



Simulation of a Lunar Surface Base Power Distribution Network for the Constellation Lunar Surface Systems

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Abstract

The Lunar Surface Power Distribution Network Study team worked to define, breadboard, build and test an electrical power distribution system consistent with NASA's goal of providing electrical power to sustain life and power equipment used to explore the lunar surface.

A testbed was set up to simulate the connection of different power sources and loads together to form a mini-grid and gain an understanding of how the power systems would interact. Within the power distribution scheme, each power source contributes to the grid in an independent manner without communication among the power sources and without a master-slave scenario. The grid consisted of four separate power sources and the accompanying power conditioning equipment. Overall system design and testing was performed. The tests were performed to observe the output and interaction of the different power sources as some sources are added and others are removed from the grid connection. The loads on the system were also varied from no load to maximum load to observe the power source interactions.

1.0 Introduction

To begin the process of exploring the design and layout of a lunar power distribution system, a breadboard power distribution system has been utilized. The objective of the power system testing is to demonstrate the ability to connect multiple independent power sources and have them operate as a single system when powering a given load or loads. This type of integration and operation is meant to simulate the connection and operation of various power sources that would be present on the lunar surface.

One of the primary considerations of this power distribution system is the ability to expand as the lunar presence grows. This is a critical aspect to the overall distribution design. Ideally the system design will enable additional sources to be integrated into the distribution system and loads added to the system as needed. This modular/expandable approach will *ideally* enable the system to expand with minimal disruption or modifications.

To provide this capability, a power distribution scheme has to be devised that is flexible and can grow as the system expands. The special requirements of the lunar environment have to be taken into account as well as the likely power sources that will be available. The main drivers for this type of system are efficiency and mass. Ideally the system will be as efficient as possible to help reduce the demands on the power generation requirements, thereby reducing the required size of the power sources. Also by enabling the various power sources to be connected together, this overall power system architecture provides the ability to maximize the use of the power producing assets distributed over the lunar surface. The system design will also be focused on minimizing the mass of the conversion and transmission components, such as cabling, inverters and transformers. The mass of these components can be influenced by carefully selecting voltages, frequencies and layout.

The objective is to define an electrical power system architecture that connects the multiple energy sources and technologies called out in the Lunar Architecture Technology II (LAT II) to the loads (habitat, rovers, robots, tools, etc.). The major design factors to be investigated will include:

- The most efficient network operating voltage level and frequency;
- Techniques for paralleling multiple sources
- Transformer design
- Energy storage options
- Transmission cable; semi-conductors and the availability and applicability of existing equipment.

There are significant differences between a typical distributed surface power system, such as the lunar surface power system, and a close-proximity/localized power system, such as a spacecraft power system. For example, first and foremost, in a wide-area distributed power system, the distances between the sources and loads are significant, therefore requiring a close scrutiny of the power distribution concepts. Second, due to the “utility-like” nature of the power system on the lunar surface, where there are dynamic and diverse sets of loads and sources, a design philosophy of power system availability would be a better concept to pursue, than mere fault tolerant design concepts.

In short, the differences between distributed and localized systems necessitate a critical upfront examination of design philosophies for a lunar surface power system which could be substantially different than concepts used for spacecraft power system design.

This study will therefore utilize the combined experience of designing spacecraft power systems (ISS-160 V DC, Shuttle 28 V 400 Hz) with the experience of the terrestrial power industry to guide the design of the power network. The power system network design should rely on mature technologies, and must be expandable, robust, and adaptable to any energy source and load combination.

2.0 Lunar Environment

The Moon (shown in Figure 2.1) is a dry, crater-filled land with no appreciable atmosphere. The temperature difference from the sunlit areas to shadowed areas can exceed 300 K. The surface is covered with a fine powdered regolith made from eons of bombardment by meteors, asteroids and comets.

The Moon orbits the Earth every 27.3 days. It is tidally locked to the Earth and therefore it rotates at the same rate it orbits the Earth. This causes the same side of the Moon to face the Earth all of the time. Having the same side continually face the Earth provides an advantage when it comes to communications. A device or system placed on the Earth-facing side of the Moon can be in constant communication with Earth without the need for a lunar satellite communication system. Another unique orbital characteristic is its low declination angle of approximately 1.5°. This angle means that there is very little variation in solar elevation throughout the year and little seasonal effect. Because of this, locations at high elevations near the poles would be in constant sunlight throughout the year. The Clementine spacecraft has identified just such a location in 1994 (Ref. 1). This location, which is continuously illuminated, is on the rim of the Peary crater at the Moon’s North Pole. An image of the lunar South Pole is shown in Figure 2.2 (Ref. 1). Some additional physical characteristics of the Moon are listed in Table 2.1.



Figure 2.1.—Image of the Moon.

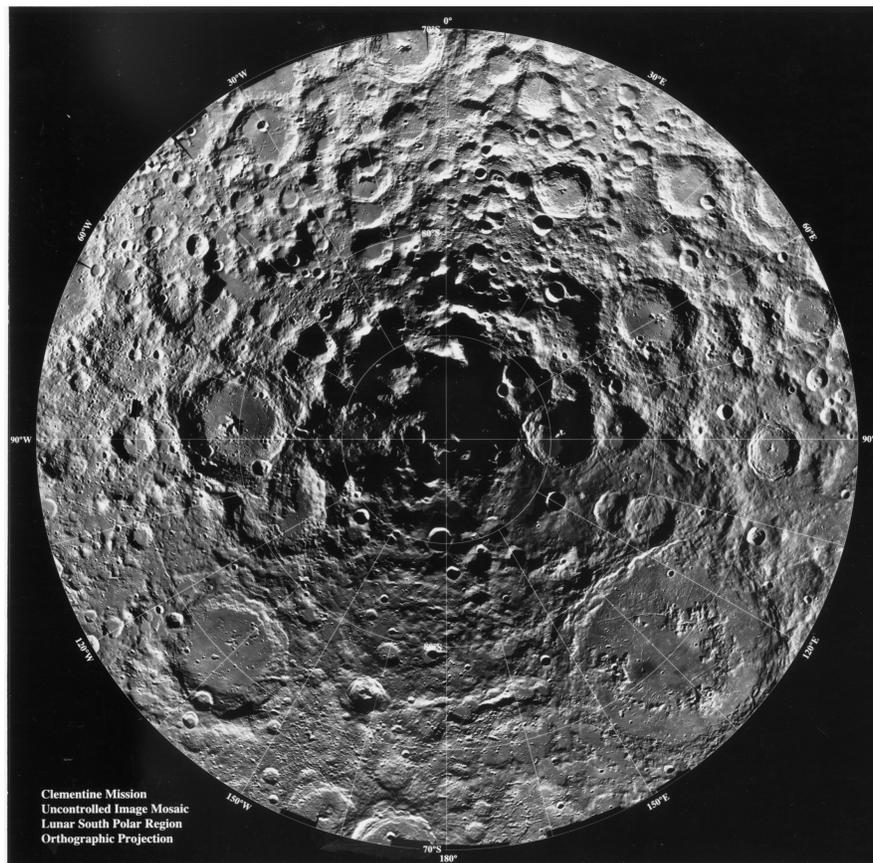


Figure 2.2.—Lunar South Pole.

TABLE 2.1.—MOON'S PHYSICAL PROPERTIES (REFS. 2 AND 3)

Parameter	Value
Declination angle	1.5°
Orbital eccentricity (ε).....	0.0549
Day length	655.7 hr
Distance from Earth	
Perigee.....	363,300 km
Apogee	405,500 km
Surface Gravity (g).....	1.623 m/s ²
Surface Temperature Range.....	102 to 384 °K

2.1 Surface Characteristics

There are two main types of terrain on the lunar surface, the highlands and the mare. The highlands are the older, brighter regions (as seen from Earth) of the lunar surface and are significantly cratered. The mare are darker regions which are basaltic lava flows. These areas can be seen in the topographic map of the lunar surface shown in Figure 2.3. The blue and purple regions are the lower-lying mare regions while the red, orange and yellow areas are the upper highland regions. The lunar regolith, which covers the surface of the Moon, consists of fragments of rocks, minerals and glass spherules formed when meteors or other bodies impacted the surface. The regolith thickness varies greatly with location on the lunar surface. In the mare the thickness can vary between 3 to 16 m whereas in the highlands it is at least 10 m thick (Ref. 2). The chemical or mineral composition of the regolith is similar to the underlying bedrock from which it was derived. There is little mixing of material between the highland and mare regions. The composition of the major materials (greater than 1 percent of the composition) in each of these regions is given in Table 2.2.

TABLE 2.2.—LUNAR SURFACE MINERAL COMPOSITION (REFS. 2 AND 4)

Compound	Highland, percent	Mare, percent
SiO ₂	44.5	41.0
Al ₂ O ₃	26.0	12.8
FeO	5.77	16.2
CaO	14.9	12.4
MgO	8.05	9.2
TiO ₂	-----	7.3

The regolith is composed of fine grains of the mineral compounds given in Table 2.2. The grain size of the regolith varies but consists mostly of particles less than 1 mm in diameter. This is similar in consistency to silt or fine sand (Ref. 2). The average regolith density is approximately 1000 kg/m³.

Figure 2.4 shows the iron content on the lunar surface. In this figure higher concentrations are in red and orange and lower concentrations are in blue. The concentrations of iron oxide within the regolith may be of interest in power transmission due to the potential to inductively couple to the regolith over long transmission line lengths. If power transmission lines are placed on or beneath the surface, inductive coupling to the iron or other elements within the regolith can produce a significant energy loss in the power transmission lines. By looking at Figure 2.3 and Figure 2.4 it can be seen that the highest concentrations of iron oxide occur in the low-lying mare regions.

