Optimization Of Power System Network For NX-Microsatellite

Ejimofor Chijioke
Department of Electrical/Electronics, Enugu State University of Science and Technology, Enugu, ejimofor.chijioke@gmail.com*

Eneh I.I
Department of Electrical/Electronics, Enugu State University of Science and Technology, Enugu **

James Eke
Department of Electrical/Electronics, Enugu State University of Science and Technology, Enugu ***

Halilu Shaba Ahmad
National Space Research and Development Agency, Abuja****

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Abstract

The power subsystem could possibly be the most under-appreciated and forgotten of all of the on-board electrical subsystems. There may be several reasons for this, but the most likely is that most people just don't find the subject interesting enough. There are, of course, exceptions to this generalization, but it is safe to say that no one is currently planning a mission to demonstrate optimization of power system network. Grabbing the attention of spacecraft engineers are subjects like; more advanced communications systems, on-board data handling, and high speed data links, imaging systems, micro-propulsion, attitude control algorithms, sensors and actuators. It is natural that the best people in a small organization focus on the more exciting aspects of a mission; these subjects will typically be the differentiator of an organization's space mission from that of the rest of the world. However, it is also clear that these systems need power, and power that is delivered reliably and efficiently. For most companies and organizations planning their own microsatellite mission, the prospect of producing a reliable, yet affordable power system for their mission is not a trivial problem. Some non-traditional spacecraft manufacturers, such as Universities, are finding out the importance of a well-designed power system the hard way. The most common cause of failure on microsatellite mission to date has been the power system. As all microsatellite missions require some sort of optimization of power system network, and since this system will differ little from mission to mission, it makes sense to provide an off-the-shelf solution for common buses. By providing such a system, the responsibility of design of the power system within smaller organizations can be removed, allowing the mission design team to focus on the design of the rest of the spacecraft.

Index Terms- Microsatellite, Network, Optimization, Power, System, Nx, BCR, PCM, PDM,

1. Introduction

Space technology worldwide is changing rapidly. I recent years, the products of the consumer electronics industry have been increasing incorporated within satellite technology. The first artificial satellite to orbit the earth was Sputnik 1. It operated for three months even though its anticipated battery life was only three weeks. This early success in space technology caused the space race within the cold war. This had both military and economic implications, due to the political confrontation between the Soviet Union and the United States of America. During this period, space technology was developing rapidly both within national organizations and within private companies. The private sector began to produce comparable devices to those of national organizations. Taking account of the economic impact, private companies gained the advantage in recent years of low cost commercial–off–the-shelf (COTS) for spacecraft. Highly miniaturized satellites are a recent development. A miniaturized satellite is categorized as follows: a Mini-satellite has been defined as a satellite with a mass between 100-500kg. During the 1980's and 1990's, the micro-satellites and Nano-satellites were developed. The term Microsatellite is usually applied to satellites with a mass under 100kg. The term Nano-satellite is applied to a satellite with a mass below 10kg. The next category of satellite is classified as a Pico-satellite, usually applied to a satellite with a mass below 1kg.

The financial issue is also worth noticing. Firstly, spacecraft size is a significant issue in considering launch costs, so significant in a competing world. The cost of a conventional small-satellite mission is of the order of $1-10 million (US). This has reached the Pico-satellite stage, where it has become possible to design practical ultra-small (1kg) satellites. The launch costs of these are just a few tens to a few hundreds of thousands of dollars (US), thus making it possible to gain low-cost access to space. This objective is to achieve a Mini-satellite with the lowest possible size and still achieve a useful million objective.

Space technology is developing rapidly worldwide. In recent years, the use of consumer electronics has been increasing within satellite technology. The mass of spacecraft varies in size from less than 1kg to well over 1000kg. This project explains the design, development and implementation of a power system for a small satellite known as Nigeria – SATX (NX) in order to overcome the particular challenges of outer space. In addition, this power system is adapted to extremely small size and financial cost. The three-axis stabilized micro-satellite carries three payloads, i.e. a multispectral camera, a communication system to access mobile remote terminals and a high speed data processing computer [1]. The satellite is designed for a three year lifetime to fly on a low earth orbit at a nominal altitude of 689 km whereby the mean local equatorial crossing time is 10:30 am. The orbit inclination of 98.13° with an orbit period of 98.58 min results in a repeat cycle of 409 orbits within 28 days. The control and operation of the satellite will be performed from the ground station while the Centre for Remote Imaging, Sensing & Processing will handle the image downlink [2]

2. Literature Review

1.2 power sub-system block diagram

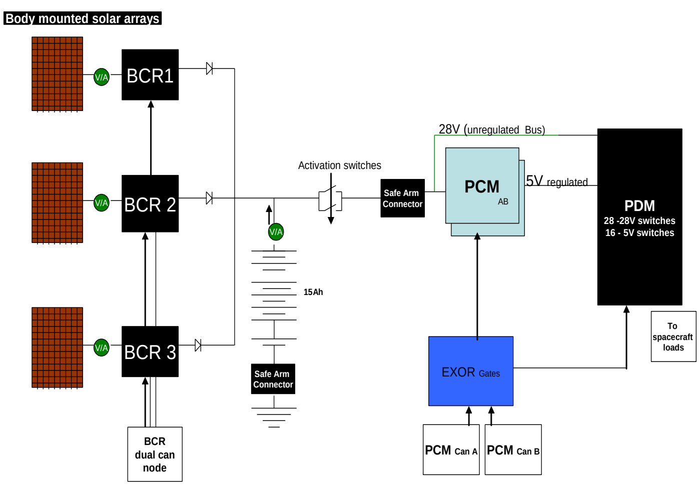

Figure 1. Power system block diagram

1.3 Overview and function

The power subsystem has the following main functions:

- Supply of continuous electrical power generated from solar panel to the spacecraft loads.
- Energy storage made possible through batteries for eclipse and when power is insufficient.
- Performs power conditioning and conversion within the spacecraft.
- Concurrent distribution of regulated +5 volt and unregulated +28 volt bus to payload and system modules respectively.

1.4 Power sub-system architecture description

1.5 Solar array

The primary power for the NX spacecraft is the light energy from the sun. The NX spacecraft will make use of the single junction high efficiency gallium arsenide on germanium ENE solar cells. The spacecraft is built with a body mounted structure of solar cells, which will make use of the solar panels to trap the incident light energy from the sun, and then convert the light energy to electrical power through photovoltaic conversion. The GaAs/Ge solar cell has a bare cell minimum average efficiency of 19.6% @ 25˚C, and the solar cell assembly minimum average efficiency of 19.2% @ 25˚C BOL. The solar array section consists of a series parallel ladder configuration of cells. The cells in series build up to provide the required voltage, and the cells in parallel supply the current. The large numbers of individual cells are arranged on an aluminium honeycomb substrate and faceskin. Each solar cell has a dimension of 20mm x 40mm, and is interconnected by ultrasonic welding. Each solar panel section consists of 6 strings of 58 cells in series and would be able to produce between 43V – 70V volts for proper functionality of the battery charge regulator depending on the solar array panel temperature. Each solar panel section consists of a total of 348 cells dedicated to each of the three BCRs.For NX, the solar panels would be located at the +X, -X, +Y facets respectively. The array configuration has been selected so that a loss of a string would still result in graceful degradation of the power generated from the solar panels. For NX, the packing factor of each solar panel section is 75% for each panel and a fill factor of 84%. The approach of switchable strings
provides an efficient and simple protection against overcharging of the two Li-Ion battery
packs. Each battery has a capacity of 5.6 Ah and provides a nominal bus voltage of
28 V ± 4 V. The end-of-life average power availability is estimated 80 W [3].

