Multiple Battery Module for the Low-Earth-Orbit Spacecraft Power system

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Abstract - In an effort to develop more reliable and cost-effective satellite power system, a multiple-battery subsystem operating in parallel become a viable solution. The idea can further be extended to the parallel-able standardized battery module concept that offers many attractive features in configuring a spacecraft power system. In this paper, Multiple Battery Modules employing the charge control scheme are proposed. In addition to the conventional voltage mode controller, the charge control scheme internally regulates and controls the battery current, resulting in the identical current distribution and balanced battery charge.

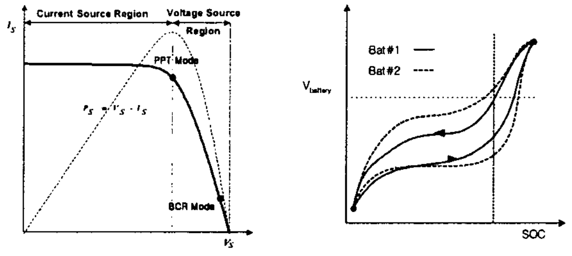
I. INTRODUCTION

In an effort of developing a more reliable and cost effective satellite power system, a viable solution is a multiple-battery system operating in parallel. The idea can be further extended to the parallel-able standardized battery module concept that offers many attractive features in configuring a spacecraft power system. The module that has pre-flight history can be used without any modification, thus increasing the reliability of the system. Implementing this concept to the Low-Earth-Orbit (LEO) satellite's power system requires the following system requirements.

First, during the eclipse, Depth-Of-Discharge (DOD) must be controlled identically since the lifetime of the battery is determined from its DOD at the end of the eclipse period. The successive unbalanced DOD during the orbit revolution can severely degrade a battery and this results in the unbalanced performance in End-Of-Life.

Secondly, during the sunlight period, the solar array power must be properly distributed to each battery module in order to fully recharge all batteries at the end of the sunlight period. And current of each battery must be regulated respectively according to the State-Of-Charge of each battery to regulate the battery current within a specified limit.

Thirdly, the available maximum power of the solar array must be utilized by employing an adaptive control technique. A Peak-Power-Tracking control can tracks the Maximum-Power-Point (MPP) which widely varies due to the temperature variation in Low- Earth-Orbit.



(a) (b)

Fig. 1. The characteristics of the solar array (a) and the battery (b)

These requirements coupling with the different characteristics among batteries and the nonlinear characteristics of the solar array as in Fig. 1, result in three possible system configurations as shown in Fig. 2 - 4. Depending on the power capacity and its operating orbits, each configuration has the advantage over the others in terms of the size, efficiency and performance. The objective of this paper is to select the best configurations for LEO small-satellite power system (under 500[W]).

In section II, results of the comparative study of these configurations are presented. In section III, multiple battery modules that can be implemented by the conventional series-configuration system without any modification by employing charge-control is proposed and discussed. Finally its verification is presented in section IV using computer simulation tool, MATLAB.

II. SYSTEM CONFIGURATIONS FOR MULTIPLE MODULES

The MBM (Multiple Battery Module) can be implemented by attaching the additional discharging regulator to the conventional series configuration power system as shown in Fig. 2. In eclipse period, the discharging regulator (DCR) regulates the battery current to control the DOD of each battery and the bus voltage at the same time. Solar Array Regulator (SAR) regulates the battery charging current depending on the State-Of-Charge of the battery by Peak Power Tracking (PPT) mode or Battery Charging Regulation (BCR) mode in sunlight period. Since the power to the payload from solar arrays is processed through two converters (SAR and DCR), the efficiency during sunlight period becomes poor.

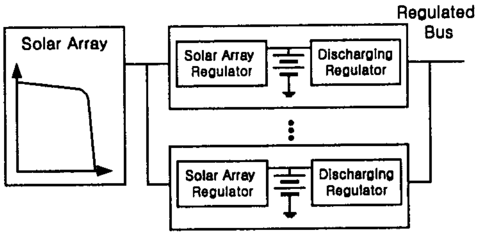
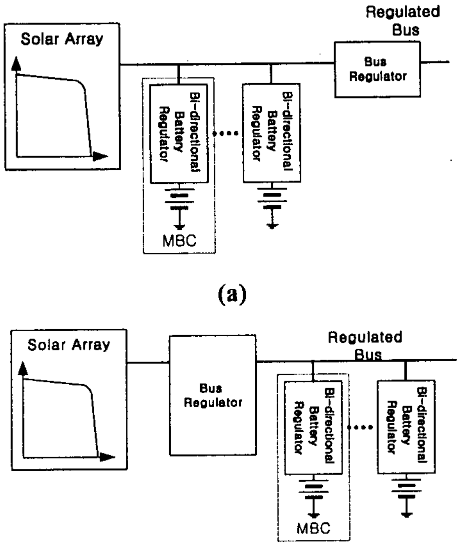


Fig. 2. Series configuration for MBM

However, the advantage of the configuration is that MBM can be realized with the conventional power stage with minimal modification. This approach is very feasible for the small-satellite under 500 watts.

