01 Jan 2007

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Recommended Citation

S. Barave and B. H. Chowdhury, "Hybrid AC/DC Power Distribution Solution for Future Space Applications," *Proceedings of the IEEE Power Engineering Society General Meeting, 2007*, Institute of Electrical and Electronics Engineers (IEEE), Jan 2007.
The definitive version is available at https://doi.org/10.1109/PES.2007.385901

Hybrid AC/DC Power Distribution Solution for Future Space Applications

Sushant P. Barave, *Member, IEEE,* and Badrul H. Chowdhury, *Senior Member, IEEE*

***Abstract*— As NASA readies itself for new space exploration initiatives starting with a human return to the Moon by the year 2020 eventually leading to human exploration of Mars, the requirements for a safe and reliable power system will become important issues. A preliminary study of a proposed hybrid AC/DC distribution system with a power electronic interface is investigated. A Static synchronous Compensator (STATCOM) is considered as the power electronic interface between the AC and the DC portions of the hybrid AC/DC distribution system. The system is modeled in EMTDC/PSCAD and tested for certain operating conditions and contingencies. High reliability and maintenance-free operation is crucial for continuity of supply on spacecraft distribution systems. Source redundancy is introduced to increase the reliability of the system. Some results pertaining to the distribution system are also presented.**

***Index Terms*—STATCOM, converter, space power, short circuit, dynamic analysis.**

I. POWER SYSTEMS FOR SPECIFIC SPACE APPLICATION

NASA envisions a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations. Initiatives include robotic missions to the Moon by 2008, followed by human expeditions to the Moon in the 2015 – 2020 timeframe. This will lead the way for conducting robotic exploration of Mars to prepare for future human exploration.

The major candidates for primary energy source for space exploration vehicles and for possible habitat on lunar or Martian surfaces currently include solar radiation, radioisotopes and nuclear reactors. Mars-bound space travel and crew exploration vehicles present extraordinary challenges mainly because of the never-before-attempted human interplanetary travel involved as well as the need to transport some payload for creating a habitat on Mars. Two complex issues need to be considered with regard to power generation and distribution:

- Type of prime mover: since solar power may not be readily available on parts of the lunar/Mars surface and also during the long duration flight to Mars, the primary source of power will most likely be nuclear power (Uranium fuel rods) with a secondary source of fuel cell (Hydrogen supply).
- Electric power source: with nuclear-based steam turbine as the main prime mover, the electric power generation source will most likely be an AC generator at a high frequency, such as 400 Hz [1]. However, it would still be possible to generate power from solar photovoltaic (PV) panels or from fuel cells, in which case, the output will be DC.

A. Distribution System Architecture

DC power generation sources are preferred for spacecraft electrical systems such as one found on NASA's space shuttle. Fuel cells and PV cells are two popular types of DC sources used as the main power source in a space vehicle [2]. Along with an electromechanical source, it is worth considering the use of such DC sources and distribution equipment. In such a situation with multiple AC and DC sources, one needs to think about the interfacing of AC and DC systems. Recent development in the area of power electronics and flexible AC transmission systems (FACTS) [3] offers some options which can help achieve this interface. One important aspect for this interface would be an appropriate control strategy for the power electronic devices. A hybrid AC/DC power distribution architecture is introduced which will take into account both AC/DC sources, loads and the necessary transfers between them.

B. AC/DC Interface Preview

As a starting point, an inverter or a bi-directional converter is necessary due to the presence of both AC and DC generation sources in the system. The interface should be capable of controlling the active and reactive power flows in both directions. After a general inspection of inverter based topologies [4], [5] and [6], a Static synchronous Compensator (STATCOM) is selected as a possible candidate for the interfacing purpose - one reason being its ability to control the reactive power flow. Another reason behind selecting the STATCOM is its ability to be connected to a battery.

A common STATCOM consists of a voltage source inverter (VSI) and a DC voltage source (usually a DC capacitor). By injecting a current of variable magnitude and almost in quadrature with the line voltage, at the point of connection with the transmission line, a STATCOM can inject reactive power to a power system. Because a DC capacitor is not a bulk energy storage device, a common STATCOM does

This work was supported in part by the Johnson Space Center, NASA.