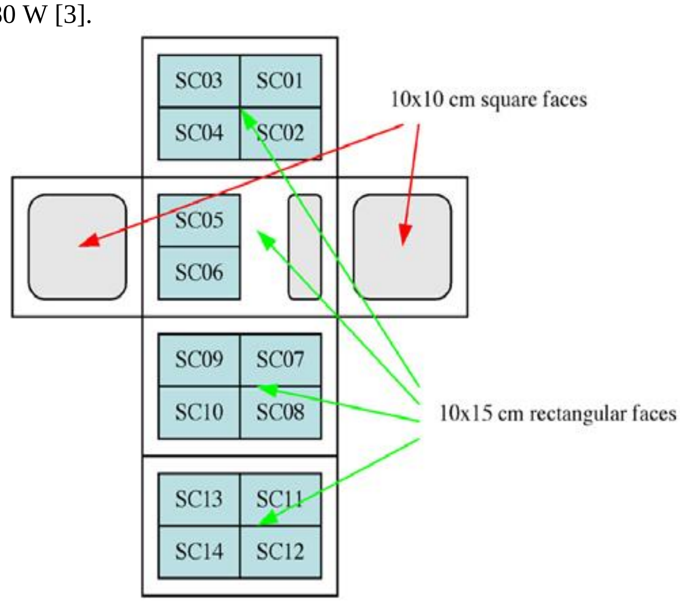

Figure 2. 2D Solar Cell Layout. Solar cells labeled as SCxx. Empty blocks represent space occupied by other system hardware

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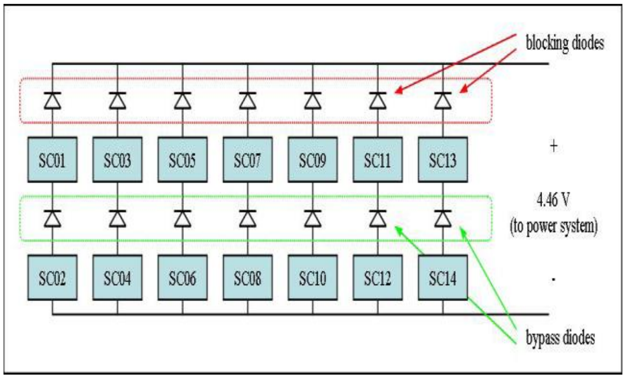

Figure 3. Solar Cell Circuit Connections

Bypass diodes are built into the solar cells to protect from series connection power drain. Blocking diodes are integrated to prevent power drain caused by unpowered pairs.

1.6 Battery charge regulator

The battery charge regulator converts the incoming array voltage from the three solar panels to the battery voltage, thereby, combining to form the main power bus. The BCR is a DC-DC switch mode converter of the forward buck type. The populated circuit board consists of 6 BCRs, but the power system for NX will be making use of three BCRs, battery current and voltage monitor, and CAN microcontrollers for telemetry and BCR computer control. Each solar panel has a dedicated BCR for estimation of the maximum power point tracking by means of temperature compensation. The BCRs are split in between each solar panel to maintain heat balance within the BCR and for fault tolerance. The maximum power point tracking of the BCR is achieved by the use of thermistors, which are placed inside the aluminium honeycomb substrate of the solar panels. Due to the harsh environment, the BCR circuitry has been manufactured with the P- channel international rectifier Hexfet (IRF9540N). The threshold voltage of the P- channel FET shifts with radiation but maintains its polarity. The N- channel FET on the other hand has a threshold voltage that reduces in value, and subsequently moves through zero, and also changes polarity .i.e. from +VE to -VE polarity in the radiation environment. Therefore, the use of the P- channel is more reliable and also makes the design of the buck regulator of the BCR much easier. The operation of the BCR is based on the UC494A pulse width modulator. This consists of a pulse width modulator, an oscillator, two error amplifiers, soft start, and 5V reference.
The BCR has two main functions:

- Estimation of MPP of the solar panel.
- Determination of the end of charge voltage of the battery

The Battery charge regulator system consists of the following:

- Pulse width modulator and buck converter.
- Solar panel maximum power point and temperature compensation circuitry.
- BCR over-voltage clamp.
- BCR supply voltage circuitry
- Computer control circuitry.

The pulse width modulator is responsible for the operation of the P- channel FET by driving the gate via a driver circuitry. The switching efficiency of the FET has been increased by including a push pull pair of bipolar transistors at the gate which helps to decrease the rise and fall times of the switching waveform thereby, increasing the conversion efficiency. The square wave signal between the source and the gate includes a capacitor that level shifts the square wave and an 18V zener diode prevents the threshold voltage from exceeding the preset 20V. The Buck converter electronics includes a capacitor at the output of the BCR which is responsible for a slow start of the BCR module, an inductor which is responsible for the rectified DC voltage within the buck regulator, and a shottky diode.
The solar panel compensation is achieved by the BCR. The MPP voltage of the solar array is indirectly proportional to the temperature of the solar panel. Solar cells usually exhibit a higher efficiency at lower temperatures. Indicating that the solar array is at its MPP is a zero output from the error op amp which refers to stability with the reference value. The positive input of the error op amp corresponds to the temperature coefficient and senses the array voltage through a voltage divider. The voltage divider on the negative input is connected to the error op-amp, which operates with thermistor network which are placed inside the aluminium honeycomb substrate. The operation of these thermistors determines the maximum power point of the solar panel.

While setting up the BCR for the solar array temperature compensation, it important to take into consideration that the MPP after the knee of the curve, therefore, the tracking set point should be set at the left in order to optimise the MPP of the solar array panel.
BCR over-voltage clamp is a function of the BCR that supports the safety of the battery. Due to the reaction of the chemistry of the Li-ion battery to overcharging, the BCR has been specially built never to exceed the Veoc of the battery and would engage a shunt load if the battery Veoc exceeds the preset level. The shunt resistance is located external to the BCR, and then connected to ground via a resistor along with the negative terminal of the battery. The shunt resistance is capable of shedding 80W watts of power. The over- voltage clamp is powered by the outputs of the BCR. This implies that the clamp would only be enabled when the BCR has a power source from the sun and is disabled during the eclipse phase.
BCR supply voltage circuitry is responsible for the initial start up of the BCR. The battery did not prove to be a reliable means of powering the main IC (UC494A) because the battery could be in a fully discharged state. This implies that there would no power to turn on the BCR. The solar array panel on the other hand supplied a voltage level above the capability of the IC. Due to this complication, the BCR circuitry was specially designed to step down the incoming array voltage to 9V, rectify the voltage through an inductor, and then discharge through a capacitor at the output

of the BCR, enabling the BCR to be self sustaining. The circuitry also includes a soft start mechanism, which reduces the turn on spikes at the output of the BCR by incorporating a capacitor. When the capacitor discharges, the BCR will start up slowly.

