NASA Mission to MARS Program

Photo Courtesy of NASA

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The Application of Lessons Learned

From DC Microgrid Technology for Spacecraft to Terrestrial Microgrids

This article examines the challenges and lessons learned from modeling DC microgrids for spacecraft designed for manned space travel to MARS and compares the properties and characteristics of DC microgrids on board spacecraft with the properties and characteristics of Terrestrial AC microgrids, explores potential applications of DC microgrids to Terrestrial AC microgrids and lastly makes an argument to address the need for Industry Wide Standards for Terrestrial AC microgrids. This article is based in part on an innovative software approach to analyzing large Terrestrial AC microgrids and providing a proof of concept for analyzing DC microgrids on board spacecraft as part of the long term NASA Mission to MARS Program. Gridquant Technologies and Battelle Memorial National Labs collaborated on a Phase I SBIR (Small Business Innovation Research) project which this article will discuss in relationship to the commonalities of AC microgrids and DC Microgrids.

Similarities of DC Microgrids on Spacecraft to Terrestrial AC Microgrids

DC microgrids are not new. They have been powering spacecraft for over 55 years and have been powering manned craft operating in hostile environments for over 100 years (the first submarines utilized DC microgrids). When operating in deep space, the importance of 100% reliability makes it necessary to have extraordinarily robust hardware and software to monitor and control the spacecraft DC microgrids. Previous manned space missions have involved "near earth orbit" travel to the Moon and the International Space Station (ISS) where telecommunication latency is manageable by thousands of ground personnel at Houston Space Center, Cape Canaveral and other tracking stations around the world. The premise for manned space travel to MARS is that telecommunication latency of up to 45 minutes is not acceptable for the reliability of the mission. Therefore, the management of the onboard DC microgrid power management and distribution (PMAD) system must be robust, autonomous and fault tolerant.

Solar arrays, batteries and DC-DC converters make up the majority of components powering the DC microgrid on board spacecraft. These components have non-linear characteristics which can lead to voltage collapse if there is a loss of a key component or if the solar arrays, batteries and converters are operated in an unstable region of the system curve. The electric loads on board the spacecraft are constant power loads. This type of loading exacerbates a component failure scenario where a single failure can cause a larger voltage drop and resultant higher losses that potentially cascade into a complete voltage collapse. Terrestrial AC grids and microgrids have similar constant powerloads as reflected back into the high voltage transmission grid and are susceptible to voltage collapse under peak load conditions particularly where the reactive (I2X) losses on the transmission grid are high. Figure 1 shows a diagram of spacecraft power system architecture.

Power Flow Analysis of large and medium scale terrestrial AC transmission grids has been performed by various software programs the first being Gauss-Seidel (Ward-Hale, 1956) and the second full Newton-Raphson (Tinney-Hart, 1967) to analyze the state of the transmission grid on the terres-

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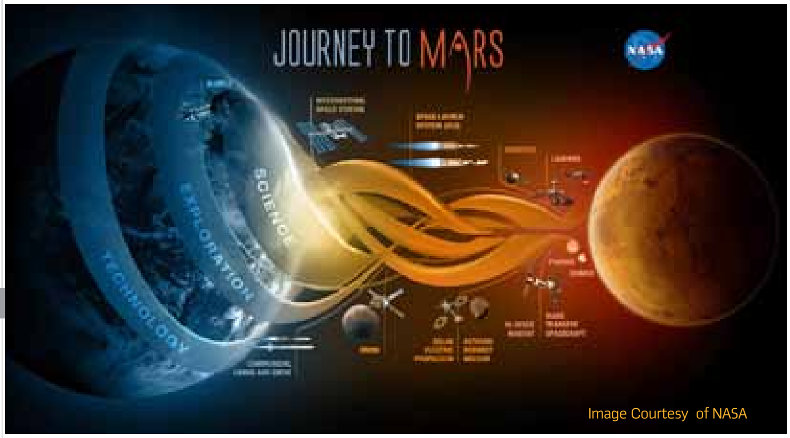

Image Courtesy of NASA

Having reliable algorithms to control and manage terrestrial AC grids and AC microgrids will provide for more reliable of operation of both the AC grid and microgrid.

