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MICROCONTROLLER-BASED INTELLIGENT POWER MANAGEMENT SYSTEM (IPDMS) FOR SATELLITE APPLICATION

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ABSTRACT

Efficient power distribution management is very crucial for satellites to navigate their orbits and achieve their mission objectives. The Satellite Electrical Power Subsystem (EPS) is responsible for power supply in satellites for housekeeping operations. This research project is aimed at the design of a microcontroller-based Intelligent Power Distribution Management System (IPDMS) for application in the efficient coordination of power savings and distribution to satellite system payloads. In the IPDMS design, 8-bits microcontroller was used to implement system intelligence. In addition, Java Programming Language was used to achieve a simulation model for virtual test for system reliability and efficiency. The IPDMS provided intelligence for real-time power storage. It managed power distribution through load shedding and power-cycling and actuated fault protection mechanism in the events of power emergencies very quickly and autonomously during eclipse and sunlight orbit periods. It monitored the battery temperature threshold levels to control destructive exothermic reaction. The IPDMS achieved an improvement over the conventional satellite power management and control systems in terms of system's size reduction, self-contained intelligence, flexibility and improved system response to power emergencies.

Keywords: satellite, power, intelligence, distribution, management, switching, payload, microcontroller, battery, charge, discharge.

INTRODUCTION

The requirement of efficient and reliable power distribution management is very crucial for satellites to fulfill their varied mission objectives. Patel (2005) described the Satellite Electrical Power Subsystem (EPS) as a system that generates, stores, conditions, controls and distributes power for satellite's housekeeping operations. Satellite Systems in orbit are often subjected to the hostile hard vacuum environmental conditions of the outer space (Pratt *et al*., 1986; Wertz *et al*., 1990). The ill-fated Nigerian Communication Satellite (NigComSat) launched by China which got missing in action after two years was reported to have suffered a failure due to power related technical hitches (Emmanuel, 2011). This unpleasant development is a proof that in the event of system and environmental emergencies in the outer-space, the satellite's Electrical Power System (EPS) is most vulnerable. Therefore, spacecraft power distribution system must be designed with some level of intelligence. This will enable the satellite to sense systems and environmental changes that may impact negatively on its power supply mechanism more quickly and accurately and intelligently invoke power management procedures to control the situation.

According to Emmanuel (2011), in the conventional satellite EPS, the system is commonly designed and configured as follows:

a) Power management embedded software program is situated in the spacecraft on-board Central Processing Unit (CPU). As a result, system intelligence is not domiciled in the satellite EPS. Hence, any CPU related problem is immediately translated to the EPS.
b) EPS system actuators are controlled by hardware logic gates circuit and relay switches. This resulted in limited accuracy and speed of system response to power emergencies. In addition, the problem of increased system size and weight. Whereas, size and weight reduction is an essential design consideration in satellite development.

The aim of this research work is to design a microcontroller-based Intelligent Power Distribution Management System (IPDMS) for automatic coordination of power distribution and savings as well as load switching in satellite using C program algorithm that is implementable with a microcontroller.

The objectives are as follows:

a) Replace hardware logic-gates circuits located within the EPS with C code embedded program for improved system response to power emergencies;
b) To achieve a self-contained intelligence and autonomous system independent of the satellite on-board Central Processing Unit (CPU);
c) To isolate CPU related problems from adversely affecting the performance of the EPS;
d) To achieve system's size and weight reduction.

Satellite's EPS design overview

According to Okoro *et al*. (2007) the Satellite Electrical Power Subsystem (EPS) is the most critical system on any spacecraft because nearly every other subsystem requires power. This makes the design of power systems the most important and complex task facing spacecraft engineers. The operation of the satellite components are energized by the EPS. Therefore, the EPS must be designed to function optimally and reliably throughout the period of satellite mission.