Computer control circuitry: In order to optimise the use of BCR and to manually override its operation, the BCR is equipped with a computer control override facility in the design which converts the BCR from hardware to software control. This also provides the means to optimise battery management. The software is controlled via the interface of the CAN microcontroller of the On-Board computer, and is capable of overriding the Veoc and MPPT of the BCR and directly controlling the output of the pulse width modulator thereby giving complete control over the output of the BCR.

The computer control circuitry includes the following:

- A CAN microcontroller and RAM
- A serial data connection from the CAN microcontroller
- A serial DAC with an active output.
- A level shifting amplifying stage, which converts the 0 V- 5 V signals to 0.5 V – 3.5 V which is full range signal to drive the PWM, thereby giving a high resolution over the control of the BCR.

The BCR includes very high efficiency converter regulators and also perform protection features. The BCR has two modes of operation:

- Current mode
- Voltage mode

The BCR operates in the current mode when the battery end of charge voltage is below the preset level. During the current mode, the BCR tracks the maximum power point of the solar panel (as discussed earlier) and all the available power is channelled into charging the battery and meeting the spacecraft power requirements. Once the BCR has determined the battery Veoc, the BCR backs off the current to the battery and,keeps the voltage constant. This method (taper charging) helps to obtain a very accurate Veoc, thus providing a safe mode of battery management. The BCR module consists of 6 BCRs, but for NX, only three would be used, which correspond to the number of solar panels of the space craft, with each of them been capable of transferring full power from the solar panel to the battery and the rest of the spacecraft. The BCR has an efficiency of 90%, and can provide 90 W at maximum operating current of 2.5A. The outputs of the BCR are connected to the positive terminal of the battery to form the main power bus.

1.7 Li-ion battery

The Li-ion battery is responsible for the supply of power during eclipse phase and when power available within the spacecraft is insufficient. The battery interfaces the BCR and the PCM module. The topology of cells consists of an 8s10p configuration, where the 8 cells in series help to maximize the achievable the voltage level of the battery and the 10 parallel configuration helps to attain the battery capacity. The loss of a string leads to a minimal loss of capacity in the series parallel topology. The Li-ion battery pack consists of 80 matched cells of US18650 hard carbon, which confirms that they have similar characteristics. The matching process also helps to prevent a cell or string of cells from been overcharged. The positive terminal of the battery forms the main bus, which provides an unregulated +28 V bus to the PCM module. The positive and negative terminals of the battery are protected by the safe arm connectors to isolate the battery from the spacecraft. The output of the BCR is connected to the positive terminal of the battery pack. The battery cells are interconnected with nickel tags in a top to bottom manner. The nickel tags allow for thermal expansion. The battery is also electrically isolated with the use of kapton sheet wrapped around the outer cell in each brick to prevent any possible shorting to the structure. For ideal operating condition of the battery, the NX battery temperature should be kept between +5˚C - +15˚C, but can be operated to -20˚C – +40˚C for certain operations without damage to the battery.The battery includes the following inbuilt safety mechanisms:

1.8 Overcharge Protection / Disconnect device:

The Li-ion battery has been designed to be able to charge to 4.2 V per cell. When the cell EMF exceeds 4.5 V and approaches 5.0 V, the dopped cathode within the cell begins to decompose. The gas emitted during decomposition causes pressure to rise within the cell, thereby distorting the aluminium disc inside the cell. When sufficient distortion has taken place, an electrical connection tag linking the cell cathode to the positive terminal would be broken. This shuts off current flow and renders the cell open circuit, preventing further damage to the battery. The disconnection is permanent and non-reversible. No propagation of failure from one cell failing open circuit is possible.

1.9 Extreme temperature device / Pressure release vent:

If the battery is exposed to extreme heat, usually at temperatures above 120C, initially, the burst disc loses its original formation and renders the cell open circuit. Further heat causes distortion of the disc until it ruptures. At this point, the cell safely releases the gas amounted from the pressure in a controlled manner so the cell does not explode and cause further damage.

1.10 Poly-switch Positive Temperature Coefficient (PTC):

The PTC is usually built into the header of every cylindrical cell. It is used to limit current in an over-charge condition (Tripped by heat). It is incorporated to prevent long duration of short circuit from generating high temperature within the cell. A very high temperature within the cell may cause degradation resulting in poor performance or burst the operation of the disc. During accidental short or excessive discharge, heat is usually generated within the cell. The PTC is often activated due to an increase in temperature and high current flow rates of about 3C, the temperature rise produces a resistance in the PTC for an interval of 1 to 2 seconds depending on the current, thereby reducing the current flow to a steady state of about 1C. The operation of the

PTC unlike the disconnect device is entirely reversible and is believed to be safe. The end of charge voltage (Veoc) of the battery is 33.6 V and the end of discharge voltage (Veod) is 20 V. The battery weighs 3.9kg, and is capable of providing 430Whr at 15 Ahr.

1.11 Power conditioning module

The power conditioning module is housed in the PCM/PDM module. The power conditioning module is also a dc- dc converter responsible for the generation +5V bus within the power system. At the input of the PCM is the main power bus which is stepped down into a regulated +5 V bus. The +5 V bus supplies the logic internal to the power subsystem and CAN system power buses. There are two identical hot redundant PCMs (PCMA and PCMB) although only one of the PCMs would be carrying out the switching process. The output of PCMA has been set to be a little higher than PCMB. In this way PCMB is normally kept off and would come on only if PCMA is faulty. The PCMs are equipped with control logic and regulation circuitry. The regulation circuitry is capable of detecting faults dictating the switching to the hot redundant PCMB.

The main component of the PCM is the UC2842A pulse width modulation IC. The PCM has been designed to identify to mitigate against an under voltage condition within the power subsystem. The main component of the circuit is the LM139 comparator, with open collector output. One comparator observes the 5 V generated by the PCM circuit for an over voltage condition. If the PCM output supplies more then the preset level, the comparator would latch off. During the latch off interval, the fault detection circuitry drives the base of the transistor low, forcing the Vcc of the pulse width modulator to zero volts, thereby disabling the PCM and preventing any further over-voltage.

The PCM has been designed to stay latched off until a suitable under voltage is detected. The PCM also has an under voltage lock out system providing further protection to the power subsystem. When PCM detects that the input voltage of the battery is below 20 V, both the PCM circuits switch off. This disables the logic internal to the power subsystem and CAN microcontroller and with it all switches in the power subsystem. The PCM has been designed to re-start once the battery voltage reaches approximately 22.5 V. These features can be overridden by the PCMB. The PCM also has a soft start mechanism responsible for the steady start up at the output of the PCM. The power conditioning module has an efficiency of approximately 65% .

