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Sequential Switching Shunt Regulator for Satellite Power Control System

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Abstract: *Optimum usage of the available resources for the spacecraft electric power system is the main key for success for the satellite EPS design process. Furthermore, implementing modular design of the satellite EPS improves the operation of the satellite because it (i) enables the EPS to work on different power levels, (ii) enhances the EPS integration with various payloads, and (iii) decreases design modifications required to operate the EPS on missions regardless of the height and duration of these missions.*
A new method for controlling the output power of the satellite solar arrays is proposed in this paper. The proposed method depends on a hybrid modular configuration where the output power of the solar arrays is controlled by linear and non-linear regulations. Moreover, the proposed hybrid configuration is implemented on a microcontroller to show the feasibility of the real-time operation. The proposed method shows its superiority over other methods previously published in literature.
Keywords: *Satellite power control– Shunt regulator – S3R*

I. Introduction

Spacecraft electric power system is a major designing driver in any space mission and it is in turn affected by a variety of environmental, mission and other spacecraft subsystems constraints as it almost directly interfaces with all spacecraft subsystems and the outer space.
The main task of EPS is the efficient provision, generation, storage, conditioning and distribution of all the available energy among spacecraft subsystems and payload.
For earth orbiting satellites EPS components are as follows:

a) Solar arrays as a primary power source responsible for conversion of solar energy and provision of electrical energy to the satellite;
b) Storage batteries as a secondary power source responsible for the storage of the electrical energy to be used in eclipse periods, solar array miss orientation periods, or overloading periods;
c) Power conditioning and control unit responsible for controlling the power flow in the satellite, balancing energy management of power source and storage elements, autonomy of EPS operation and power bus voltage regulation;
d) Power switching units and cable network responsible for the distribution of electrical power among satellite subsystems and components.[1]

Power conditioning and control unit is the brain of electric EPS as it maintains main power bus voltage level within a predesigned constant margin irrespective of any changes in the input electrical power or disturbances in the load current. The power bus with fully regulated voltage is a popular architecture for space missions with power level in the KW range [2]. This architecture includes a shunt regulator for the solar arrays and charge/discharge regulators for the storage batteries and the main objective of this architecture is to keep the main bus voltage regulated within small margin from the bus voltage level approximately 1% during the whole life time of the space mission [1]. In this paper, a control strategy is proposed, implemented and synthesized to regulate the output of the solar arrays subjected to different modes of operation of the spacecraft. The layout of this paper is as follows, in section 2 different modes of operation of the spacecraft are discussed and the shunting mode in the EPS is highlighted. In section 3 different concepts of solar array shunt regulators are explained and their concept of operation is illustrated. In section 4 a proposed architecture is presented with an illustration for the operating domains and control strategy of the regulator .In section 5 the strategy of the microcontroller code is discussed and the results are shown in section 6 with a conclusion to summarize the effect of the work on EPS design of the spacecraft.

II. Electric Power System Shunting Mode Explanation

In order to understand different operating modes of EPS as a part of the spacecraft modes of operation an illustration for current balance equation [I (solar array)-I (load)] need to be given, during the absence of solar illumination due to eclipse period or solar arrays miss-orientation or when the load current is more than the current generated from the solar arrays the current balance equation is clearly negative [I (solar array)-I (load)] < 0 and then the storage battery will be responsible for delivering electrical power to the satellite loads in a mode called discharging mode where the discharging regulator of the storage battery is active and both the charging regulator of storage battery and shunt regulator of the solar arrays are inactive. As the current generated from the exceeds the load current demand then the current balance equation will be clearly positive [I (solar array)-I (load)] > 0 and the solar arrays feed the load and the difference in the current is used to charge the depleted storage battery in a mode called charging mode where the charging regulator of the storage battery is active. After certain charging time and as the storage battery is fully charged the current balance equation is still positive and the available solar array current is more than the load current and the small current required to maintain the storage battery fully charged, then the system operates in another mode of operation called shunt mode where the excess solar array current is properly shunted away from the power bus to protect the main power bus voltage level and the rest of this paper is mainly concerned by the shunt mode.

III. Solar Array Shunt Regulator

Most EPS architectures with fully regulated main power bus voltage use shunt regulators to control the solar array output during sunlight periods in order to maintain the power bus voltage within the predesigned margin by dissipating the excess solar array current away from the main power bus[3]. Different classifications are available that represent various methodologies for implementing the shunt regulator concept some of them are shown in figure 1.

