPDS is written in MATLAB. We used Yalmip [13], which is a well-known toolbox for modeling and optimization. Yalmip consists of high level algorithms while depending on external solvers such as IBMs Cplex for actual computation [14]. For this synthesis, we used IBM ILOP CPLEX Optimization studio 12.4. GraphViz4MatLab is a MATHLAB add-on package to display directed and undirected graph within a figure.

Use either SI (MKS) or CGS as primary units. (SI units are encouraged.) English units may be used as secondary units (in parentheses). An exception would be the use of English units as identifiers in trade, such as “3.5-inch disk drive”.

A. EPDS Topology with Four Loads

In the first synthesis example, consider the following design objective.

Given four different input loads requirements, we want to design a topology which gives maximum reliability, continuous connectivity, and minimum cost. In Table II, there are four input loads from user input with different power requirements. We predefined aircrafts power capabilities in Table III with a 5kW high power generator and a 3kW low power generator on each side. Note that generators power capabilities can change depending on the type of aircraft systems.

TABLE II. INPUT LOAD REQUIREMENTS IN WATTS

Component	User Input Loads (W)
LL1	4000
LL2	3000
LR1	2000
LR2	3000

TABLE III. POWER CAPABILITY IN WATTS

Component	Power Capability (W)
LG1	5000
LG2	3000
RG1	5000
RG2	3000
APU	10000
DCB	5000

In Table IV, the predefined failure rates are represented according to aircraft safety regulations and guidelines. The costs of individual components are shown in Table V. Note the meaningful differences in the costs of different components.

TABLE IV. PREDEFINED FAILURE RATE

Component	Failure rate (λ)
Generator	$5 * 10^{-5}$
Rectifier	$2 * 10^{-4}$
AC Bus	$5 * 10^{-6}$
DC Bus	$5 * 10^{-6}$
APU	0.1
DCB	5000

TABLE V. COST OF INDIVIDUAL COMPONENT

Component	CostPer(\$)
Generator	$Gen_{pow}/10$
Rectifier	200
AC Bus	150
DC Bus	100
APU	$APU_{pow}/10$
DCB	$DCB_{pow}/10$
Switch (contactor)	50

Fig. 7 shows the synthesis output of the topology after the first iteration of the algorithm. In this topology, for each load the power can be provided only in one path from the generators which guarantees connectivity while considering the minimum component cost. Since the total loads requirements for LHS is 8kW, the system will need two generators to power the LHS loads while the RHS requires 5kW and therefore only one generator is needed. Both the APU and the DCB (DC Battery) are connected to the buses at all time for emergency handling. The APU will be activated when all generators fail, while the battery will operate to power essential loads when all rectifiers fail. The horizontal connection between the RHS and LHS DC

buses will be added after the second iteration which is shown in Fig. 8. the reliability improves by adding connections closer to the loads. In an example failure situation in which the rectifier "LR1" or the AC bus "LB1" fails, the LHS loads can still receive the power from the APU through "RB1", "RR1", "RD2" and "LD2"

According to the cost objectives, adding an extra component is more expensive than adding a switch. As a result, we can see this fact in the third iteration of the algorithm which is shown in Fig. 9. We can see that a horizontal connection is added between the LHS and RHS AC buses for improving reliability without sacrificing the cost. In an example of a failure situation, if the LHS rectifier "LR1" fails, the power can still come to the loads from the generator through "LB2", "RB2", "RR2", "RD2", and "LD2".

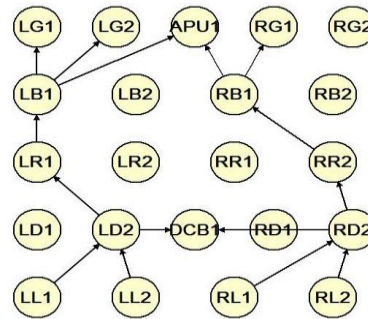


Figure 7. First iteration

Fig. 10 shows the final iteration results from an optimal topology. The algorithm added extra DC buses and rectifiers to improve the reliability of the system. In conclusion, the synthesis for four user defined loads and final iteration gives optimal topology with a total of three generators needed (two on LHS and one on RHS).

