Design Criteria for Electrical Power Subsystem's Topology Selection

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***Abstract*— Choosing an appropriate topology is a key step in the process of electrical power subsystem design. This selection should be done based on the design requirements implied from higher level like mission, system and subsystem levels. In this study the essential criteria selecting a suitable topology are discussed. This paper starts with an overview on EPS design process with emphasizing on EPS architecture and topology selection. Two concepts of energy transfer, i.e. Direct Energy Transfer and Peak Power Tracker, are reviewed and compared in details. For each concept different methods of main bus voltage regulation, like unregulated bus, regulated bus, semi-regulated bus, quasi-regulated bus and hybrid bus are discussed. They have been evaluated by comparing their advantages, disadvantages, and their applications in different space missions. These comparisons are carried out based on essential criteria for EPS design such as efficiency, complexity, reliability, weight and cost.**

Keywords—Topology; Electrical Power Subsystem; Satellite; Criteria; EPS Design

I. INTRODUCTION

Electrical Power Subsystem (EPS) is a vital subsystem for any spacecraft and satellites. It provides energy for the operation of all parts and subsystems of the spacecraft during in its mission. Each EPS is composed of several parts and components like power sources, power storages, convertors, regulators, and also distribution, monitoring and protection units. As the core of subsystem architecture concept, EPS topology defines which one and what kind of these parts exist, and how they are connected to each other. Therefore the selection of topology is a major part of EPS architecture design. Besides the topology, EPS architecture specifies the geometry of Solar Arrays (SA); and the number, configurations and other specifications of the primary voltage buses as well as the secondary voltage buses.

Since the topology can significantly impact on the EPS efficiency, size, mass and cost; it may be considered as the essential characteristic of the subsystem architecture. Hence it is really important for EPS designer to select an adequate topology according to the satellite top level requirements, and based on the achieved knowledge and experiences from the previous or similar missions.

II. EPS DESIGN PROCESS

EPS design process contains several steps that must be taken in certain phases. One of the most important steps in this process is the selection of subsystem architecture. This task usually is done during conceptual design (CoD) phase where the designer shall define the overall subsystem architecture and present the subsystem high level block diagram. As shown in Fig .1 this process can be summarized in five steps. The first step is dedicated to the requirements analysis. In the second step it is needed to evaluate and compare the different possible architectures according to mission requirements. This step is highly depends on the level of knowledge and experience of the designer. In the next step power sources and power storages, usually solar arrays and batteries, must be sized. This step and its following step are totally programmatic. They are carried out and repeated in iterative manner whenever the requirements are modified or the specifications of any parts are changed. Finally by choosing the appropriate architecture this part of design process is completed [1].

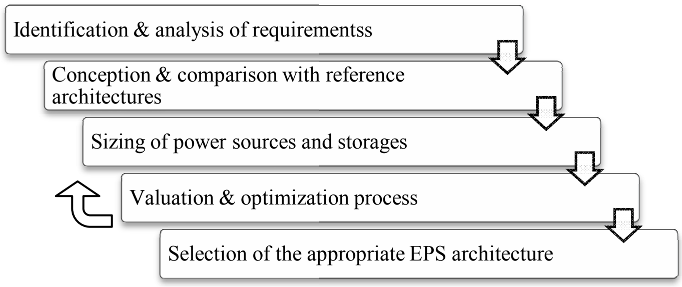

Fig. 1. Major steps to EPS architecture selection

EPS design process is depicted in Fig. 2 with more details. This diagram is slightly modified in compare to the original one in [2]. According to this diagram topology selection is a sub-activity of the EPS architecture design procedure in which the designer shall determine the types and specifications of primary and secondary buses.

The diagram also shows that the selection of solar arrays and battery is depends on primary bus specification, while the battery type and size can change the specification of secondary buses. This figure also shows that all the selection processes are depended on the level of knowledge and experiences of the subsystem designer [2].