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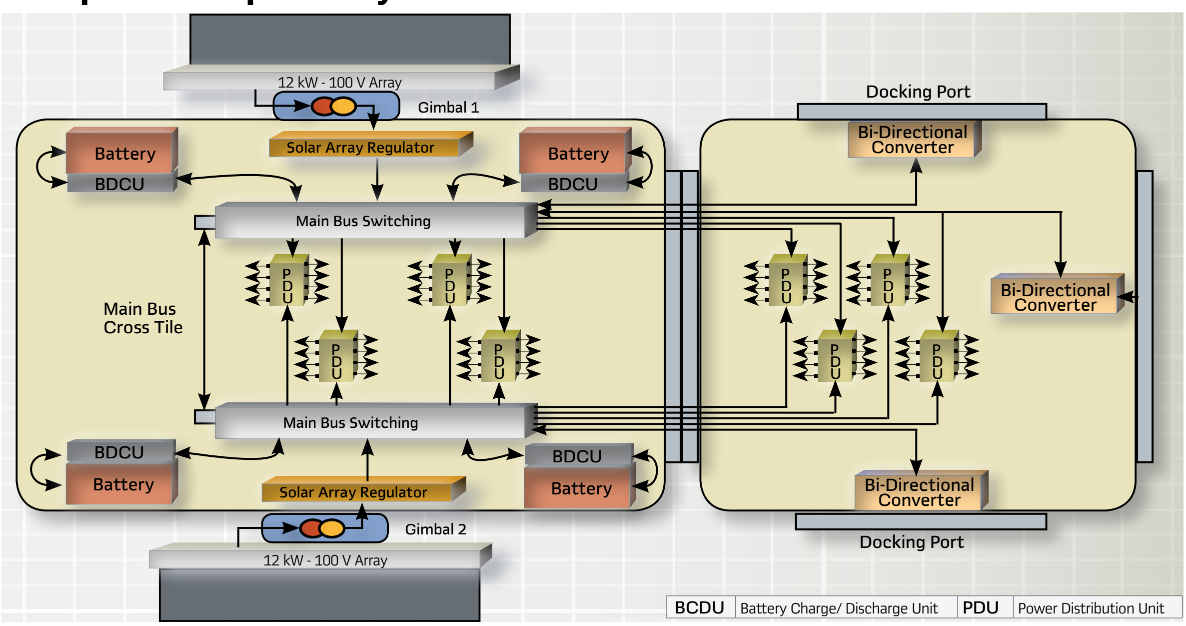
trial grid. While these programs have provided excellent analysis over the years, they have had known problems solving power flows near the limits of voltage collapse because they rely on iterative methods and are dependent on the quality of the initial starting point. In the past three decades terrestrial transmission grids have been moving operationally closer to the voltage collapse limit for a variety of reasons including the retirement of older fossil fuel power plants near load centers. As the trend toward operating closer to the voltage collapse limit continues, the ability to analyze the grid and provide command and control signals in real-time has become extremely important.

This mirrors NASA's concerns regarding voltage collapse limits for the DC microgrid. As part of a Phase I project to support NASA's Mission to MARS program, Gridquant Technologies and Battelle Memorial National Laboratories proposed using a holomorphic embedding load flow (HELM™) algorithm invented by Dr. Trias in the late 1990s. The HELM™ algorithm is an extremely robust deterministic power flow that can solve at the point of collapse regardless of the initial starting point which is crucial for autonomous control of DC microgrids. The Gridquant/Battelle team demonstrated the capability of HELM™ by comparing the solution of a 300 bus IEEE AC model with HELM™ power flow versus a Newton-Raphson power flow. The 300 bus IEEE AC model was chosen because it represented the complexity of a DC microgrid on board a spacecraft. Figure 2 presents a Sigma curve from HELM™ showing when load is added to Bus 528 of the 300 bus IEEE model, there are several points near

1 Spacecraft power system architecture



the boundary of the Sigma curve indicating conditions near voltage collapse.

While this is not an actual AC transmission grid, it demonstrates that many transmission buses are very close to voltage collapse and if additional load were added or loss of a single transmission element were to occur, the transmission grid would collapse. The deterministic holomorphic embedding load flow demonstrated the capability to solve right up to the point of collapse and can be utilized in a proactive way to measure the electrical distance to collapse from any steady state point on the AC transmission grid. (Figure 3).