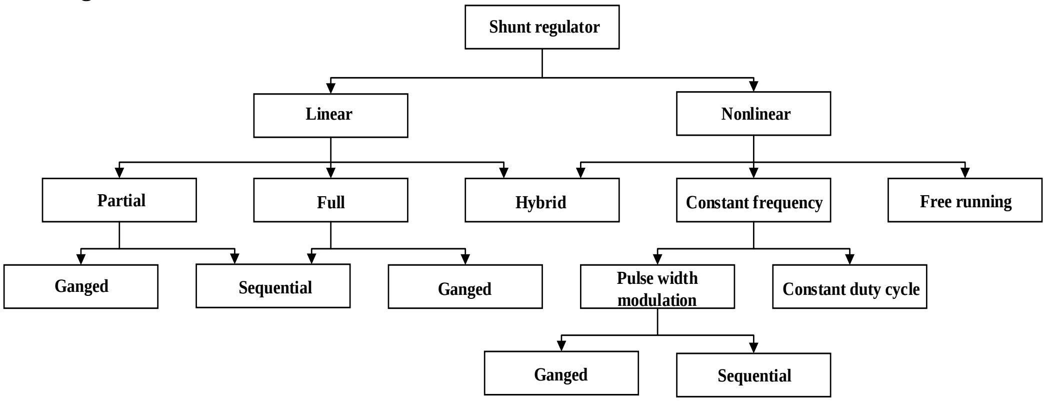

Figure 1 Solar arrays shunt regulators methodologies

The solar array sequential switching shunt regulator abbreviated S3R provides a robust way to dissipate the solar array excess current at BOL of the solar arrays and at periods following shadow periods when the solar arrays are very cold and operates with very high efficiency. The relation between the available current from the solar arrays and the load current demand could be clearly sensed from the change in the main bus voltage and accordingly the control action from the power conditioning and control unit sweeps the operation of the EPS through the previously mentioned modes, as we can see in figure 3 taking a (28.5 ± 0.5 V) voltage bus as an example when the bus voltage increases by value V_e the control signal generated by the main error amplifier follows accordingly and activates in sequence the battery discharging regulator then the battery charging regulator and finally the shunt regulator.