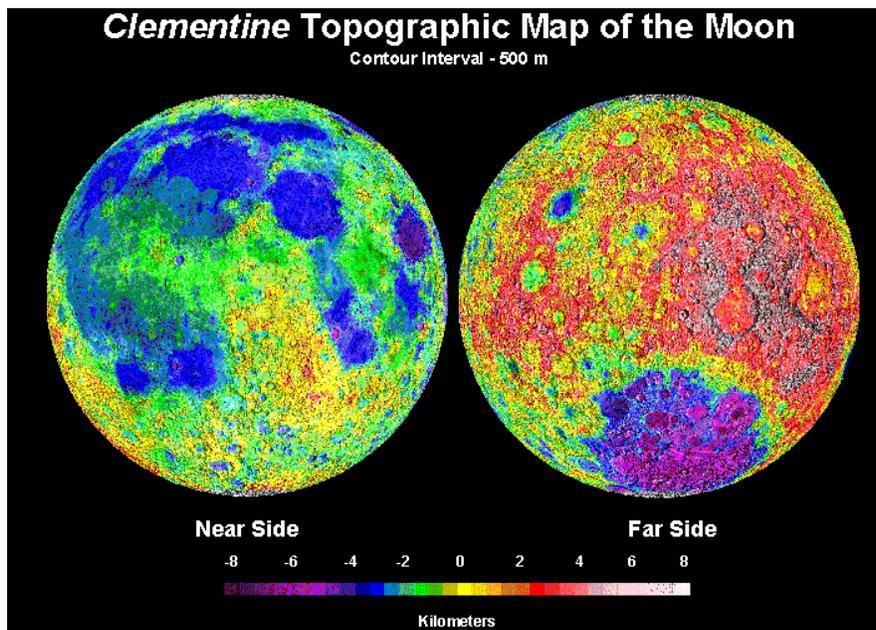


Figure 2.3.—Lunar topographic map (Ref. 4).

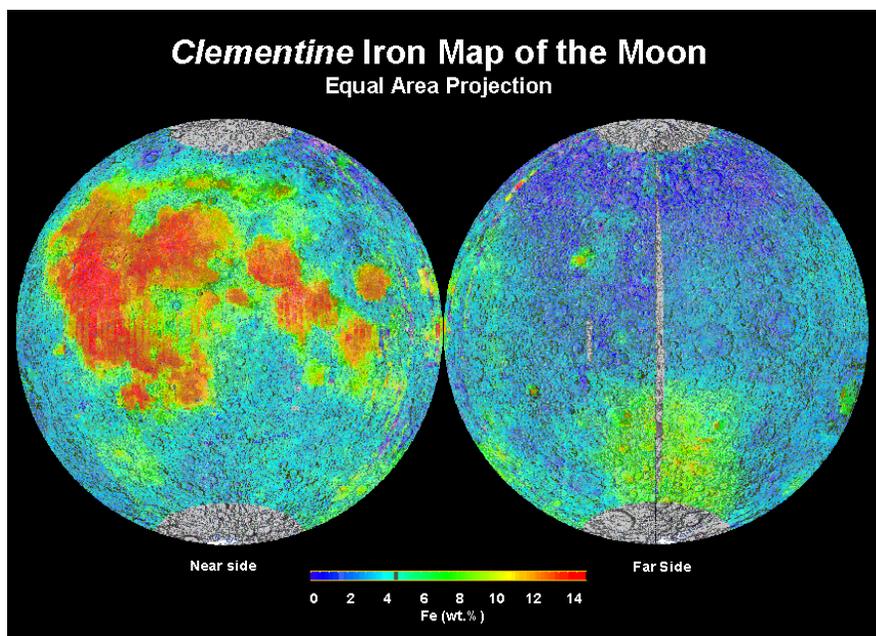


Figure 2.4.—Iron concentration on the lunar surface (Ref. 3).

2.2 Incident Solar Radiation

With the absence of an appreciable atmosphere, the solar intensity at the lunar surface is fairly constant. There is a slight variation throughout the year due to the Earth's orbital eccentricity about the Sun. The mean solar intensity (I_m) at Earth's orbital location is 1353 W/m^2 (Ref. 5). The variation in Earth's orbital radius (r_{orb}) from the mean orbital radius (r_{orbm} , which has a value of $1.496 \times 10^8 \text{ km}$) is represented by the eccentricity (ϵ) of Earth's orbit that has a value of 0.017. The actual solar flux (or intensity, I) in W/m^2 for a specific day of the year is determined by Equations (2.1) and (2.2). This variation in solar intensity throughout the year is shown in Figure 2.5.

$$I = I_m \left(\frac{r_{orbm}^2}{r_{orb}^2} \right) \quad (2.1)$$

$$r_{orb} = \left(\frac{1 - \epsilon^2}{1 + \epsilon \cos(\alpha)} \right) \quad (2.2)$$

The day angle (α) used in Equation (2.2) is defined as 0° on January 4 (perihelion of Earth's orbit) and increases by 0.98° per day. The solar output varies from approximately 1400 W/m^2 (on January 4) to 1308 W/m^2 (on July 9). The variation on the solar intensity at the lunar surface due to the orbit of the Moon around the Earth is very slight. The distance between the Moon and Earth varies between $360,300 \text{ km}$ (at perigee) to $405,500$ (at apogee). The greatest effect on solar intensity produced by the Moon's orbit about the Earth is a decrease of about 0.56 percent ($\sim 6 \text{ W/m}^2$) in the solar intensity at the lunar surface. This small change in intensity will vary as the Moon orbits the Earth or in other words throughout the lunar day. Therefore it was assumed to be negligible and the solar intensity at Earth orbit was utilized in the subsequent analysis.

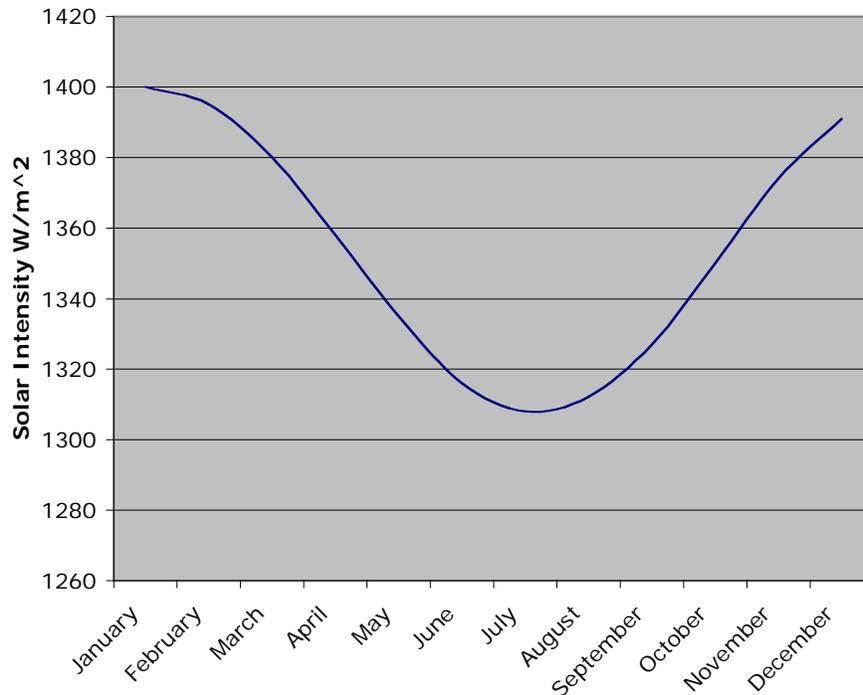


Figure 2.5.—Variation in solar intensity at Earth orbital location.

3.0 Power Distribution Test System

The planned exploration and ultimate colonization of the lunar surface will require a power infrastructure that can grow to accommodate the increase in power supply and demand. For this reason a power distribution system similar our terrestrial one will need to be implemented on the lunar surface. Although the terrestrial power grid is a good model for a lunar system, some modifications will have to be made to accommodate the environmental conditions, reducing component mass, enhancing reliability and operating mainly with solar DC power sources.

Initially a DC power distribution system will be a cost saving installation, as demand for power grows this will prove to be expensive in terms of payloads and deployment. An AC multi phase high frequency system will provide reduced lift loads, and the smaller gauge power cables will prove to be easier to deploy. In addition, any DC system that has been deployed can be upgraded to the AC power system without discarding any equipment. We may or may not have to replace the power lines in converting from a DC to an AC distribution system and we will need to provide DC to AC inverters.

A testbed was set up to simulate the connection of different power sources and loads together to form a mini-grid and gain an understanding of how the power systems would interact. Within the power distribution scheme, each power source contributes to the grid in an independent manner without communication among the power sources and without a master-slave scenario. The grid consisted of 4 separate power sources and the accompanying power conditioning equipment. Overall system design and testing was performed. The tests were performed to observe the output and interaction of the different power sources as some sources are added and others are removed from the grid connection. The loads on the system were also varied from no load to maximum load to observe the power source interactions.

This scenario would simulate various situations that might be encountered by the power system on the lunar surface. These would include varying power demands as well as varying power sources, such as operating with a solar array. Solar array output can vary significantly throughout a day period due to the change in solar radiation incident angle on the array surface.

The power grid system included battery storage consisting of four 48 V DC, 36 Ah batteries per grid system. The batteries are included in the system as a means of voltage stabilization and as a means of providing short-term peak power to the loads. On the lunar surface energy batteries, capacitors in conjunction with hydrogen and oxygen fuel cells, could accomplish storage. The excess power production by the system during times of low power demand would be used to charge the batteries or used to power an Electrolyzer that would convert water to hydrogen and oxygen gases for use within the fuel cells. When the power demand exceeds the power generation, fuel cells would convert the hydrogen and oxygen back to water and generate additional power.

The proposed power grid system would be capable of operating with whatever type of energy storage and production systems are available. Whatever energy storage system capacity is available would be utilized.

The initial design for the lunar power distribution demonstration system is for a 5 KV at 400 Hz Delta distribution system. The delta system uses three conductors and does not require carrying the neutral as in the Wye system that uses four conductors. The power quality on the transmission lines is less of a concern with an AC system. At the point of use (power distribution) we will need to use Delta to Wye step down transformers with circuitry to regulate the power quality. The secondary Wye configuration on the step down transformer will provide a neutral and a ground path to the transformer. This will enable us to have clean and safe power for use. At this time we do not see a need to have a common ground wire running with the Delta power distribution cables.

The 5 KV requires smaller conductors than a more standard 110 V or 220 V AC system and is a lead in to much higher voltages, similar to those used with the terrestrial power grid. A higher voltage distribution system reduces weight and makes lunar deployment easier. To provide an AC power distribution we would need to provide DC to AC inverters and at 400 Hz this will reduce the conversion system weight by 85 percent compared to a 60 Hz system. At the load end we would step down the voltage for direct use. Direct current to DC step-up and step-down systems are very complex and weight intensive. The 400 Hz AC

transmission frequency is a proven power system frequency used in the aircraft industry and in some military applications for its superior performance and reduced weight. As with any other lunar application, the electrical systems will have to be adapted to the lunar environment. Concerns such as heating and cooling of the power management components, dust mitigation, UV radiation degradation and vacuum operation are some of the environmental concerns that would have to be addressed.