The Satellite's EPS is responsible for electrical power generation, energy storage for peak-power demands and eclipse periods, power regulation to prevent

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overcharging and undesired spacecraft heating, power switching and distribution to other subsystems as well as power management Ulrich *et al*., (2006). To achieve this the EPS incorporates both solar panels for power supply while the satellite is in sunlight and batteries for storing and providing power when the spacecraft may be in Earth's shadow (Harty *et al*., 1993; Agrawal, 1986). Keeping the satellite powered in the dark adds considerable complexity to the design, since the power system must be responsible for determining the power levels of the batteries and maintaining them at an adequately charged level. Other duties assigned to the EPS as noted by Obland *et al*. (2003) are to determine which solar panels are active at any given time (for attitude control analysis) and cycling of switchable subsystems (communication subsystem) on or off to conserve power. Figure-1 shows the functions to be provided by the EPS.

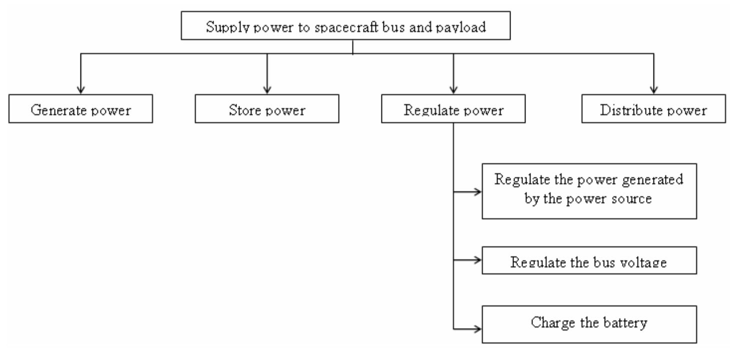

Figure-1. EPS functions requirements.

Typical mass and power distribution

As noted by Takashi (2006) a satellite's mass and electrical power distributions are limited by the space available inside it, and the capacity of the power sources. Consequently, the mass and power distributed to each subsystem of a satellite are determined in the design and strictly managed. These distributions are based on the consideration of the values of the mass and power consumption of each subsystem as specified in the table below:

Table-1. Mass and power distribution in a typical satellite system.

#	**Satellite Sub-Systems**	**Mass** (kg)	**Power** (W)
1	Attitude control system	67	156
2	Propulsion system (total) Apogee propulsion system Gas jet device Ion engine	259 135 29 95	1613 - 42 1571
3	Power supply system (including solar cells paddles)	357	47
4	Thermal control system	90	222
5	Structural system	278	-
6	Telemetry/command system	44	65
7	Cables, harnesses etc	168	31
8	Fuel (total) For apogee motor For gas jet For ion engine	1852 1738 79 35	- - - -
9	Mission payload	674	1656
10	Mass at launch	3797	-
11	Battery supply capacity	-	4492
12	Solar cell paddle capacity	-	4720
13	(Battery charging)	-	(113)
14	Margin	8	702

Power demand assessment

According to Okoro *et al*. (2007) the Satellite System Power Demand Assessment (SPDA) is the benchmark for electrical power delivery capacity of the EPS. Therefore, wrong power demand assessment of satellite subsystem may result to serious system catastrophe. Power requirement usually will defer from one satellite mission profile to the other, which is largely determined by intended orbit of operation, payload among other technical and regulatory stipulations and standards, the SPDA helps to determine realistic and dependable quantity of such electricity to be generated and distributed over a period of time.

Given that;

$$P_{Load} = \sum_{1}^{n} V_n I_n \quad (W) \tag{1}$$

Where n is the no. of sub systems in the satellite to achieve mission objectives, $V_n I_n$ are rms values.

Energy consumption, E_c by load over a period t_n is given as:

$$E_c = \sum_{1}^{n} \left(V_n I_n\right) \times t_n \quad (J) \tag{2}$$

For sub- systems that may require high start up currents, that need to be captured in terms of; frequency of startups, start up and running power (I*V) demand.

$$E_{Load} = \sum_{1}^{n} \left(\frac{E_{cn}}{\eta_n}\right) \quad (J) \tag{3}$$

E_{Load} gives the total energy demand for the entire system load over time t_n in hours for every sub-system. Evaluation of equation (3) will guide in evaluating the power requirement. The E_{Load} provides the consideration for determining power generation and distribution requirements at begin of life (BOL) and end of life (EOL) periods, in relation to the battery discharge and recharge life, the orbit path and the life of the mission.