Similarly, voltage collapse is a major concern on a DC microgrid due to the nonlinearity of dc-dc converters, solar generators and batteries. An additional complication on board spacecraft are solar eclipses. These may happen abruptly and when they occur the DC microgrid must be able to rely solely on storage devices such as batteries and flywheels to maintain voltage stability. During these periods the DC microgrid must be prepared to shed load if a critical voltage limit is approached. The loads in spacecraft may be categorized into the following types: essential; semi-essential and non-essential. Non-essential loads such as crew off-duty loads will be shed first to maintain voltage stability. Of note is that both AC and DC microgrids use special protection systems (SPS) to maintain stability.

The HELM™ algorithm was adapted to model the nonlinearity of DC microgrids on board spacecraft. The unique non-linear characteristics of solar arrays and DC to DC Buck Converters presents challenges for modeling that are not present in the AC terrestrial grids. While large scale solar PV projects are connected to terrestrial AC grids, the DC to AC inverters and interposing transformers mitigate the effect of the non-linearity.

Figure 4 illustrates the schematic of the solar-array-buck-converter power system for spacecraft:

The system equations for the spacecraft are defined by sets of differential algebraic equations where the equilibrium of the system can be found by setting the derivatives of all the state variables to zero. Finding the equilibrium of the simplified spacecraft is non-trivial. Figure 5 demonstrates there are a number of sets of equilibrium points of which one set is in the desirable and stable region.

The DC-based HELM™ power flow demonstrated on the simplified spacecraft power system the ability to find the desirable and stable region for equilibrium.

Potential Terrestrial Microgrid Applications and Technical Challenges

While the reliability requirements for Terrestrial AC microgrids may not always be as stringent as for spacecraft DC microgrids, there are certainly many applications where the consequences of failure can entail loss of mission, loss of substantial value, and in worse cases loss of life. Therefore, it is important to manage Terrestrial AC microgrids in a similar fashion.

A brief discussion to define an AC microgrid is appropriate at this point. The term microgrid has become widely used in recent years. To many non-technically oriented persons it is as though microgrids are a new breakthrough technology. However, a microgrid is not a single technology, A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. When nontechnical policy persons refer to "microgrids" as the answer to power reliability problems, what they are actually referring to is the ability to create an integrated sustainable system comprised of traditional small scale generation technologies such as: reciprocating engine-gensets, turbines, micro-turbines, and fuel cells; renewables such as local solar PV and wind; and advanced storage technologies maintained by an intelligent control and monitoring system. (That is operated in parallel with the main

2 Sigma curve for 300 bus IEEE model with load added to Bus 328

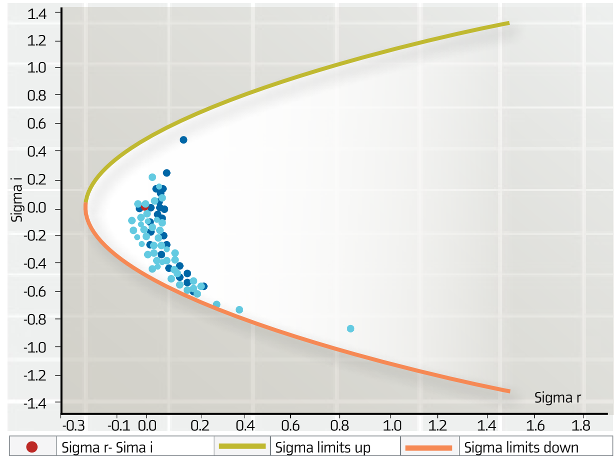
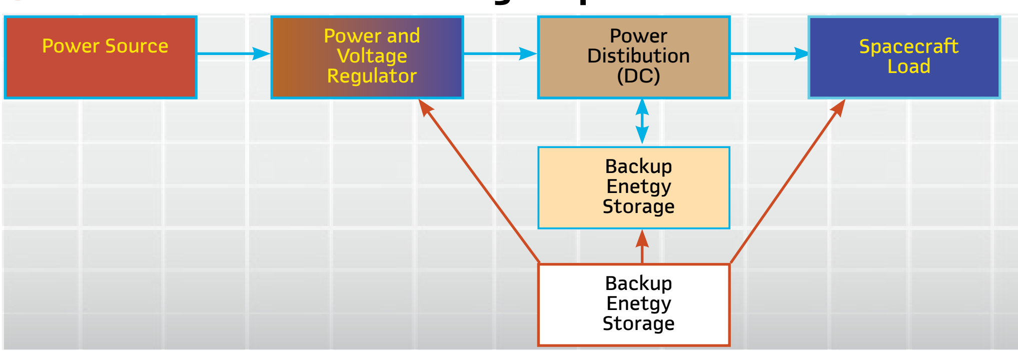


Figure 2: shows that there are several points near the boundary of the Sigma curve indicating conditions near voltage collapse.

