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DESCRIPTION OF THE CONTROL SYSTEM DESIGN FOR THE SSF PMAD DC TESTBED

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ABSTRACT

NASA Lewis Research Center and Rockwell International, Rocketdyne Division, are responsible for the design, development, and testing of the Space Station Freedom (SSF) Electrical Power System (EPS). The SSF EPS has evolved from an early baseline of a Hybrid Solar Dynamic/Photovoltaic Power Generation with 20kHz AC power distribution system to a Photovoltaic power generation with a DC power distribution system. In order to help identify technology risks and system level issues during this EPS evolution, and during the design and development phase, a supporting development end-to-end Power Management and Distribution (PMAD) DC testbed program has been initiated and various phases completed. One of the testbed program main objectives is to build a power system testbed that will serve as the platform for the evaluation of various power system control techniques. These power system control techniques have been developed based on high level EPS system requirements and operating scenarios.

Because of the Space Station Program Restructure that took place in November/December 1990, the allocation of control functions between ground and on-orbit is being reassessed. However, because of the maturity of the work, it was decided to complete the original implementation of the control system described in this paper. Efforts are currently underway to adapt to this revised allocation of functions.

The PMAD DC Testbed Control System has been developed using a top down approach based on classical control system and conventional terrestrial power utilities design techniques. The design methodology includes the development of a testbed operating concept. This operating concept describes the operation of the testbed under all possible scenarios. A unique set of operating states has been identified and a description of each state, along with state transitions, was generated. Each state is represented by a unique set of attributes and constraints, and its description reflects the degree of system security within which the power system is operating. Using the testbed operating states description, a functional design for the control system was developed. This functional design consists of a functional outline, a text description, and a logical flowchart for all the major control system functions.

The detail design phase consists of performing functional decomposition and allocation of the functional design, and generating detailed flowcharts, or pseudo code, input/output descriptions, timing and data format constraints, and software implementation considerations. A software implementation of the detail design includes the generation of a Software Requirement Specifications and a Software Development Plan.

This paper describes the control system design techniques utilized, a brief description of the various control system functions, and the status of the design and implementation.

INTRODUCTION

The NASA LeRC DC PMAD Testbed is a reduced scale representation of the EPS on the SSF. The testbed program's main objective is to support the identification of electrical power system technology risks and system level issues during the design and development phase of the SSF EPS. In addition, the unique capabilities afforded by the testbed will allow the evaluation of candidate power system design concepts, and early prototypes of space power components. System level issues like end-to-end system stability, power system protection, power system control, and subsystems interactions, among others, are being evaluated in the testbed. A complete description of the development and evolution of power system testbeds to support the Space Station Freedom Program is found in reference [1].

In its final configuration, the PMAD Testbed will consist of two DC power channels as shown in Figure 1. Each power channel consists of a Solar Array Sequential Shunt Unit (SSU), a DC Switching Unit (DCSU), Battery Charge and Discharge Units (BCDU), Battery Simulators, a Main Bus Switching Unit (MBSU), DC to DC Converter Units (DDCU), Secondary Power Distribution Units (SPDU), Tertiary Power Distribution Units (TPDU), and Load Converter Units (LCU). A detailed description of the DC Testbed architecture and all its major components is found in reference [2].

CONTROL SYSTEM DESCRIPTION

The SSF EPS, because it spans the entire SSF structure,lends itself to a distributed control system architecture. The DC testbed control system, in its final configuration, will consist of eleven standard controllers arranged in a distributed, hierarchical architecture as shown in Figure 1. This hierarchical control system provides the monitoring and control functions for the testbed power system. The testbed control system requirements are to continuously monitor and determine the state of the testbed electrical power system, and to periodically provide its status to the Operator Interface System (OIS). The control system design will augment power system fault protection and provide manual and automatic power component control.

The overall testbed operation is overseen by the OIS. The OIS serves as the testbed operator interface and provides some of the functions that the Operations Management System (OMS) will perform for the SSF EPS. The Power Management Controller (PMC) is the highest level controller in the EPS, and serves as the overall EPS coordinator. The PMC performs all high level functions associated with the operation of a safe and robust power system. The PMC coordinates the various levels of the hierarchy; it receives high level commands from the OIS and provides EPS status information to the testbed operator.