RESEARCH METHODOLOGY

Intelligent power distribution management system (IPDMS) design

It is evident that the issue of electric power generation, storage and distribution in satellites demands intelligent management and control. The essence of the intelligent power management and control system is to ensure the following:

a) monitoring of the entire EPS performance in relation to the desire objectives, battery current, and voltage charge/ discharge ratio, threshold values and limits (Okoro *et al.*, 2007);
b) run embedded decision program and issue control instructions;
c) power stability, reliability and adequate system protection at all times;
d) fault isolation and system recovery and power regulation and economics in compliance to the design technical specifications and standards.

System modular functions

The modular functions of the IPDMS are categories as:

a) Battery charge/Discharge
b) Power monitoring
c) Power savings
d) Voltage/temperature control
e) Orbit period control

Battery charging module

The battery charging module is designed to allow the EPS batteries to be intelligently and effectively charged and maximize their lifetime. All functions necessary to charge the batteries intelligently are implemented in a battery charger chip and 8-bit microcontroller. The battery charging module additionally monitors the power draw from the load and allows the batteries to be charged with the difference between load and a preset maximum (typically solar array maximum output). With the actual generation of power differing from moment to moment, a current sensor will be used to monitor the power generation by the solar cells the output of which thresholds would be used by the embedded decision program to determine the batteries' state of charge (SOC).

The batteries will not be charged at the same time as they are providing to the satellite system load. This allows the battery a long life and ensures that the battery will charge only when enough power is generated by the solar cells.

Power monitoring module

The power system may literally be tasked beyond what it is capable of generating when all systems are in operation. Therefore several key procedures are implemented to allow the power system to function adequately and the mission to succeed.

The power generated by the solar cells must be monitored to keep from crashing the system by asking too much of power (Rauschenbach, 1990).

Power savings module

To save power the satellite will cycle its receiver, transmitter and terminal node controller on and off. The cycle is expected to be 1 minute on and 6-7 minutes off. This saves enough power to charge the batteries while still allowing the satellite to be contacted by the Earth station. And when the ground station contacts the satellite, it will keep the communication package on until it finishes its downlink of data. It will then resume the cycling, this will produce significant amount of power savings.

During eclipse periods, if for any reason the battery drops below an acceptable level indicating a low

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SOC, the IPDMS will respond by shedding non-critical loads in idle mode. This reduces or sheds the load on the battery and allows its voltage to recover from the undesirable low level.

Voltage/temperature limit control

If the power generated by solar array exceeds the power requirement of the subsystem loads, that excess is taken up by the batteries. The purpose of the IPDMCS is to manage the dissipation of excess solar array power not needed for battery charging. This is achieved by software control of digital switches to shunt out individual solar array circuits to regulate supply of power for battery charging. To best maintain battery health, the IPDMS provides automatic charge cutback if it detects excessive battery voltage, pressure, or temperature. The battery recharge controller allows all available solar current to charge the battery as long as the charge efficiency is high and the charge is not stressing the battery. As the battery approaches full SOC, the charging becomes less efficient and the process becomes increasingly exothermic. Before the heat dissipation becomes excessive, the controller (IPDMS) must lower the charge rate from full to reduced charge; when the battery is full, it must reduce the rate further to trickle charge. The point where the controller should reduce the charge rate depends partly on the amount of exothermic stress that the battery can safely tolerate and partly on the heat rejection characteristic of the battery thermal design (Krummann, 2000).

Battery charge rates (Vandenberg *et al.*, 2002; Ulrich *et al*., 2006):

i) Fast/maximum charge rate
ii) Reduced/cut-back charge rate
iii) Trickle charge rate

The Charge Control Algorithm (CCA) of the IPDMS bases its charge rate selection on battery voltage, pressures/temperatures, and SOC based on the design of Bonnema (2003). Assuming that during a normal charge no excessive pressures/temperatures, voltages show up, the SOC is the sole factor determining which charge limit to use. The most important element in the algorithm is the charge counter which computes the battery SOC (Panneton *et al*., 1996).