3.1 Lunar Surface Power Network Test System

We brought online a system of several power sources that simulate solar power generation and created an independent power grid, shown in Figure 3.1 through Figure 3.3. The system supplied an independent power grid with parallel AC sources and a variable load. The system that was constructed in the GRC lab incorporated existing and proven technology and is being directed to a lunar application. Primary considerations of the system layout were for testing operating reliability, safety, ease of deployment and reduced transportation weight

The tested power system operated at 120 V AC and 60 Hz. Direct current sources that simulated solar panels included power supplies rated at 150 V DC and 40 A. A charge controller interfaced between the DC supplies and the batteries. The batteries included a set of four rated at 48 V and 36 A-H per set. Our system consisted of four identical and independent setups. This gave us the flexibility to operate systems in parallel as well as master-slave configuration and observe the power sharing as we vary the combined load.

This system constructed was selected for preliminary investigation of paralleling power sources and power sharing. The same theories would apply to the 5 KV, three-phase, 400 Hz system previously discussed.

We initiated the grid with a single DC to AC inverter. Once the inverter's AC output stabilized we installed a bidirectional inverter in parallel with the initial inverter. The second inverter was drawing power from the grid. Once the second inverter located a DC source that was greater than its demand, it synchronized with the grid and started supplying power to the grid. As the second inverter came on line we observed a load reduction on the first inverter. When the first inverter was turned on and off the second inverter continued outputting power to supply the load. The controller for this was solely within the second inverter and did not require communication with the first inverter.



Figure 3.1.—Electrical grid test setup.



Figure 3.2.—Resistive load bank and power supplies.



Figure 3.3.—View of test instrumentation.

The second inverter had the capability of directing AC power in both directions, which would make it ideal for power storing devices such as Fuel Cells. This operation illustrated that independent power sources can come on line or be removed from contributing to the power without affecting the quality of

the power on the grid. As a result of this independence, failure in a power source will be invisible on the load side.

We have looked into communication protocols that transmit data over power lines and through transformers, which will have to be implemented to provide a central Power Control Station the status of each power source.

An AC power distribution system will enable us to connect other forms of power generating sources. The solar power panels are the most complex because of the inverter requirement. When generating power from rotating equipment inverters are not required. When employing solar heat collectors or any other heat source to enable rotating alternators, no inverters will be required. The same control circuits will be used to synchronize with the power grid whether we utilize an inverter or a rotating alternator.

The test plan and procedures that were devised are for the characterization of a system of four parallel 120 V AC output inverters with the power input provided by four 48-V DC power supplies. Ultimately the goal is to replace the DC power supplies by solar arrays to more accurately model the system and gauge the system's response. Energy storage for each of the systems is provided by a bank of batteries in a series parallel combination to obtain 48 V DC output and capable of being charged at 48 V.

The objective of these tests is to characterize and test the ability of four parallel strings of inverters and power sources to power various loads. The response of the system to loads of specified impedances will be determined.

All equipment has been installed and wired in conformance to IEE C2-2007, the "National Electrical Safety Code" (Ref. 6), and grounded as specified in Section 100 of the "National Electric Code (NEC). Operating Procedures" shall be in accordance with Section 8 of GLM-QSA-1700.1, "Glenn Safety Manual" (Ref. 7). Data acquisition methods shall comply with the applicable safety procedures specified in IEEE STD 4-1995 (Ref. 5), "IEEE Standard Techniques for High Voltage Testing."

3.2 Power System Hardware Test Equipment and Configuration

The components listed in Table 3.1 were used to construct the power system testbed and collect data. These components were mainly "off-the-shelf" commercial items. They were selected to provide the capability of setting up a simulated power system grid and evaluating how it reacted to varying input power and load requirements.

The test configuration consists of four DC power supplies representing solar arrays providing power to four parallel inverters capable of powering loads either individually or in parallel combinations. One of the four parallel strings will be inactive and used as spare in the event of failure in any of the other strings. Initial Testing was performed using four independent power supplies to allow each leg to be powered independently. This configuration is shown schematically in Figure 3.4.

Programming of the system is accomplished via the MATE. Four FX inverters combined into a single system are referred to as a Quad Stack. The FX inverter installed at the bottom of the stack is plugged into Port 1 of the HUB. The second, third, and fourth FXs are plugged into Ports 2, 3, and 4 respectively as listed below. For more detailed information on the operation of the MATE, inverters and charge controllers refer to the Outback Manuals (Refs. 8, 9, and 10).

- Port 01 to Master FX
- Port 02 to OB Slave L1
- Port 03 to OB Slave L1
- Port 04 to OB Slave L1

At completion, each Slave FX in ports 02, 03, and 04 will be in parallel with the Master in port 01. Additional slaves can also be programmed as "OB Slave L1" following the same approach. The next step is to rank the Slaves in relation to the Master. After paralleling and establishing the master-slave order, power to the system is shut off and the system can be checked via the MATE screen.

TABLE 3.1.—GRID POWER SYSTEM HARDWARE AND DATA ACQUISITION COMPONENTS

Unit	Description	Manufacturer/part number
Inverter A-D	3600 W, 48 V DC input, 120 V AC, 60 Hz output	Outback VFX3648
Controller A-D	Maximum Power Point Tracking (MPPT) Charging controller	Outback MX60
Hub A-D	4-port communication manager	Outback HUB
SDC A-D	System Display and Controller	Outback MATE
RTS A-D	Remote Temperature Sensor	Outback RTS
Breaker S1 –S4	Panel Mount Breaker 50 A, 125 V DC—2-pole	Outback OBB-50-125VDC
Breaker S5-S12	DIN Mount Breaker 20 A, 120V AC/V DC	Outback OBB-20-120VAC
Breaker S13-S16	DIN Mount Breaker 15 A, 120V AC/V DC	Outback OBB-15-120VAC
DC Power Supply (2) (Option A)	0-150 V DC, 0-44 A, Switching Regulator	Power Ten P63C-150-44
DC Power Supply (Option A)	0-60 V DC, 0-35 A, Switching Regulator	Sorensen SRL 60-35
DC Power Supply (Option A)	0-150 V DC, 0-10 A	Sorensen Nobatron150-10A
DC Power supply (Option B)	Dual channel DC output; each channel 8 to 420 VDC @ 0 to 265 A	Aerovironment ABC-150/DCU
Batteries	Lead Acid, 12 V 32.5 Ah	Deka 8AU1H (T873) AGM
DC Safety Switch	Fused disconnect, 60 A. DC	Square D PN H222N
Data acquisition system (DAC)	10-channel midi LOGGER	Graphtec GL200
Oscilloscope	4-channel 0-100 mHz	Tektronix 2216A
Differential Probe	TBD	
Current Probe		
DC Voltmeter		
AC Voltmeter		
DC Ammeter		
AC Ammeter		
Wattmeter	Wide-band	Clarke Hess 255
Harmonic Analyzer		Fluke 41B
Load	As specified in paragraph 10	Avtron model K595
Instrument transformer	(Optional) Reduce 120 to 5 V AC for measurement	Hammond PT120PC or equivalent

The MX60’s default setting is for a 12 V DC battery system. After powering up the MX60 the proper settings for the 48 V DC battery system being used in this application need to be applied. The DC power supply voltage (acting as the PV array source) is automatically detected by the charge controller. It should be noted that the battery voltage must be at least 10.5 V or higher to power up the MX60.

The STATUS screen on the MX60 displays system information. The MATE also displays the same STATUS screen. The status screen shows the PV or DC power supply voltage and current, battery voltage and current, instantaneous watts into the system and daily energy into the system. The MX60 also has data logging capability the can be used to record this power input and output information.

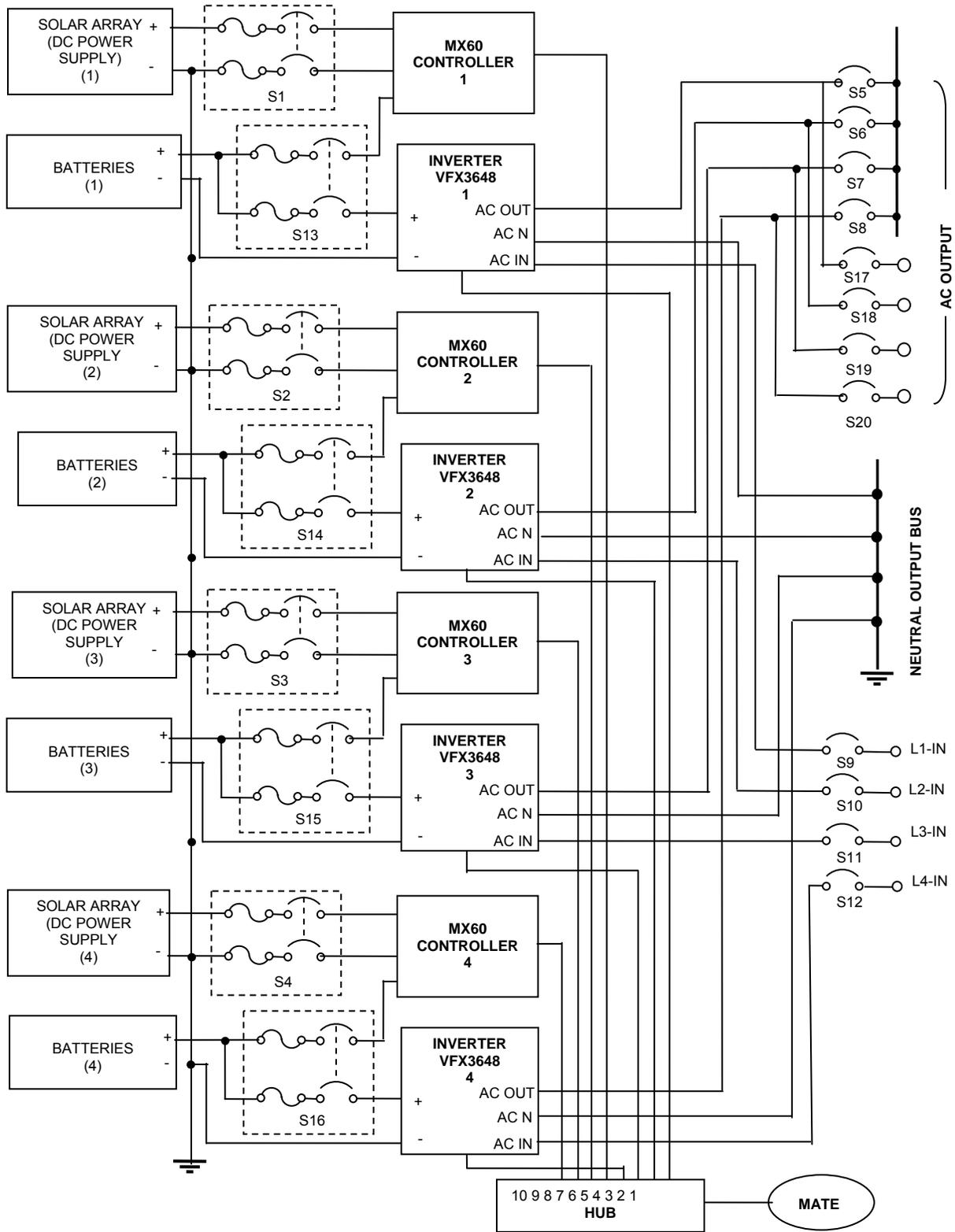


Figure 3.4.—Power system configuration for parallel operation.