The PMC coordinates the operation of the control system subsidiary controllers. The lower level controllers consist of Photovoltaic Controllers (PVC) and Main Bus Controllers (MBC). The PVCs provide monitoring and control functions to the SSUs, BCDUs, and switchgear (Remote Bus Isolators, RBIs) that comprise the DCSU. The MBCs monitor and control the operation of the DDCUs and the RBIs that comprise the MBSUs. A Load Management Controller (LMC) serves as the secondary and tertiary power distribution controller and coordinates the operation of the Secondary Power Controllers (SPC) and Tertiary Power Controllers (TPC). The SPCs control the operation of the switchgear that comprises the Secondary Power Distribution Units and the TPCs control the operation of the switchgear that comprises the Tertiary Power Distribution Units. The secondary and tertiary switchgear consists of RBIs and Remote Power Controllers (RPCs). The LMC provides the PMC with secondary and tertiary power distribution status information; although this function is not currently in WP-04, it is needed to demonstrate end-to-end operation of the testbed. A hierarchical, functional breakdown of the control system is shown in Figure 2. In this diagram, the major functions associated with the different levels of the architecture are shown allocated to the various controllers.

The control system standard controllers are 20 MHz, Compaq 386/20e personal computers. Each standard controller is configured with operating software and the appropriate peripheral hardware to perform its given function. The PMC provides command and control data to the subsidiary controllers via an 802.4 Token Bus, local area network. The subsidiary controllers provide command and control data to the testbed power components via a MIL STD 1553B Data Bus.

CONTROL SYSTEM STATES

The operation of the DC Testbed power system can be represented using state space analysis and conventional terrestrial utility power system design techniques. A state transition diagram of the DC testbed power system is shown in Figure 3. The testbed power system is considered to have seven operating states. Each state is described by a unique set of attributes and constraints, and characterizes the degree of system security within which the power system is operating. The operating states can be classified as being either MANUAL or AUTOMATIC, based on the degree of operator intervention that is required to operate the testbed. The testbed is operating in the MANUAL mode when the testbed operator is in complete control of the testbed components. The operator can select a testbed configuration and can set testbed component operating parameters to satisfy a specific component or subsystem test. The MANUAL mode of operation is unique to the testbed and is being used extensively during integration of the various elements of the testbed and during evaluation of power system design concepts.