Software design and implementation

The system specifications and configurations based on the design template provided by Patel (2005) are as highlighted below:

- The system design shall provide for the storage and management of electrical power to the spacecraft payloads and housekeeping loads during the entire mission life of five years;
- Operational orbit load: during sunlight 1500Watts, during eclipse 1000Watts;
- Bus voltage 28Vdc ±1V regulated direct energy transfer bus. Telemetry System parameters to monitor the power system operation;
- Autonomous operation in all normal functions, unless overridden by ground command;
- Power management software to control the battery state of charge/discharge, temperature, charge/discharge balance between batteries, power cycling and load shedding, if and when necessary;
- Two batteries, each with Li-ion cells with 60 A-hr ratings;
- Maximum worst-case battery Depth of Discharge (DOD) is set 60 percent during operational orbit;
- Battery charge rates: Fast = 3A; Reduced = 1.5A; Trickle = 0.5A.
- Battery temperature to be maintained between 0oC and 70oC ±5oC;
- Battery cell lifetime (number of discharge-recharge cycles that the cell can withstand before failure) = 20,000 cycles.

Power storage and management algorithm

System initialization

At power up, system checks for faults and starts control variables monitoring loops to determine battery presence, battery SOC, DOD, temperature levels. See program flowchart (Figures 2 and 3).

Power monitoring module

Battery charging

Checks solar array output power. If solar power generated exceeds the power requirement for subsystem loads, excess power is used to charge battery. If excess power for battery charging exceeds battery's charge requirement enable power shunt mode and send telemetry alert to ground station for analysis.

Battery discharging

System checks solar array output power, if it is insufficient to service power requirement by subsystem loads and battery charging, batteries operate in discharge mode to make up for insufficient solar power supply. If power supply inadequacy is due to excessive power demand by subsystem loads, system triggers alarm and send telemetry alert to ground station. System checks battery Depth of Discharge (DOD), if it is less than 60 %, the system responds by enabling shedding of non-critical loads and send telemetry alerts to ground station for analysis. If DOD decreases to 10 %, system aborts any operation in progress, sends telemetry alerts and resets the spacecraft to parked attitude. At the park mode, if the aborted operation was holding the solar array fixed and away from the sun, then the park mode allows the solar array to reorient towards the Sun and begin recharging the battery.

Power storage module

At orbit sunlight period, the battery charge mode is enabled, system checks battery SOC, through the instrumentation of current sensor, if it is less than 60% and

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in normal operating temperature, system operate at Fast Charge Mode. If SOC is equal or greater than 80% and less than 98%, and, in normal operating temperature, system operates in Reduced Charge Mode. If SOC is above 98%, system operates in Trickle Charge Mode.

Temperature control module

During battery charge mode, system checks batteries for overcharge or exothermic reaction. If temperature is greater than 28^{o}C, batteries charge at trickle charge mode.

Orbit period control module

System checks solar output current sensor. If sensor output value is set to LOW, it indicates eclipse period, then battery discharges to power subsystem loads. Then, enable power cycling and load shedding modes. If solar output current sensor is set to HIGH, it indicates sunlight period and solar output is sufficient to power subsystem loads as well as charge battery, then battery operates in charge mode. Then, disable power cycling and load shedding mode.

