Comparing the Topologies of Satellite Electrical Power Subsystem Based on System Level Specifications

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Abstract— This paper focuses on evaluating three main design criteria including efficiency, reliability and cost for different topology schemes of Electrical Power Subsystem (EPS) of a satellite in Low Earth Orbit. Selecting an appropriate topology may increase the overall EPS efficiency and extend the lifetime of satellites. In this article, ten basic EPS topologies are studied, evaluated and compared. In order to choose a more efficient and more reliable EPS topology, along with cost considerations, the mentioned parameters would be calculated for each topology separately. In the next step, these topologies can be compared by defining an overall cost function composed of all three criteria.

Keywords— Efficiency; Reliability; Cost; Topology; Electrical Power Subsystem

I. INTRODUCTION

Electrical Power Subsystem (EPS) provides energy for all the satellite parts and subsystems in a 24/7 service throughout the whole mission life. The role of EPS is very similar to that of the heart in human body, which supplies the vital materials to the whole body by circulating blood.

Therefore, EPS has a critical role in a satellite system. In order to satisfy these critical functional requirements, EPS needs to regulate, control and distribute the generated power by solar arrays and/or batteries. Electrical power is essential for the operation of all active satellite systems and subsystems. The electrical power system (EPS) of a satellite comprises of power conversion unit, power conditioning unit, energy storage unit, overvoltage and overcurrent protection unit, and power distribution to the various users via the on-board low-voltage power distribution systems. Fig.1 shows the block diagram of a generic EPS.

Each of EPS functions consists of sub-functions, with several design characteristics which must be developed to meet mission requirements. Different methods and techniques exist to design and develop an EPS, each of which contains certain key steps.

One of these steps is the selection of an appropriate topology for EPS. Selection of an appropriate topology may increase the overall EPS efficiency. It may prevent battery over charging and undesired spacecraft heating which can consequently extend the mission life time. It can also lead to a lighter, more reliable or a cost-effective EPS.

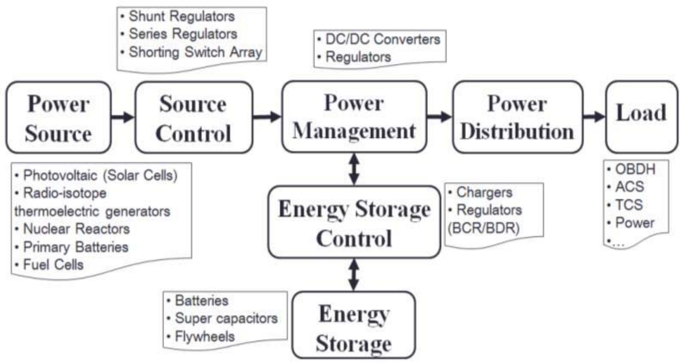

Fig1. General block diagram of Electical Power Subsystem

EPS reliability has been evaluated in several papers before. In [3] reliability analysis has been carried out for power subsystem of a LEO Satellite only for Direct Energy Transfer (DET) systems. Also [4] optimizes the power subsystem design which may not be more reliable. In [5] a new power distribution and control subsystem for a satellite has been presented, in which power distribution has a higher contribution to the unreliability of power subsystem.

II. RESEARCH METHODOLOGY

In this study, some of the basic EPS topologies are evaluated and compared based on three essential criteria i.e.: efficiency, reliability and cost. For the sake of simplicity, we just consider the basic topologies without redundancy for any

EPS parts. In order to select the optimum topology, a cost function is defined to evaluate the real and overall impact of these factors. Finally, all studied topologies are sorted according to their cost function.

A. Review of Basic EPS Topologies

Several basic topologies are introduced for satellite EPS in books and papers. These topologies can be classified based on two main criteria: 1) their method of energy transfer and 2) their voltage bus regulation method

All EPS topologies can be divided in two classes from the viewpoint of energy transfer techniques: Peak Power Trackers (PPT) and Direct Energy Transfer (DET) subsystem. On the other hand each EPS topology may use various types of voltage regulation method for its primary voltage bus regulation and control (before the EPS's local or distributed DC-DC convertors or secondary regulators).

