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Analysis and Testing of Optimal Power Control Strategy for NASA Moon Base Interconnected DC Microgrid System

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Abstract

As a part of NASA's efforts in space, options are being examined for an Artemis moon base project to be deployed. This project requires a system of interconnected, but separate, DC microgrids for habitation, mining, and fuel processing. This in-place use of power resources is called in-situ resource utilization (ISRU). These microgrids are to be separated by 9-12 km and each contains a photovoltaic (PV) source, energy storage systems (ESS), and a variety of loads, separated by level of criticality in operation. The separate microgrids need to be able to transfer power between themselves in cases where there are generation shortfall, faults, or other failures in order to keep more critical loads running and ensure safety of personnel and the success of mission goals. In this work, a 2 grid microgrid system is analyzed involving a habitation unit and a mining unit separated by a tie line. A set of optimal controls that has been developed, including power flow controls on the tie line, dispatch of PV generation, and dispatch of non-critical loads, is analyzed, and validated in hardware on the Secure Scalable Microgrid Testbed (SSMTB). This testbed includes hardware emulators for a variety of energy sources, energy storage devices, pulsed loads, and other loads.

Introduction

One component of NASA's plans for the Artemis missions is the construction of a habitation and mining base on the lunar surface [1]. The proposed system consists of several load centers separated by 9-12 km. Each of these load centers acts as an independent DC microgrids with their own loads, sources, and controls. Grid tie lines are used to connect these disparate microgrids with power electronics used to step up the line voltage and control power flow between grids. The tie lines are required to transport power between grids in cases of anticipated or non-anticipated shortfalls between power generation and load demands.

DC microgrids have been examined in terrestrial systems for the purposes of integration of renewable energy systems such as PV and wind [2]. DC systems are well suited for this purpose because many of these renewable sources are natively DC, such as PV and energy storage, and there are reduced losses at steady state compared to AC systems [3]. These reason also make DC microgrids the ideal technology for a moonbase system largely powered by PV and energy storage sources.

Due to the high consequences of the loads in the system, it is important that critical loads remain uninterrupted during interruptions, the design of the control system governing the power flow through the tie line is of critical importance. This paper develops a control strategy for the power flow through a grid tie and examines the performance using a hardware testbed.

System Description

The system under consideration in this paper is shown in Fig. 1. The full scale system consists of a habitat module, an in-situ resource utilization (ISRU) mining module, and an interconnection line between them [4].

The habitat module, shown on the left side of Fig. 1, consists of a generation bus and two load buses. The generation bus houses photovoltaic generation resources and energy storage systems. The load buses contain the loads needed for the operation of the habitation module. The load buses also have their own energy storage systems to support the operation of the loads. There is also a connection between the load grids to allow for rerouting power flow in the case of fault or failure [4].

Secure Scalable Microgrid Testbed (SSMTB)

The SSMTB was developed to validate controls for networked microgrids [5, 6, 7] and was later configured to represent an all-electric ship power system with multiple busses (or zones) and analyse potential components to be implemented in the system [8, 9]. The testbed includes three DC microgrid systems, a central bus cabinet for connecting components and microgrids, control computers, a data acquisition system, and a graphical user interface. The testbed is designed to operate at voltages up to 400 V dc; primary components include: several 5 kW rated Arbitrary Response Energy Storage Emulators (ARESE), photovoltaic emulators, power electronics based grid-to-grid converters, and high-power programmable digital resistors (0-6.7 kW). In addition, a master control console scripts the experiments with designated source and load profiles to ensure that experiments with highly variable sources and loads are run exactly the same each time. The laboratory layout is pictured in Fig. 2. This section will discuss the components that were used in this testing and the representative system that was constructed to analyse the control performance during power transfer between buses.