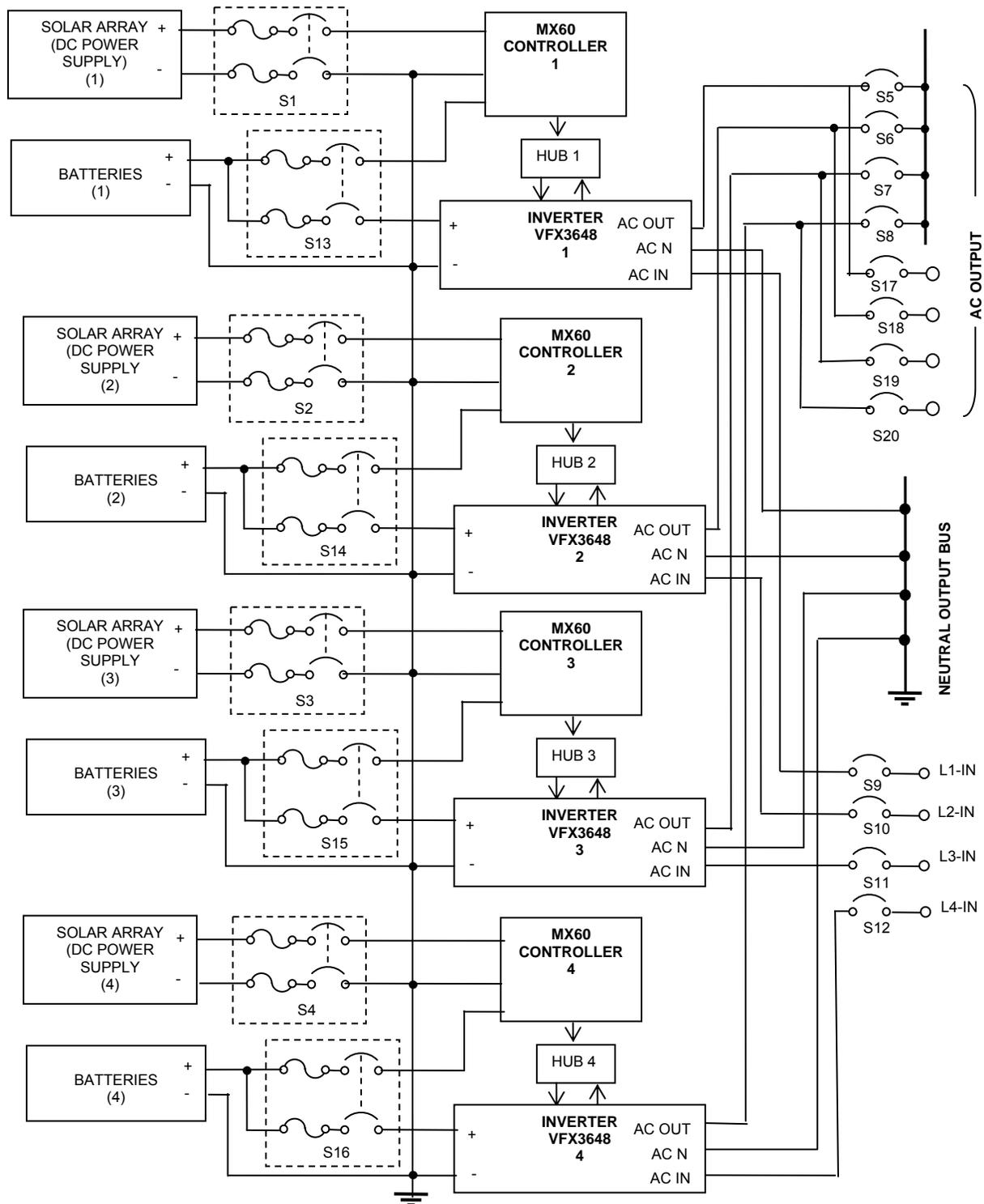


Figure 3.5.—Power system facility configuration: Option A.

Figure 3.5 shows the configuration for four independently operating inverters. This configuration uses four independent DC power supplies. An optional configuration using an Aerovironment ABC-150 is shown in Figure 3.6. This power supply in this option is limited to two independent channels. However, it

has the capability of configuring its output to simulate the output characteristic of a solar array more realistically than can be done with conventional DC power supplies.

The MPP function on the MX60 is not used for operation in the Option A configuration using DC supplies to provide power to the system. This mode should be disabled by setting “mini-sweep” to 00 according to the procedures in the MX60 programming manual.

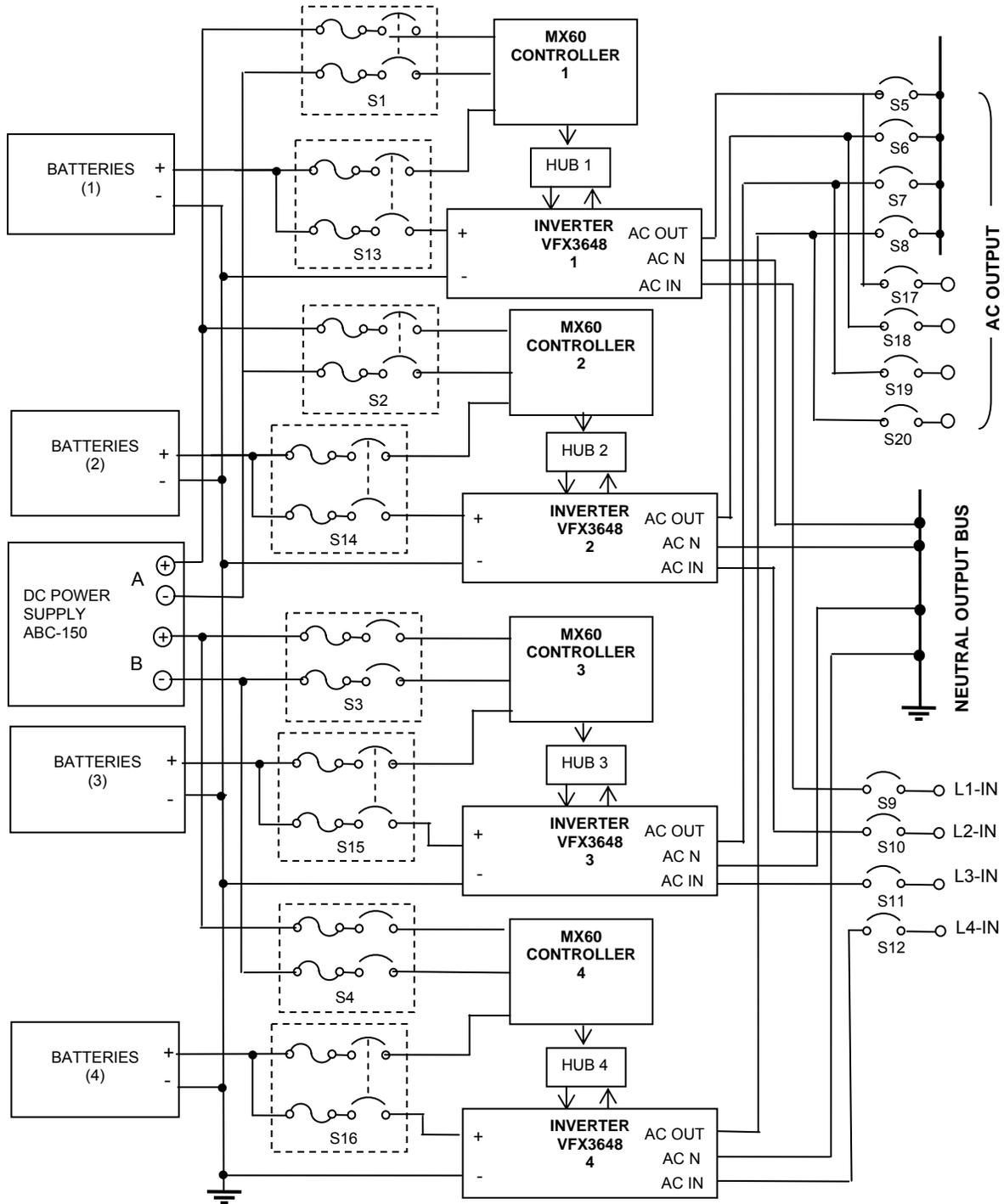


Figure 3.6.—Power system facility configuration: Option B.

When operating in option B configuration, the ABC150 Power supply is capable of emulating the output characteristics of a solar array on two channels by employing the appropriate “analog signal control” on each output channel.

3.3 Electrical Performance Testing

A number of characteristics of the power grid system were tested and evaluated. Some of the main electrical characteristics included:

- DC input voltage
 - The DC voltage at the input to the Inverter will be measured and recorded. Measurement shall be made at no-load
 - The DC voltage measurement shall be repeated with the inverter loaded to ≥ 90 percent of its maximum output
- AC voltage (output of inverter)
 - The total rms value of the inverter voltage output shall be measured and recorded at open circuit.
 - The measurement shall be repeated at ≥ 90 percent of maximum output
- Electrical power dissipation
 - The true power of the inverter shall be measured with load set at various levels
- Apparent power
 - The apparent power output of the inverter shall be determined as the product of the total rms voltage and the total rms current with load set at various power levels
- Power factor
 - The power factor of the inverter shall be determined as ratio of the true power to the apparent power with load set at various power levels

Additional items that will be measured address the power quality. Details on these items are given in the following sections.