1.12 Power distribution module

The power distribution module (PDM) is responsible for the distribution of required voltages to the payloads and platform, and also protects the power subsystem. The power distribution module for NX is housed inside the PCM/PDM module and interfaces with the PCM and the spacecraft loads.
The power distribution module consists of two different way of distribution:

- Fuses
- Power switches

The fuses cannot be reset when they break. To reduce the risk of an accidental break or loss of one of the fused lines, all fuses are doubled .i.e. two fuses in parallel and a resistor is placed in series with one of the fuses. The resistor would allow the passage of more current through one of the fuses thereby allowing the fuse with more current to trip first in an over current condition.

The power subsystem has two back door links from the PDM to the receivers via the fused lines. The back door link allows commands to be sent to the power subsystem in the event of a CAN system bus failure on the power system. The reason for using fuses is mainly dictated by the spacecraft requirement. Fuses take little space in comparison to switches, they are lighter, very reliable and represent a straight forward solution.
The power switches also carry out distribution of the unregulated voltage, and the regulated +5 V to all power dependent modules. The power switches serve two main purposes: They would help to switch on and off any subsystem via the ground station as required in order to maintain the power budget. The telecommand control can also be used to reset a subsystem
The second feature of the power switch is protection. The power switch can be considered as an electronic fuse that automatically trips off when the current drawn by a subsystem is more than the preset level. The output, (.i.e. the interface between the PDM and the rest of the spacecraft) includes the capability to trip off when the current drawn by any subsystem is more than a preset level. This is achieved by the use of a current limiting circuit. The circuit breakers would automatically isolate a faulty system and protect the power subsystem. The power distribution makes use of the fold back current limiter and the latching current limiter.
The power distribution module for NX provides three basic types of switches:

- High power 28 V switch FET switches
- High power 5 V switch FET switches
- Low power 5 V switch based on the BJT transistors

The power distribution unit consists of 16 X 5V switches and 28 X 28 V and 6BJTs switches
Each solar panel section is regulated by one of the 3 BCR units.
The BCR is able to estimate the maximum power point of the solar array panel by using the array temperature as a parameter. The end of charge voltage of the battery is also determined by the BCR. The BCR outputs are isolated from the solar array output by the use of blocking diodes, and are connected to the battery pack. When the power available is insufficient, power is obtained from the batteries for operations of payload and respective subsystems. The main power bus is fed directly into the PCM/PDM, which carries out conditioning of the incoming power and generates a centralised +5 volt bus via the PCM, and subsequently distributes required voltages to subsystems via the PDM.
1.13 Design Justification
The existing power system topology and heritage modules fit well into the requirements of the NX mission.
The NX power subsystem has been designed to operate autonomously with the use of converter regulation methods and through total redundancy. The power subsystem has also been designed to adapt to the harsh environmental changes during nominal operation. The power subsystem is responsible for the functionality of other power dependent modules which make up the entire spacecraft, therefore, a tested and proven power

subsystem must be implemented.
The power system for NX consists of the following:

- Solar arrays (GaAs/Ge)
- Three battery charge regulators
- ABSL Li-ion battery
- Power conditioning module
- Power distribution module
- CAN microcontrollers

1.14 Solar Array:

The solar array design for NX is based on the use of highly efficient single junction gallium arsenide on germanium ENE solar cells. The solar cell assembly has a conversion efficiency of 19.2% @ 25˚C BOL.
Each solar panel consists of 6 strings of 58 cells in series on each solar panel, and a total of 348 cells per panel.
The solar array design consists of a series parallel configuration, where the cells in series build up to give the right voltage, and the cells in parallel to give the current. This c configuration allows the solar array to continue working after a cell or string failure. A loss of a string would result in graceful degradation of the power generated from the solar panels.
The large numbers of solar cells are arranged on an aluminium substrate which prevents the cells from cracking during thermal expansion due to careful matching of cell, adhesion and substrate material.
Each solar array section has been manufactured to provide between 43V – 70V for proper functionality of the battery charge regulator, depending on the solar array panel temperature.
The BCR are joined together by blocking diodes and fed into the battery. The blocking diodes prevent the battery from being damaged by BCR failures. The interconnections between the solar cells are made with the use of ultrasonic welding because of its high level of reliability and proven flight heritage.

1.15 Battery charge regulator:

The battery charge regulator regulates the incoming array power and then provides +28V unregulated bus, thereby charging the battery and supplying power to the modules. The power subsystem has been designed by dedicating one BCR to each solar section. This helps to maintain the heat balance within the BCR and allow for fault tolerance.
Due to the harsh environment, the BCR circuitry has been manufactured with the P- channel international rectifier Hexfet. The threshold voltage of the P- channel FET shifts with radiation but maintains its polarity. The N- channel FET on the other hand has a threshold voltage that reduces in value, and subsequently moves through zero, and also changes polarity in the radiation environment. Therefore, the use of the P- channel is more reliable and also makes the design of the buck regulator of the BCR much easier. Each BCR has been manufactured to be capable of transferring the full power from the solar section to the battery and the rest of the spacecraft. Therefore the power subsystem would still operate on the principle of graceful degradation if there is a loss of one BCR module or solar panel.
In order to optimise the use of the BCR, each BCR is incorporated with a computer control override facility in the design which converts the BCR from hardware to software. This provides the means to optimise battery management. The software is controlled by the On-Board computer, and is capable of overriding the Veoc and MPPT of the BCR and directly controlling the output of the pulse width modulator thereby giving complete control over the output of the BCR.
The output of the pulse width modulator drives the gate of the FET via a driver circuit. The switching efficiency of the FET has been increased by including a push pull pair of bipolar transistors at the gate which helps to decrease the rise and fall times of the switching waveform thereby increasing the conversion efficiency.
Due to the reaction of the chemistry of the Li-ion battery to overcharging, the BCR has been specially built never to exceed the Veoc of the battery and would engage a shunt load if the battery Veoc exceeds the preset level.
The BCR also incorporates a soft start mechanism within the circuitry to allow a steady start up operation at the output of the BCR by reducing the start up spikes.