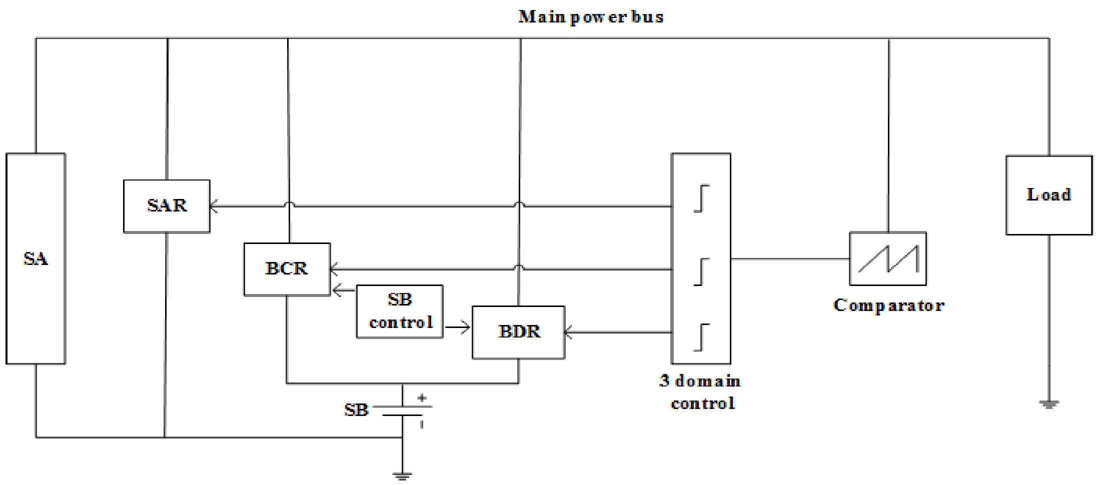

Figure 2 Ordinary control components in fully regulated voltage power bus

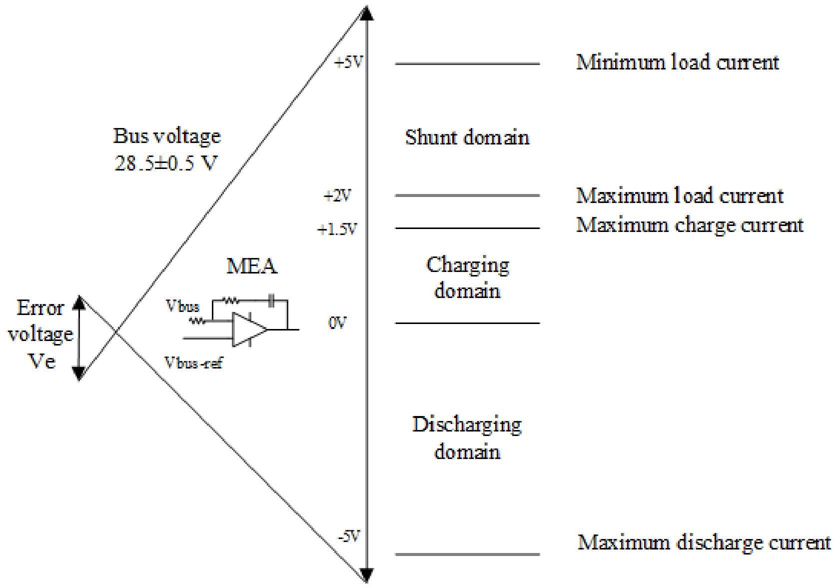

Figure 3 Operating domains of PSS versus bus error voltage

The solar arrays are divided into a number of sections all connected to the bus and each section has a parallel switch controlled by a hysteresis comparator with designed reference. The main error amplifier in the power conditioning and control unit compares the bus voltage to the designed bus reference voltage then the output signal of this amplifier is sent to all the hysteresis comparators of solar array sections accordingly each comparator respectively responds to the error signal according to the comparator settled reference value and its corresponding section is either connected or disconnected from the main power bus depending on the magnitude of the error signal in the bus voltage.

The operating domains of the different modes are separated by dead zones and inside the S3R itself the solar array sections are also swept by the control signal and m sections are switched ON (disconnected from the bus) and other sections are switched OFF (connected to the bus) continuing feeding current to the loads and the section with the upper reference is pulse width modulated and regulates alone the bus voltage, in other words the reference values of the hysteresis comparators are distributed in sequential order such that in steady state only one section is operating in switching mode whereas all other sections are in ON or OFF states.

IV. Proposed Shunt Regulator Architecture

The ordinary configuration of the sequential switching shunt regulator has a lot of advantages including simplicity, high efficiency, minimum thermal dissipation, truly modular design with high reliability and low mass but for large power platforms like in GEO satellites small parameters like the capacitance of the solar array becomes with significant values taking also into consideration the triple junction technology of solar cell construction that achieves much higher efficiency than silicon technology with great reduction in mass and volume but on the other hand has five times higher parasitic capacitance than the preceding technology for the same voltage and power, the increase in the parasitic capacitance affects negatively the performance of the shunt regulator as follows:

a) Large power losses in the shunt switch and accordingly less efficiency and difficult thermal conditioning
b) Increasing the bus ripples and degrading the transient response by increasing the turn on delay in the shunt transistor and possible double section functioning situation will increase[4]

The logic solutions for these drawbacks is the use of more number of solar array sections in order to reduce the parasitic capacitance and also to increase the bus capacitance in order to reduce the switching frequency and the output impedance but those solutions are not practical from the spacecraft system level as increasing the number of solar array sections complicates the solar array cabling and reduces the window between the hysteresis controllers settled references upon which the regulator response is qualified whereas the increasing of the bus capacitance penalizes the total mass and volume of the whole system[5].

The proposed method in this work in order to overcome the drawbacks of S3R with the large power platforms is the usage of digital shunt regulator with the ordinary configuration of the S3R and construct a hybrid analog and digital control technique.

In the proposed configuration instead of dividing the solar array into smaller sections the array will be divided into two types of sections; (1) low power solar array section with capacity of 1 ampere and (5) high power solar array sections each with capacity of 3 amperes as shown in figure 4.