3.3.1 Inverter Output Impedance

The output impedance and phase shift as a function of frequency of a device which supplies power can have an important role in the stability of certain loads connected to it. In general the technique is to measure the ratio output voltage to current with various frequencies modulating an otherwise static load as shown in Figure 3.7. This test will not be performed during the initial sequence of testing.

3.3.2 Ripple, Spikes, and Transients

The output voltage ripple is the maximum AC voltage present on a DC or low-frequency AC voltage stated in peak-to-peak voltage. The intent is to characterize the residual component associated with the switching action at the output switching frequency (or twice the output switching frequency). Figure 3.8 is presented to illustrate the parameters defining ripple.

Also these effects will be monitored during transients in the load demand. The measurement of transient effects is illustrated in Figure 3.9.

Hold-up time is the time, under the worst case conditions, during which the inverter’s output remains within specified limits, when the input voltage drops below a certain voltage or with the loss or removal of the input power, DC source, inrush current.

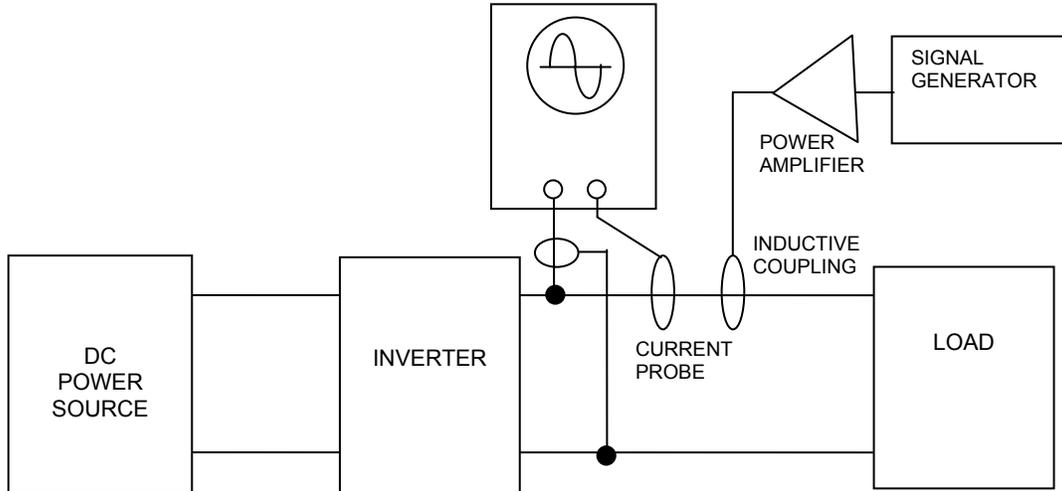


Figure 3.7.—Output impedance measurement diagram.

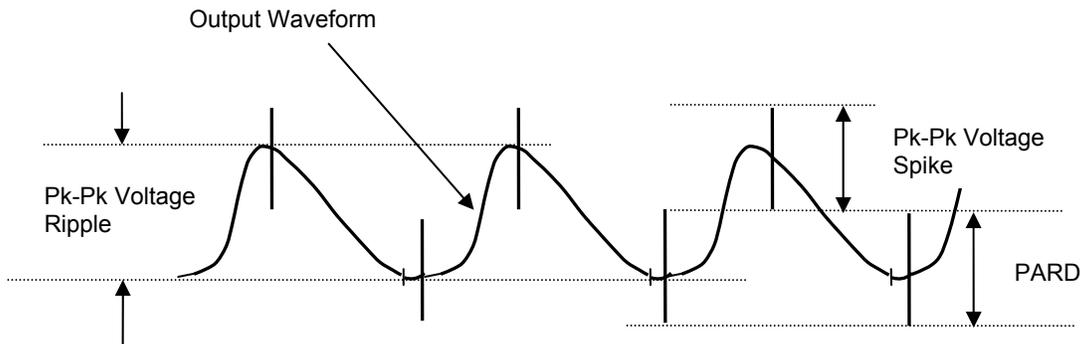


Figure 3.8.—Ripple parameters.

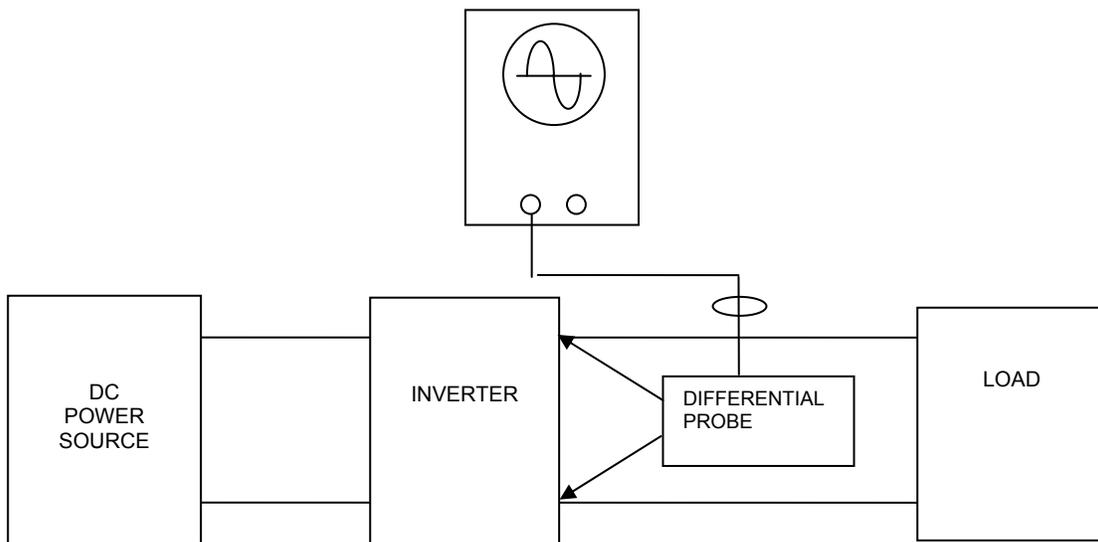


Figure 3.9.—Transients measurements.

The following steps are used to perform the hold-up time measurement.

- Connect the test setup as shown in Figure 3.10 with S1 in the closed position. (There should not be any energy storage components externally connected to the Unit Under Test (UUT).)
- Use S1 to trigger the oscilloscope.
- Open S1 to interrupt the input.
- Measure the voltage, V_o , as close as possible to the UUT output terminals.
- Record the time V_o ramps down below a specific voltage limit.

DC source inrush current is the waveform of the current drawn by the UUT when power is initially applied. The setup to measure the DC source inrush current is shown in Figure 3.11. It should be noted that prior to performing this test the inverter should be fully discharged.

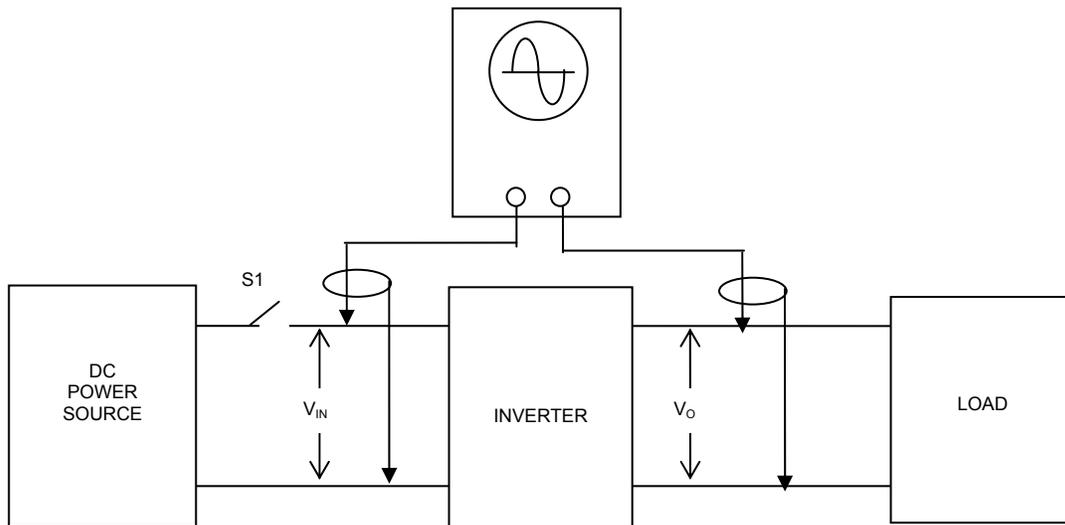
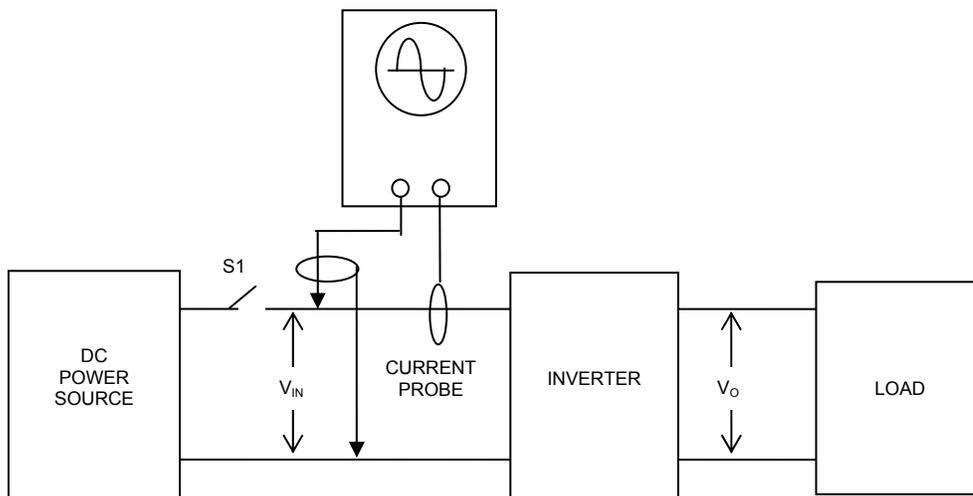


Figure 3.10.—Holdup current measurement.



