NON-SEQUENTIAL POWER BUS FOR LEO APPLICATIONS
'THE 7TH EUROPEAN SPACE POWER CONFERENCE', 9-13 MAY 2005

Peter Alcindor[1], Craig Clark [2]

[1] *Surrey Satellite Technology Ltd, Surrey Space Centre, University of Surrey, Guildford, Surrey, GU2 7XH United Kingdom, p.alcindor@sstl.co.uk*

[2] *Surrey Satellite Technology Ltd, Surrey Space Centre, University of Surrey, Guildford, Surrey, GU2 7XH United Kingdom, c.clark@sstl.co.uk*

ABSTRACT

Typical solar powered spacecraft implement sequential power regulation (sunlight mode, then BCR mode and finally battery regulation mode). Transferring between each mode is managed by a triple redundant majority voted Main Error Amplifier (MEA) system. Solar array power is maintained at it's maximum capability by solar array drive mechanisms which ensure sun pointing.

At the low end of the power spectrum, from 10 to 150W, solar power is typically derived from solar panels fixed to different faces of the spacecraft and/or fixed angular wings. Solar flux and panel temperature variations along the orbit path results in unequal section currents and constantly changing sunlight loop gain making sequential power management extremely difficult to achieve. A novel highly efficient yet simple power conditioning concept applied to 21 in-orbit applications is described.

1 OVERVIEW OF SEQUENTIAL POWER GENERATION

The traditional power configuration for solar powered spacecraft above 500W is the fixed spacecraft Body pointing the payload antenna towards a fix object and a rotating solar array panel with sensors to maintain sun pointing. Other options include spinning skirt arrays but these tend to be not so popular.

Power from the arrays are divided into strings of series connected cells to provide an EOL section voltage that is slightly higher than the main bus voltage. Strings are connected in parallel to form sections of approximately equal size currents. Each section is then transferred to the fixed body of the spacecraft by a Solar Array Drive Mechanism (SADM) containing a Bearing and Power Transfer Assembly (BAPTA). During the sunlight period of the orbit power from the solar sections remain approximately equal as does the transconductance gain (Gm) of the sunlight power system. Seasonal variation alter the gain by 12% due to the earth's inclination and distance variations from the sun. Another variation over life due to panel damage and radiation reduces the gain further. The degree of this variation depends on the type of cell and it's resistance to radiation. In general though, these changes apply equally to each section resulting in homogenous contributions as the demand for power increases.

The allocation of solar sections to the power bus is determined by the Main Error Amplifier (MEA) as illustrated in **Figure 1** (without redundancy).

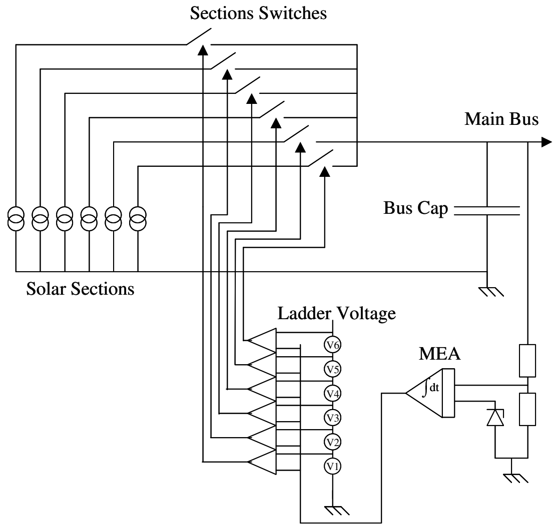

Figure 1 Sunlight Regulation Mode

The gain of this stage is determined by the potential divider ratio (β), the proportion gain of the MEA (K_{mea}), the total array current (6 x $I_{section}$) and the ladder Voltage (V_{ladder}).

$$Gm = \beta * K_{mea} * \frac{n*I_{section}}{V_{ladder}} \quad (1)$$

Proc. 'Seventh European Space Power Conference', Stresa, Italy, 9-13 May 2005 (ESA SP-589, May 2005)

The bus voltage can be kept within 2% of it's regulation voltage for a load change of 50% of the maximum power by fixed values of (β), Kmea and Vladder because $I_{section}$ can be assumed constant (knowing the worst case EOL value).