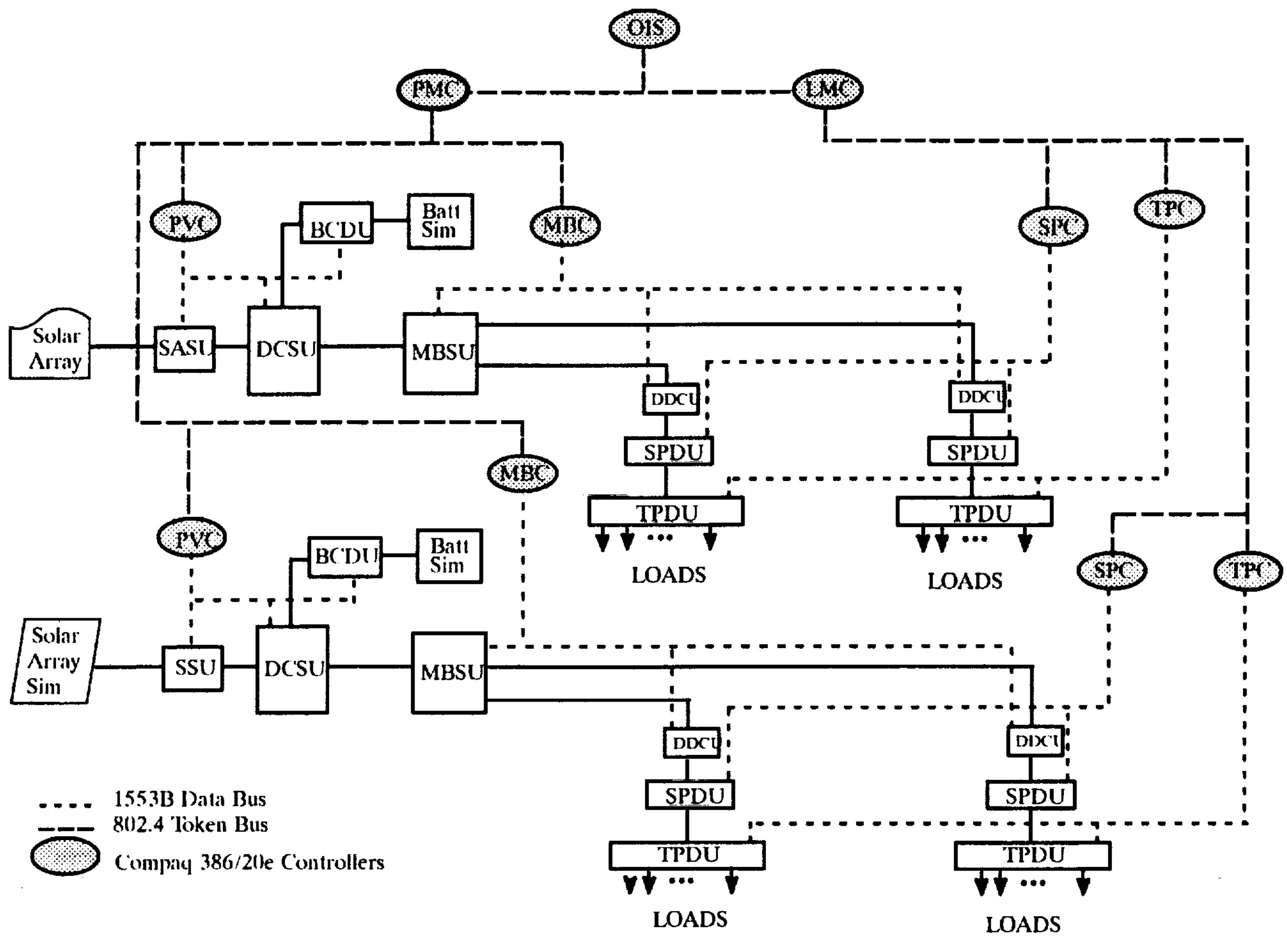

Figure 1 DC PMAD Test Bed Control System Block Diagram

The AUTOMATIC mode of operation is characterized by the autonomous operation of the testbed EPS. The functions that comprise the AUTOMATIC mode of operation are designed to maximize the degree of power system security. System security is a function of the robustness and efficiency with which the power system reacts to disturbances. Power system disturbances include overloading by the users and faults and failures within the power system. Unlike a terrestrial utility power system where loads can be turned on and off without being scheduled, the SSF will have to scheduled loads carefully due to limited power source capacity. Consequently, the SSF will require a highly autonomous EPS for maximum power utilization. The functions that comprise each of the AUTOMATIC states will consist of a combination of power system hardware, and power system control software and hardware. Scheduled disturbances within the operating constraints are dictated by a Short Term Plan (STP). The STP is a time correlated load schedule that is provided to the testbed control system by the OIS, and represents the users load requirements as a function of time.

The six autonomous states of operation are: START-UP, SHUT-DOWN, NORMAL, ALARM, EMERGENCY, and RESTORATIVE. The Start-Up and Shut-Down states are unique to the testbed and are considered for completeness in the state space analysis. These states comprise the necessary functions to perform an orderly and safe start-up and shut-down of the testbed components. The other four states are commonly found in utility power system security monitor designs [5].

The NORMAL state of operation is characterized by a high degree of system security. The power system is operating in the NORMAL state if the STP is being serviced autonomously, the power distribution hardware is operating within rated values, sufficient energy is available to satisfy the users, and power system constraints are not violated.