NOTES:

1. The voltage probe is used to trigger the oscilloscope when power is applied.
2. The low-impedance source is turned on with the switch S1 (solid state or mechanical) initially open.
3. The scope period should be of sufficient duration to capture all input current settling time.

Figure 3.11.—Source inrush current.

3.3.3 On/Off Control

On/Off control encompasses a number of aspects of operating the system. These include the initial start-up, turn-off, under voltage and hysteresis. Each of these is briefly described below.

- Start-up sequencing/remote on/off control is the sequence in which a power system's outputs reach their normal operating voltage following application of input power and/or remote on/off control.
- Turn-off sequencing/remote on/off control is the sequence in which a power system's outputs shut down following removal of input power and/or remote on/off control.
- Input turn-on is the input voltage at which the UUT starts when the input voltage is rising from zero (or from below the operating range).
- Input under voltage lock-out (UVLO) is the voltage at which the UUT shuts down when the input voltage is falling from within the operating range
- Hysteresis is the difference between the threshold voltage for the UVLO and the threshold voltage for turn-on.

The following steps are used to perform the On/Off control test.

- Connect the input of the Inverter to a power source and connect the output to an load, as shown in Figure 3.12.
- Monitor the output voltage across the load with an oscilloscope.
- With the UUT operating at nominal input voltage and load current, slowly reduce the input voltage until the UUT shuts down (output voltage decays to zero).
- Repeat several times to find the exact trip point.
- Record the shutdown voltage.
- Slowly raise the input voltage until the UUT restarts.
- Record the restart voltage.
- Calculate the hysteresis by finding the difference between the shutdown (UVLO) and restart (turn-on)

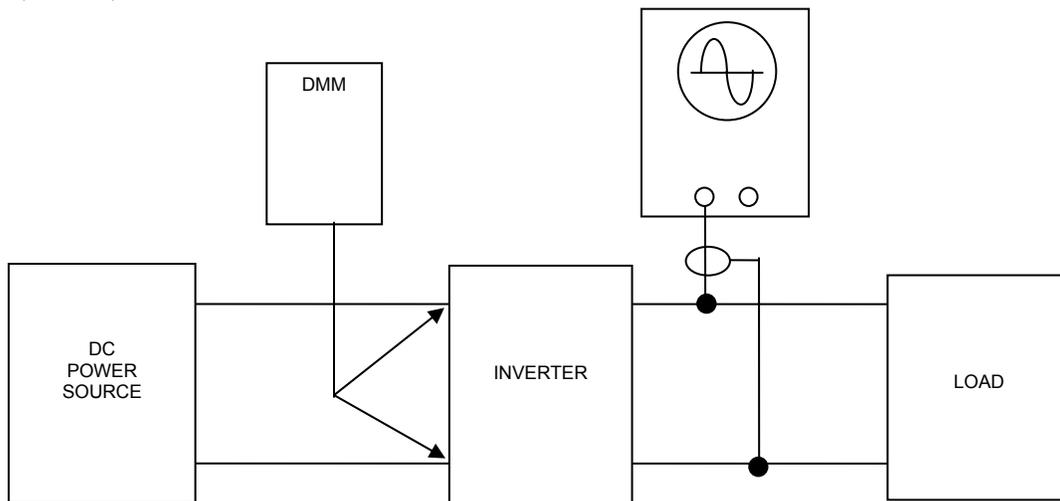


Figure 3.12.—On/off control measurements.

3.3.4 Distortion

The individual harmonic content is the voltage or current, as applicable, at a given harmonic frequency, expressed as a percentage of the fundamental. Equation (3.1) provides the formula for defining individual harmonic content (IHC). The variable X represents voltage or current, and may be expressed as a percent RMS value or a peak value. The fraction expresses the amount of distortion at the n th harmonic.

$$IHX = \frac{X_n}{X_1} \times 100 \tag{3.1}$$

Where,

X_1 is the fundamental value of current or voltage

X_n is n th harmonic value of current or voltage

For PV based power systems, the maximum limit for the total harmonic distortion (THD) of the output current is set to 5 percent according to the IEEE 1574 (Ref. 11) standard. In order to comply with this, the current controller should have a very good harmonic rejection, especially for low order harmonics which have a higher content in the power system. Table 3.2 shows the maximum allowed distortion limits for the first 33 current harmonics.

TABLE 3.2.—DISTORTION LIMITS FOR DPGS SYSTEMS INTERCONNECTING TO A UTILITY GRID

Odd harmonics	Distortion limit, percent
3rd – 9th	< 4.0
11th – 15th	< 2.0
17th – 21st	< 1.5
23rd – 33rd	< 0.6

To perform the harmonics testing the system was configured as shown in Figure 3.13.

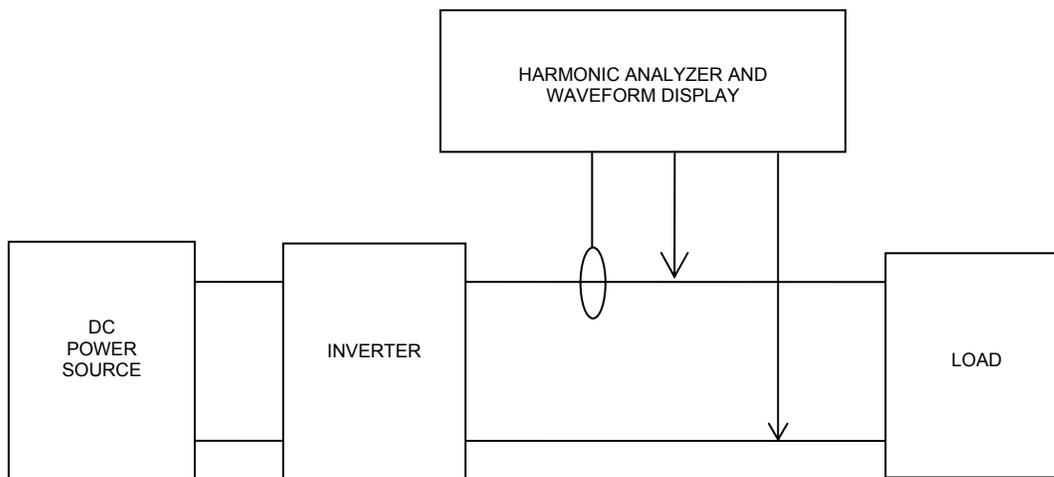


Figure 3.13.—Harmonic content measurements.

3.3.5 Parallel Operation

Parallel operation consists of operating the power supply/inverter strings in groups of two in parallel and three in parallel. Capability of power sharing and waveform synchronization will be determined. Configuration for this series of tests is shown in Figure 3.14.

3.3.5.1 Two-Channel Operation

The procedure for performing the two-channel test is outlined below. The numbering in the procedure refers to Figure 3.14.

- Adjust programmable load to 90 percent of single channel capacity
- Activate S-1
- Activate S-4
- Measure and record DC input current I1
- Measure and record DC input voltage V1
- Measure and record AC output current and wave shape
- Measure and record AC output voltage and wave shape
- Determine phase shift
- Determine harmonic content according to Section 3.3.4
- Activate S-2
- Activate S-5
- Adjust load to 90 percent of two-channel capacity
- Activate S-1
- Activate S-4
- Measure and record DC input current I1
- Measure and record DC input voltage V1
- Measure and record DC input current I2
- Measure and record DC input voltage V2
- Measure and record AC output current and wave shape for Inverter 1
- Measure and record AC output current and wave shape for inverter 2
- Measure and record AC output voltage and wave shape
- Determine phase relationships
- Determine harmonic content according to procedures in Section 3.3.4

Under fault conditions with two-channel operation the following procedure is used to restore system operation.

- Adjust load for single channel capacity.
- Reduce input voltage to channel 1 to a level below UVLO as described in Section 3.3.3
- Record oscilloscope traces:
 - Channel 1 AC voltage
 - Channel 1 AC current
 - Channel 2 AC voltage
 - Channel 2 AC current
- Evaluate system stability

3.3.5.2 Three-Channel Operation

The procedure for performing a three-channel test is similar to the two-channel procedure with the addition of some steps to account for the third channel. The three-channel procedure is outlined below the numbering in the procedure refers to Figure 3.14.

- Adjust programmable load to 90 percent of single channel capacity
- Activate S-1
- Activate S-4
- Measure and record DC input current I1
- Measure and record DC input voltage V1
- Measure and record AC output current and wave shape
- Measure and record AC output voltage and wave shape
- Determine phase shift
- Activate S-2
- Activate S-5
- Adjust programmable load to 90 percent of two-channel capacity
- Measure and record DC input current I1
- Measure and record DC input voltage V1
- Measure and record DC input current I2
- Measure and record DC input voltage V2
- Measure and record AC output current and wave shape for Inverter 1
- Measure and record AC output current and wave shape for inverter 2
- Measure and record AC output voltage and wave shape
- Determine phase relationships
- Determine harmonic content according to procedures in Section 3.3.4
- Activate S-3
- Activate S-6
- Adjust programmable load to 90 percent of three channel capacity
- Measure and record DC input current I1
- Measure and record DC input voltage V1
- Measure and record DC input current I2
- Measure and record DC input voltage V2
- Measure and record DC input current I3
- Measure and record DC input voltage V3
- Measure and record AC output current and wave shape for Inverter 1
- Measure and record AC output current and wave shape for inverter 2
- Measure and record AC output current and wave shape for inverter 3
- Measure and record AC output voltage and wave shape
- Determine phase relationships
- Determine harmonic content according to procedures in Section 3.3.4

Under fault conditions with three-channel operation the following procedure is used to restore system operation.