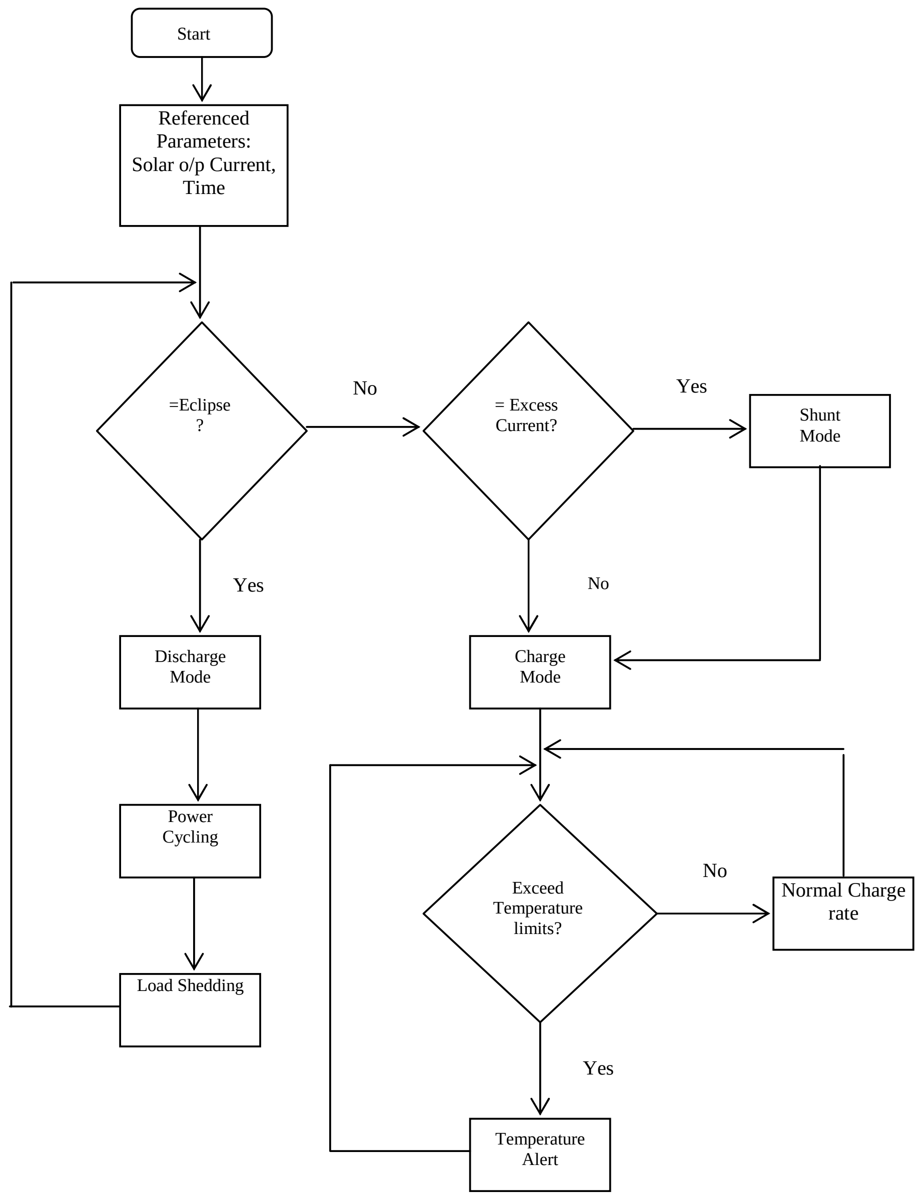

Figure-2. Power distribution management program flowchart.