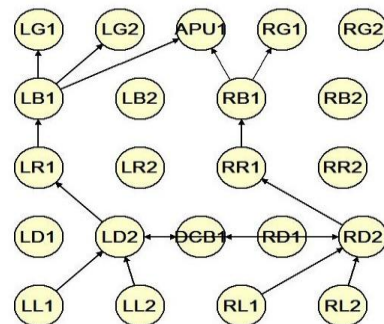


Figure 8. Second iteration

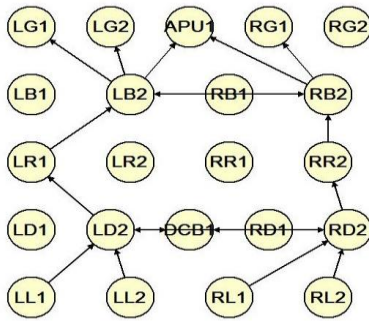


Figure 9. Third iteration

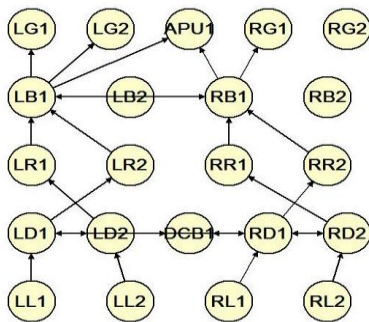


Figure 10. Final iteration

In Table VI and VII, we present the average failure rate and reliability value of the four loads in different iterations of the algorithms. The performance of the original method which was mentioned in [7] is shown in the table to indicate the improvements in our proposed synthesis algorithm. Generally, with every new iteration the average failure rate decreases as the average reliability value increases. In comparison to method [7], our proposed algorithm synthesizes the system with safety features such as DC battery to improve reliability values.

TABLE VI. AVERAGE FAILURE RATE OF LOADS USING ORIGINAL METHOD AND PROPOSED METHOD

Iteration	Failure Rate of Original System	Failure Rate of Improved System
Iteration 1	2.31E-04	1.25E-04
Iteration 2	5.54E-08	1.80E-08
Iteration 3	5.40E-08	1.73E-08
Iteration 4	1.83E-12	9.30E-13

TABLE VII. AVERAGE RELIABILITY VALUE OF LOADS BETWEEN ORIGINAL AND IMPROVED SYSTEM

Iteration	Reliability Value of Original System	Reliability Value of Improved System
Iteration 1	4.33E+03	8.00E+03
Iteration 2	1.81E+07	5.56E+07
Iteration 3	1.85E+07	5.78E+07
Iteration 4	5.46E+11	1.08E+12

Fig. 11 shows the average failure rates of loads (λ) changes in different iterations of the original algorithm and the proposed algorithm. By adding a safety feature to the system, we can see that the proposed method has a reduced failure rate at all iterations compared to the original method. There is significant improvement in failure rate going from iteration 1 to 2 and from iteration 3 to 4. However, at iteration 3, in which the horizontal AC bus connection is added between LHS and RHS. As a result, there is not a considerable improvement since the AC buses are located far away from loads.

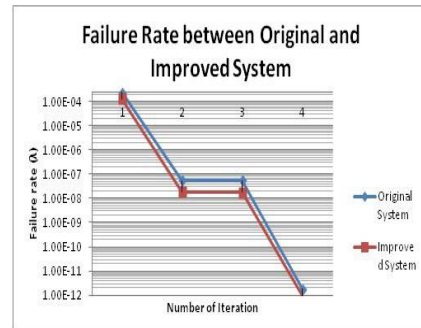


Figure 11. Graph comparing average failure rate of loads between original and improved system

According to Fig. 12, we observe that as failure rate (λ) values decreases, reliability values ($1/\lambda$) increases. This in effect reduces the possibility of load failure.