- Adjust load for single channel capacity.
- Reduce channel 1 input voltage to a level below UVLO as described in Section 3.3.3
- Record oscilloscope traces:
 - Channel 1 AC voltage
 - Channel 1 AC current
 - Channel 2 AC voltage

- Channel 2 AC current
- Channel 3 AC voltage
- Channel 3 AC current
- Evaluate system stability

MULTI-CHANNEL OSCILLOSCOPE

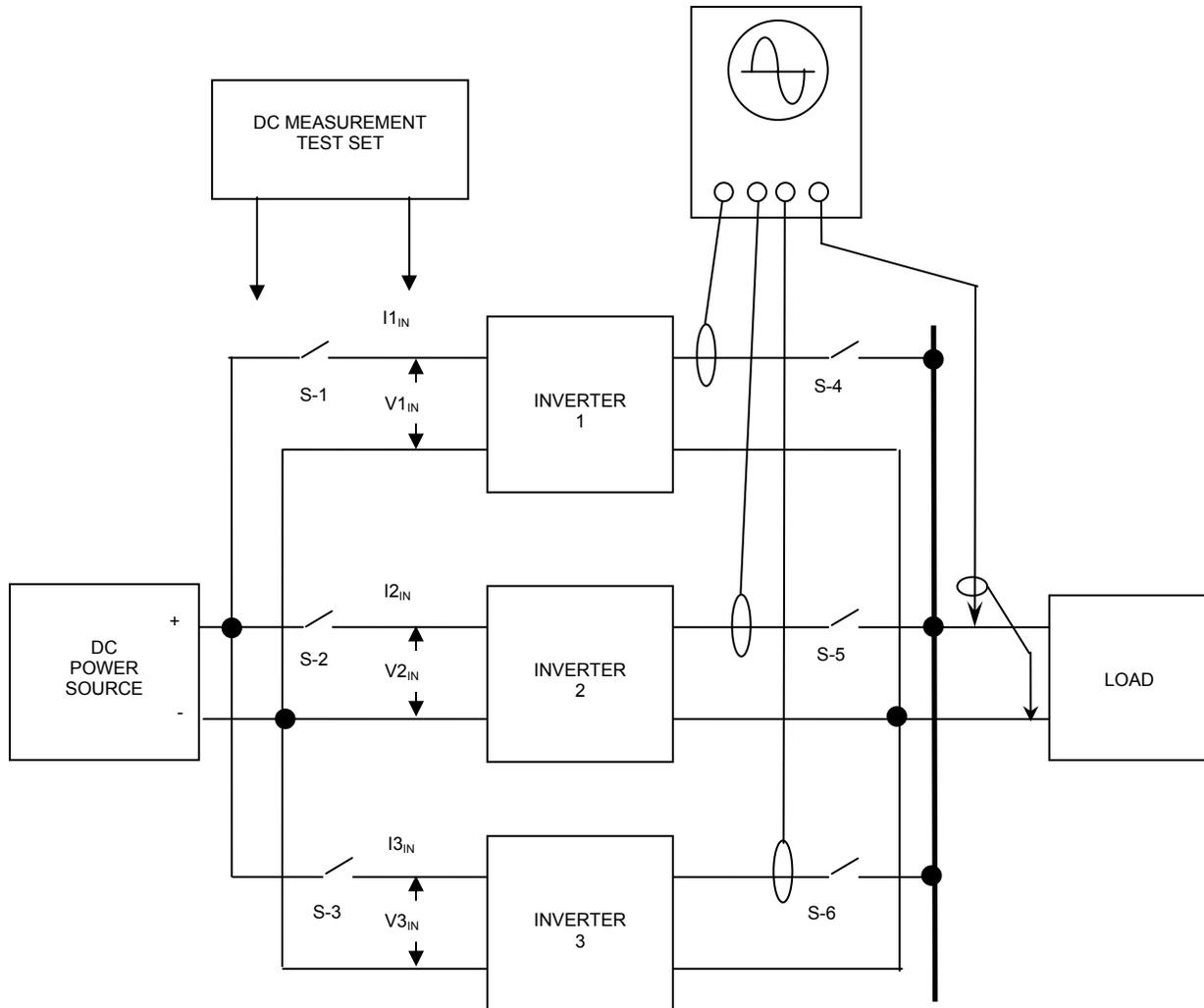


Figure 3.14.—Parallel operation test setup.

4.0 Electrical Power Loads

A resistive load bank, Avtron model K595 will be used to provide the various electrical load level to the power system. This unit is rated at 55.5 kW, 240 V, three-phase, 60 Hz. The unit is wye-connected and capable of testing a 120 V, single-phase power source.

A transmission line simulator, shown in Figure 4.1, may be used if testing is required to simulate a power system having loads at a large distance from the load (on the order of a km or greater).

For long lines the voltage level may need to be increased for transmission between the source and the loads as shown in Figure 4.2. Typical commercial practice by utility companies is to distribute power from the substation to the distribution transformer near the user at voltages ranging from 2.4 kV to as high as 33 kV.

4.1 Leading Power Factor Load

Including an inductor between the output and the load was used to simulate the effect of a leading power factor. Figure 4.3 shows the value of inductance in series with a resistive load to obtain power factors of 0.70, 0.80, and 0.90. Real Power is plotted along the x-axis.

4.2 Lagging Power Factor Load

The effect of a lagging power may be simulated by including capacitors (Power Factor Correcting Capacitors) between the output and the load. Power correcting capacitors are typically specified in VARs or KVARS for a specific voltage and frequency. Figure 4.4 shows the PFC size required at 120 V AC 60 Hz. to obtain a specified power factor.

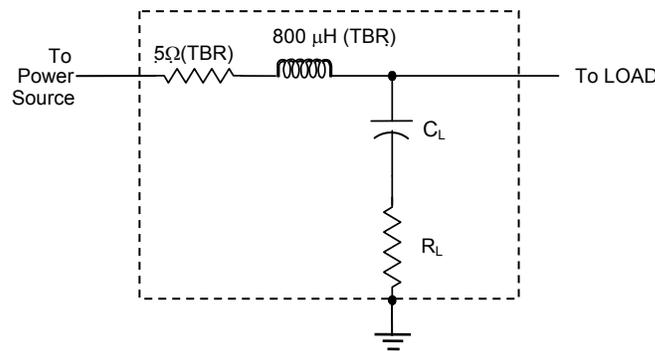


Figure 4.1.—Transmission line simulator.

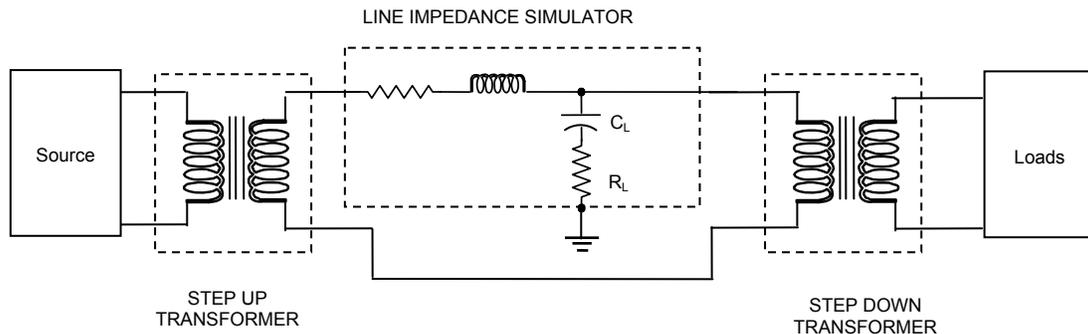


Figure 4.2.—High voltage transmission line simulator.

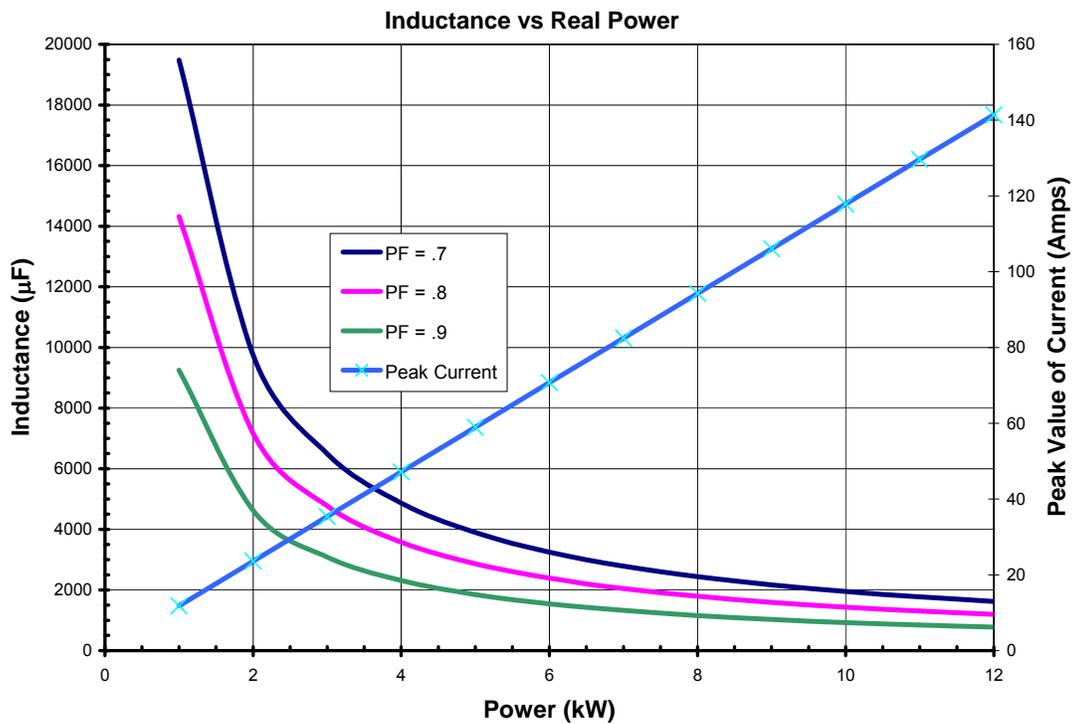


Figure 4.3.—Inductance required for given power factor.