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not have the ability of active power compensation. It can only affect the active power flow in the power system indirectly by regulating the voltage at the point of connection with the transmission line. If a bulk energy storage device, such as a battery, is connected to the DC capacitor, the power regulation ability of a common STATCOM can be expanded to both reactive and active power compensation. The ability of a STATCOM to be used with a DC source makes it a viable candidate for the interfacing purpose. Keeping in mind the necessity for high reliability of the system, one has to design a system wherein the DC sources will at times act as a back-up supply for the AC sources and vice-versa. Fig. 1 shows a conceptual hybrid architecture for the system. It consists of both an AC and a DC ring bus structures with generation sources located on both subsystems. The AC bus will have primary generation, while the dc bus hosts the backup/standby generation. The system allows cross-strapping between the AC and DC subsystems for added reliability. Both ring bus structures allow isolation of specific segments for fault clearing while providing power to all load distribution centers from either the primary or the standby sources. Each section of the system is supplied by at least two sources. This accounts for better supply reliability. The most attractive feature of this system is the ability to sectionalize itself and serve loads from healthy sources be it AC or DC. The portion simulated for this study is shown inside the dashed rectangle.

II. INTERFACE MODULE AND SYSTEM SCHEMATIC

The aim is to design a building block that can be used at multiple locations in the system to provide an interconnection point between the AC and DC supplies. Fig. 2 shows a block diagram of the system. The system schematic has been built using EMTDC/PSCAD platform. The main building blocks of the system to be simulated are an AC source, a DC source connected to the AC system through STATCOM and a load.

The diagram shows an AC source on the leftmost side. This acts as the primary source for the load. The AC source has a line-to-line voltage of 102 kV. Source impedance is assumed to be 15Ω. A 3-phase-to-ground fault is induced at this node at a certain point of time in the simulation. Voltage level at the load terminal is continuously monitored and compared against the desired voltage level. In addition to the AC source, there is a battery connected to the system through a STATCOM. The battery terminal voltage is set to 50 kV with the internal resistance assumed to be 80Ω. The switching scheme for AC and DC branches depends on the voltage level. If the voltage falls below a certain level the DC branch supplies the load via the STATCOM. The STATCOM acts as an inverter and generates an appropriate AC waveform to supply the AC load.