Another MBM configuration can be realized by introducing paralleling concept as in Fig. 3. Depending on the location of the bus-regulator (BR) and Multiple Battery Cells implemented by integrating a battery and a Bi-directional battery regulator, two possible configurations can be implemented.



(a)

(b)

Fig. 3 Parallel Configurations for MBM

In the configuration as in Fig. 3(a), Multiple Battery Cells are located in front of the bus regulator and battery regulator in each cell operates in PPT mode or BCR mode. The input voltage of the batter regulator is widely varies according to PPT control since Maximum Power Point (MPP) is changed according to the wide temperature variation in LEO. This wide input voltage range can give severe limitations on designing the Bi-directional topology for battery regulator. Furthermore, this configuration has the poor efficiency in eclipse period since the power to the payload from battery is processed through two converters, battery regulator and bus regulator, resulting in the increase of DOD of battery and shorter system lifetime.

This disadvantage can be avoided by changing the location of the multiple battery cells and bus regulator as in Fig. 3(b). In this system, bus regulator operates with PPT mode or bus regulation mode. When solar array power exceeds the battery charging power and the payload power, bus regulator regulates the bus voltage and when solar array power is insufficient, bus regulator tracks MPP of solar array and the bus voltage is regulated by battery regulator. In this configuration, the input voltage of battery regulator can be maintained to the fixed voltage.

However, comparing the system in Fig. 3(a), the size of the bus regulator must be increased since it processes the more power. The sum of payload power and the battery charging power is processed through the bus regulator in this system while only the payload power in the system of Fig. 3(a).

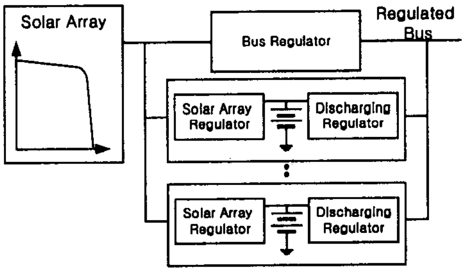


Fig. 4. Series-Parallel Configuration

In fact, the best configurations in terms of the efficiency can be realized by combining the paralleling concept and the series configuration as in Fig. 4. In this configuration, the power in each mode is processed through only single converter. However, since the additional converter is required, this approach is not feasible for the small-satellite.

III. SERIES CONFIGURATION MULTIPLE BATTERY MODULE

From the comparative study in the above section, it can be concluded that for the LEO small-satellite power system, the series configuration has much advantages over the other configurations in terms of size, efficiency and redesign costs. As shown in Fig. 2, each battery module consists of the Solar Array Regulator, the discharging regulator and the battery.

As discussed in introduction, the proposed system must be designed to be able to regulate SOC of batteries identically during orbital revolution. The battery current must be properly and intelligently regulated in spite of the variable characteristic of the battery depending on the environmental factors such as temperature, aging factor and SOC as in Fig. 1(b).

In this paper, the Multiple Battery Module (MBM) employing the charge control scheme is proposed. In addition to the conventional voltage mode controller, the charge control scheme internally regulates and controls the battery current, resulting in the identical current distribution between SAR's and balanced DOD among batteries.

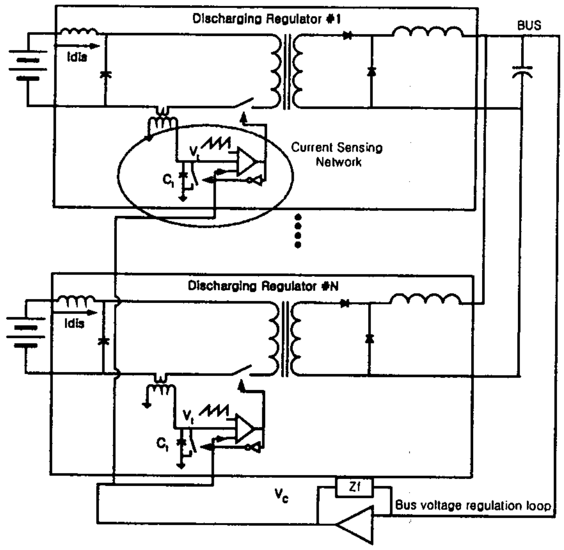


Fig. 5. The discharging regulator for MBM

A. *The discharging regulator for MBM*

In the proposed scheme, the discharging regulator in the battery module has two loops; the charge current mode loop for identical current distribution and the voltage loop for the output voltage regulation as shown in Fig. 5. The capacitor in the current sensing network integrates the switch current to obtain the charge information of the switch current per cycle, while the voltage loop regulates the bus voltage by controlling the charge value. In this scheme the following condition is satisfied in each switching cycle.