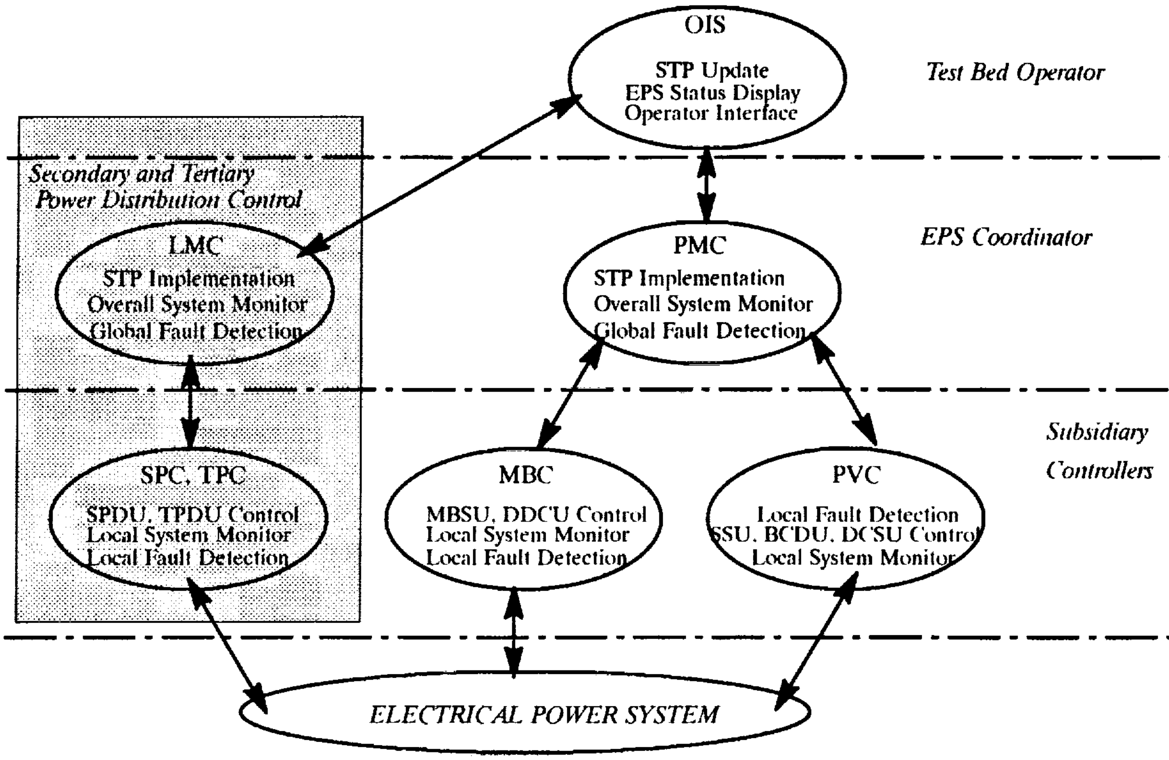

Figure 2 Hierarchical Functional Breakdown

The ALARM state of operation is characterized by a decrease in the system security level. The power system monitoring function has detected a contingency that decreases the operating margins. The functions that comprise the ALARM state are suited to try to remove the contingency and return the power system to its NORMAL state of operation. The ALARM state is not a secure state and consequently the power system control will try to transition the system to NORMAL state. If these control functions fail, the system transitions to the EMERGENCY state.

The EMERGENCY state of operation is characterized by a drastic reduction of system security. In this state the power system operating conditions are degrading and operator intervention has been requested. In this unsecured state, the operator will manually reset parameters in order to transition the system to a more secure state. The users load requirements in the STP cannot be fully met and system operating parameters are violated. The operator takes the appropriate actions to transition the power system to the RESTORATIVE state. In the testbed, the operator has the option to shut-down the testbed power system partially or completely to avoid further damage. In the Space Station Freedom the scenario will be slightly different with the station management system taking appropriate action to transition the system to a secure state by either shutting down portions of the power system or sending repair crews to fix the problem.

The RESTORATIVE state is a transitional state and its major function is to restore the power system to a safe operating condition. The functions that comprise this state are designed to transition the power system to the NORMAL state. The power system can transition back to the EMERGENCY state, from which automatic safing again is implemented. The ALARM, EMERGENCY, and RESTORATIVE states of operation can be collectively referred to as Off-NORMAL States.

CONTROL ALGORITHMS DESCRIPTION

The state diagram shown in Figure 3 represents the operation of the testbed power system. The power system is composed of three elements: the power distribution system hardware, power system control hardware, and the power system control software. The functions that comprise each one of the states depicted in the testbed state diagram are implemented by a combination of the three elements described above [3]. The remainder of this paper will address the functions being implemented by the control system hardware and software.