Arbitrary Response Energy Storage Emulator (ARESE)

Energy storage systems are a vital component of the proposed moon base system. Due to the limitations of generation in space environments, the primary source of generation will be photovoltaic panels similar to those used in satellite and space station applications

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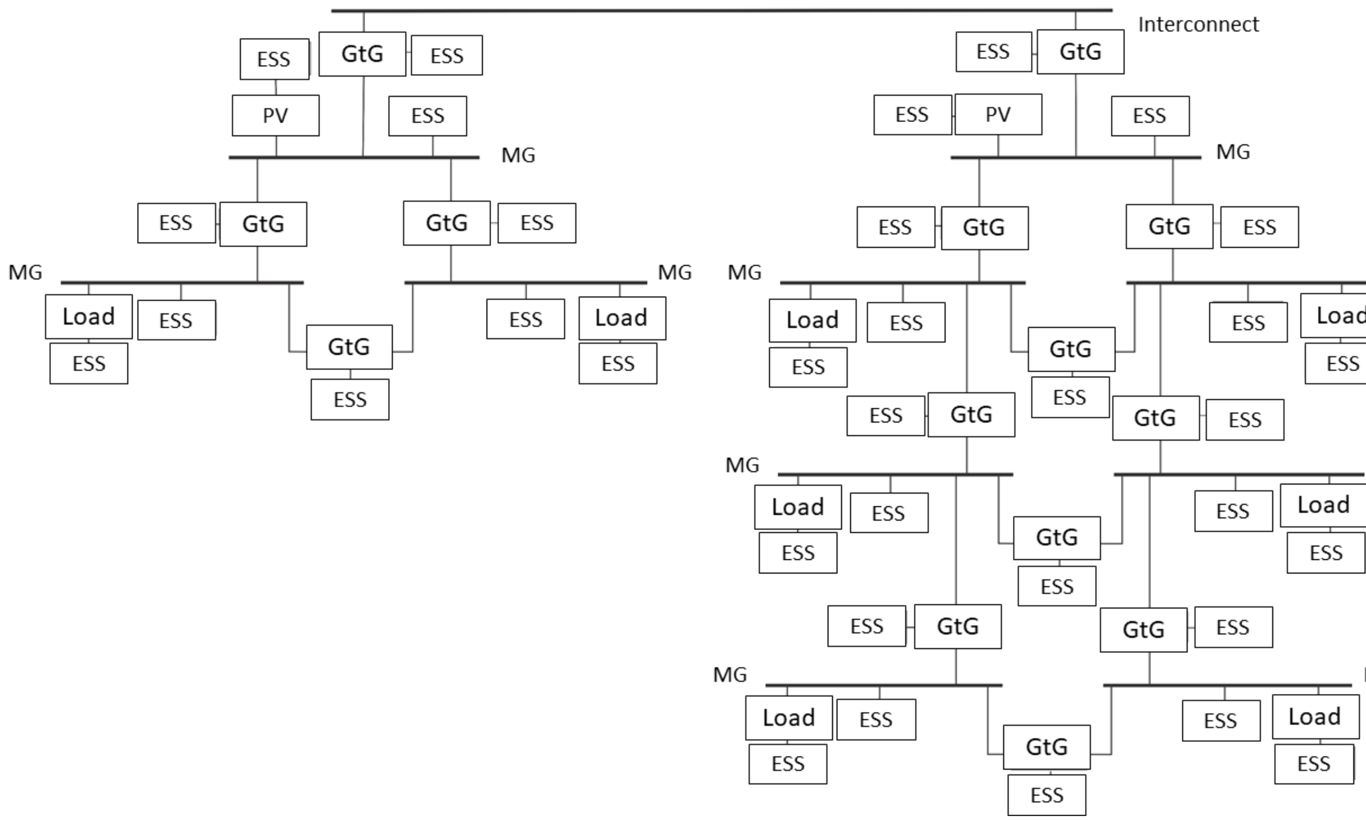

Figure 1: Moonbase model incorporating habitat, ISRU, and tie line between them.