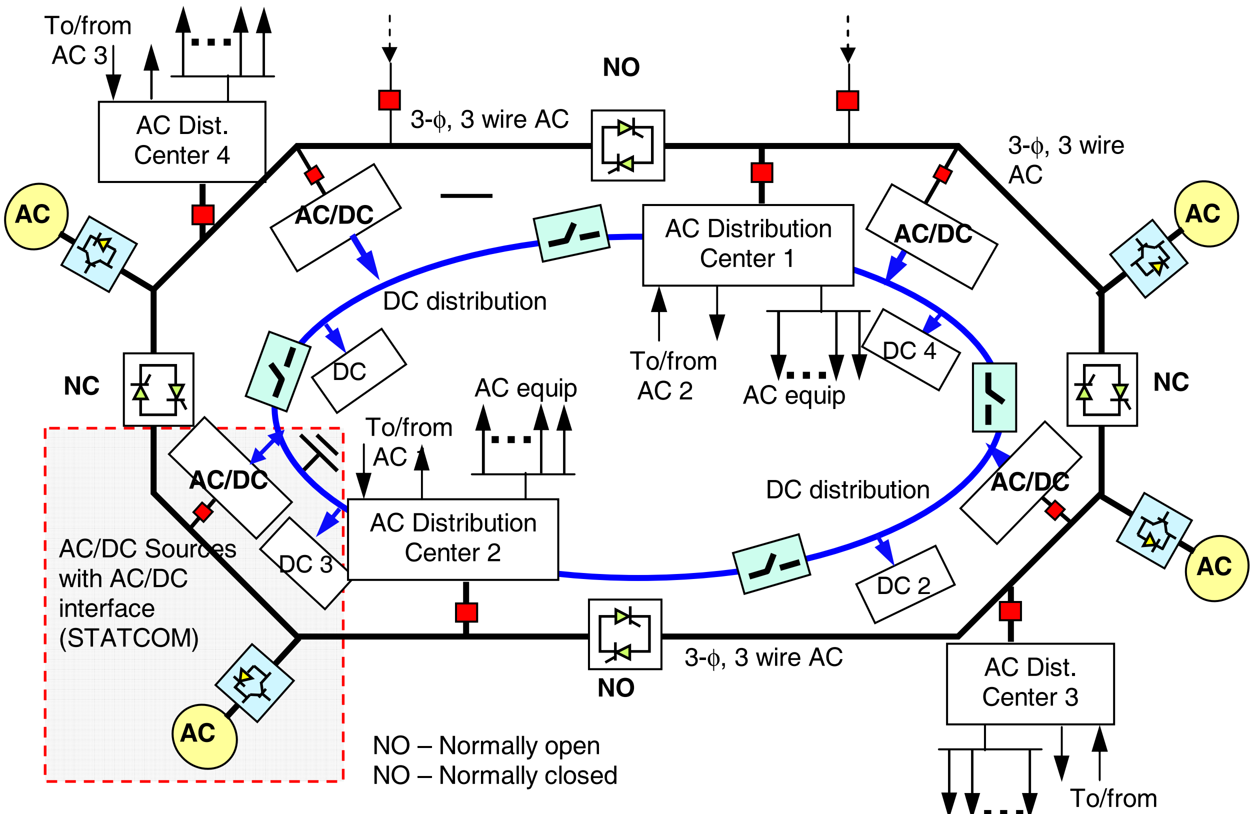

Fig. 1. Overall distribution system for lunar/Mars habitat.

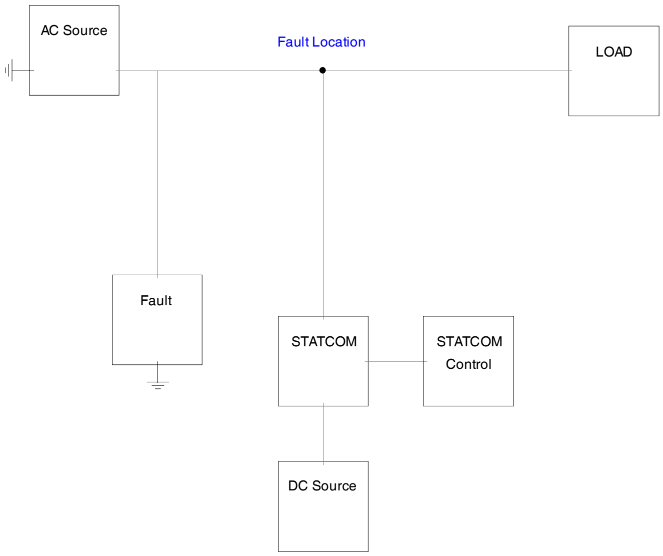

Fig. 2. Block diagram of the interface scheme.

The STATCOM has its own control system which will translate the voltage error into an appropriate conduction angle for the GTOs (Gate turn-off) in the STATCOM. In the face of a fault which will cause a drop in voltage at the load, the AC source will be cut off and the DC source will supply power through the STATCOM.

The STATCOM operation is described in [5], [6], [7]. A solid state voltage source inverter connected to the system acts as an alternating voltage source in phase with the line voltage to control reactive power/voltage at the point of connection. Depending on the extent of the voltage support required, the control system for STATCOM acts accordingly. If connected to an energy storage device such as a battery, it can provide simultaneous real and reactive power injection.

III. SIMULATION RESULTS

In the simulation study, a 3-phase fault is induced near the AC source. This is achieved through a 'Timed Fault Logic' block as shown in Fig. 3. One can specify the type of fault and the duration in this particular block provided in EMTDC/PSCAD library.

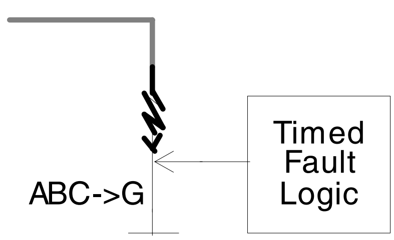

Fig. 3. Timed fault created on the system

The fault is introduced in the system at t = 1 sec and persists till t = 1.75 seconds. The AC system outage is illustrated in Fig. 4, which shows how the voltage drops to zero in the absence of any back-up arrangement through STATCOM.

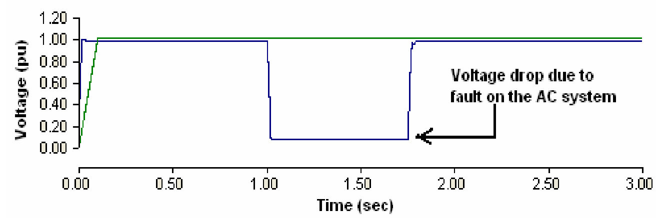

Fig. 4. Voltage drop due to AC system outage.