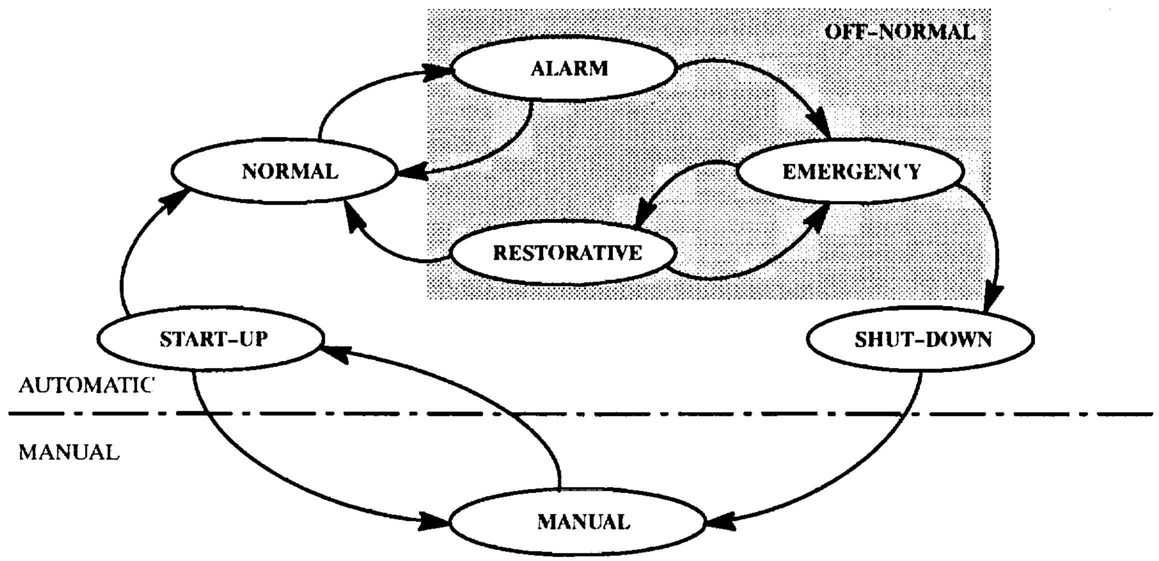

Figure 3 DC PMAD Testbed Control System State Diagram

Table 1 lists the allocation of the major control algorithms for the different states of the power system. A complete functional design of the control system algorithms that implements the state diagram shown in Figure 3 has been completed at the NASA LeRC. Each power system state is characterized by a unique set of attributes, which can be translated into functions that can be implemented either as algorithms or hardware functions. All the functions defined up until now can be classified either as cyclic, or synchronous, or event driven. A cyclic function is based on the periodic occurrence of a task or a known disturbance. Event driven functions are activated by the detection of an unscheduled disturbance in the power system. Most of the work completed at NASA LeRC has been in the area of NORMAL state of operation. The following is a detailed description of the major functions that comprise the NORMAL state of operation and provides an insight into the specifications needed for software implementation.

The NORMAL State algorithms are classified as either event driven or cyclic functions, and are collectively referred to as NORMAL State Processing. The cyclic functions include Short Term Plan (STP) Implementation, System Monitoring, and Off-NORMAL Detection. The event driven functions include Operator Override and Off-NORMAL Processing.

Optimal operation of the power distribution system will require that:

(1) The control computers pre-approve user loads for operation during specific time slots.

(2) The control computers accurately monitor the power system.

(3) The control computers backup the hardware protection schemes.

		CONTROLLER			
State	**ALGORITHM**	**PMC**	**PVC**	**MBC**	**SDC**
Normal	STP Implementation	✓			✓
	System Monitor	✓	✓	✓	✓
	Fault Protection	✓	✓	✓	✓
Alarm	STP Implementation	✓			✓
	System Monitor	✓	✓	✓	✓
	Fault Protection	✓	✓	✓	✓
	Contingency	✓			
Emergency	System Monitor	✓	✓	✓	✓
	Fault Protection	✓	✓	✓	✓
	Contingency	✓	✓	✓	
	Manual Override	✓			
Restorative	STP Implementation	✓			✓
	System Monitor	✓	✓	✓	✓
	Fault Protection	✓	✓	✓	✓
	Contingency	✓			

Table 1 Functional Allocation

SHORT TERM PLAN & SYSTEM INITIALIZATION

System Initialization can be defined as the sequence of procedural calls which, based on present system constraints and parameters, determines the appropriate setpoints for the system to operate in a NORMAL State during the upcoming user demand cycle.