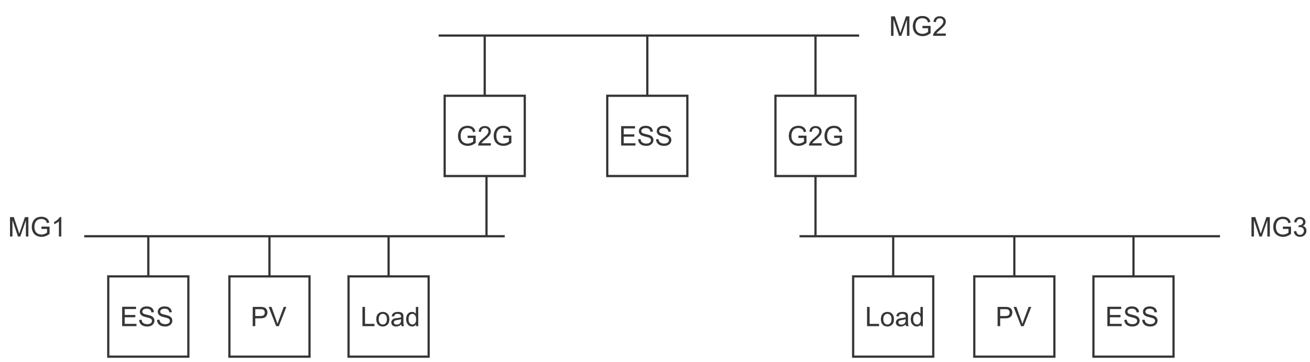

Figure 2: Simplified moonbase model used for SSMTB analysis and testing.

[4]. Due to the orbit of the moon, these panels will be unable to generate power when the sun is in eclipse. During eclipse, the system will need to draw energy from battery storage.

The SSMTB uses ARESE units to emulate the behavior of an energy storage system. These units consist of a power supply and a dump load connected to an internal capacitor through power electronics boost converters with another converter managing power flow out from the capacitor to the bus. The power electronics are controlled by Versilogic industrial control boards running the servo-level controls that operate on the microsecond scale, including the switching signals and Proportional-Integral (PI) control loops. These servo-level controls can be dispatched to control the output voltage or output current of the ARESE unit to conform to either internal set points or external set points from the communication system. For grid connected energy storage units, the ARESE will be used to control the output voltage [5].

Photovoltaic Solar Emulator

Photovoltaic (PV) resources are emulated by using an ARESE unit setup for current control. The current command for these units are determined by the simulated results.

Grid-to-Grid Converters

In order to control power flow between grids, power electronics grid-to-grid converters are used. These converters are back to back boost converters with a capacitor in the middle. These converters use a servo controller to manage the voltage of the internal capacitor and respond to power flow set points sent from supervisory controllers.

Digital Loads

In order to simulate a wide variety of loads, the SSMTB uses digital loads that consist of a bank of parallel 1500 Ω resistors. Sets of parallel resistors can be turned on or off from 0 in parallel up to 63 in parallel. This allows for a wide range of resistance settings that relate to the load power level for a constant bus voltage [5].

Control System

The SSMTB provides Gigabit Ethernet IP communications for the master console and supervisory controllers for each component shown in Fig. 1. Custom TCP and UDP data protocols were developed to support adequate measurement and controls signaling during experimentation.

Optimal Controls

An optimal controller is utilized to monitor and control the SSMTB components. The definition of the moonbase model components, connectivity, and signaling are defined in an external JSON (JavaScript Object Notation) formatted file. Then, the optimal controller processes the configuration to construct a model of each SSMTB component and associated signal at each IP address and port.

The optimal controller manages the moonbase power system by processing periodic measurements and sending control updates. The controller incorporates a nonlinear optimization engine to improve the power system performance [10]. The moonbase model state, cost functions, and constraints are used to formulate optimization problem statements. The controller runs the optimization engine against these problem statements, processes returned solutions for set points, and sends the set points to components [11].