When the STATCOM is connected to the system, the DC source supplies the load and voltage is restored to the desired value as shown in Fig. 5. As soon as the fault is initiated on the AC system, the DC system supplies the load through the STATCOM. At t = 1.0 sec the difference between the desired voltage level and actual voltage level increases. It can be seen that the voltage is restored very close to the desired level.

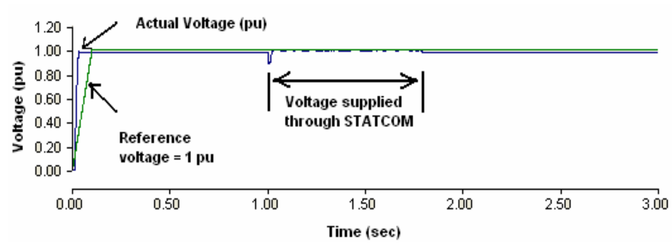

Fig. 5. Voltage support provided by the DC source.

One aspect which greatly affects the ability of this system to provide voltage support is the internal resistance of the battery used as a DC source. One can observe how the internal resistance of the battery affects the voltage profile. Fig. 6 illustrates the effect of an increased internal resistance of the battery. The internal resistance of the battery is increased by 10Ω and the voltage profile is plotted against time. It is evident that during fault condition, the measured voltage is not as close to the desired voltage as it was in Fig. 5.

Since the nature and magnitude of load supplied by the AC/DC hybrid system will have an impact on the system operation, it is interesting to see if the system reacts in the same way to a constant power and constant impedance load.

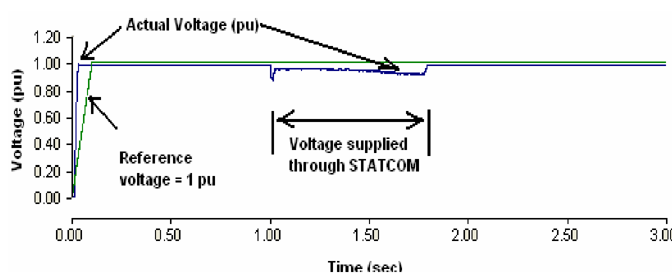

Fig. 6. Voltage support provided by the DC source with increased internal resistance.

A. *Constant P Load*

Fig. 7 shows the load voltage profile, and the active and reactive powers supplied to a 1 MW constant power load. The results obtained were quite close to what one would expect.

There are some spikes observed in the waveforms at the instant of fault initiation and fault clearing. These spikes are the result of switching taking place in the STATCOM.

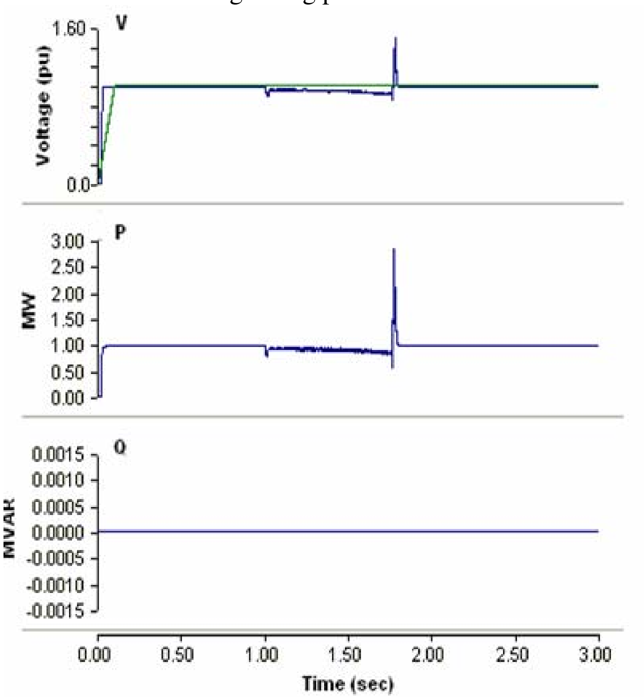

Fig. 7. Performance of the distribution system for a constant P load.