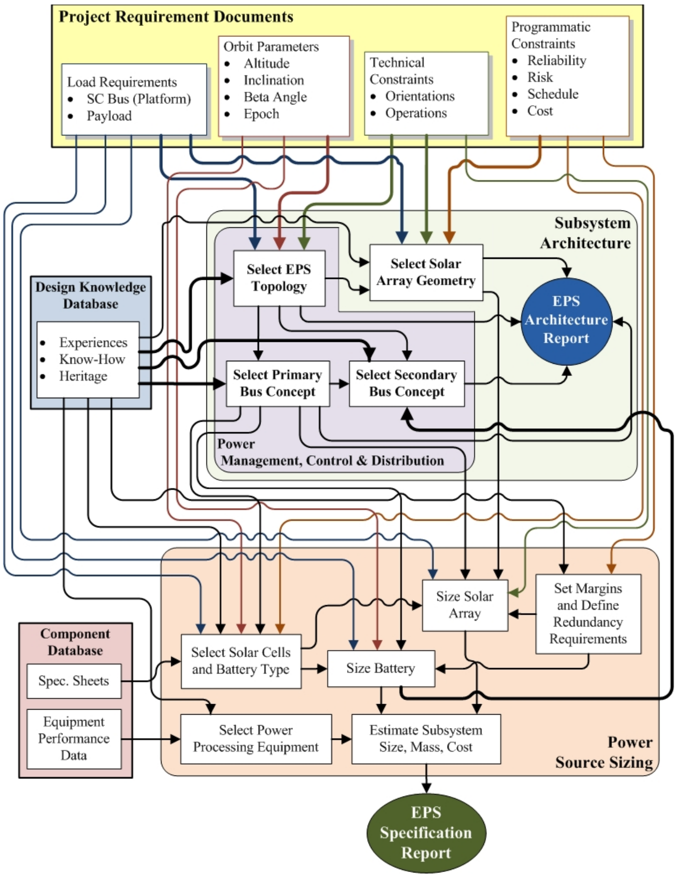

Fig. 2. EPS design process

Referring to the items in "subsystem architecture" box in the middle of Fig. 2, the following topics will be discussed in continue of this paper:

- EPS topologies
- Main bus concepts and voltage regulation methods
- Secondary bus concepts and power distribution methods

III. Topology Classes

There are two main classes of topologies for EPS architecture: Direct Energy Transfer (DET) and Peak Power Tracker (PPT). In DET topology concept the required power is delivered to the loads directly from the Solar Array (SA) bus and the excess power is dissipated in Shunt Regulators (SR). In PPT topologies the provided energy by SA is delivered to the loads through DC/DC convertor units. These convertors are mostly PWM controlled regulators which are controlled so that the maximum power could be extracted from SA.

Regarding the phenomena of the operation of DET and PPT topologies they are also named as dissipative and non-dissipative topologies respectively [1,3]. In photovoltaic systems PPT is also widely known as Maximum Power Point Tracking or MPPT.

A. *DET versus PPT*

Both DET and PPT topology classes are widely used in the structure of satellites EPS. However each one is more adequate for certain missions and applications. Their advantages and disadvantages are discussed in different references like [1-4], and summarized in TABLE I as well.

TABLE I. Comparing DET and PPT topologies, and their applications

	DET	PPT
Advantages	▪ Fewer parts ▪ Lower mass ▪ Higher total efficiency at EOL ▪ Lower noise and EMI ▪ Less complexity ▪ Higher reliability	▪ Smaller SA area ▪ More power availability in different sun projection conditions ▪ Higher efficiency in powering the loads (at BOL) ▪ Preventing the lockup effect
Applications	▪ GEO & GTO missions ▪ Large LEO satellites ▪ Miniature satellites	▪ LEO missions with wide range of variation in sun projection over the solar arrays ▪ Small satellites with $200<P_{Lmax}<1000$ watt ▪ Miniature satellites with "P_{Lmax} / mass" ratio more than 2 ▪ Interplanetary missions

The main drawback of PPT topologies is due to using PWM switching regulators which is noisy and requires filtering units. The other disadvantage of PPT topologies which is resulted from the first drawback is increasing the level of design complexity as well as the EPS weight and cost. It should be noted that similar problems exist for DET shunt regulators that use PWM switching controllers [2].

In the earlier EPS structures it was common to use DET for both high power and low power satellites, and PPT was typically used to be considered for a specific mid-range of power consumptions (200~1000 w). But nowadays it is more possible to find the application of PPT topology in miniature satellites because of using solar cells with higher efficiencies, better maximum power point tracking techniques and low cost/less weight MPPT modules.