Scaled Hardware Test System

In order to implement a representative moonbase system and examine the power transfer between grids, a simplified version of the system, shown in Fig. 2, was implemented on the SSMTB. In this system, all loads, PV generation, and energy storage systems (ESS) on a grid were condensed into one unit. In this experiment, the optimal controller monitored the load demands and PV generation. The PV1 profile causes a significant decrease in generation, then increased back to full production. The optimal controller compensates for the PV1 generation loss by pushing power across the tie line.

Results

In order to implement the controls on the hardware, the optimal control used a simulated reduced order model of the hardware system to make the calculations based on the same profiles that were used in the hardware test. The bus voltages of all three grids was set to 200 V. The loads were held at a constant 1066 W in the simulation, which is equivalent to a resistive load of 37.5 Ω at 200 V.

The PV power generation used in the simulation is shown in Fig. 3. This same generation profile was also applied to the SSMTB hardware system, resulting in the response shown in Fig. 4. The hardware response is a fairly close match to the simulated version when examined with a windowed average value, but due to low damping in the system with zero-power-flow between grids, there is more oscillation in the supplied power from the PV supplies. This is a servo level control issue that was not accounted for in the model.

The power flow commands for the grid-to-grid converters obtained from the optimization based on the simulation is shown in Fig. 5. This commanded value was fed into the hardware system and resulted in the power flow through the grid-to-grid converters shown in Fig. 6. As with the behavior of the PV generation, this response is a decent fit with the commanded values in the average value sense, but there is more oscillation in the response when zero-power-flow between grids is commanded.

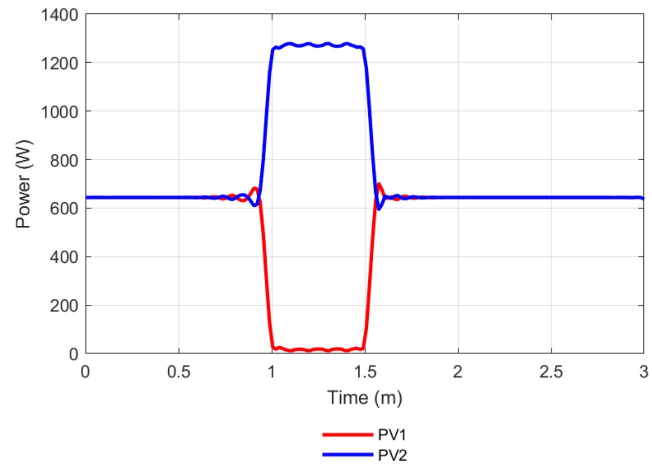

Figure 3: PV power generation in simulated test.

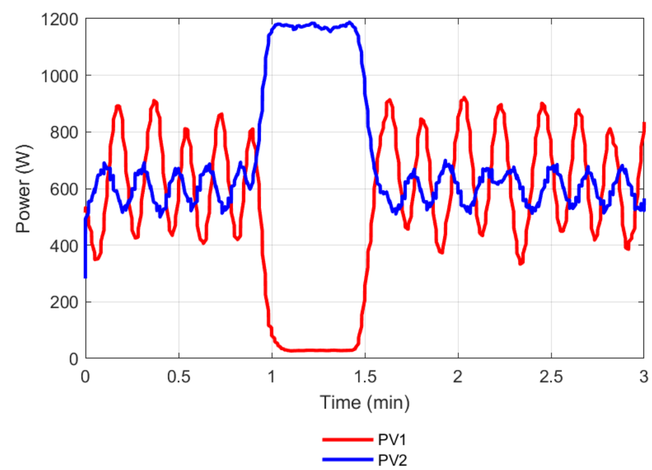

Figure 4: PV power generation in hardware SSMTB test.