It can also be noticed that the active power consumption remains more or less steady at 1 MW even under fault condition. When the fault occurs, the DC supply takes over the responsibility of supplying the load, this can be observed in Fig. 8 which shows that during the fault condition (i.e. t = 1 sec to 1.75 sec), the STATCOM supplies current and the current flowing from AC source becomes zero during this time period. The current flowing out of the STATCOM terminals is measured in the DC branch of the system.

Fig. 8 illustrates that the DC source is capable of supplying equal amount of current under fault condition and it maintains the voltage close to the desired value.

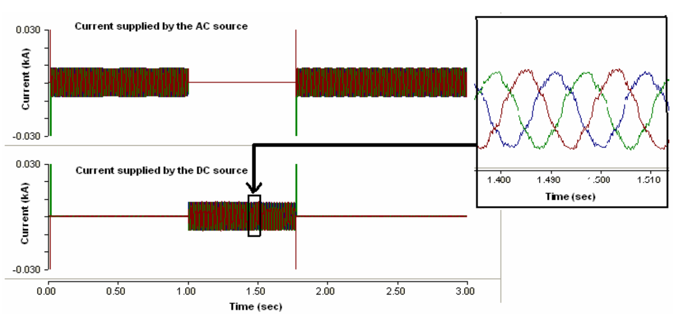

Fig. 8. Load current supplied by STATCOM during fault condition.

B. Constant Q Load

In this particular test case, a 1 MVar load is connected to the system and simulation results are observed. Fig. 9 shows the voltage profile, P and Q consumption at the load. The load voltage is restored to the desired level very quickly. The plot for reactive power shows an oscillatory nature which is mainly due to absence of damping due to resistance. If some resistance is added to the load, then the oscillations disappear.

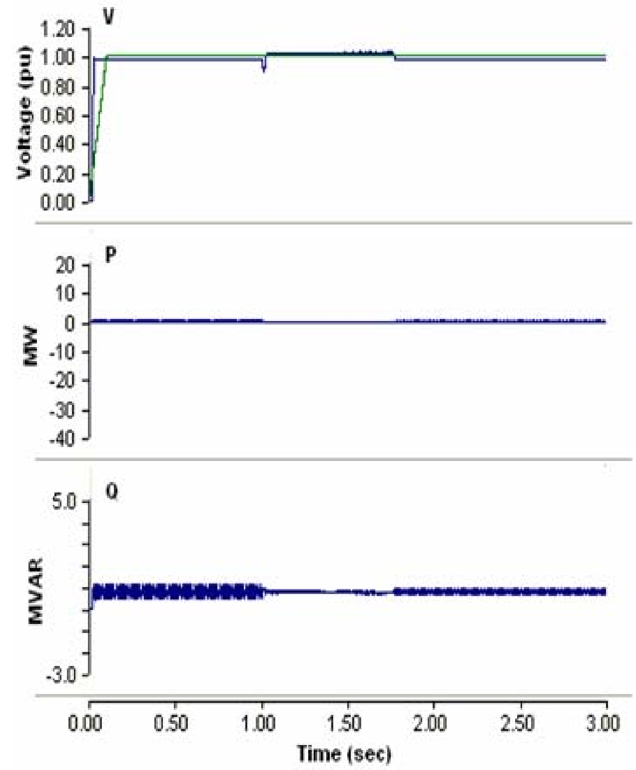

Fig. 9. Performance for a constant Q load.

C. Performance with a DC Load Connected to the System

It is interesting to see the distribution system performance with both AC and DC loads included. The purpose is to ensure that the system is capable of supplying AC as well as DC loads, which is a very real scenario on crew exploration vehicles or surface distribution systems. Variation in DC load can affect the system performance to a great extent. Fig. 10 shows the block diagram with a DC load included with the DC source. Figs. 11 (a) and (b) show the results obtained for variations in the DC load resistance of 100Ω and 5000Ω respectively.

It is evident that when the DC load resistance is very low, it extracts more current from the DC supply. In this case, the AC voltage profile drops well below the desired value of 1 pu. In case of a DC load with large resistance, this is not the case, because the DC load current is low. For any specific system, there will be a certain balance between the magnitude of AC load and DC load that it can supply. This particular simulation highlights the fact that there exists a particular combination of AC and DC loads for which the system will perform better.