There are different EPS primary bus voltage control techniques, which fall into the various categories such as unregulated, quasi regulated, fully regulated and hybrid buses. Since the EPS topology can be composed of at least one energy transfer method and any type of primary bus voltage regulation technique, it is possible to talk about various EPS topologies.

In [1] and [2] several types of basic EPS topologies are presented and discussed. These two references have considered different categories for basic EPS topologies. Many text books, literatures, papers and technical reports have used the method of topology classification of [1] and [2] as conventional EPS topologies.

In this study we offer to extend these categories to ten basic topologies instead of eight topologies in [1] or six topologies in [2]. Figure.2 shows the schematics of these ten topologies. All of the evaluations in this study have been carried out for all the topologies in Fig.2. The evaluation and comparing results are presented in the following tables in this paper.

B. System level parameters and factor for topology selection

The design and operation of a spacecraft EPS can be evaluated by various criteria. In this article three main criteria, efficiency, cost and reliability are considered as the system level parameters.

- *Efficiency and Efficiency Index*

Efficiency, defined as the ratio of useful output power to the total input power can be stated for each element or part of the EPS. In this study we assume typical efficiency values for the essential parts of the EPS, i.e.: PPT module, shunt regulators, battery charger/discharger, linear charge, current control recharge control, battery, boost regulator, and solar arrays.

The system overall efficiency is calculated easily for each topology by considering whether a certain part is actively operational, in different operating modes, for the studied topology or no?

In order to have a better sense about the efficient operation of each part when the satellite is turning in its orbit, we offer to define a new parameter named "Efficiency Index". This parameter is defined as the efficiency of a certain EPS part multiply by its operation time. Therefore, a duty cycle factor would be considered for each part reflecting the duration for which the components would be active in one orbit cycle.

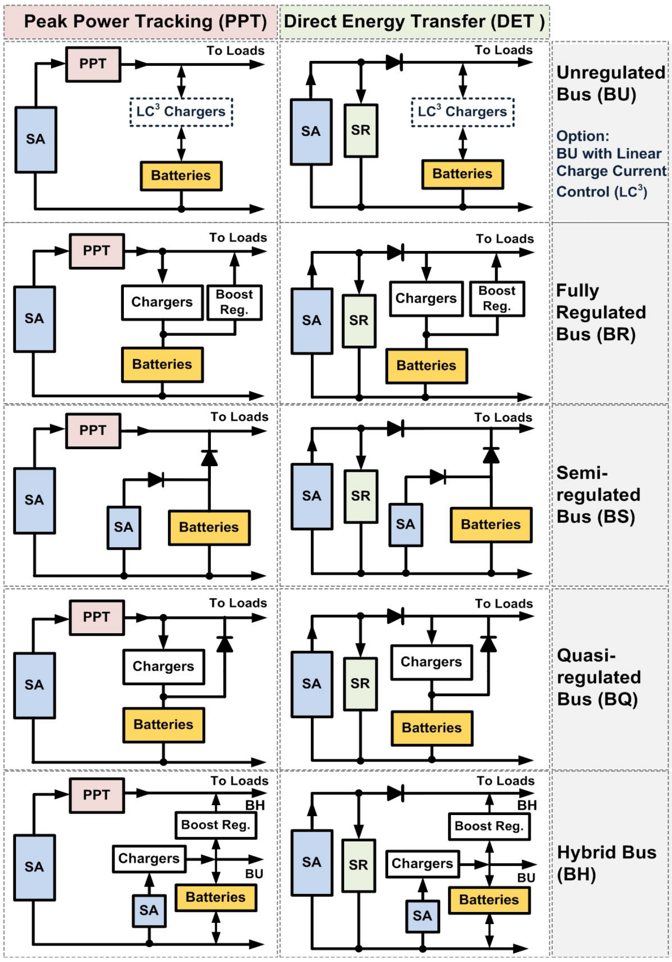

Fig.2. Techniques for Power Regulation. The basic approaches are Peak Power tracking (PPT) which places a regulator in series with the solar arrays and the load, and Direct Energy Transfer (DET) which uses a regulator in parallel with the solar arrays and load.