1.16 ABSL Li-ion Battery:

The ABSL rechargeable Li-ion battery is responsible for the supply of power during eclipse and when power within the spacecraft is insufficient.
Lithium is the lightest metal and therefore reduces the overall weight of the spacecraft. This is cost effective in terms of launch cost when compared to the former NiCad battery. The ABSL Li-ion battery pack consists of 80 matched cells of US18650 hard carbon. The matching process confirms that they have similar characteristics.
The topology of cells consists of an 8s10p configuration, where the 8 cells in a series string achieve the voltage level of the battery, and the 10 parallel string configurations attain the battery capacity. The loss of a string leads to a minimal loss of capacity in the series parallel topology. The battery voltage of the Li-ion battery is unaffected by all failures, which makes battery management a lot easier. The positive and negative terminals of the battery are protected by the safe arm connectors to isolate the battery form the spacecraft.
The Li-ion battery exhibits steady or stable voltage characteristics along with temperature, therefore, the Veoc of the battery can be determined without temperature compensation. This makes the design of the BCR easier.
In order to avoid extreme conditions which may lead to degradation of the battery, the battery has been equipped with certain safety devices which prevent the battery from explosion, overcharging, and long duration short circuits which may lead to generation of high temperatures within the cell. Nickel tags have been used to make connection in a top to bottom manner. The nickel tag connection however results in stress relieving forms to allow thermal expansion.

1.17 Power Conditioning Module:

The PCM is responsible for the generation of the +5V power bus that supplies the logic, CAN system and the switches within the power subsystem .There are two hot redundant PCMs that ensure that a regulated +5V bus is available to the spacecraft. The event of a loss in one of the PCMs would virtually have no effect on the power subsystem. The PCMs are equipped with control logic and regulation circuitry

When a fault s detected, the power subsystem will switch over to the next PCM. For further protection to the power subsystem, the PCM has a battery under voltage lockout system. This would automatically switch off the CAN microcontrollers, and all the power switches until the voltage level gets back to the preset level.

1.18 Power Distribution Module:

The power distribution unit is responsible for the distribution of the unregulated battery voltage and 5 V to the payloads and platform, and also protects the power subsystem.

The PCM/PDM board is controlled via two hot redundant CAN nodes. This would switch autonomously to the other CAN system in the event of a failure of one of the power system CAN buses. The distribution of power is tolerant of any single point failure. For NX, there are two receivers which are placed on fused lines. The fused lines are essential because they ensure power is fed to the receivers even if the CAN system is not working. The power subsystem obtains commands from the ground station if there is a failure within the power subsystem CAN buses via a back door link to the receivers. The PDM switches are commanded by the ground station. This would enable us to switch on and off any subsystem as required in order to maintain the power budget. The telecommand control can also be used to reset a subsystem. The output, (.i.e. the interface between the PDM and the rest of the spacecraft) includes the capability to trip off when the current drawn by any subsystem is more than a preset level. This is achieved by the use of a current limiting circuit. The circuit breakers would automatically isolate a faulty system and protect the power subsystem.

The power subsystem has been designed to avoid a single point failure node where required. The solar array consists of a series parallel configuration that would result in graceful degradation of power generated form the solar panels in the event of a string failure. Each of the BCRs is capable of transferring full power to the battery and the rest of the spacecraft. The software override control can also take over the main functionality of the BCR. The PCMs have a dual hot redundant system, the CAN system also exhibits dual hot redundancy. The power distribution module protects the power subsystem with the use of the current limiting circuits. Therefore, the power subsystem is well thought-out and will prevent damage to the spacecraft.

1.19 Redundancy

For NX spacecraft, autonomy is obtained by having dual redundant systems. To ensure that the spacecraft would operate properly in orbit, the power system has been manufactured to exhibit a high level of tolerance to failures. This is necessary in order for the spacecraft to meet its life time requirement. Redundant systems automatically switch between each other in the event of a failure of the primary system. The solar array has been manufactured to consist of a series parallel configuration. The configuration however would allow the solar array section to continue generating power after a cell or string failure. A loss of a string would result in graceful degradation of the power generated from the solar panels.

In order to optimise the use of the BCR, and to be able to manually control the BCR, a computer control override system has been equipped into the design. An analogue input controlled via the interface of the CAN microcontroller, can override both the MPPT and EOC set point, thereby giving direct control over the PWM. This is an internal module redundant system that converts the operation of the BCR from a hardware control to a software control. Each BCR has been designed to be capable of transferring full power from the solar panel to the battery and the rest of the spacecraft. Therefore, the loss of a BCR would result in graceful degradation of the power subsystem. The BCR also provides a protection feature for the battery. The Li-ion battery cannot withstand overcharging, therefore, the over voltage protection circuit of the BCR prevents the battery from been overcharged. The over-voltage protection circuit consists of two hot redundant circuits that must sense the over-voltage for the clamp to engage.

The baseline battery for NX is the 8s10p Li-ion battery. When spacecraft goes into eclipse there is no power from the solar panel. Therefore, battery must supply the power required for a nominal operation of the spacecraft in eclipse. In order to optimise the reliability of the battery within the power subsystem, the battery consists of a series parallel configuration. The configuration prevents the occurrence of a single point failure within the power system. The loss of a string results in graceful degradation of the battery.

The power conditioning module (PCM) is a critical unit within the power system. The PCM is responsible for stepping down the battery voltage, and generates a centralised +5 V line to power the logic internal to the power subsystem, the power switches, and the CAN microcontroller. The PCM module is equipped with a dual hot redundant system (PCMA and PCMB) which can automatically switch between each other in event of a failure. The hot redundant system has a shorter outage during change over, and the secondary PCM (B) can be used to check the operation primary PCM (A). Therefore the generation of the +5 V line is fully redundant to prevent a failure condition within the power system.

The power distribution system is an internal redundant system. The PDM unit is responsible for the distribution of the regulated +5 V and unregulated +28 V line to the payload and platform. In order to ensure that the distribution unit is tolerant to errors, distribution is achieved through the use of fused lines and power switches. The fused lines cannot be reset, therefore they are placed in parallel via a resistor in order to have an extra fuse if the primary fuse breaks. The power switches interface with the PDM and the rest of the spacecraft. Each power switch is equipped the capability to trip off when the current drawn by any subsystem is more than preset level. This is achieved by the use of current limiting circuit. The circuit breakers would automatically isolate a faulty system to allow fault detection and reset or allow continuing operation of the spacecraft through graceful degradation

The power subsystem is capable of obtaining command via the CAN system and the back door link within the power subsystem. This shows the diversity of redundancy designed for the power subsystem. The power subsystem depends on the CAN microcontroller for telemetry and telecommand purposes. The CAN system within the power subsystem is dual hot redundant. Both CAN systems are capable of carrying out the monitoring and command signalling for the operation, health and status of the

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power subsystem. The back door link to the power subsystem is via the receivers. The receivers are reliable to serve as the back door link because they will be switched-on throughout the mission. The back door link can be used to obtain command for the power subsystem in the event of the entire failure of the CAN bus. Therefore, the power subsystem has the ability to prevent and keep operating nominally in the event of a failure within the power subsystem.

1.20 Sub-System Capability Overview

Supply power required at peak, average, worst case at beginning of life and end of life. Provide tele-command and telemetry capability for the health and status of the power system. Provide protection against reasonable expected faults of itself, and other subsystems. During the eclipse phase, the spacecraft would make use of power from the battery and re-charge in sunlight.