Table VIII shows the CPLEX solver time for the original algorithm and our proposed algorithm. We could improve the synthesis time by simplifying the algorithm and removing unnecessary loops. Table VIII shows how the solver runtime changes for different iterations. The solver time is improved after each iteration since the algorithm is just adjusting the constraints in iterations after the first iteration.

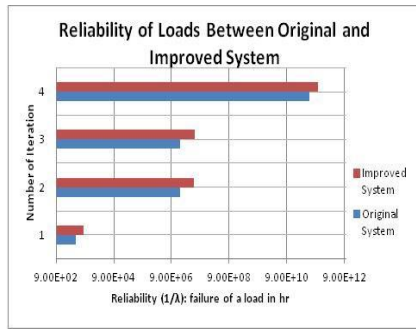


Figure 12. Graph comparing average reliability of loads between original and improved system

TABLE VIII: SOLVER TIME OF FOUR ITERATIONS

Iteration	Solver Time of Original System (sec)	Solver Time of Improved System (sec)
Iteration 1	0.202	0.189
Iteration 2	0.104	0.096
Iteration 3	0.106	0.090
Iteration 4	0.092	0.088

Yalmip time is the time it takes to solve optimization problem after CPLEX computation. Table IX shows the time for each iteration. According to Fig. 14, the Yalmip run time in second iteration is improved compared to the first iteration. However, this run time in iteration 3 and 4 takes longer than second iteration due to rerouting time and adding more constraints to the optimization problem.

TABLE IX. YALMIP TIME OF FOUR ITERATIONS

Iteration	Yalmip Time of Original System (sec)	Yalmip Time of Improved System (sec)
Iteration 1	2.25	2.18
Iteration 2	1.40	1.31
Iteration 3	1.68	1.52
Iteration 4	1.69	1.55

B. EPDS Topology with Six Loads

Given six different input loads requirements, we want to design a topology which gives maximum reliability, continuous connectivity, and minimum cost. In Table X, there are six input loads from user input with different power requirements. We predefined aircrafts power capabilities in Table XI with a 5kW high power generator and two 3kW and 2KW low power generators on each side. Note that generators power capabilities can change depending on the different type of aircraft systems.

TABLE X. INPUT LOAD REQUIREMENTS IN WATTS

Component	Power Capability (W)
LG1	5000
LG2	3000
LG3	2000
RG1	5000
RG2	3000
RG3	2000
APU	10000
DCB	5000

The algorithm in the third iteration (Fig. 17) adds bi-directional path between LHS and RHS AC buses to improve reliability without sacrificing component cost. Moreover, extra DC buses and rectifiers have been added to the system to achieve maximum reliability and connectivity. After the final iteration (Fig. 18), the algorithm outputs the optimal topology with a total number of three generators (two of LHS and one on RHS) to provide power for the six loads.

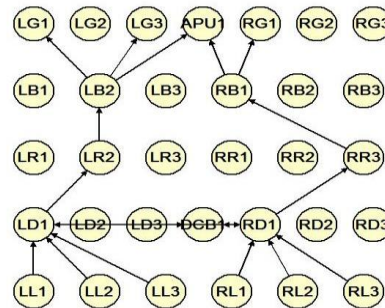


Figure 16. Second iteration

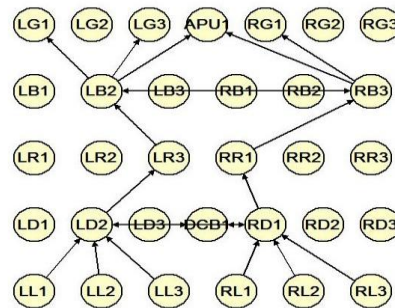


Figure 17. Third iteration

The algorithm in the third iteration (Fig. 17) adds bi-directional path between LHS and RHS AC buses to improve reliability without sacrificing component cost.