In TABLE I, each EPS parts' efficiency is determined approximately.

TABLE I. EFFICIENCY OF EPS ELEMENTS

EPS ELEMENTS	EFFICIENCY (Typical Value)
Solar array	0.3
PPT	0.9
Batteries	0.95
Shunt regulator	0.85
LC3 chargers	0.9
Boost regulator	0.85
Chargers	0.9

In TABLE II a duty cycle are defined for each operational mode in one LEO cycle. It should be noted that all of the mentioned values for efficiencies and duty cycles are estimated and only for this case study.

TABLE II. DUTY CYCLE OF EACH OPERATIONAL MODE IN ONE LEO CYCLE

Operational modes	Duty cycle (Typical Value)
Sun_CR	0.3
Sun_DR	0.2
Sun_CR/DR	0.15
Sun	0.05
Eclipse	0.3

In the TABLES III to VII the efficiency calculation results can be found for the ten basic topologies for one cycle duration in a LEO orbit. Each table presents the results for two topologies in five operational modes including:

1- Sun_CR mode: Battery charging in sun light while power is provided by solar arrays and simultaneously batteries are charged

2- Sun_DR mode: Battery discharging in sun light while solar arrays and batteries together provide the satellite power

3- Sun_CR/DR mode: Battery discharging and charging in sun light while solar arrays and batteries supply the power and simultaneously batteries are charged

4- Sun mode: Solar arrays lonely support the satellite power in sun light.

5- Eclipse mode: Batteries are alone source of the satellite power in eclipse

The summation of calculated efficiency indexes of the EPS operation is named “Overall Efficiency Index”. This index is calculated for one complete LEO cycle in order to take all the operational modes into account, and presented in TABLE III for each topology as the overall efficiency criteria of that EPS topology.

TABLE III. EFFICIENCY INDEXES OF FULLY REGULATED BUS IN ONE LEO CYCLE

Topology	Modes	Efficiency Index
Fully Regulated - MPPT	Sun_CR	21.80
	Sun_DR	13.73
	Sun_CR/DR	9.27
	Sun	4.25
	Eclipse	20.59
	Overall (in a LEO Cycle)	69.64
Fully Regulated - DET	Sun_CR	23.09
	Sun_DR	14.54
	Sun_CR/DR	9.81
	Sun	4.50
	Eclipse	21.80
	Overall (in a LEO Cycle)	73.73

TABLE IV. EFFICIENCY INDEXES OF QUASI- REGULATED BUS WITH CONSIDERING BATTERY CHARGER IN ONE LEO CYCLE

Topology	Modes	Efficiency Index
Quasi Regulated- MPPT	Sun_CR	21.80
	Sun_DR	16.15
	Sun_CR/DR	10.90
	Sun	3.83
	Eclipse	24.23
	Overall (in a LEO Cycle)	76.90
Quasi Regulated - DET	Sun_CR	23.09
	Sun_DR	17.10
	Sun_CR/DR	11.54
	Sun	4.05
	Eclipse	25.65
	Overall (in a LEO Cycle)	81.43

TABLE V. EFFICIENCY INDEXES OF SEMI REGULATED BUS IN ONE LEO CYCLE

Topology	Modes	Efficiency Index
Semi Regulated - MPPT	Sun_CR	24.23
	Sun_DR	16.15
	Sun_CR/DR	12.11
	Sun	4.25
	Eclipse	24.23
	Overall (in a LEO Cycle)	80.96
Semi Regulated - DET	Sun_CR	25.65
	Sun_DR	17.10
	Sun_CR/DR	12.83
	Sun	4.50
	Eclipse	25.65
	Overall (in a LEO Cycle)	85.73

TABLE VI. EFFICIENCY INDEXES OF UNREGULATED BUS USING LINEAR CHARGE CURRENT CONTROL IN ONE LEO CYCLE.