D. Source Redundancy for Improving Reliability of the Hybrid AC/DC System

In this variation, the AC/DC hybrid distribution system essentially remains the same, but the number and orientation of AC and DC sources is considered to be flexible. If the load has a provision to be supplied by two or more sources, the overall reliability of the system will improve. Fig. 12 is the block diagram of the hybrid distribution system with multiple sources. The system now has two AC sources and two DC sources which are capable of supplying the same load under different network conditions. This system is then subjected to multiple fault conditions.

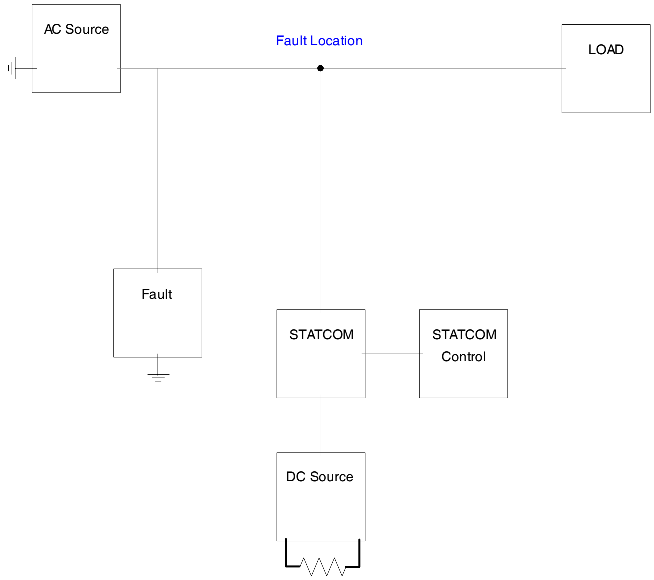

Fig. 10 Block diagram for the AC/DC hybrid system with a DC load included.

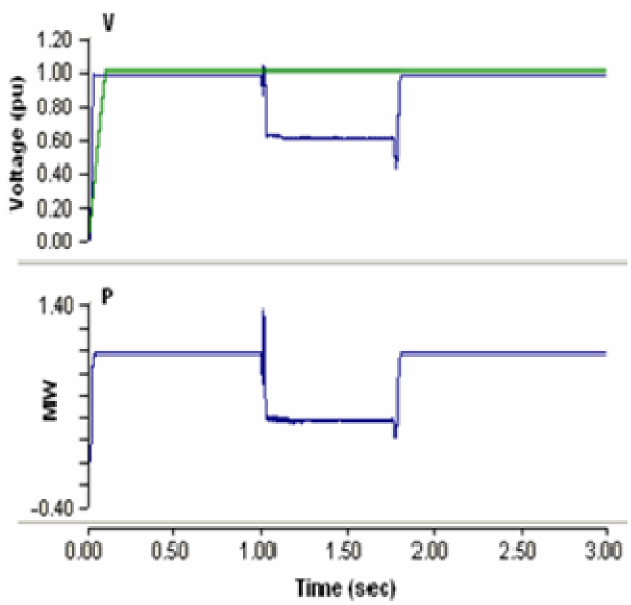

Fig. 11a. Effect of a DC load of 100Ω (large load current).

A three phase-ground fault is induced to the right of AC source 1 at 'Fault Location - 1', due to which DC source 1 takes up the responsibility to supply the load. A three phase-ground fault is initiated at 'Fault Location - 2' on the AC side of STATCOM-1. System performance is observed under such condition of multiple failures including failure of the primary back-up.

The network connections are controlled based on the voltage profile at the load. The control system works so as to ensure that the desired voltage is maintained at the load terminals. The two AC sources are on the right and left extremes and the two DC sources 1 and 2 are connected to respective STATCOM – 1 and STATCOM - 2 respectively.

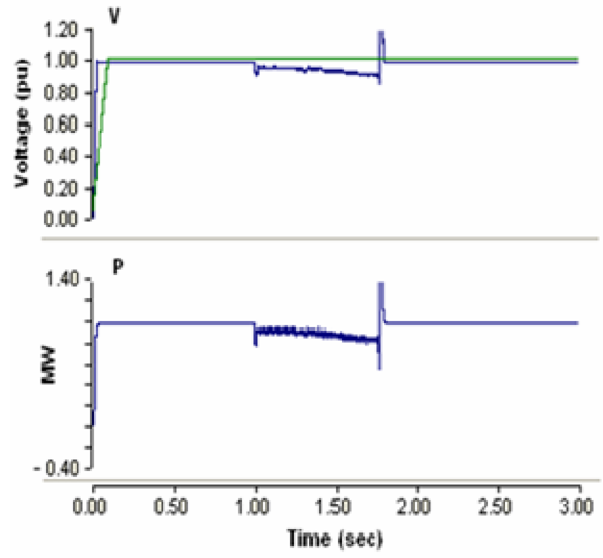

Fig. 11b Effect of a DC load of 5000Ω (smaller load current).