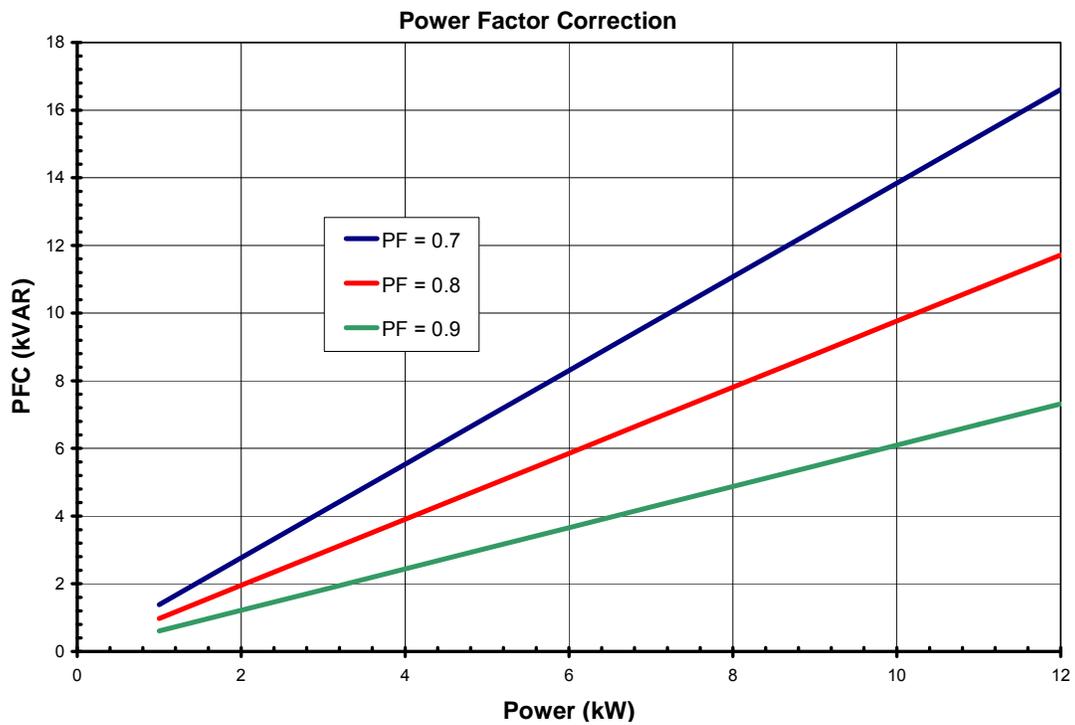


Figure 4.4.—Required power correction capacitor for given power factor (120 Vac-1φ).

5.0 System Battery Monitoring and Charging

The system utilizes a bank of 16 Absorbed Glass Mat (AGM) batteries. They are arranged in groups of 4, each group being dedicated to a specific inverter and battery charge controller. The recommended Charging procedure for AGM batteries is given in Table 5.1. Parameters derived from this table will be used to program the MX60 Charge Controller, which is used to maintain the batteries and monitor the batteries' state of charge.

The first stage in a 3 or 4 stage-charging algorithm is the “Bulk Stage”. Typically the Bulk Stage is a “Constant Current” (CC) charge but may also be Constant Power, Pulse Current or Taper Charge. In this stage the optimum charge current should be limited to less than or equal to 30 A per 100-Ah (20 hr rate) of battery capacity or 0.3C. This stage should end when the cell voltage is equal to 2.4 to 2.45 V/cell at 25 °C/77 °F. The maximum time in hours should equal to 1.2 times the DOD (in Ah) divided by the average charge current in amps. If this time is exceeded, charging should be stopped and the battery and/or charge process should be analyzed. This stage will represent approximately 60 percent of the total charge time. The battery will be nearing 80 to 90 percent charged at the end of this stage.

TABLE 5.1.—AGM BATTERY CHARGING

Stage	End conditions	Comments
Bulk Stage Maintain Current, $I_1 = 30$ A per 100 Ah or to achieve 0.3C Typically, Constant Current (CC) charge is preferred but may also be Constant Power, Pulse Current or Taper Charge.	Voltage = 2.40 to 2.43 V/cell $t_{\max} = 1.2 \times D / I_{\text{avg}}$ Where t_{\max} = maximum time (hr) D = depth of discharge I_{avg} = average current (A)	Stop Charge when maximum time is exceeded
Absorption Stage Maintain Constant Terminal Voltage, V_1 , (Adjust for changing battery temperature) $V_1 = 2.40$ to 2.43 V/cell	Without Finishing Stage Maintain charge until current acceptance drops by less 0.10 A over 1-hr time period. Max time = 12 hr	If max time is exceeded go to next stage
	With Finishing Stage End when current = I_2 Max time = 6 hr	Stop If current exceeds 8 A after dropping below 6 A
Accelerated Finishing Stage (Optional) Maintain Constant Current $I_2 = 1$ to 2 A per 100 Ah cell	Charge for 1 to 4 hr based Ah accumulated in first two stages. $<25\%$ C – 1 hr 25 to 50% C – 2 hr $> 50\%$ C – 4 hr	If voltage exceeds 2.80 per cell go to next stage
Float Stage (Optional) Maintain Constant Terminal Voltage, V_2 (Adjusting for changing battery temperature) $V_2 = 2.25$ to 2.30 V/cell	This step is generally not needed if no load is present when the batteries device is not in operation	No time limit

All voltage values are at 20°C. Subtract 0.005 V/cell for each 1°C above 20 °C and add 0.005 V/cell for each 1 °C under 20 °C

The second stage is the “Absorption Stage”. Typically this stage is a Constant Voltage (CV) stage where the terminal voltage is maintained at 2.4 to 2.45 V/cell at 25 °C/77 °F (adjusting for temperature). The charge current is maintained until current acceptance drops by less than 0.1 A over a 1-hr period. This stage should take the battery to 100 percent charged and should not take longer than 10 to 12 hr. If this time is exceeded, charging should be stopped and the battery and/or charge process should be analyzed.

The third stage is the “Float Stage” or maintenance and monitor stage. This step is generally not needed if; no load is present when the batteries device is not in operation; the batteries device is used on a regular basis and does not sit idle for lengthy periods of time. Float voltage should be maintained at 2.25 to 2.30 V/cell.

If a “Balance Mode” is included in the charging algorithm it would typically happen after the “Absorption Stage”. This would become the third stage and the “Float Stage” would then become the fourth stage. A balance mode is similar to an Equalize function for flooded batteries but is performed at a lower voltage.

6.0 Test Procedure

The test operator shall indicate the completion of each of the following items by checking off the appropriate step. The test operator shall note any deviations from the procedures herein. The Test Operator shall be familiar with and shall follow all of the safety procedures as outlined in any applicable instrument operating manuals and NASA Safety Permit.

Prior to turning on the system the following items should be verified.

- Assure that AC INPUT BREAKERS are in OFF position
- Assure that AC OUTPUT BREAKERS are in the OFF position
- Assure that the DC DISCONNECT SWITCH is in the OFF position
- Connect loads to be tested

The procedure for the system startup is broken down into three categories, pre-test, test set-up and test procedures. Each of these is outlined below.

- Pre-Test Procedure
 - Turn Off AC Output Breakers
 - Turn Off AC Input Breakers
 - Turn Off DC Input Breakers
 - Turn Off the Battery Disconnects
 - Unplug AC Source to Inverters
 - Unplug AC Loads from the Test Rig
 - Unplug DC Source from the Test Rig
- Test Set-Up Procedure
 - Connect Test Equipment
 - Plug-In the DC Supply Outputs to the Test Rig Inputs
 - Set DC Supply Settings not to Exceed a Maximum of 150 V DC and 50 A DC
- Plug-In the AC Input Power to the DC Supply
 - Plug-In the Loads to the Inverter Output Individual Loads to the Discrete Outputs or the Single Resistive Load Bank to the Common Output
 - Plug-In the AC Source to the Inverters
 - Turn-On the AC Input Breakers
 - Verify the Charge Controller Information
 - ◆ 48 V DC Battery Selection
 - Verify the Hub Information
 - ◆ 1
 - ◆ 2
 - ◆ 3
 - ◆ 4
 - Turn-On the Battery Disconnect Switches

Note: The auxiliary output in the charge controller is used to power the current probes, located behind the control panel. The auxiliary output, in the charge controller, resets to “Off” upon power down. To reactivate the output, reinitiate programming of the charge controller.

Test Procedure

- Turn On the Circuit Breakers for the AC Input
- Verify the Inverter LEDs for the Proper Function
 - Green LED = Normal Battery Voltage
 - Yellow LED = AC Source is Connected
 - Red LED = Error Indication (Must be Off)
- Measure and Record Inverter Input Voltage
- Turn On the DC Charge Controller Double Breakers
- Verify the Charge Controller Information
 - 48 V DC Battery Selection
 - Auxiliary Power is On
- Verify the Hub Information
 - 1
 - 2
 - 3
 - 4
- Turn on the Battery Safety Switch
- Measure and Record the Battery Voltage
- Compare the Measured Readings to the Charge Controller Displayed Battery Voltage
- Verify the Inverter LEDs for the Proper Function
 - Green LED = Normal Battery Voltage
 - Yellow LED = AC Source is Connected
 - Red LED = Error Indication (Must be Off)
- Check and Record the DC Current
- Turn on the AC Output Circuit Breaker
 - Measure and Record Inverter Input DC Voltage
 - Measure and Record Inverter Output AC Voltage

Test Reporting Requirements

The following details on the testing shall be recorded:

- Load Impedance
- DC Voltage input to inverter; open circuit and at load
- Total AC rms Voltage Output of inverter
- Total AC rms Voltage input to load (same as above if line length simulator is not used)
- Total rms current delivered to load
- Apparent Power delivered to load
- Power Factor
- Power quality: DC input ripple and PARD
- Power quality AC: rms values of significant harmonics to 1 percent of fundamental.
- Recorded waveshapes

This data can be recorded on the summary tests sheet given below.

7.0 Summary

The objective of the program was to design and construct a testbed for modeling a lunar power distribution system. The goal of the design was to provide a means of connecting up separated power sources and has them operate as a single system. The system design was intended to sync the AC output from each source and combine them so the a given load could draw from any combination of sources and would not be affected if one or more source dropped off-line, as long as sufficient power was still available from the remaining sources.

The system constructed met the initial goals of the program. It was designed and assembled based on four independent DC power sources. Some initial testing was performed on the system to verify its operation. This testing, although limited, verified that the inverters synced to an AC signal and provided a uniform output to the load. During the initial checkout testing some of the DC sources were shut down and the system adjusted to the loss of incoming power with minimal signal distortion and ripple. Detailed testing of the system was not part of this build-up portion of the program. This testing will be performed under a follow-on effort.

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14. ABSTRACT The Lunar Surface Power Distribution Network Study team worked to define, breadboard, build and test an electrical power distribution system consistent with NASA's goal of providing electrical power to sustain life and power equipment used to explore the lunar surface. A testbed was set up to simulate the connection of different power sources and loads together to form a mini-grid and gain an understanding of how the power systems would interact. Within the power distribution scheme, each power source contributes to the grid in an independent manner without communication among the power sources and without a master-slave scenario. The grid consisted of four separate power sources and the accompanying power conditioning equipment. Overall system design and testing was performed. The tests were performed to observe the output and interaction of the different power sources as some sources are added and others are removed from the grid connection. The loads on the system were also varied from no load to maximum load to observe the power source interactions.					
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