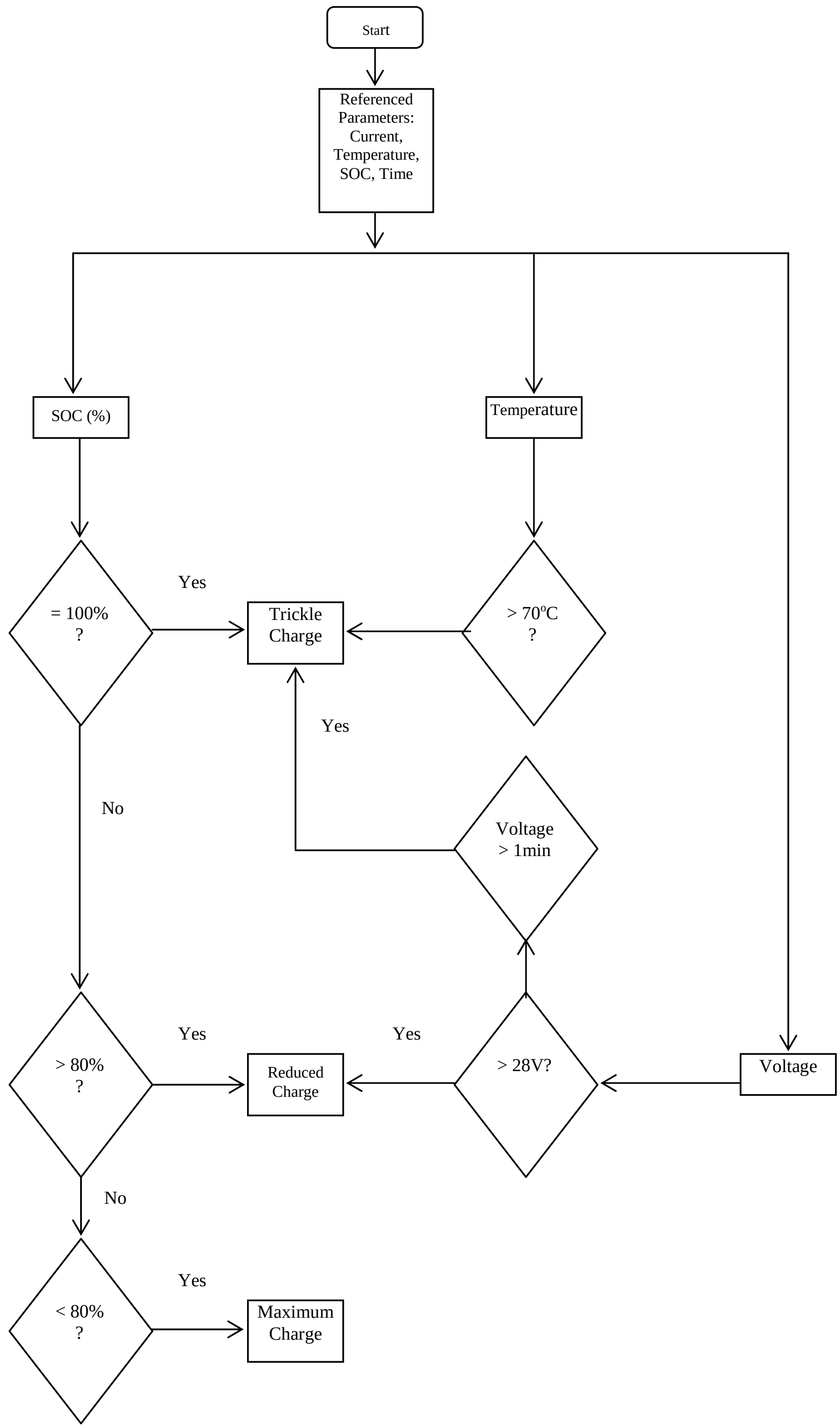

Figure-3. Battery charge program flowchart.