Unlike a terrestrial utility's load profile which is statistically predicted, Space Station Freedom's STP must be carefully planned and regulated due to the limited energy availability. The STP defines the load type, location, and the peak and nominal requirements for users, batteries, and DDCUs. The STP is created by the *Operator Interface System*, using a default topology and ideal hardware parameters, and is verified before the testbed is "turned-on." However, the runtime conditions will cause these parameters to change and preclude certain topologies (e.g., sources available). Thus, the objectives of STP Implementation, which is a dynamic process, are to ensure energy availability throughout the operating orbit, ensure safe operation of the power distribution hardware, accommodate changes in the distribution system's runtime parameters (e.g., topology, line parameters, DDCU efficiencies, actual energy available), and adjust setpoints (e.g., battery operation mode, source balancing, and hardware trippoints).

Because the user loads are fed by DDCUs, each channel of the testbed power distribution system is broken into a primary and two subsidiary distribution systems (Figure 1). This leads to three initialization procedures: one for the PMC and two for the LMC. The tool used to initialize the subsystems is *Load Flow* [Ref. 6], because constant power, current, and resistive loads are defined.

The LMC implements two STPs which define the specific user loads (i.e., the loads connected to the *Tertiary Power Distribution Units*). The PMC implements an STP which characterizes the loading of the DDCUs (as predicted by the LMC and reflected to the primary distribution system).

Each subsystem initialization requires two load flows. One is for nominal load requirements, and the other for peak requirements. The objectives of each are given below.

Nominal requirements must be analyzed to:

(1) Initialize the digital filters.

(2) Assure nominal operating voltages are acceptable.

(3) Assure sufficient energy and power for users.

(4) Assure that the steady state ratings of hardware are not exceeded.

Peak demands are analyzed to:

(1) Set the "soft limits" on switchgear. These are the maximum expected current flows and minimum voltages, and serve as thresholds to set Caution & Warning flags. The "soft limits" of hardware are the expected maximum values, which are below the ratings of a device.

(2) Determine the maximum energy and power required from the sources.

(3) Seed the Power Interrupt Detection algorithms.

Limited, predictive, autonomous, batch-contingency analyses are implemented whenever the present system setpoints and topological parameters would result in an unsafe or unacceptable operating point. Violations include insufficient energy, over-stressed sources and hardware, and unacceptable bus voltages.

Upon completion of an acceptable operating point, the LMC and PMC send the results of their respective initialization procedures to the subsidiary controllers. The subsidiary controllers (MBC, PVC, SPCs, and TPCs) control and monitoring functions are then initialized, according to the load flow results. The system is then ready to implement the setpoints at the onset of the next demand period and continue system monitoring.

SYNCHRONOUS SYSTEM MONITORING & POWER SYSTEM PROTECTION

System Monitoring can be defined as the process in which controllers periodically and synchronously sample and collect sensor data, smooth it, analyze it for acceptable system performance, and prepare an appropriate message for a control node, which implements the required control function.

By definition, the power system must be monitored for the following reasons:

(1) To ensure the safe operation of the system.

(2) To track energy consumption and storage.

(3) To verify locally detected power interrupts and faults.

(4) To smooth data and update the Operator Interface System with EPS operating parameters.

System Monitoring occurs at two levels. The local processors (PVC, MBC, SPCs, and TPCs) collect data synchronously, and the PMC asynchronously receives the MBC and PVC data to perform an asynchronous, but periodic, state estimation (SE) [Ref. 7].

Power system operating points, voltages and currents, are sampled at a 10Hz rate in the testbed [4]. All sampled data is digitally filtered by a third order, Butterworth algorithm, which smooths out load modulations, reduces the effects of sample skewing, and reduces the occurrences of "bad data identification" by the SE. Data which is smoothed by the Butterworth filter is referred to as *prefiltered*.

It should be stressed that the software monitoring and protection schemes are intended to be a backup to the hardware. As such, the response times of the software are slower than the worst case hardware times, but not so slow as to cause continued, degraded or dangerous system operation. An overview of the levels of backup is:

(1) At the tertiary distribution levels the controllers implement undervoltage detection (UVD), power interrupt detection (PID), and overcurrent detection (OCD) algorithms.

(2) At the secondary distribution levels the controllers provide backup protection to the DDCUs and secondary subsystems. Thus, in addition to UVD, OCD, and PID, bus and line hard fault detection (HFD) are implemented. HFD is implemented in the LMC because the TPCs and SPCs do not have access to all required data.