1.21 Unit Descriptions and Specifications:

1.21.1 Solar Panels

There are 3 solar panels in total: 1 large solar panel in +X direction, 1 large solar panel in the -X direction, 1 large solar panel in the +Y direction, No solar panel in the –Y direction
Solar panel orientation of NX solar panels

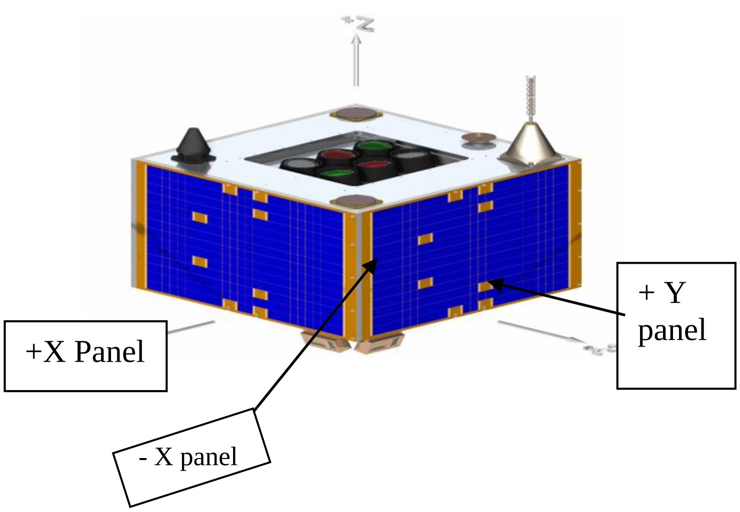

Figure 4: Solar panel configuration

Each array section must generate a minimum of 43 volts for the BCR to carry out optimal operation. Each panel consists of 6 strings that have 58 cells per string.

Each array section has a dedicated BCR that produces power independently of the other BCRs for that array

Solar Cell Performance Curve Typical ENE 20 X40 mm solar cell (19.2 efficiency) 5 degrees C Air Mass Zero

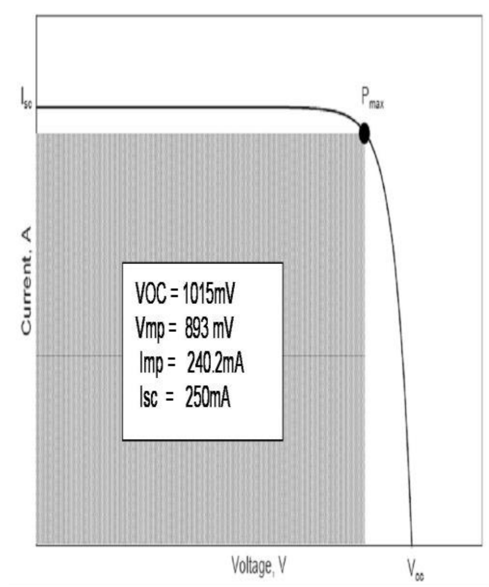

Figure 5. Solar cell performance curve

Each array section must generate a minimum of 43 volts for the BCR to carry out optimal operation. Each panel consists of 6 strings of 58 cells per string.
Each array section has a dedicated BCR that produces power independently of the other BCRs for that array.
The figure above represents the performance of an individual GaAs/Ge ENE solar cell under a load. The need for high efficiency solar cells, which are larger and thinner, is the GaAs grown on germanium substrate. The IV curve is used to measure the electrical characteristics of the cell. The shade portion refers to the load resistance on the solar cell. The IV curve passes through two significant points, the short – circuit current (Isc) and the open circuit voltage (Voc). The Isc refers to the current when the output terminal of the cell is short – circuited. The Voc is the voltage measured at the open circuit condition. The current and the voltage at Pmax are denoted by Imp and Vmp.

BCRs
Each BCR channel is rated to handle an input power of 90W. For NX, the BCR units are expected to be distributed to the solar panels as follows:
BCR 1: –X panel 1
BCR 2: +Y panel 2
BCR 3: +X panel 3
BCRs 1-3 are placed on the BCR module.
BCR redundancy is dealt with at a system level, by ensuring that the power budget can still be met in the event of a single BCR failure.
The BCRs are tested to ensure their efficiency meets the performance specified in figure 2.0. This is tested across temperatures at varying levels of input power and output power.

http://dx.doi.org/10.29322/IJSRP.11.07.2021.p11551

The outputs of the 3 BCR units are connected to the battery pack and the unregulated +28V main power bus.

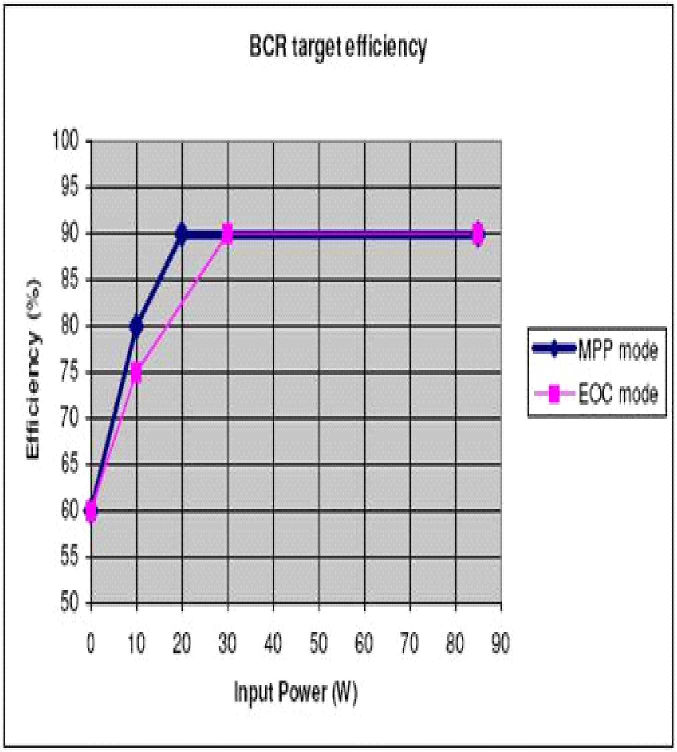

Figure 6: BCR efficiency graph

Figure 7: BCR module

1.21.2 Battery

The baseline battery for NX is a Li-Ion pack from ABSL (Advanced Battery Solutions, formerly AEA Technology plc). SSTL has previous experience with the 8s10p pack size (430Wh) for two missions and a similar size for a third mission. The cells are arranged in a series of 8 cells and 10 parallel strings. The configuration helps to avoid a single point failure of the battery pack. The battery mass is expected to be approximately 4kg.