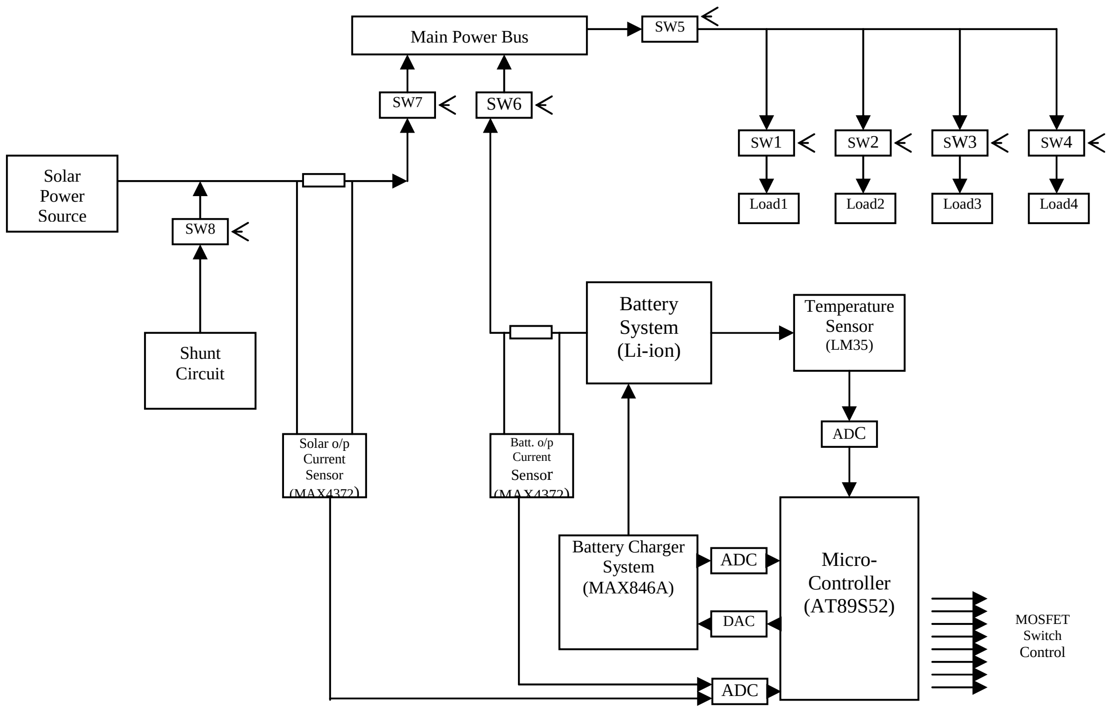

Figure-4. IPDMS functional block diagram.

RESULTS AND DISCUSSIONS

Following the complexity of satellite electrical power sub system and the peculiar conditions in the outer space, simulation of the controlled system variables for virtual system test is inevitable. The Java programming language was used to realize the concept of "simulating before developing". The system controlled parameters which were derived from the outputs of the current and temperature sensors were simulated.

Battery charge mode

Java Simulation model was used for virtual testing of IPDMS to assess the satellite IPDMS system performance and reliability. The IPDMS provided intelligence for real-time power storage during sunlight orbit period. The system operated in charge mode when the satellite is in sunlight. The charge rate regimes of fast, reduced and trickle charge rates were actuated for the battery state of charge (SOC) threshold levels of less than 60%, between 60% and 98%, and greater than 98% respectively. At the battery temperature threshold value of greater than 70^{o}C, IPDMS actuated the trickle charge rate to cutback charge rate and to prevent the battery from experiencing irreversible and destructive exothermic reaction. As a result, the battery lifespan is preserved.

Battery discharge mode

During eclipse period, the IPDMS detected this condition by monitoring the output of the solar source through a current sensor and actuated the battery discharge mode through a microcontroller energised digital switch to supply power to the satellite. The IPDMS economised power through load shedding and power-cycling. The power cycling and the load shedding modes conserved energy supplied from the battery during eclipse period. IPDMS cycled power supply to idle loads off and on for 6 minutes and 1 minute, respectively. It shed switchable loads that are not in use during eclipse period to isolate them from unnecessary power consumption.

Solar output monitoring

In the event of excessive solar power supply, IPDMS through the current sensor connected to the output of the solar source detected this condition and energized a shunt circuit to absorb excess power to prevent it from destroying the system. On the other hand, in the event of insufficient solar power supply, IPDMS actuated battery discharge mode to make up for the insufficient power supply to satellite loads for reliable and efficient operation

CONCLUSIONS

This project achieved the design of a microcontroller-based Intelligent Power Distribution Management System (IPDMS) for application in the automatic coordination of power storage, power savings, load switching and battery temperature control in a satellite EPS. The system achieved an improvement over the conventional satellite power management and control systems in terms of system's size and weight reduction; independence of Electric Power Subsystem's operation from satellite onboard Central Processing Unit (CPU); self-contained intelligence for improved system responses to power emergences; and simplified programming and reprogramming possibility using high level C language codes.

Finally, the work provided a basis for the design and implementation of system intelligence for satellite's power generation management in the future.

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