$$V_t = \frac{1}{C_t}\cdot \int_{0}^{dT_{sw}} I_L(t)dt = \frac{T_{sw}}{C_t}\cdot \bar{i}_{sw} \qquad (1)$$

where T_{sw} : Switching period

$\bar{i}_{sw}$: Average Switch Current

The time average value of the switch current has the same dynamic information as the input current of the discharging regulator. Thus, the battery-discharging current of each module is regulated identically and the common outer voltage loop regulates the output bus voltage by changing the input current level and DOD can be equally controlled.

The effects of the difference of the voltage on the dynamic performance must be considered in designing of the bus voltage loop as in [3].

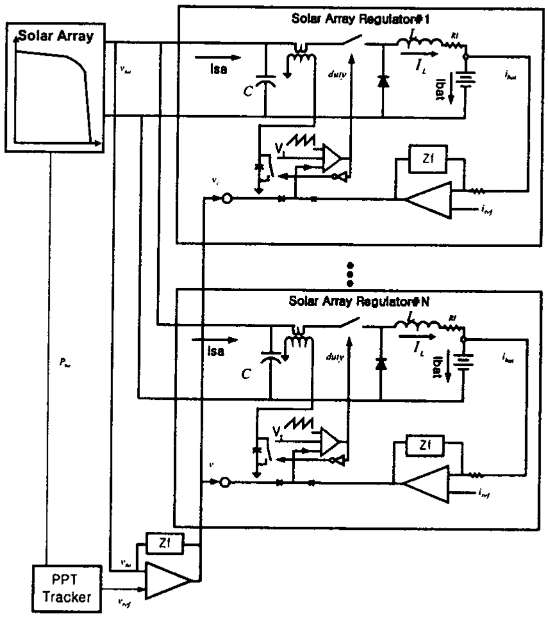


Fig. 6. The Solar-Array-Regulator for MBM

B. *The Solar-Array-Regulator for MBM*

Solar-Array-Regulator (SAR) regulates the solar array power according to the State-Of-Charge (SOC) of the battery and the status of the payload with two different operating modes; Peak-Power-Tracking (PPT) mode and Battery-Current -Regulation (BCR) mode.

As shown in Fig. 6, each Solar-Array-Regulator in the proposed system has one internal current loop; the charge-current-loop to regulate the input current of the module to the control signal from the external loops. Thus, when all modules operate in PPT mode, the solar-array power can be identically distributed among modules and the balance of State-Of-Charge of each battery can be maintained. The external voltage loop regulates the solar array voltage to the reference value generated from the PPT tracker while the battery current loop is deactivated and saturated. Then the PPT tracker tracks the Maximum Power Point of the solar array by changing the reference value.

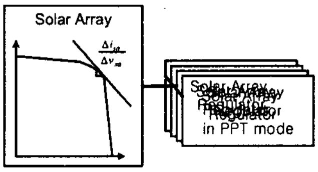
However, the difference characteristics among batteries can result in the different mode among modules; some modules operate in PPT mode and others in BCR mode. When some modules operate in PPT mode, input current must be controlled identically among modules and the dynamic interaction with the other module in BCR mode must be considered.

With the conventional current-mode control, the system can suffer from the instability due to the dynamic interaction with the nonlinear dynamic characteristics of the solar array [6]. The instability originates from the fact that the conventional current-mode control incorporates the solar array power information. Employing the charge-current mode control that uses the solar array current information instead of the solar array power information, the system stability can be achieved [1].

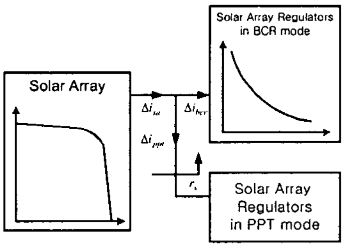
When all modules are in PPT mode, the source impedance (r_s) of each module can be obtained as in Fig. 7(a) and Eq. (2) under the assumption of the identical power distribution.

$$r_s=\left(\frac{\Delta v_{sa}}{\Delta i_{sa}}\right)\Big/ n, \qquad (2)$$

where n : the number of the modules



(a) All modules in PPT mode



(b) Effect of SAR in BCR mode

Fig. 7. Dynamic interactions in MBM

As SOC of battery increases, some modules change its mode to BCR mode for the battery current regulation; thus the battery current loop is activated. In this case, the different mode among modules can affect the dynamic characteristics of the system. The load line of SAR in BCR mode becomes the constant power line as in Fig. 7(b) and the source impedance of each module can be obtained as Eq. (3). This value must be incorporated in the design of the battery current loop and the solar array voltage loop.

$$\frac{1}{r_s}=\frac{\Delta i_{ppt}}{\Delta v_{sa}}=\frac{\Delta i_{sa}}{\Delta v_{sa}}-\frac{\Delta i_{bcr}}{\Delta v_s}=\frac{1}{r_{sa}}-\frac{1}{r_{bcr}} \qquad (3)$$

With the small-signal analysis of the system, the transfer function from the control signal to the solar array voltage can be derived. However, the variations of the dynamic source resistance of each module derived in Eq (2) and (3) must be considered in the control loop.