Topology	Modes	Efficiency Index
Unregulated - MPPT	Sun_CR	21.80
	Sun_DR	14.54
	Sun_CR/DR	10.90
	Sun	3.83
	Eclipse	24.23
	Overall (in a LEO Cycle)	75.29
Unregulated - DET	Sun_CR	23.09
	Sun_DR	15.39
	Sun_CR/DR	11.54
	Sun	4.05
	Eclipse	25.65
	Overall (in a LEO Cycle)	79.72

TABLE VII. EFFICIENCY INDEXES OF HYBRID BUS USING LINEAR CHARGE CURRENT CONTROL IN ONE LEO CYCLE.

Topology	Modes	Efficiency Index
Hybrid - MPPT	Sun_CR	21.80
	Sun_DR	13.73
	Sun_CR/DR	9.27
	Sun	4.25
	Eclipse	20.59

Topology	Modes	Efficiency Index
	Overall (in a LEO Cycle)	69.64
Hybrid - DET	Sun_CR	23.09
	Sun_DR	14.54
	Sun_CR/DR	9.81
	Sun	4.50
	Eclipse	21.80
	Overall (in a LEO Cycle)	73.73

As the results show, Unregulated Bus has a high efficiency than other topologies for this case. But the overall efficiency is sensitive to duty cycles which are varied for different orbits. Therefore, for different duty cycles or different orbits, the efficiency of these topologies would be different. In addition, the efficiency is a function of technology level used in the EPS elements.

- *Reliability*

Reliability is a measure of the frequency of equipment failures as a function of time. Reliability has a major impact on maintenance and repair costs and on the continuity of service. Reliability is a number between 0 and 1, and can be assumed for each EPS elements, parts and components individually. Fig.3 shows the reliability for series and parallel EPS models. For an EPS with no redundant parts, the system reliability is calculated by multiplying all the essential parts' reliability. If an EPS system consists of n parallel elements as redundant parts the reliability would be calculated by:

$$R_P = 1 - \prod_{1}^{n}(1 - R_i) \quad (1)$$

Note in (1) R_P is the reliability of the parallel system, and R_i is reliability of each element. In this paper all the topologies are considered without redundancy, so the reliability of the EPS system is the product of the reliabilities of all essential parts.

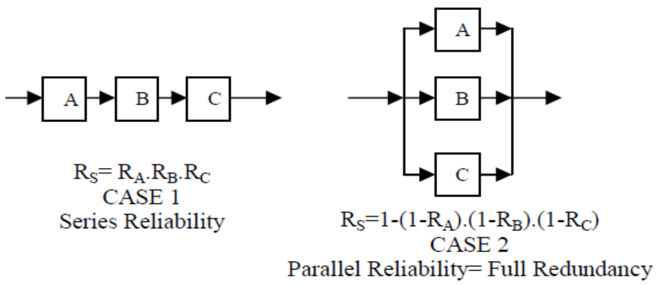

Fig.3. Series and parallel Reliability Models, R_S is the system reliability R_A, R_B and R_C denote the reliability of the A, B and C components [6]

The details of reliability calculations for each of the topologies have been explained step by step in [7], and the final results are shown here in TABLE VIII. As we can see in the table, "Semi Regulated – DET" topology has the best reliability among the studied topologies.

TABLE VIII. RELIABILITY RANKS OF THE SCHEMES OF FIG 2

Topology	Reliability	Rank No.
Semi Regulated - MPPT	0.787	2
Semi Regulated- DET	0.8303	1
Unregulated - MPPT	0.707	4
Unregulated - DET	0.747	3
Quasi Regulated- MPPT	0.668	6
Quasi Regulated - DET	0.705	5
Fully Regulated - MPPT	0.560	8
Fully Regulated - DET	0.599	7
Hybrid - MPPT	0.568	8
Hybrid - DET	0.599	7

- *Cost*

Cost is an engineering parameter that varies with physical parameters, technology, and management methods. System cost depends on size, complexity levels, technological innovation, design life, development time, and other characteristics.