An in depth knowledge of the subsystem and its interface technologies is required to correctly specify and configure systems such as these. There are several constraints needed on the solar section switches to prevent high stresses on the array sections through too rapid rates of voltage change. Principally the peak current rating of the cell bypass protection diodes may need to be rated at several time the cells normal forward current if the cell is shadowed or is slightly weaker than the other cells in the string. Likewise, recent developments in array technology to enhance power density has resulted in higher solar section capacitance characteristics. This has resulted in the need to impose peak current awareness and possibly control on the array regulator design.

Variations in BCR and BDR gain are predictable given battery voltage range, characteristics and allowing for module failures.

2 OVERVIEW OF NON-SEQUENTIAL POWER GENERATION

The typical solar panel configuration for a small satellite of 10 to 150W are boxes of anywhere between 3 and 9 sides weighing from 8.5kg to 200kg (see **Figure 2**).

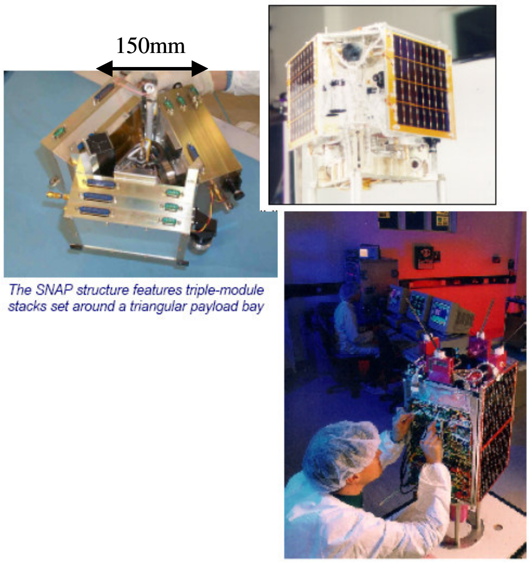

Figure 2 Nano and MiniSats

Solar panels are mounted on side walls and restricted to areas not used by the payloads of platform sensors and antenna (see Figure 3). Each face receives different solar fluxes depending on it's orientation to the sun. The larger of the spacecraft may have deployable fixed wings that fold into position once the spacecraft has separated from the launch vehicle.

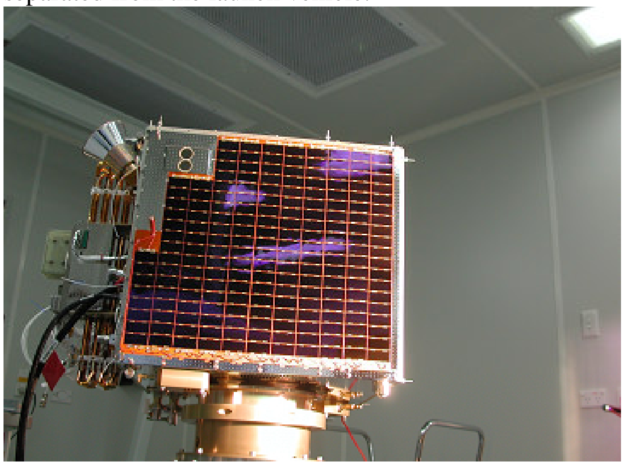

Figure 3 Panel Utilisation on a Nano Sat

A solar array model has to be constructed depicting each panel and its orientation relative to the spacecraft flight co-ordinates. As Figure 4 shows, the solar power from each panel, located on different faces of the spacecraft would result in the MEA of a sequential system moving UP and Down the ladder network to balance the Load/Array power balance:

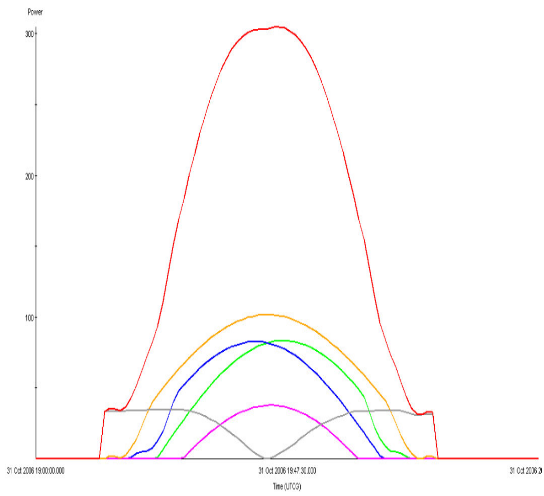

Figure 4 Panel Power vs Orbit Path

The model is then run for the spacecrafts orbit around the earth and the rotation of it's orbital plane relative to the sun. At the same time operational requirements are simulated to determine the spacecrafts requirements for power. Periods of terrestrial observation and data down and up loading need to be considered and their power demands. Finally a balance has to be established between the energy provided by the battery and the power needed to maintain operations and recharge of the batteries during sunlight. Quite often the orbits are highly incline relative to the equator and the penumbra can be significant compared to the period in sunlight. Under these conditions it is necessary to simulate the entire mission to establish that sufficient power/energy resources have been provided.