Based on the selected class of energy transfer (DET or PPT), different implementations and regulation methods are possible for EPS architecture. Figure 3 shows a hierarchical diagram of different configurations for each topology classes.

B. *DET Concept Implementation*

For DET topology three configurations are more common and each class may be implemented in different ways [1,2]. They are:

- Shunt regulation; which dissipates the excess SA power by shorting the corresponding amount of solar cell strings. It can be implemented in linear, digital or PWM forms of form of SR modules
- Series regulation; which regulates the SA power delivery by means of a linear power regulator in series with the SA bus
- String switching; which connects the solar cell strings to the bus according to the demanded power by the loads

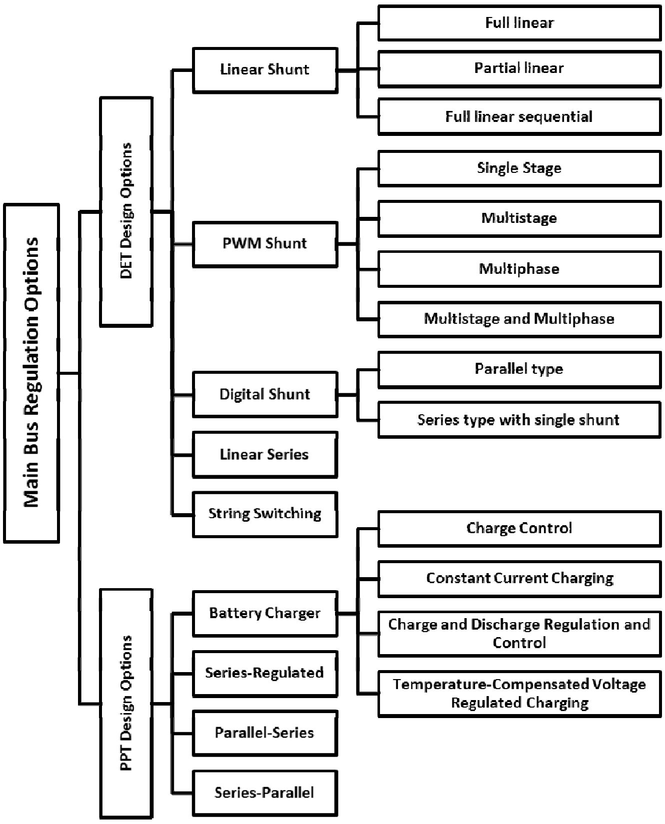

Fig. 3. Different options for DET and PPT topology implementation

C. PPT Concept Implementation

PPT based topologies can be realized in various classes such as 1) Battery Charger PPT, 2) Series-Regulated PPT, 3) Parallel-Series PPT and 4) Series-Parallel PPT. Each class can be implemented by using single or multiple MPPT modules, connected to the unified or individual SA buses, in order to charge single or multi battery systems. A simplified configuration diagram of these PPT concepts is shown in Fig.4. The most comprehensive implementation of PPT topology can be done by using individual MPPT module for each solar panel, which offers the following advantages [5]:

- Using different solar cell technologies and string lengths on each panel
- Tracking the pick power point of each panel individually over the changing thermal conditions and sun projection (especially for spin stabilized LEO satellites with body mounted solar panels, because their solar panels experience totally different conditions for received solar irradiance and temperatures)
- Improving the system reliability and being more failure tolerant in case of the loss of a panel or a MPPT module
- Charging the battery for the majority of the sunlit period. It permits to not worry about the impacts of using PWM controllers on the overall EPS efficiency
- Reduction in the discharge path loss by directly connecting the battery to the bus during eclipse

Due to these various advantages and drawbacks, it is an essential decision for EPS designer to select the appropriate energy transfer method between DET and PPT. The flowchart of Fig.5 describes the process of selection of an optimal configuration for the satellite main bus [2]. Like the diagram of Fig.2, a partial modification is made for the diagram of Fig.5 relative to the original flowchart in reference 2. This modification is done for the process of selection of PPT topology for satellites with power loads less than 200 watts (the dotted line box). By this modification we suggest to define a criterion for using PPT based topologies, even for the satellites with less than 200 watts power consumption. According to this criterion, if the “P_{Lmax} to mass ratio” will be greater than 2, choosing PPT topology can be reasonable.