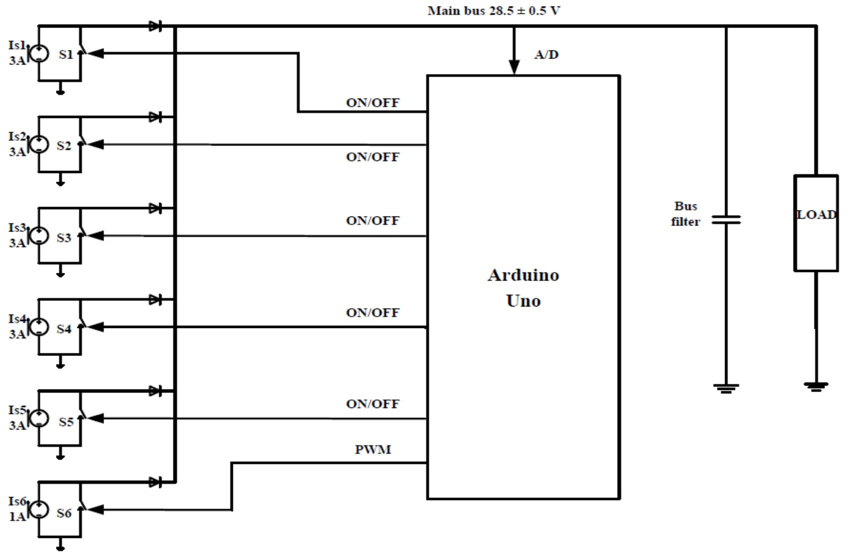

Figure 4 Proposed shunt regulator architecture

The control strategy is that the small section is the only section used to fine regulate the bus voltage in pulse width modulated mode and so keeping the same closed loop response of the ordinary configuration of S3R while the high power sections are only switched during large load changes and act as coarse regulation for the bus voltage. In order to achieve the previously mentioned control strategy for the shunt regulator a spacecraft 28.5 ± 0.5 V voltage bus is taken as an example and an approximated linear mapping is done between the acceptable margin of bus voltage (from 28.00 V till 29.00 V) and the corresponding error voltage signal (from -5.0 V till +5.0 V) which will be the input signal for the microcontroller, then a definition is done for the electric EPS operating domains as illustrated in table 1. The shunt domain of the bus voltage was taken as the operating domain under study and a code was constructed for the microcontroller Arduino-Uno with the bus voltage error signal from +2V till +5V taken as an input signal for the controller, after applying the code to the input signal the microcontroller issues two controlling actions the first control action is a switching pattern for the (5) solar array sections of the high power capacity and the second control action is a pulse width modulated signal for the solar array section of the low power capacity with an appropriate duty cycle.

Table 1 Electric EPS operating domains

Satellite bus voltage	Bus voltage margin	Error voltage signal	PSS operating domain
28.5 ± 0.5 V	28.00	-5	Discharging domain
	28.10	-4	
	28.20	-3	
	28.30	-2	
	28.40	-1	
	Dead zone		
	28.50	0	Charging domain
	28.60	+1	
	28.65	+1.5	
	Dead zone		
	28.70	+2	Shunt domain
	28.80	+3	
	28.90	+4	
	29.00	+5	

The logic sequence of the controlling algorithm of the microcontroller code is illustrated in table 2 showing also the controlling margins of each individual solar array section.

Table 2 Control actions and margins of each solar array section

Bus voltage V_b(V)	Error E (V)	Coarse control					Fine control	
		S1	S2	S3	S4	S5	S6	DC %
V_b=28.70	E=2.0	OFF	OFF	OFF	OFF	OFF	OFF	0
28.70<V_b<28.75	2.0<E<2.5	OFF	OFF	OFF	OFF	OFF	PWM	5 : 95
V_b=28.75	E=2.5	ON	OFF	OFF	OFF	OFF	OFF	0
28.75<V_b<28.80	2.5<E<3.0	ON	OFF	OFF	OFF	OFF	PWM	5 : 95

V_b=28.80	E=3.0	ON	ON	OFF	OFF	OFF	OFF	0
28.80<V_b<28.85	3.0<E<3.5	ON	ON	OFF	OFF	OFF	PWM	5 : 95
V_b=28.85	E=3.5	ON	ON	ON	OFF	OFF	OFF	0
28.85<V_b<28.90	3.5<E<4.0	ON	ON	ON	OFF	OFF	PWM	5 : 95
V_b=28.90	E=4.0	ON	ON	ON	ON	OFF	OFF	0
28.90<V_b<28.95	4.0<E<4.5	ON	ON	ON	ON	OFF	PWM	5 : 95
V_b=28.95	E=4.5	ON	ON	ON	ON	ON	OFF	0
28.95<V_b<29.00	4.5<E<5.0	ON	ON	ON	ON	ON	PWM	5 : 95
V_b=29.000	E=5.0	ON	ON	ON	ON	ON	ON	100

V. Implementation Of The Proposed Control Logics Using Microcontroller Code And Results

Arduino-Uno microcontroller was chosen for the implementation of the mentioned control strategy as it has all the hardware features required, including input voltage range up to 5 dc volts and output digital pins for switching signals of the SA sections to perform coarse control also it contains pulse width modulated output pins to perform the fine control of the regulator. The Arduino-Uno board features an Atmel ATmega328 microcontroller operating at 5V with 2KB of RAM, 32KB of flash memory for storing programs and 1KB of EEPROM for storing parameters. The board has 14 digital I/O pins and 6 analog input pins and the clock speed is 16 MHz. A USB connector is available for connection with the host computer and the headers are provided for interfacing to the I/O pins using solid wires or header connectors. The microcontroller programming language is a simplified version of C/C++. Arduino-Uno has an open source software which facilitates implementing the control logics strategy on the board. The code defines the ranges of operation of each solar array section as we have (5) sections for the coarse control and (1) section for fine control as in table 2 the definition of ranges is mapped with 1024 bits for the input of the microcontroller.