Moreover, extra DC buses and rectifiers have been added to the system to achieve maximum reliability and connectivity. After the final iteration (Fig. 18), the algorithm outputs the optimal topology with a total number of three generators (two of LHS and one on RHS) to provide power for the six loads.

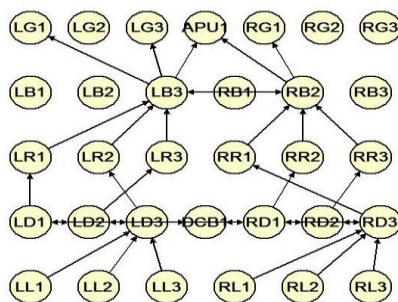


Figure 18. Final iteration

C. EPDS Topology with high number of nodes

Finally, in order to evaluate the proposed algorithm in more complex cases, we try to synthesize an EPDS consisting of higher number of nodes than the previous two syntheses. The number of different elements in various synthesis setups are described in table XII.

Like the previous syntheses, different power requirement values are assumed for each of the elements in each synthesis. Moreover, we assumed different failure probabilities and cost values for each of the components. Finally, the proposed algorithm could synthesize the EPDS in satisfactory times in all of the setups. The YALMIP time and solver time for each synthesis setup are represented in table XIII and XI

TABLE XII. NUMBER OF COMPONENTS IN DIFFERENT SYNTHESIS SETUPS

	Synthesis 1	Synthesis 2	Synthesis 3	Synthesis 4
Generators	4	6	6	6
AC buses	6	8	6	6
Rectifiers	8	6	6	6
DC buses	6	6	8	6
Loads	20	40	60	80

7. CONCLUSION

In this paper, we presented a need-based design approach for the aircraft electric power distribution system. We treated EPDS as an optimization problem by using integer linear programming (ILP) to achieve minimum cost while having maximum reliability, continuous connectivity, and fulfilling power requirements. The use of recursive algorithms was to calculate the failure probabilities of the loads. In this proposed synthesis algorithm, the EPDS design engineer can get the optimal topology by just proving input loads power requirements.

We run different syntheses according realistic applications. Our proposed synthesis of algorithm runs multiple iterations to achieve the optimal topology. We compared reliability values, and synthesis runtime with previous work and we believe the proposed algorithm is more robust, and able to handle nodes failures while improving reliability of the loads.

Our need-based algorithm can handle as many loads as the system requires. However, for further improvements we should consider designing a graphic user interface (GUI), where users can easily adjust loads requirements, power capabilities, safety requirements, and reliability values using the GUI an as a result the program will generate an optimal topology based on user defined criteria.

TABLE XIII. SYNTHESIS YALMIP TIME FOR DIFFERENT SETUPS (SECONDS)

	Iter.1	Iter.2	Iter.3	Iter.4	Iter.5	Iter.6	Iter.7	Iter.8	Iter.9	Total
Synthesis 1	1.62	1.34	1.68	1.69	1.68	1.68	1.69	1.68		13.13
Synthesis 2	1.7	1.43	2.03	2.05	2.05	2.04	2.06	2.05	2.13	17.54
Synthesis 3	1.69	1.71	2.06	2.06	2.07	2.1	2.09			13.78
Synthesis 4	1.58	1.33	1.68	1.7	1.68	1.68	1.69	1.69	1.68	14.71



TABLE XIV. SYNTHESIS SOLVER TIME FOR DIFFERENT SETUPS (SECONDS)

	Iter.1	Iter.2	Iter.3	Iter.4	Iter.5	Iter.6	Iter.7	Iter.8	Iter.9	Total
Synthesis 1	0.24	0.23	0.08	0.08	0.16	0.16	0.15	0.02		1.12
Synthesis 2	0.25	0.15	0.15	0.16	0.03	0.04	0.17	0.19	0.03	1.17
Synthesis 3	0.25	0.11	0.09	0.22	0.18	0.16	0.05			1.06
Synthesis 4	0.26	0.16	0.15	0.21	0.03	0.03	0.15	0.03	0.03	1.05

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