3 DC-based HELM for intelligent power control



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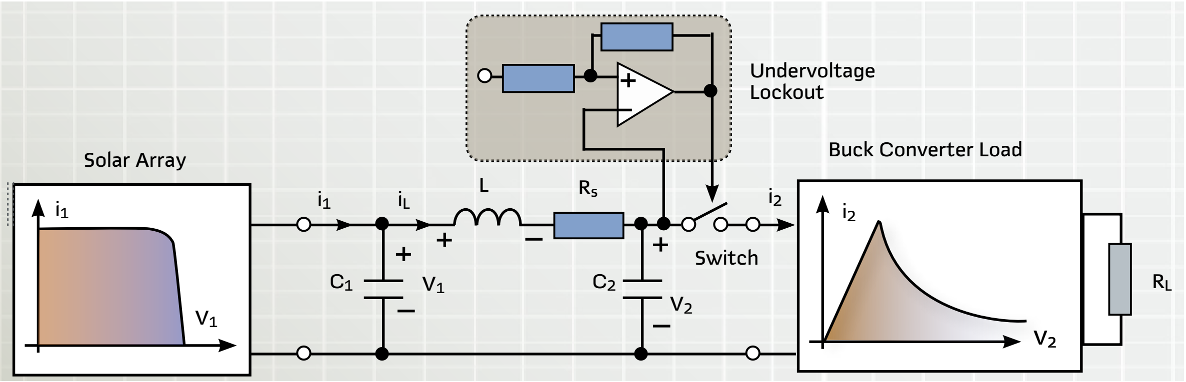
4 Simplified structure of a spacecraft power system



grid and can be separated and operated as a much smaller grid).

On a smaller scale, roof top solar for residential and commercial buildings will play a larger role in the energy mix of microgrids. Roof top solar coupled with battery storage and gensets could be a good combination for energy efficiency and reliability. The recent announcement by Tesla of its 10 kwh battery for home use that complements a solar roof top array and charges electric vehicles is an interesting proposition for a microgrid given the proper means of autonomous control and safe means of disconnection. Military bases are excellent candidates for larger microgrids, as they generally have enough land for larger scale solar projects, diesel generators for critical facilities, and a significant transmission and distribution grid. Autonomous control of prospective military microgrids would be very critical. Figure 6 shows some examples of potential microgrid configurations.

Terrestrial AC microgrids as compared to DC microgrids, have the advantage of being connected to a much larger AC grid which provides frequency and voltage stability a significant portion of time. When the main AC grid experiences problems or collapse, the AC microgrid must be able to sense this and reliably and quickly disconnect from the AC grid and then maintain stability for the duration of the event. There are several challenges for the terrestrial AC microgrid intelligent control system to overcome in managing its reliability and stability.

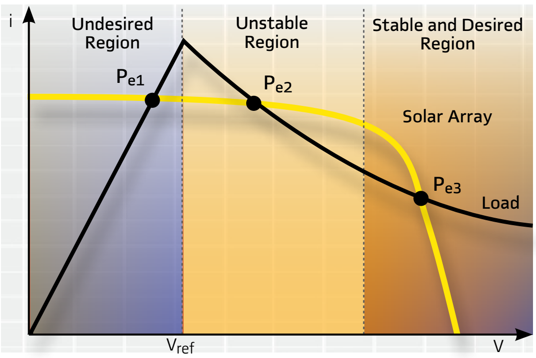
Terrestrial AC micro grids pose some unique scenarios for autonomous control as the situation is substantially different when the micro grid is connected in parallel with the main grid, versus operating in a standalone mode when islanded.

The first question is what is the intended application? Spacecraft microgrids spare no expense to deliver the level of reliability and performance needed for long-term completely isolated operation. The hardware and software are extraordinarily robust. This is compared to typical terrestrial back-up systems which are designed to run for a very limited period of time and where capital considerations usually are a deciding factor in technology selection. A key consideration that is often not well understood when acquisition decisions are made is that the level of robustness needed to provide a 72 hour solution is dramatically different then when a 72 plus hour solution is needed. The cost for the extra robustness is an exponential rise the further out on the time scale the solution is. For all intents and purposes, a 30 day solution is a full scale continuous operational system and the costs for the components can be as much as 5 times greater as the cost for a 72 hour solution.