8s10p Batteries from ABSL

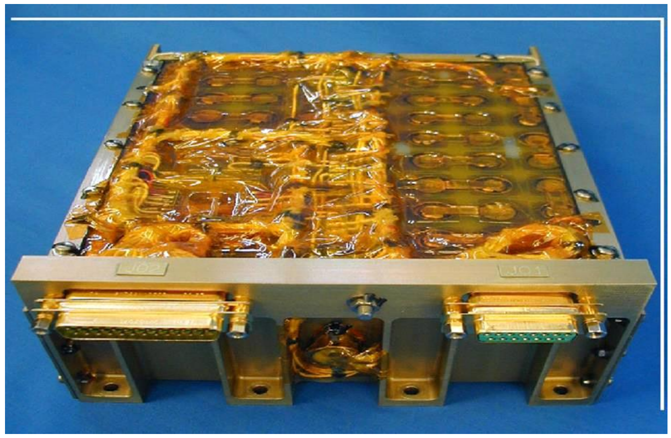

Figure 8: Flight Battery

1.21.3 PCM/PDM

The PCM/PDM has two main functions. The PCM generates a centralized +5 volt supply, and the PDM distributes the regulated +5V and the unregulated +28V from the battery power bus for distribution to the rest of the spacecraft.
At present, the NX mission has a total switch requirement of:

- 15 – 5V switches
- 17 – 28V switches

The PCM/PDM can provide:

- 16 - 5V switches
- 26 - 28V switches

The configuration for NX based on the above modules would consist of
1 PCM/PDM Module
1 BCR Module
Therefore the mission has a total switch count of:
16 - 5V switches
28 - 28V switches
There are two fused lines form the 28V bus that powers the receivers. The PCM/PDM module occupies a full microtray in the power stack. A photo is shown in Figure 1-0-7

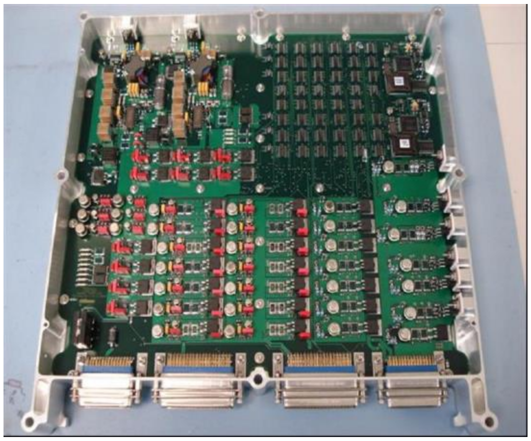

Figure 9: PCM/PDM module

3. RESEARCH METHODOLOGY, ELABORATIONS, AND DESIGN CALCULATIONS

OUTPUTS:

a) Calculate total radiation fluence for the mission in (1 MeV electrons)

To calculate the radiation fluence in 1 MeV electron, the use of SPENVIS.oma.be is required. SPENVIS.oma.be gives the forecast space condition in which the satellite will be subjected to during a period time. Using the period from 28-Jan-2010 to 28-Jan- 2015 with given data, a datasheet generated from SPENVIS.oma.be gave the following values for the cover glass thickness (microns) and the total power (P max). The values and graph plotted for P max against the cover glass thickness (microns) are shown below;

Cover glass thickness (microns)	P max
0.00	2.861E+18
25.41	3.378E+14
76.36	2.055E+14
152.27	1.414E+14
305.00	8.861E+13
509.09	5.648E+13
761.36	3.537E+13
1522.73	1.447E+13

Table 1: Pmax against microns

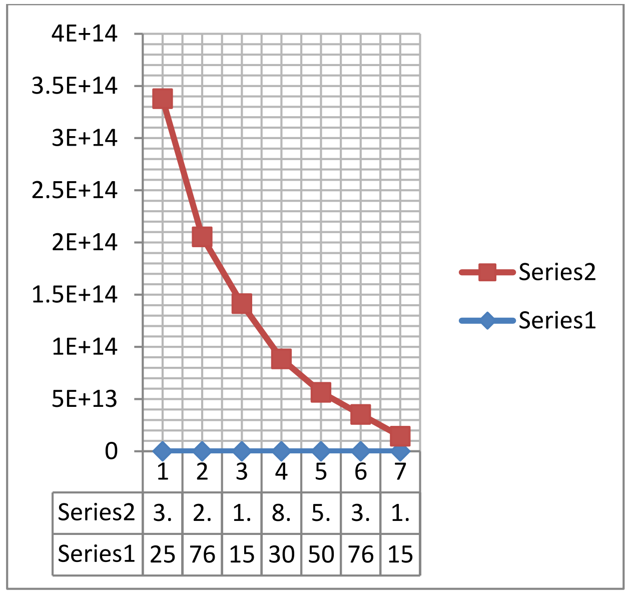

Figure 10: Graph of Pmax vs microns

For a single GaAs/Ge with Dimension 20×40mm, 150microns is used. At 150 microns the P max is 1.50E+14 eV.
Therefore, the radiation fluence is 1.50E+14 eV.

b) Calculate P max degradation and Vp max from charts

Using the datasheet GaAs/Ge space solar cell (MGE Series) EEV and the graph NOMINAL RADIATION DEGRADATION (1 MeV electrons), VL = 0.999 and IL = 0.98.
Power (P max) = VL × IL = 0.999 × 0.98 = 0.98 (Maximum Voltage per String)

c) Calculate the Optimum string length at EOL (End of Life) at maximum operating temperature using datasheet for temperature coefficients.

The values are gotten from the datasheet; Electrical Characteristics, BOL; MGE-4020-3A (40×20mm Bare Cell) from GaAs/Ge space solar cell (MGE Series) EEV. The formula is used to find the voltage of 1 cell at maximum voltage 80V; the formula is shown below;

$$V_{25} + \left[\Delta T \times \frac{\delta V_{oc}}{\delta t}\right]$$

At minimum temperature, $\delta V_{oc} = -40$ ℃
$V_{25} = V_{oc}$ at 25 ℃ is 1013mV
$\Delta T = T_2 - T_1 = -40 - 25 = -65$℃
$\frac{\delta V_{oc}}{\delta t} = -2.13$mV/℃
Substituting the values into the formula,
$1013mV + [-65℃ \times -2.13mV/℃]$ = 1151.45mV
Therefore, the number of cells is $\frac{80V}{1.15145V}$ = 69.47 cells ≅ 69 cells

The formula is used to find the voltage of 1 cell at minimum voltage 43V; the formula is shown below;

$$V_{EOL} + \left[\Delta T \times \frac{\delta P_{max}}{\delta t}\right]$$

Given, Beginning of Life (BOL) Vp max = 852mV

V_{EOL} = Vp max × 0.98 (Maximum Voltage per String) = 852mV × 0.98 = 834.96mV
$\Delta T = T_2 - T_1 = 80 - 25 = 55$℃
$\frac{\delta P_{max}}{\delta t} = -1.8$mV/℃
Substituting the values into the formula,
$834.96mV + [55℃ \times -1.8mV/℃] = 735.96$mV
Therefore, the number of cells is $\frac{43V}{0.73596V}$ = 58.427 cells ≅ 58 cells
The Average number of cells needed on assumption is $\frac{69+58}{2}$ = 63.5 cells ≅ 64 cells
Check voltage at BOL minimum operating temperature to ensure the maximum operating temperature is not exceeded.
As shown above

d) Calculate the power of a string at EOL operating temperature:

BOL losses:

- 2% interconnection (0.98 loss)
- 1% mismatch (0.99 loss)
- 2% calibration (0.98 loss)
- Sun angle (cosine loss)

EOL losses:

- Radiation loss (calculated from above)
- Ultraviolet darkening (0.25% per year)
- Micrometeorite and orbital debris (0.25% per year)

The Cosine loss is gotten using the angle 60 degrees to the plane of the panel which is 30 degrees to the normal. Therefore, Cos 30° = 0.866
The Total BOL loss = 2% interconnection (0.98 loss) × 1% mismatch (0.99 loss) × 2% calibration (0.98 loss) × Sun angle (cosine loss) = 0.98 × 0.99 × 0.98 × 0.866 = 0.8234
The Total EOL loss = Radiation loss (0.99) × Ultraviolet darkening (1.25/100) × Micrometeorite and orbital debris (1.25/100) = 0.99 × 0.9875 × 0.9875 = 0.965
Therefore, the total loss = BOL loss × EOL loss = 0.8234 × 0.965 = 0.7949
64 cells in total for single junction cell LEO with dimensions 20×40mm. Therefore, typical voltage = 0.852V and typical current = 0.234A.
Power = V×I = 0.852 × 0.234 = 0.199375 watt
1 cell gives 0.20watts at 25℃; 64 × 0.199375 = 12.76 watt
EOL power at 25℃; 12.76 watt × 0.8 = 10.21 watt
In order to find the EOL power at 80℃, we need to find the power of 1 cell using the formula below;

$$\frac{\frac{\delta\eta}{\delta t}}{\eta} \times \frac{P_{max}}{1} = \frac{-0.036}{18.5} \times \frac{0.2}{1} = -0.4mW$$

EOL power at 80℃; $-0.4mW \times 64 = -25.6mW$
Total loss = $-25.6mW \times \Delta T = -25.6mW \times (80 - 25) = -1408mW℃ = -1.408W℃ \cong -1.41W℃$
Therefore, Remaining loss – Loss of String = 10.2 − 1.41 = 8.79 watt ≅ 8.8 watt

e) Calculate how many strings are required to fulfil the power requirement at EOL. (assume 1 string lost due to random loss)

Power requirement in our design in 60W
Number of Strings required = $\frac{Design\ Power}{EOL\ Power\ at\ 80℃} = \frac{60}{8.8} =$ 6.818 ≅ 7 Strings

f) Calculate how many sections required (BOL maximum power)

BOL power at −40℃
$\Delta T = T_2 - T_1 = -40 - 25 = -65$℃
For every ℃, we lose $-0.4 \times 10^{-3}W \times 64\ cells = -0.0256$W
Total Loss = −0.0256W × −65℃ = 1.66 Watt
Therefore, Remaining Power = 12.72 + 1.66 = 14.42 watts

Number of Sections required for single cell at 80 watt power best case scenario;
1 String gives 14.42 watts
7 Strings gives 100.94 watts
For 2 sections,
4 Strings gives 57.68 watts (BCR 1)
1 Strings gives 43.26 watts (BCR 2)

g) Calculate how panel area (assume packing factor of 70%) + 20mm border around panel

The formula for finding the parking factor is as follows;

$$Parking\ Factor = \frac{Active\ total\ cell\ area}{Active\ total\ panel\ area}$$

$$Active\ total\ panel\ area = \frac{Active\ total\ cell\ area}{Parking\ Factor} + \frac{0.02m}{1}$$

Where 0.02m is the border around the panel
For a single cell its dimension are (20 × 40) mm = (0.02 × 0.04) m. Therefore its area is 0.0008m2
Therefore, the area of 1 string = 0.0008m2 × 64 cells = 0.0512m2
Total active area for 7 Strings = 7 × 0.0512 = 3.584m2
Therefore, Active total panel area = $\frac{3.584}{0.7}$ = 0.512m2
Area = Length2
Length = $\sqrt{Area} = \sqrt{0.512}$ = 0.7155m
To find the panel dimension, 0.7155m + (2 × 0.02) = 0.7555m
Therefore, Total area = (0.7555)2 = 0.57m2

h) Calculate mass of panel (GaAs: 3.5kg/m2; Triple 3.25kg/m2; Silicon 3kg/m2)

Given, Area density = 3.5kg/m2
Calculated Area = 0.57m2
Mass of Panel = Area density × Calculated Area = 3.25kg/m2 × 0.57m2 = 1.95kg ≅ 2kg

Conclusion

This work concludes that it is possible to achieve the design, development and implementation of a low cost small power subsystem to simulate and demonstrate how power subsystem would work in the space environment. It supports the mission of Nigeria experimental satellite (NX) and provides a stable supply of electric power and enabling the ground receiving station to monitor the conditions of the satellite to know each point's voltage, current and battery status. The power system could achieve this by using high quality available technologies based on state of arts commercial off the shelves devices.

This paper was organized as follows: first a historical introduction. Second a description of Solar Panels, the Battery Charge Regulator, BCR over- voltage clamp, BCR supply voltage circuitry, Computer control circuitry, Li-ion Battery, Power conditioning module, Power distribution module, Design justification, Redundancy adapted to space environment Thirdly, experiments are described which are aimed to demonstrate the correct working of the power system. Thus, the design of the NX microsatellite power system was actualized using the stated solar cell calculation concepts.

REFERENCES

[1] B. Ramesh, D. Mohan, I. McLoughlin and N. Madhusudhanan, (2004) On board data handling system for the X-Sat mission. *Proceedings of the Asian Space Conference*, 63–68

[2] E. Gill, O. Montenbruck, K. Arichandran, S.H. Tan and T. Bretschneider, (2004) High-precision onboard orbit determination for small satellites – the GPS-based XNS on X-Sat. *Proceedings of the Symposium on Small Satellites Systems and Services*, ESA-SP 571

[3] [4] N. Nagarajan, S.G. Goh, S.H. Tan and K. Arichandran, (2004) Attitude determination and control system (ADCS) design for X-SAT mission. *Proceedings of the Asian Space Conference*, 69–74

[5] S.H. Tan, C.H. Goh, K. Arichandran and W.E. Koh, (2004) X-Sat mission: Development and operation. *Proceedings of the Asian Space Conference*, 51–56

[6] T. Bretschneider, (2003) Singapore's satellite mission X-Sat. *Proceedings of the International Academy of Astronautics Symposium on Small Satellites for Earth Observation*, 105–108

[7] T.W. Chua, K.I. Thimothy, K.Y. Li, Y.W. Yeap, E.C. Teh, S. Lim, S.H. Tan, K. Arichandran, (2004) X-Sat communications system. *Proceedings of the Asian Space Conference*, 75–80

[8] Z. Jin, S.C. Joshi, S.C. Fan, Q. Yu, N. Nagarajan and S. Shukla, (2004) Challenges in meeting thermal, structural and power requirements for X-Sat. *Proc. of the Asian Space Conference*, 57–62