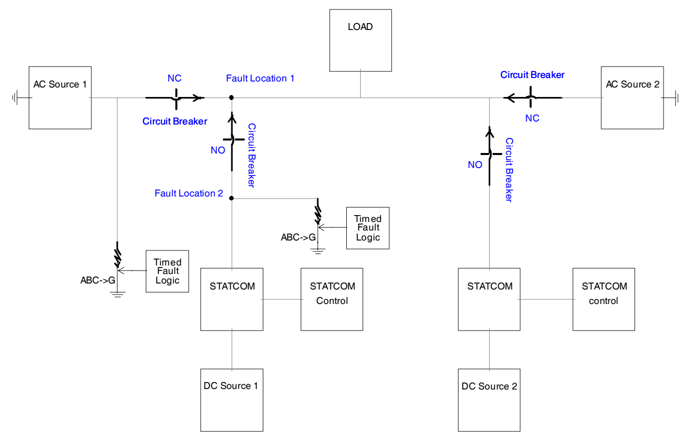

Fig. 12. Block diagram of the hybrid AC/DC system for improved reliability.

The simulations run on this system were similar to those discussed earlier. The faults are introduced on the system to test whether different possible power sources cater to the load under different network conditions. The first fault initiated on the system is a three phase-ground fault near AC source-1 which is the leftmost AC source in the system. Outage of this source forces the DC source-1 to supply the load. Now again a fault is initiated on the AC side of STATCOM – 1. Now AC source-2 at the rightmost end starts supplying the load. As soon as the first fault on AC system is cleared, the system returns to the original state wherein AC Source 1 supplies the load.

- t = 0.5 sec – A fault occurs near the AC Source-1
- t = 1.0 sec – A fault occurs in the branch which connects DC Source-1 and the load
- t = 2.0 sec – Fault on AC Source-1 is cleared.

A fault is placed on AC source 1 from t = 0.5 sec to t = 2 sec. The fault initiated on the DC branch lasts from t = 1 sec to t = 2 sec. At t = 2 sec the first fault is cleared and AC Source 1 can supply the load.

Fig. 13 shows the voltage profile at the load. One can notice small disturbances at t = 0.5 sec, t = 1 sec and t = 2 sec.

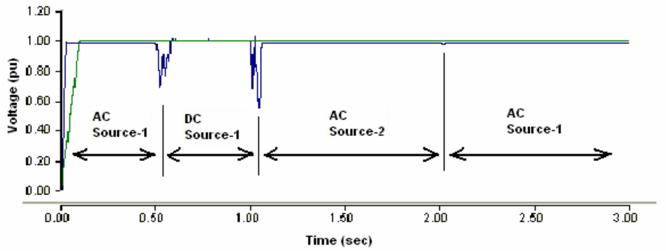

Fig. 13. Voltage profile in case of multiple faults on the system.

DC Source-1 and AC Source-2 respectively supply the load during the fault conditions. These changes are depicted clearly in Fig. 12. The sequence of events in terms of power sources can be described as follows:

- AC Source-1 supplies the load till the first fault occurs at t = 0.5 sec.
- DC Source-1 supplies the load during t = 0.5 sec to t = 1 sec.
- At t = 1 sec there occurs a fault on the DC branch and the DC Source can no longer cater to the load. Thus from t = 1 to t = 2 sec AC Source-2 takes up the responsibility of supplying the load.
- When the first fault get cleared at t = 2 sec, then AC Source-1 again starts supplying the load.

Fig. 14 shows the currents supplied by the three sources. It can be observed that all the three sources supply equal amount of current, thus maintaining a reliable and continuous supply to the load in the face of multiple faults on the system.