Secondly, assuming the appropriate level of robustness has been determined and the components budgeted for, there are operational considerations that must be addressed. When an AC microgrid is connected to the main utility grid, frequency and voltage are controlled by the main AC grid and generators within the micro grid are on "droop" control. Note that solar PV inverters can be designed to operate in a line commutated mode when connected to the main AC grid or in a standalone mode when islanded. When disconnected and operating in a standalone island, the microgrid must now control its frequency and voltage very efficiently without support from the main AC grid. Generators with isochronous governors or solar generators in a standalone mode must autonomously control the frequency and voltage on the microgrid. Maintaining frequency and voltage must be coupled with managing power demand and flow against generation

Figure 5: demonstrates there are a number of sets of equilibrium points of which one set is in the desirable and stable region.

5 Stability regions for a simplified spacecraft power system



and storage, all the while maintaining the storage component. When connected to the utility grid, the grid acts a giant capacitor absorbing sudden changes in demand and power flow both up and down. Even very large motors or resistive load have little effect on the grid, although an individual facility may see brief voltage spikes when large loads are turned on an off. In the AC microgrid, large load changes can have a devastating effect on the system and can quickly cause system collapse as a series of cascading events occurs as individual component protection systems initiate isolating the equipment to protect it from damage.

Our experience includes multiple commercial, defense and space mission critical and essential systems. In all of these applications once the appropriate technology components are selected the operational control and monitoring system is the key to maintaining system stability and reliability. And it is in this application that the greatest level of uncertainty exists. We address this issue in the next section.

Industry Wide Standards needed for Terrestrial Microgrids

At this point in time, the microgrid is very immature. There is little standardization for definitions, let alone component technologies and control technologies. Without standardization it is very difficult to create a cost effective solution that would be operational with a high degree of confidence in its ability to work. That is because each component has to be individually created and married to the system and then tested and retested to achieve a stable system. In effect, each system has to be designed and built from scratch and there is no acceptable level of certainty that the system will work as a whole when completed. We are very much in the early PC days when Apple, IBM, Microsoft and Oracle were vying for control. Yet instead of only a few main competitors, there are dozens upon dozens of technology providers. The regulated utility industry has not provided a standardized solution as microgrids are not currently in their economic interest. The unregulated energy industry has not provided a solution, although one would look to IEEE. In the US, the federal government has yet to put forth a solution set. The economic stakes are very high and the vested interests will jealously protect their positions. As with many technological breakthroughs, we would look to the US Department of Defense or NASA to establish standards that would then de facto carry over to the private sector. This area is getting a high degree of attention at the Pentagon and perhaps that will be where the genesis of a solution is derived.

Conclusion: The non-linearity of DC microgrids on board spacecraft designed for deep space travel where communication latency is an issue has driven the need for autonomous control of the DC microgrid where the ability to robustly solve power flow equations is paramount. While AC terrestrial grids have similar voltage collapse issues at the limit, traditional numerical methods have been used for the last several decades to model the AC terrestrial grid. Interesting synergies between the DC microgrid, large AC terrestrial grids and AC terrestrial microgrids have developed, requiring more robust and precise means of solving the real-time power management problems and equations in increasingly non-linear situations. Knowing and predicting the distance to collapse allows for proactive control to prevent collapse in the first place and to restore any of the grid from a flat start if multiple events were to occur.

The terrestrial AC grid of the 21st century will increasing look and perform differently than that of the 20th century. Exponential growth of solar and wind displacing older less efficient fossil fuel resources and distributed generation and combined heat and power all create a decentralized grid. The 21st century will also see significant growth of AC terrestrial microgrids due to financial and reliability reasons. Having reliable algorithms to control and manage terrestrial AC grids and AC microgrids will provide for more reliable operation of both the AC grid and microgrid. Having reliable, robust algorithms to monitor and control DC microgrids is essential for deep space exploration. ■

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Dr. Trias is the principal inventor of the HELMT method and the driving force behind its application to electrical power systems. After 11 outstanding years in academia where he created a PhD program in Physics and led research that resulted in more than 50 scientific publications in prestigious journals, Dr. Trias transitioned his career efforts to transferring basic science to the most pressing needs of industry. He also did most of the research work for the Phase I NASA DC Microgrid project.

6 Schematic of potential Microgrid