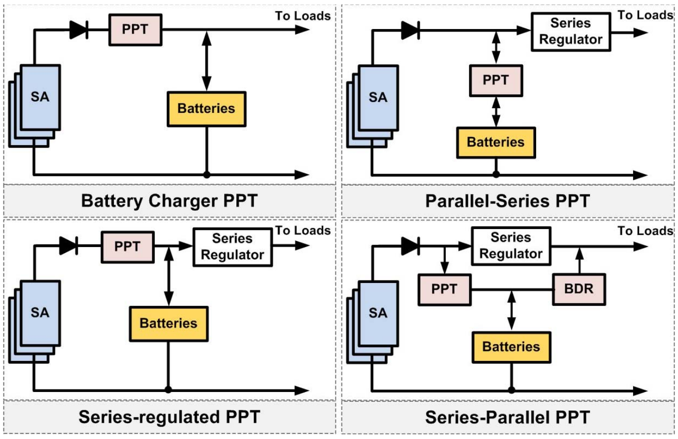

Fig. 4. Battery charger based PPTs versus PPT topologies with series regulators.

IV. Main Bus Voltage Regulation Methods

In addition to the selection of energy transfer concept, it is a critical decision how to select an appropriate voltage regulation method for the EPS primary bus. Each DET or PPT topologies can be implemented by means one of the following primary bus voltage regulation concepts [1, 3]:

- Unregulated Bus (BU)
- Regulated Bus (BR)
- Semi-regulated Bus (BS)
- Quasi-regulated Bus (BQ)
- Hybrid Bus (BH)

By the combination of the energy transfer methods and the main bus regulation methods, it is possible to have a variety of topologies for EPS architecture. In [1] and [3] 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 [3] as conventional EPS topologies. In this study we offer to extend these categories to ten basic topologies instead of six topologies in [1] or eight topologies in [3]. Figure.6 shows the schematics of these ten topologies.

A. Unregulated Bus (BU)

This topology provides a direct energy transfer from the main bus to loads. BU is regulated by shunt controller or PPT module during sunlight and is unregulated only during eclipse. For this reason, such bus is also known as the partially regulated bus, sunlight regulated bus, or sun-regulated bus. BU is an approach to minimize the complexity of the power distribution from solar array and battery to the loads. In BU the load voltage is equal to battery voltage which controls the primary bus voltage. Periodic changes in battery operation mode from charge to discharge lead to variation in the bus voltage up to 20% and it requires the loads tolerate this bus voltage variations. In BU topology, SR is used for SA excess power dissipation when the battery is fully charged and the loads required power is fully supplied. There is no need to Battery Charge Regulator (BCR) and Battery Discharge Regulator (BDR) in BU, therefore it is possible to supply the high peak power loads (like payload of the SAR satellites or transmitters of the communication satellites above their ground stations). With BU topology it is optional to use linear charge current controller (LC3) which improves the battery operation and its life time but it doesn't reduce the reliability or the efficiency of the EPS significantly. BU topology is also suitable for AC powered satellites.