In this study cost is just a monetary valuation of the EPS electrical components. It is difficult to define a criteria based on the cost for all the EPS components' design and integration, however it is possible to define the percentage of the whole EPS cost for components and modules (for example as $/Watt). To use the simplest possible form of cost estimation, development cost is assumed to be linearly higher for a more complex topology. An estimated cost is considered for each part. The overall cost is the summation of all the costs for all the possible parts in topologies. In next step, cost ratio is defined as the ratio between each cost (attributed to each part) to the overall cost. TABLE IX shows the cost ratios for the typical elements of spacecraft EPS.

TABLE IX. COST RATIOS OF EPS ELEMENTS

EPS Element	Cost Ratio (Typical Value)
Solar array	0.25
PPT	0.15
Battery	0.2
Shunt regulator	0.1
LC3 charger	0.1
Boost regulator	0.1
Chargers	0.1

The summation of all the calculated cost ratios makes the overall cost ratio for the specific topology. This process is repeated for all the aforementioned topologies.

The final results of cost ratios for each topology are shown in TABLE X. As we can see in this table, DET using semi regulated bus is the best from the cost point of view.

TABLE X. COST RANKS OF THE SCHEMES OF FIG 2

Topology	Cost Ratio	Rank No.
Semi Regulated - MPPT	0.6	2
Semi Regulated- DET	0.55	1
Unregulated - MPPT	0.7	4
Unregulated - DET	0.65	3

Topology	Cost Ratio	Rank No.
Quasi Regulated- MPPT	0.7	4
Quasi Regulated - DET	0.65	3
Fully Regulated - MPPT	0.8	6
Fully Regulated - DET	0.75	5
Hybrid - MPPT	0.8	6
Hybrid - DET	0.75	5

C. Evaluation

In the previous section three parameters are defined for evaluation of a typical topology.

To calculate the efficiency indexes of each topology, a typical efficiency supposed for each part and then overall efficiency index is calculated. Similar to the efficiency calculation, assigned reliability value of each part with respect to its configuration in the topology is calculated. The overall cost in each topology is simply calculated by the summation of the existed parts in each topology.

To compare the topologies with each other, one should extract an overall criterion based on the mentioned parameters. To this end a cost function is defined, and then a weighting factor for each three parameters is assigned with respect to their impact on the EPS design and operation for a specific mission. The cost function will be the summation of the total parameters quantity which multiplies to their weight factors:

$$F(T_i) = w_E E(T_i) + w_R R(T_i) - w_C C(T_i) \quad (2)$$

In which w is the weighting factor for each criterion, E is efficiency value, R is reliability value and C is the cost for each topology T_i.

TABLE XI shows default weighting factors for design criteria; however these factors may be different for different missions, depending on mission needs, stakeholder requirements and programmatic and design constraints.

TABLE XI. WEIGHTING FACTOR OF DESGIN CRITERIA

Design Criteria	Weighting Factor
Efficency	0.35
Reliability	0.4
Cost	0.25

TABLE XII shows the final topology ranking based on the mentioned cost function. As it is obvious, diagram 5 in Fig 2 would be the best choice among the others, i.e. a DET with using semi regulated bus regarding to the chosen cost function and weighting factors.

TABLE XII. TOPOLOGIES RANKING BASED ON THE ASSUMED COST FUNCTION

Topology	Cost Function Index	Rank No.
Semi Regulated- DET	0.477355	1
Semi Regulated - MPPT	0.46548	2
Unregulated - DET	0.39932	3
Quasi Regulated - DET	0.387315	4
Unregulated - MPPT	0.389705	5
Quasi Regulated- MPPT	0.37615	6
Fully Regulated - DET	0.297755	7
Hybrid - DET	0.297755	7
Hybrid - MPPT	0.26774	8
Fully Regulated - MPPT	0.26774	8

III. CONCLUSIONS

In this paper the importance of three main factors and characteristics of EPS are considered and calculated for several basic topologies. By defining a cost-function the overall and simultaneous impacts of the factors is analyzed and calculated for each topology. Finally, all the studied topologies are sorted based on the cost-function results. Such analyses would be useful in selecting the optimum topology in the design of satellite EPS.

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