2.1 POWER REGULATION SYSTEM

One of the chief aims of this sector of the satellite market is to promote Affordable Access to Space. Solar array design and development is not cheap. Therefore affordability to space requires optimum use of all solar array power, high power conversion efficiency, low mass and simple yet highly robust design technology. This obviously includes the use of Maximum Power Point Tracking (MPPT) regulation concepts.

To maintain modularity and thereby limiting the effects of failures on the system power budget a dedicated relationship between a section and a single BCR is necessary. Finally, because each solar section is illuminated by the sun at different times, at different fluxes and operates at different temperatures, it is essential to operate in a non-sequential manner. Power must be converted for supply to the bus and battery charging as and when it can.

The need to reduce power utilisation is only required once the battery is fully charged. Then the system may enter into a trickle charge mode or voltage taper charge mode, depending on the battery technology being used.

These type of systems are mostly employed in Low earth Orbit (LEO) where as many as 16 orbits and sun/eclipse cycles are encountered. Within a year as many as 6,000 charge/discharge cycles may be experienced. The Depth of Discharge (DOD) per cycle is usually kept relatively low by the manufacturer in order to reduce ware and maximise battery life time. A typical DOD for such applications is 10 to 15%.

Defining the End of Charge (EOC) requires battery temperature since most battery voltages are temperature dependant. This too must be taken into consideration.

To summarise, the key requirements of the system are therefore:

- One BCR power solar section
- Section temperature sensor for each BCR(1)
- Section voltage sensor for each BCR
- Vmp > Vbus at EOL
- Battery temperature sensor for each BCR
- Battery voltage sensor for each BCR

(1) Note since solar panels are fixed instead of rotating, a temperature sensor per section does not represent a demand on slip rings.

The simplified power system configuration is illustrated in Figure 5

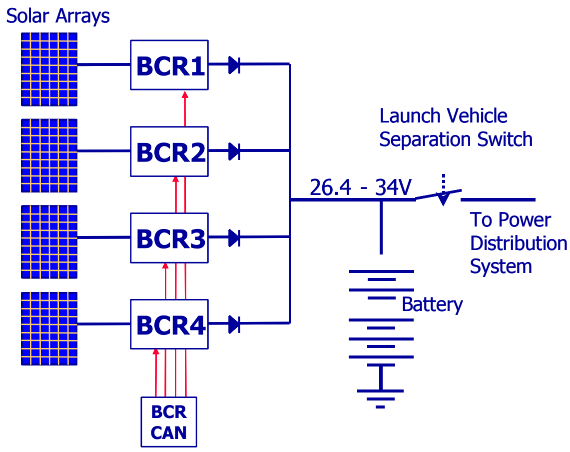

Figure 5 Simplified Power System Diagram

2.2 BCR DESCRIPTION

The key to managing the LEO small satellite power system is to let each BCR extract the maximum power from it's dedicated section. For this reason a centralised MEA control system would not work since it would demand the same power from each BCR in the same way that the sequential system described in paragraph 1 of this paper describes BCR and BCR operation. By utilising a Pulse Width Modulator (PWM) Integrated Circuit (IC) that has dual error amplifier input simultaneous array voltage and battery voltage control can be performed.

The BCR is a DC - DC switch mode converter of the Forward-Buck (or Step-down) type. The current design of the BCR is based around the UC494A Pulse Width Modulation control IC. This IC incorporates a complete Pulse Width Modulator, an oscillator, two error amplifiers, soft-start and a 5V reference.
The main switching transistor of the circuit is a P-Channel International Rectifier HEXFET, namely the IRF9540N. The FET drive circuit for the P-channel MOSFET for the buck regulator is more cost effective than the N-channel MOSFET alternative.