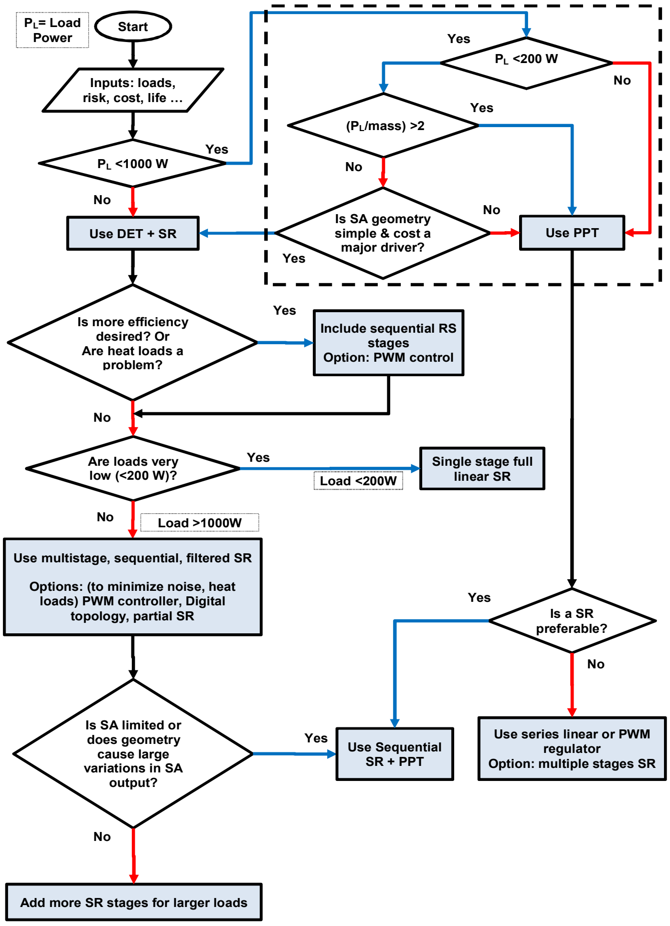

Fig. 5. The process of main bus topology selection

B. Regulated Bus (BR)

In this regulation concept it is important to control three parts (sub-buses) of the main bus i.e.: SA, BCR and BDR buses. The efficiency of BR is comparatively low because it uses charge and discharge regulators. So it is good for satellites with low instant power demands and with relatively high voltage bus but BR is not practical for miniature spacecraft [6]. In contrast to BU, this bus is adequate for non-parallelized multi-battery power systems. Each battery may have own BCR and BDR. Each regulator unit in BR has 1~4% higher overall efficiency than the regulators in BU because the DC/DC convertors usually acts in their optimal operation points. In BR the heaters of the battery system(s) are operating at a fixed voltage and dissipate constant heat, so the thermal design is simpler.

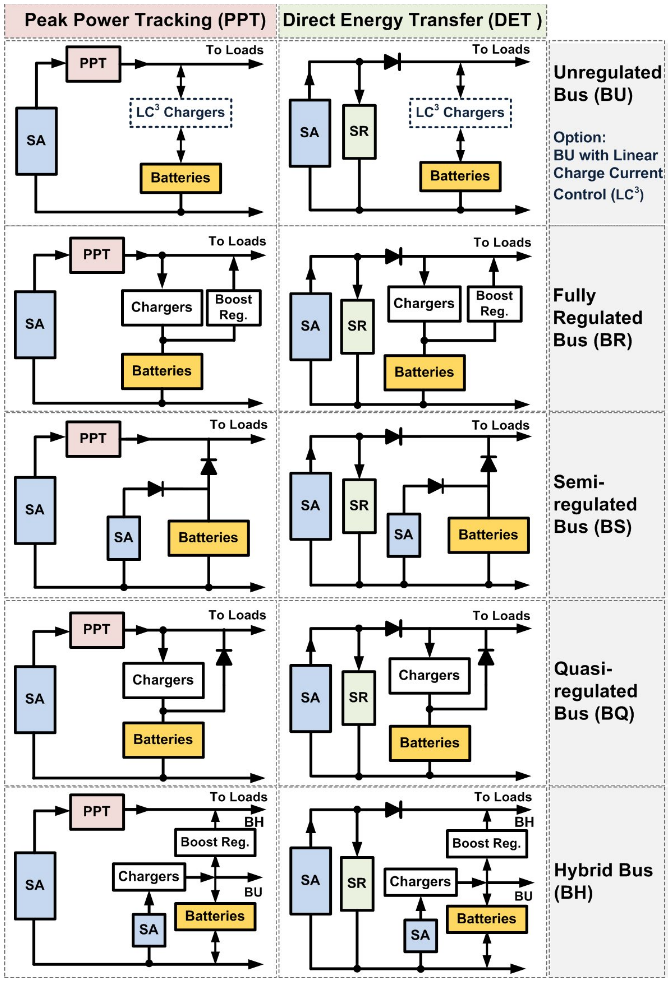

Fig. 6. Different basic topologies categorized based on different energy transfer and voltage regulation concepts for a spaccraft EPS main bus

Since BU and BR are the most common main bus concepts, the electrical specifications of them are compared in TABLE II. This table shows that BR is more suitable for high power and high voltage spacecraft.