The main power voltage is increased due to the following factors

a) Disconnection of certain loads and corresponding reduction of load current demand in accordance with different scenarios of operation of the spacecraft

b) Excess of the available power from the solar array either at the beginning of life period or after exiting from the shadow periods and the panels are very cold[1]

A transient period of main bus voltage variation during 6 minutes of time is simulated as shown in table 3

Table 3 Main power bus voltage in accordance with spacecraft operation

Period (sec)	Bus voltage (V)	Mode	Actions
From 1 to 100	28.74	Preparation for Standby mode	Normal flight
From 100 to 149	28.88		Exiting shadow
From 149 to 250	28.97		Switching off heaters
From 250 to 300	28.82		Switching off communication
From 300 to 359	28.73	Standby mode	Normal flight

The main power bus voltage behavior before and after applying the corresponding coarse and fine control actions are shown in figure 5.

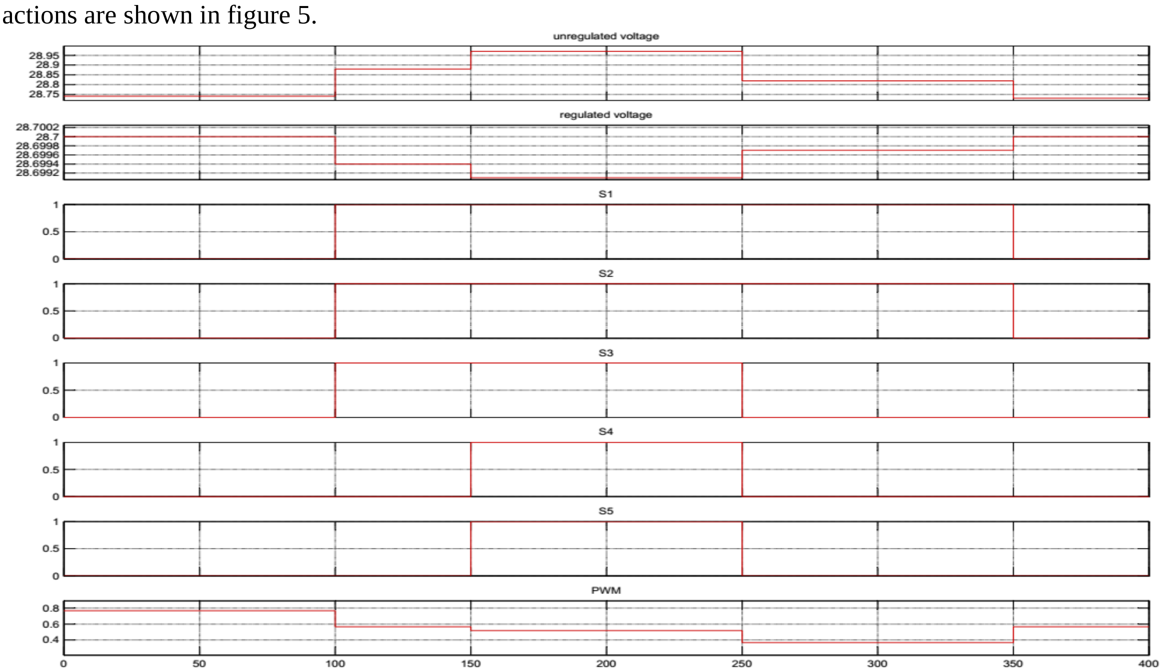

Figure 5 Bus voltage response and corresponding control actions

The hybrid modular configuration including both linear and non-linear regulation presented as coarse and fine control actions respectively has all the advantages of the basic topology of the ordinary sequential switching shunt regulator including high reliability and simplicity, another important advantage is that the proposed scheme is modular and therefore could be utilized in a big range of power ratings and without the need of considerable changes as it depends on the amount of controlled solar array sections and the current capacity of each one.

The use of microcontroller allows more intelligent and flexible control solutions and a huge potential for different control strategies corresponding to different operational scenarios.

The usage of nonlinear regulation for the fine tuning helps in the reduction of the bus ripples and in accordance minimization of parasitic capacitance of solar array, reduction of bus filter capacitance and reduction of overall mass and volume of power control unit of the EPS.

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