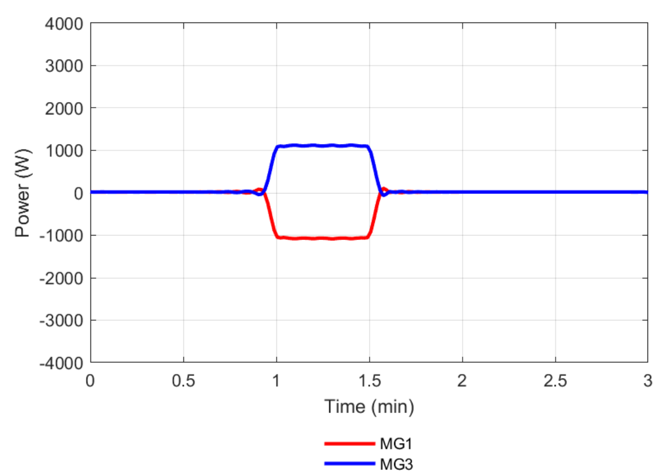

Figure 5: Power flow through tie line in simulated test.

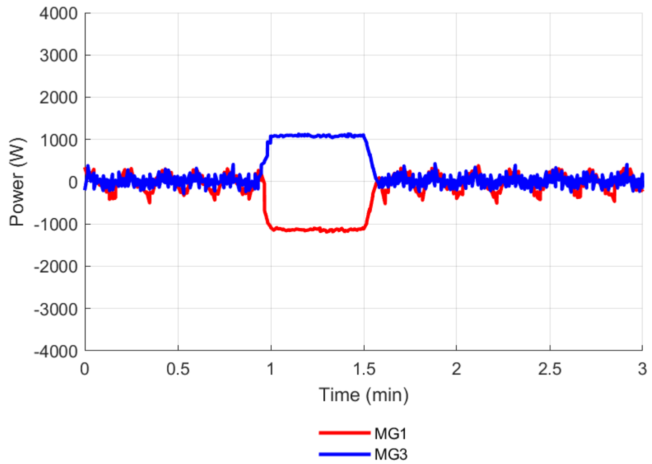

Figure 6: Power flow through tie line in hardware SSMTB test.

The resulting bus voltages are shown in Fig. 7. As shown, the bus voltages are held within 10% of the regulation voltage of 200 V on all three buses, even during the eclipse time period.

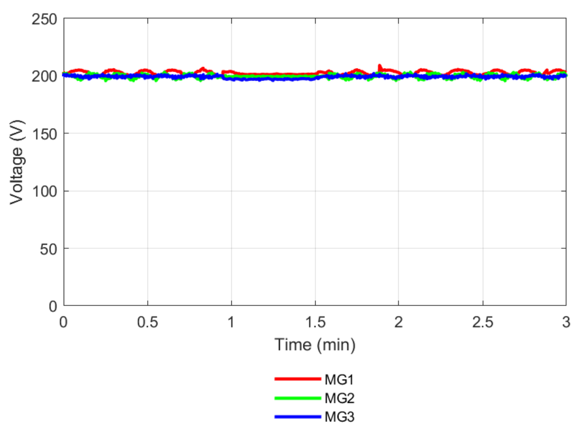

Figure 7: Bus Voltages during hardware test.

Conclusions

This paper examines a moonbase design with isolated DC microgrids and a tie line between them. As a contingency, it is required that power can be transported between these microgrids in the case of a generation short fall in one. This requires a controller that can determine the power flow between the grids and power electronics that can supply that power through the tie line. An optimal control method using a simulated system to determine power flow was implemented and tested using the SSMTB hardware testbed.

The results show that the controller is capable of determining the power flow required to maintain the bus voltages. However, there are noticeable oscillations in the controlled values when the system is under-damped.

Future work in this analysis will need to include raising the voltage of the tie line so that for the real system more power can be transported between each system, including a longer line length so that transmission line effects are included, and performing simulation studies on the full system with all loads and sources included. Additionally, a real time control that can react to the changing nature of the hardware system can be used in the future to improve the behavior and better respond to the system oscillations.

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Definitions, Acronyms, Abbreviations

ARESE	Arbitrary Response Energy Storage Emulator
ESS	Energy Storage System
GtG	Grid-to-grid converter
ISRU	in-situ resource unit
PV	Photovoltaic
SSMTB	Secure Scalable Microgrid Testbed