TABLE II. ELECTRICAL SPECIFICATIONS OF BU & BR

Bus Type	Voltage Ranges	Power Ranges	Voltage Regulation Precisions
BU	28 ± 6 V	2 kW	• Bus voltage variations of up to ±20%. • The tolerances of the voltage ranges may be slightly different based on the used battery technology.
	35 ± 7 V	3.5 kW	
	42 ± 8 V	5 kW	
BR	28	<2.5 kW	• Steady-state mode: ±0.5% of the nominal voltage.
	50~70	2.5 up to 8.0 kW	

Bus Type	Voltage Ranges	Power Ranges	Voltage Regulation Precisions
	100~125	>8 kW	• Load changes: ±1% (at load changes of up to 50% of the nominal load) • Transient induced voltage swings: maximum of ±5% of the nominal voltage.

C. Semi-Regulated Bus (BS)

Semi-regulated Bus (BS) topology is formed by making a compromise between the specification of BU and BR topologies. BS profits two independent SA buses which increase the level of solar power availability and the whole subsystem reliability. During battery discharge the bus voltage level normally remains multi volts lower than bus voltage level during its charge when the battery is detached from the bus by a blocking diode.

D. Quasi-Regulated Bus (BQ)

The main difference between BU and BQ is the utilization of a battery charger. Using BCR prevents lockup while elimination of BDR reduces the mass, cost and contrarily increases the reliability of EPS. During light phase, battery charges through BCR but in eclipse it discharges through a diode to provide an unregulated bus. The operation of BQ topology is similar to a BU configuration which uses parallel batteries with LC3 chargers, especially during the sunlight period. BQ provides more reliability and efficiency and requires smaller solar arrays than BU, with an acceptable and reasonable higher level of complexity.

E. Hybrid Bus (BH)

This bus is composed of BU and BR topologies and benefits from the advantages of the both topologies at the same time. BH is a more complex form of BS topology because in BH it is needed to use BCR and BDR instead of those diodes that connect SA and battery to the main bus in BS topology. In BH a part of SA forms a BR by using a boost regulator as BDR, while the other part of SA provides a BU by means of a BCR. This topology is suitable for satellites with both normal loads and pulse current loads. Normal loads are supplied by BR and pulse current loads are connected to BU. In GEO mission applications of BR and BH topologies, the charge converter rating is much smaller than the discharge converter. In such situations, designing the charge and discharge converters separately would be beneficial, as their individual designs can be better tuned to their own ratings and requirements. In LEO missions, on the other hand, a bidirectional converter may be a better choice because the charge and the discharge converter ratings are comparable. As a part of this study's results, we suggest to consider "P_{Lmax} to mass" ratio>2.5 as the criterion for using hybrid bus in the EPS structure. TABLE III summarizes the properties, advantages, drawbacks, and the applications of the main bus regulation methods.

V. SECONDARY BUSES

Various subsystems, payloads and equipment operate with different input-voltage levels which may be higher, lower, or even the inverse of the primary bus voltage. These secondary voltage levels are not necessarily compatible with the primary bus voltage level, whether in regulated or unregulated bus. Therefore, different DC/DC converters are needed to provide these required voltage levels. This power conditioning can be carried out in two methods. If it takes place for each load individually in specific Power Distribution Units (PDU) the system is called distributed or decentralized. However, if it happens in one module or board, prior to reaching the loads, it called centralized.