(3) At the primary distribution level, the software should provide backup protection for the sources, roll rings, switchgear, and distribution lines, and it should ensure energy availability. Thus, UVD, PID, OCD, and HFD are all implemented in the MBC and PVC. Furthermore, SE is implemented in the PMC to detect "soft faults" on lines and buses.

PID, which is resident in all subsidiary controllers, uses two consecutive, unfiltered values and a boolean expression (Eq. 1) to identify a power interrupt condition in switchgear that is expected to be closed (E=1) and carrying power. Unfiltered values are used because fast action is required. The required electrical values are voltage and current. If the readings are greater than 60% of the expected minimum values, then the logical terms V and I are set to "1," else they are set to "0." Also, switchgear provides the following additional information: a relay status bit (1=closed, 0=open) and a trip bit (1=tripped, 0=not tripped). The trip bit is used to indicate whether the PI is a result of a local (T=1) or upstream (T=0) "fault."

$$\boxed{\begin{array}{c} PI = E\,(\bar{V}_k\bar{V}_{k-1} + \bar{I}_k\bar{I}_{k-1}) \\ k = \text{present sample} \end{array}} \qquad \text{Eq. 1}$$

Under Voltage Detection uses prefiltered data to identify bus voltages operating under 90% of the expected minimum value, but over the 60% "power interrupt value." Thus, this is "brownout detection." Furthermore, because there are redundant (at least two) voltage measurements at each bus, the UV condition is detected only if a majority of readings agree to within sensor accuracies.

OCD scans the switchgear readings for currents in excess of the expected peak values ("soft" overcurrents) and over the device ratings ("hard" overcurrents). Because *caution & warnings* or *preventative control* should not be implemented due to transients, OCD uses prefiltered data.

HFD (bus and line) is also performed in the subsidiary controllers with prefiltered values, and is referred to as "hard" because the level of faults detectable is limited to values greater than full-scale, sensor accuracies of the actual current flow. (Thus if a line is carrying 100Amps, 5% measurements can only detect faults greater than approximately 5Amps.) The method used to detect such faults is differential protection, which simply requires that the sum of currents into a node equal zero. Applied to measurements in the testbed, this requirement translates to the generalized nodal equation (Eq. 2).

$$\boxed{\begin{array}{c} \dfrac{1.0 - Acc}{1.0 + Acc} < \dfrac{\Sigma \text{ input currents}}{\Sigma \text{ output currents}} < \dfrac{1.0 + Acc}{1.0 - Acc} \\ Acc = \text{Measurement accuracy} \end{array}} \qquad \text{Eq. 2}$$

A description of the software implementation of the above mentioned functions in the Ada programming language is found in reference [4].

CONCLUSIONS

Unlike terrestrial utility power systems, the SSF EPS will have to carefully schedule and monitor loads, due to the limited available energy. The EPS control system will play an important roll when maximizing the use of electric power in the Space Station Freedom. In its initial configuration, the SSF EPS control system functionality will be kept to a minimum to comply with program constraints. As the SSF EPS evolves and becomes operational, the EPS control system functionality is expected to approach that of an autonomous electrical power system. The SSF EPS control system functions will be implemented on board the space station and in the ground based control center. This paper has presented power system control algorithms, being implemented in the PMAD DC Testbed, that are considered to be essential to the operation of an autonomous electrical power system. These algorithms are candidates for implementation on board the Space Station Freedom, or in the ground control center.

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NASA Lewis Research Center and Rockwell International, Rocketdyne Division, are responsible for the design, development, and testing of the Space Station Freedom (SSF) Electrical Power System (EPS). The SSF EPS has evolved from an early baseline of a Hybrid Solar Dynamic/Photovoltaic Power Generation with 20 kHz AC power distribution system to a Photovoltaic power generation with a DC power distribution system. In order to help identify technology risks and system level issues during this EPS evolution, and during the design and development phase, a supporting development end-to-end Power Management and Distribution (PMAD) DC testbed program has been initiated and various phases completed. One of the testbed program main objectives is to build a power system testbed that will serve as the platform for the evaluation of various power system control techniques. These power system control techniques have been developed based on high level EPS system requirements and operating scenarios. Because of the Space Station Program Restructure that took place in November/December 1990, the allocation of control functions between ground and on-orbit is being reassessed. However, because of the maturity of the work, it was decided to complete the original implementation of the control system described in this paper. Efforts are currently underway to adapt to this revised allocation of functions. The PMAD DC Testbed Control System has been developed

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