Each Battery Charge Regulator is illustrated in Figure 6 and comprises the following components:

- PWM Driver circuitry and Buck Converter
- Battery Temperature Compensation circuitry

- Solar panel Maximum Power Point and temperature compensation circuitry
- Computer control circuitry.
- Supply voltage circuitry for the IC.

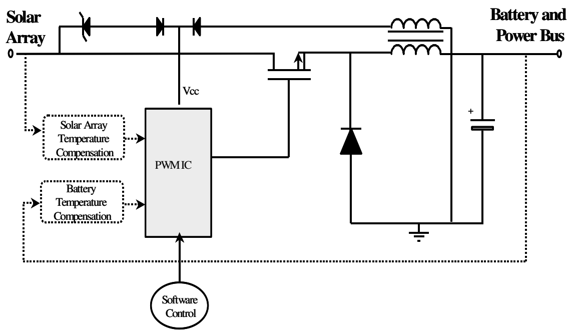

Figure 6 BCR Block Diagram

The PWM output from the UC494A drives the gate of the FET via an inverting buffer circuit. A capacitor is used to level shift the drive from the ground base PWM IC to the MOSFET in the positive line circuit. Other components that combine to form the BCR, buck converter electronics are a 250µF CASTANET capacitor, a SHOTTKY diode and an inductor. The inductor has a value of approximately 250mH, and is constructed using a RM12 inductor core set.

The EoC voltage of the battery is inversely proportional to the battery temperature, and likewise, the solar array MPP voltage is inversely proportional to the temperature of the solar panel. In order for the BCR to compensate for variations in temperature, temperature compensation thermistors are placed in the battery packs and on each panels (a panel being defined as a group of sections physically mounted on the same thermal structure).
Non-current-carrying sense wires from the battery measure the exact battery voltage. Each sense line is protected at the battery against short circuit in the harness or at the BCR. Loss of sensing and BCR failure protection is discussed later in this paper.

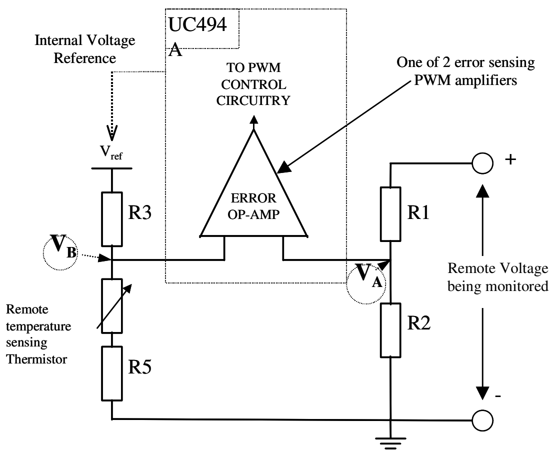

Figure 7 Temperature sensing network

The temperature compensation network is illustrated in Figure 7.

NiCd battery cells have a negative temperature coefficient of approximately –3.3mV/°C per cell (-72.6mV/°C per 22 cells in series). When the battery voltage is equal to the temperature compensated voltage reference of the PWM IC (i.e. the op-amp inputs are equal) the output of the error amplifier is low and the width of the PWM output is zero. As the battery temperature increases, the negative temperature coefficient of the thermistor reduces the thermistor's resistance and thus lowers the EOC voltage reference. The circuit is set-up resulting in the actual EoC voltage of the battery corresponding to the predicted EoC voltage. The positive input of the error op-amp correlates to the battery temperature coefficient and senses the battery voltage via a voltage divider (R1 and R2). The voltage divider on the negative input of the error op-amp incorporates the thermistor network. The selection of these resistors sets the end of charge voltage of the battery.

The solar panel maximum power point setting, temperature compensation system uses the second error amplifier in the PWM IC and operates in the much same way as the battery temperature compensation. Using a single junction GaAs/Ge, solar cells with a MPP voltage temperature coefficient of -1.9mV/°C and 48 cells in series, the overall MPP voltage temperature coefficient of -91.2mV/°C.