TABLE III. ADVANTAGES AND DRAWBACKS OF DIFFERENT MAIN BUS VOLTAGE REGULATION METHODS

Bus	Advantages	Drawbacks	Applications
BU	▪ Reduction in mass & cost ▪ Reduction in the needed solar panels area ▪ Increasing the efficiency in the absence of BCRs & BDRs ▪ Increasing the reliability because of the simpler electronics ▪ Powering the hi-power pulse loads	▪ Reduction in efficiency in case of using individual DC/DC convertors for each load ▪ Occurring Lock Up ▪ Not suitable for multi battery systems	▪ LEO missions with high peak power profiles ▪ AC powered spacecraft
BR	▪ Suitable for multi battery systems ▪ Suitable for individual loads regulation ▪ Suitable for applications with small range of variations in solar panels output ▪ Using of low weight and simple efficient regulators ▪ Simplified thermal design ▪ Good EMC characteristics	▪ Low overall efficiency ▪ Higher mass & cost ▪ Need for more solar panel area because of loss in BCR & BDRs ▪ Need for three efficient control blocks for controlling of power production, ▪ Problem with powering the hi-power pulse loads ▪ Several regulation blocks	▪ Mainly GEO missions ▪ Large communication satellites
BS & BQ	▪ High efficiency ▪ Higher reliability than BU ▪ Lower mass and cost in compare to BR ▪ Less complexity and electric/electronic parts ▪ No Lock Up ▪ Suitable for multi battery systems ▪ Suitable for low variations in loads' power ▪ Suitable for low variations in sunlit phase	▪ Low efficiency of DC/DC convertors when the bus operates in non-regulate mode ▪ Higher EMI level than BU in using with PPT ▪ Need for larger areas of solar arrays	▪ GEO mission with relatively low power in eclipse
BH	▪ Having the advantages of both BU and BR ▪ Supplying instant high power loads ▪ More power availability	▪ More complexity because of using three different types of controllers /regulators	▪ Small compact satellites with "P_{Lmax}/ mass" ratio>2.5

When the number of subsystems and the variety of their required voltages are considerable the distributed power conditioning method is preferable, while in the satellites with a few subsystems and secondary voltage levels the centralized architecture is more efficient, less complex, lighter and more economical. Indeed the most common EPS architecture for miniature satellites like Cubesats is centralized. A centralized architecture distributes all or most of the voltages from one central location; however some centralized topologies implement point-of-load regulation for special voltages. [7] For example PANSAT with only three major subsystems, and secondary regulated voltages of +15, -15, and +5 Vdc, profits a centralized conditioning and PDU in its EPS structure [8]. The most obvious advantage of the centralized architecture is the need for less number of regulators, because one regulator can provide the same regulated voltage to electrically similar loads in different subsystems or components. However this advantage comes with a significant disadvantage at the same time. Since such regulator must be sized to fit all of the loads that will be connected to it, the EPS designer must size it for the worst case condition. This usually leads to decries in the regulator efficiency because the load will not be necessarily in its worst condition in most of the times; and it simply means a non-optimized design for the secondary bus. In contrast to centralized topology, the decentralized regulation concept can also be attractive for Cubesats for several reasons. Firstly, they usually don't have a fully mature design and the user power requirements will change as their design evolves. With this specification, a decentralized approach allows modifying the load requirements by simply changing the subsystem's convertor without altering anything else. Secondly, for many types of Cubesats, BU main bus can be used which can reduce the need for power conditioning and make a decentralized system more practical. In large satellites a tradeoff shall be performed between the advantages of distributed topology and its side effects, because there is a noticeable power loss in the extended cables form the main bus to the loads which also leads to increase in harness weight and volume. Distributed topology provides the following additional advantages [9]:

- More flexibility in large satellites EPS modular design
- Easy design or selection of DC/DC converters to supply each equipment and instruments according to its electrical characteristics.
- Better EMC characteristics because of using single-point ground philosophy and providing higher isolation for Conducted Emissions and better immunity against Conducted Susceptibility.
- Using individual electronic switches for turning each load ON or OFF separately, which provides a more reliable full bus control and protection

VI. Comparisons and Evaluations

In order to compare the application of these topologies based on their mission types, the EPS architectures in more than 20 satellites are investigated and their specifications are presented in TABLE IV and V [7, 10].

TABLE IV. Comparing the applied topologies in different spacecraft.

Topology	Main Bus	Efficiency	Complexity	Reliability	Spacecraft	Orbit	Power [W]
DET	BU	Average	Low	High	OUFTI-1	LEO	4.7
					Φrsted	LEO	40
					CHAMP	LEO	140
					CryoSat	LEO	810
	BR	Average	High	Low	STRV-1 a/b	GTO	32
					Meteosat	GEO	2000
					GPS IIR	MEO	1050
					SOHO	Interplanetary	1500
					SMART-1	Interplanetary	1975
	BS	High	Low	Average	AdeSat	LEO	2.5
					XTE	LEO	800
					Ocean Sat	LEO	1700
					Eurostar	GEO	3000
					Alcatel	GEO	3000
	BH	Average	High	High	CBERS-1	LEO	1100
					GMP	GEO	2500
					ENVISAT	LEO	6750
PPT	BU	Average	Average	Average	OPTOS	LEO	7.2
					Danish SAT	LEO	10
					Radarsat-2	LEO	2400
	BR	Low	High	Low	Aalborg	LEO	10
					Rosetta mars express	Interplanetary	1500

TABLE V shows more information for the topologies which are used in different Cubesats as well as their secondary buses specifications. This table confirms that the centralized power distribution is more appropriate for Cubesats [7].