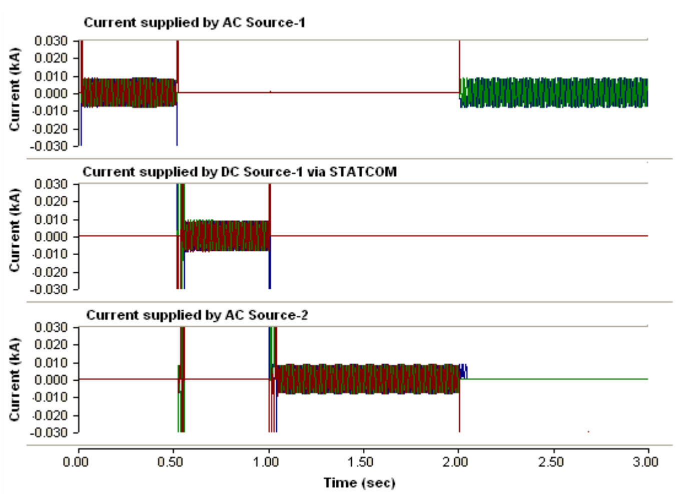

Fig. 14. Load current supplied by different sources under multiple-fault condition.

E. System Adequacy in Case of High Current Demanding DC Loads

In Section III.C, it was shown that the AC voltage support provided by the DC source is inadequate when the DC load demands a large current. To overcome this problem, one can take advantage of the fact that there will be more than one DC sources on the DC distribution system. The architecture of Fig. 12 can be modified to increase the ability of DC distribution system to supply large current demanding loads. When the simulation is run with the same DC load supplied by one DC source and then by two DC sources the system performance in the latter case is better in terms of AC voltage support and power delivered to the AC load. Fig. 15 presents the voltage profiles and plots for the supplied power in both the cases. Compared with Fig. 11a which is the result of a 100Ω DC load, the system performance with two parallel DC source is improved considerably. This case illustrates the fact that under fault condition (t = 1 sec to t = 1.75 sec), one DC source proves to be inadequate but two DC sources connected in parallel can satisfactorily provide voltage support.

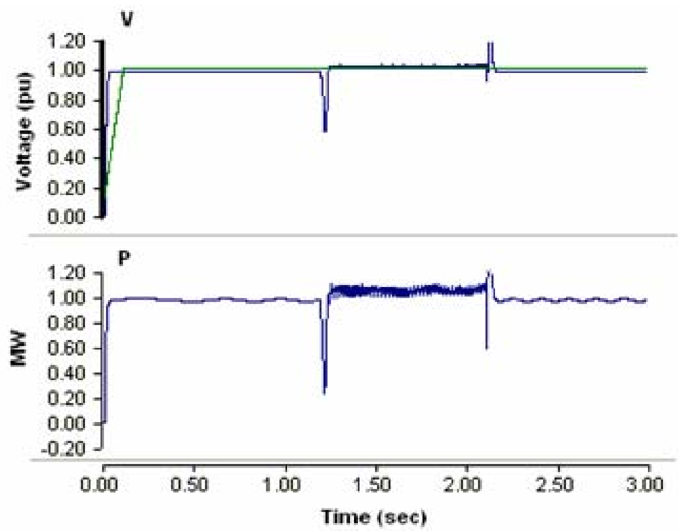

Fig. 15. System performance with two DC sources in parallel and 100Ω DC load.

IV. CONCLUSION

This study investigated a suitable hybrid AC/DC distribution system for an electrical distribution system onboard a spacecraft or for future lunar/Martian surface. A STATCOM is selected as a possible candidate for the interfacing purpose. One reason is its ability to be connected to a battery source. The AC/DC hybrid system was simulated in EMTDC/PSCAD environment. The results obtained from various simulations prove that hybrid AC/DC distribution systems with STATCOM-based power electronic interface are capable of providing reliable power to both AC and DC loads. Various system scenario simulations have provided a better insight into the behavior of the hybrid distribution system. Source redundancy is proposed to improve the reliability and operational flexibility of the system. The results illustrate that this kind of system will be able to work under multiple fault conditions.

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BIOGRAPHIES

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Badrul H. Chowdhury (M'1983, SM'1993) obtained his Ph.D. degree in Electrical Engineering from Virginia Tech, Blacksburg, VA in 1987. He is currently a Professor in the Electrical & Computer Engineering department of the University of Missouri-Rolla. From 1987 to 1998 he was with the University of Wyoming's Electrical Engineering department. Dr. Chowdhury's research interests are in power system modeling, analysis and control and distributed generation. He teaches courses in power systems, power quality and power electronics.