IV. SIMULATION RESULTS

To verify the proposed MBM system, the computer simulation using MATLAB is performed. In this simulation, by changing the battery current reference, the dynamic response of the system in mode transition is investigated and verified. Figure 8 shows the simulation results during sunlight period. At first, all modules are in BCR mode since all Iref's are set to 1[A]. At 0.002[s], the Iref in module #1 is changed from 1[A] to 5[A]. And at 0.006[s], the Iref in module #2 is changed from 1[A] to 5[A], thus the module #1 and #2 are changed to PPT mode and input currents of these modules are identically distributed. And at 0.01[s], Iref of module3 is changed to 5[A], then all modules are operates in PPT mode. In this simulation, battery voltages are set to 24[V], 25[V], 26[V], respectively.

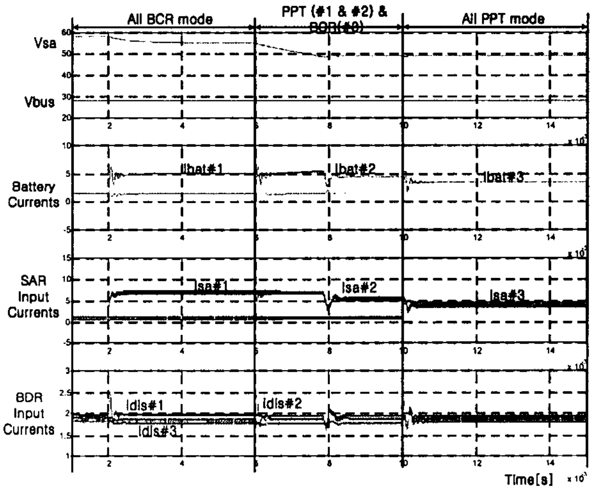


Fig. 8. Simulation results #1 (BCR mode to PPT mode)

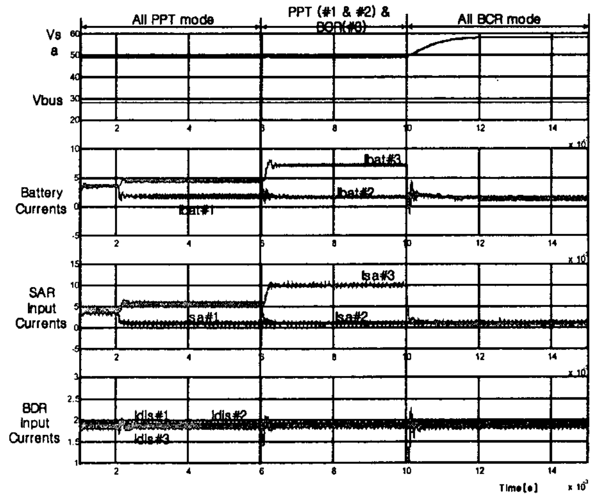


Fig. 9. Simulation results #1 (PPT mode to BCR mode)

The reverse mode transition is verified in Fig. 9. In this case, all Iref's are set to 20[A], and all modules operates in

PPT mode. At 0.002[s] and 0.006[s], the reference value of module #1 and module #2 are set to 1[A] respectively, thus, these modules are changed to BCR mode. Finally all modules are returned to BCR mode since Iref#3 is set to 1[A] in 0.01[s].

Note that input currents of discharge regulator are regulated equally in all operating modes and mode transition.

V. CONCLUSION

In an effort to develop more reliable and cost-effective satellite power system, a multiple battery subsystem operating in parallel becomes a viable solution. The idea can further be extended to the parallel-able standardized battery module concept that offers many attractive features in configuring a spacecraft power system.

The system requirements for LEO satellite, coupling with the different characteristics among batteries and the nonlinear characteristics of the solar array, result in three possible system configurations, series, parallel, series -parallel configuration. Form the comparative study of these configurations, it can be concluded that for the LEO small-satellite power system, the series configuration has much advantages over the other configurations in terms of size, efficiency and redesign costs.

In this paper, Multiple Battery Modules in series configuration employing the charge control scheme are proposed. In addition to the conventional voltage mode controller, the charge control scheme internally regulates and controls the battery current, resulting in the identical current distribution and balanced battery charge. The proposed system is verified with the computer simulation.

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