TABLE V. Comparing the applied topologies in different Cubesats.

Name	Size	Topology	Distributed /Centralized	# of Buses	Bus Voltages
CUTE-I	1U	DET	Centralized	3	5R, 3.7bat, 3.3
RXI-IV	1U	DET	Centralized	3	5R
XI-V	1U	DET	Centralized	4	5, 3.8bat
DTUsat	1U		Distributed	1	3.6R
AAU	1U	MPPT	Centralized	1	5R
QuakeSat	3U	DET	Centralized	2	5R, -5R
CUTE-1.7	2U	PPT	Centralized	4	3.3R, 5R, 6R, 3.8Bat
Sacred	1U		Centralized	2	5R,3.3R
KUTEsat	1U		Centralized	3	5R,3.3R, 12bat
HAUSAT	1U		Centralized	3	5R, 3.3R, 3.6bat
MEROPE	1U	PPT	Centralized	5	5R,-5R,6R, 8R,5R,5R
CP1	1U	DET	Centralized		
CP2	1U	PPT	Centralized	4	
CP3	1U	PPT	Distributed	6	3R,3R,3R,3R,3R, 3.7bat
CP4	1U	PPT	Distributed	7	3R,3R,3R,3R,3R, 3.7bat
Delfi-C3	3U	DET	Distributed	1	12R
Compass One	1U	PPT	Centralized	3	3.3R,5R,5R
Hermes	1U	DET	Distributed	4	7.4R,7.4R,5R,3.3R
KySat	1U	PPT	Centralized	3	12bat,5R,3.3R
AtmoCube	1U	DET	Centralized	6	3.3R,5R,6R,-6R,-10,3.3R
e-st@r	1U	PPT	Centralized	3	7.4bat,5R,3.3R
Goliat	1U	DET	Centralized	>1	7.4bat, others
OuFTI-1	1U	DET	Centralized	3	7.2bat,3.3R,5R
DICE	1.5U	PPT	Centralized	3	7.2bat,3.3R,5R
Colony 1	3U	PPT	Centralized	3	7.2bat,3.3R,5R

References

[1] Ley, W., Wittmann, K. and Hallmann, W., *Handbook of Space Technology*, 1st ed, John Wiley & Sons, 2009, Chaps. 4.2.

[2] Eakman, D., Lambeck, R., Mackowski, M. and Slifer, L., "Small spacecraft power and thermal subsystems," NASA contractor report 195029, McDonnell Douglas Aerospace, Dec. 1994.

[3] Larson, W. J., *Space Mission Analysis and Design*, 3rd ed, Microcosm Press, 2005, Chaps 11.

[4] Patel, M. R., *Spacecraft Power Systems*, CRC Press, 2005, Chaps 3,4.

[5] Bonin, G., Sinclair, D., and Zee, R.E, "Peak Power Tracking on a Nanosatellite Scale: The Design and Implementation of Digital Power Electronics on the SFL Generic Nanosatellite Bus," 23rd Annual AIAA/USU Conference on Small Satellites, Logan, USA, 11-14 August 2009.

[6] Clark, C. S., Mazarias, A.L., and Strain, A., "A High Performance Very Low Cost Power System for Micro spacecraft," 2008 European Space Power Conference, Konstanz, Germany, 14-19 September 2008.

[7] Burt, R., "Distributed Electrical Power Systems in Cubesat Applications," Master of Science Thesis, Utah State University, Logan, Utah, 2011

[8] Hand, G.F., "Intermediate Design and Analysis of the PANSAT Electrical Power Subsystem," Master Thesis, Naval Postgraduate School, March 1994.

[9] Hansen, F., "EPS Architecture for Small Satellite," Danish Small Satellite Programme of Danish Space Research Institute, June 1999.

[10] http://www.eoportal.org