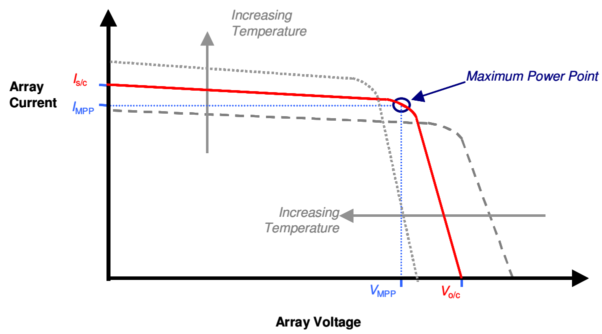

Figure 8 Typical Solar Array Characteristic

Figure 8 shows how a typical solar array I-V characteristic varies with temperature. The figure shows also where the MPP of the array is on the characteristic. When configuring the BCR for a solar array there are a number of factors that must be taken into consideration. Firstly, the panel output power drops considerably as you move along the characteristic towards the right of the knee. For this reason, it is prudent to ensure that your set point errs to the left hand side of the knee. The resistivity of the cell interconnects and harness must also be taken into account as these will result in a slight voltage drop in the path between the panel and the BCR. This loss can be estimated to approximately 1% of the actual MPP voltage. BCR should be set up to reflect the array's performance at end of life, so the effects of radiation degradation must be considered. This will vary from orbit to orbit due to differences in the orbits relation to the Van Allen radiation belts. The length of the mission is also important. The dose that is experienced by the spacecraft is usually presented in rads/s. Therefore, it is clear that the longer the spacecraft is exposed to radiation, the higher the received dose, and hence degradation, will be. Due to the relatively benign radiation environment of the DMC orbit, and the relative radiation hardness of the single junction GaAs solar cells, over the 5-year mission duration the panels will degrade by only 1%. Due to the fact that the majority of the panel degradation manifests in the voltage characteristic, as oppose to the current, it is therefore assumed that the MPP voltage will be 1% less at end of life than at beginning.

Providing a suitable and reliable supply for the BCR circuitry (mainly the UC494A) presented a problem. The battery is not considered to be a reliable supply because, if the battery was fully discharged, there would be no power to turn-on the BCR, meaning that it would be impossible to re-charge the batteries. Connecting the supply directly to the solar panels also provided a problem as the panel voltage is generally between 35V and 45V, where as the IC is rated to operate with a supply voltage of 10V to 15V. Current consumption in the IC increases with an increase in supply voltage, so a great deal of power would be wasted, decreasing BCR efficiency.

The solution involves implementing a linear regulator directly dropping the solar array voltage to a level compatible with the BCR control circuits. The output from the linear regulator is fed via a blocking diode. Once the BCR is operating a secondary supply derived from the Buck inductor is also fed to the control circuits. Since the buck supply is at a higher voltage than the linear regulator output, the buck supply is used in normal operation. The consumption is only minor compared to the charge power to the battery so the overall efficiency remains high.

3 BATTERY PROTECTION

In the above description we have proposed a system comprising individual BCRs. However, rather than implement a local protection facility to counter act BCR failure, a global protection method is implemented.

A series redundant set of power switches are activated by a battery voltage monitor. Should a BCR fail ON or should it's EOC interface fail resulting in the battery being charged beyond the EOC voltage, then both protection switches activate and a load equivalent to the largest array section is connected across the battery.

The seroes redundancy in the protection system prevents a single failure in the protection system from accidentally putting the load on the battery.

4 BUS IMPEDANCE

Since the battery is in circuit all the time, the bus impedance is dominated by the battery. Load switching inrush characteristics are governed by the power distribution system where every non-essential load is fed by a current limiting power switch. This together with the low impedance of the battery maintains a satisfactory response to system power demands.

5 LAUNCH INTERFACES

These spacecraft are intended to be launched in the OFF state. Access is provided to the battery to monitor state of health and charge the battery while the spacecraft is attached to the launch vehicle. This access may be direct to the battery or via the on-board BCRs sharing an interface with the on-board solar arrays. In the latter case, the local battery temperature compensation ensures that the battery is not over charged. Battery temperature sensors are provided to the AIT port to enable ground based test equipment to facilitate remote charge compensation.

6 CONCLUSION

This power system approach is designed to provide access to space at affordable budgets. To date 21 systems have been launched based on this or similar concepts.

All system elements from the array to the battery are provided internally. Consequently the responsibility for interface control and correct implementation uniquely rests with the satellite supplier.

Furthermore, the same internal control extends between the power system and all other systems on the spacecraft, brining un-rivalled concurrent engineering practises to the fore.