

Designing Hybrid Energy Storage Systems: A Tool for Teaching System-Level Modeling and Simulation

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Abstract

Hybrid energy storage systems (HESS) are becoming an increasingly attractive option for energy management in high performance automotive and avionics systems. Modeling, designing and simulating HESS using the Matlab/Simulink software is presented herein. Investigating various HESS configurations based on generator, ultracapacitors, rechargeable batteries, and dc-dc converters provides a platform to introduce system level modeling and simulation to advanced undergraduate students. From a pedagogical point of view, modeling and simulation of HESS integrates various curricular content including modern energy storage devices, electrical and electronic circuits, electrical machines and power systems, electromechanical systems, signals and systems, control systems, and power electronics. Simulation results of various HESS configurations are discussed in relation to power bus regulation, load sharing among multiple energy sources, energy storage amount, and optimal interfacing of energy storage devices to the dc bus to support dynamic actuator loads.

Introduction

The hybrid energy storage system (HESS) concept is gaining importance in applications requiring load leveling, high-density energy storage, and emergency power. Energy sources used in modern HESS¹⁻⁶ in automotive and avionics sectors include high performance batteries such as Li-Ion, ultracapacitors, and flywheels. HESS provides an excellent platform to teach system-level modeling and simulation while integrating aspects of electrical power, control systems, and power electronics. Circuit-level models of energy storage devices such as batteries and ultracapacitors can be developed from manufacturer provided performance characteristics. Similarly, circuit-level model of a generator can be developed from its terminal characteristics and electromagnetic parameters. An example HESS for avionics applications, shown in Figure 1, connects various energy sources to the dc power bus via dc-dc power converters. These bidirectional power converters play a key role in designing HESSs since they let energy sources of various voltage and power levels support the bidirectional system load in a controlled and predictable manner. Additionally, energy-dense and power-dense storage devices can be integrated to optimize the weight and performance of HESSs by effective use of dc-dc power converters. Accordingly, modeling of a switching power converter of the type shown in Figure 2 is an integral part of the HESS design and implementation process.

From a pedagogical point of view, modeling and simulation of HESSs presents an excellent platform to integrate various curricular content including modern energy storage devices, electrical and electronic circuits, electrical machines and power systems, electromechanical systems, signals and systems, control systems, and power electronics. Through this modeling and simulation activity, students become familiar with system-level design from both top-down (system-level to component-level) and bottom-up (component-level to system-level) perspectives including an appreciation for multimode systems.

The following sections present model development/usage and simulation of various HESS subsystems and systems using the Matlab/Simulink⁷ software. A 270 VDC bus based HESS configurations for avionics applications include generator-ultracapacitor, generator-battery, generator-ultracapacitor-battery, and generator-battery with dc-dc power converter. Discussion of simulation results focuses on load sharing, voltage regulation of dc bus, ripple voltages/ currents, and the benefits of using dc-dc converters in interfacing energy storage devices to the power bus.

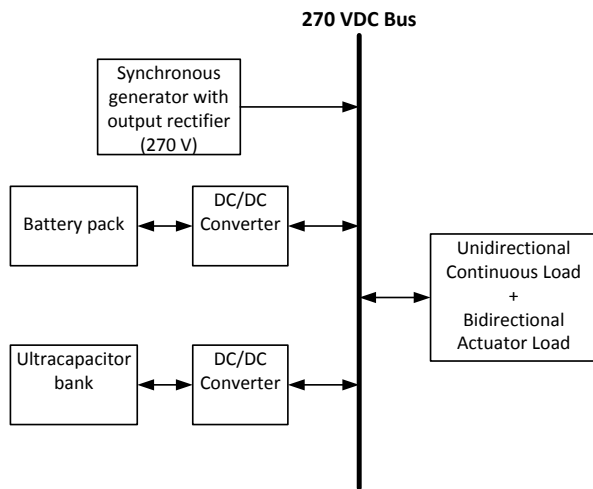


Figure 1: An example HESS for avionics.

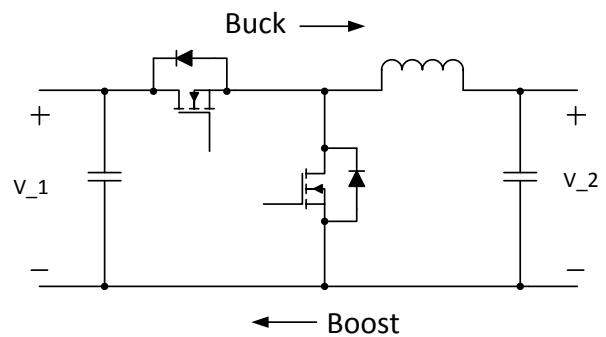


Figure 2: Bidirectional buck/boost dc-dc converter.

Modeling Actuator Load, Generator, and Energy Storage Devices

Actuator load

An actuator load profile representing a low power avionics application is considered for this study. The bidirectional actuator load used in designing and simulating various HESS configurations is shown in Figure 3. For a 270 V dc bus, the actuator load sinks 27 kW and sources 24.3 kW, with a power slew rate of 10 kW/ms.

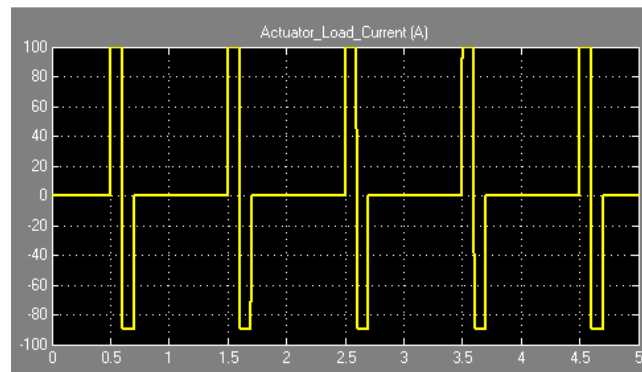


Figure 3: Profile of a bidirectional actuator load.

Synchronous generator model

The *Simplified Synchronous Machine SI Units*⁷ model within Matlab/Simulink is used to model a synchronous generator. The electrical system of the machine is modeled using the induced excitation voltage, stator winding resistance and synchronous reactance. The mechanical system of the generator is modeled using the following parameters: generator speed, inertia, electromagnetic and electromechanical torques, and damping factor representing the effects of damper winding. Figure 4 shows the model schematic used to test the 400 Hz synchronous generator supplying a dynamic 270 VDC load via a three-phase bridge rectifier and L-C filter. The 270 VDC output is regulated by adjusting the excitation voltage of the generator under closed loop via output voltage feedback. The excitation voltage, dynamic load current, and load voltage waveforms are shown in Figure 5. For the given load, the output voltage undershoots or overshoots by about 24 V but the generator system recovers to within ± 10 V in about 10 ms. The 2.4 kHz peak-to-peak ripple of 0.4 V (corresponding to about 0.15% of the 270 V bus) is shown in Figure 6.

Ultracapacitor model

The K2 series 1200 F ultracapacitor (BCAP1200) from Maxwell⁸ is used for this study. These 2.7 V high power density ultracapacitors have a maximum ESR of 0.58 m Ω and are capable of carrying up to 930 A with a usable specific power of 5.8 kW/kg and can store 1.22 Wh of energy. These devices are modeled as a simple first order R-C circuit. More detailed models using multiple time constant circuits are also available⁹.

Li-Ion battery model

Ultra high power VL5U Li-Ion cells from Saft¹⁰ were used to design the battery pack. These 5 Ah/3.65 V cells are optimized for 10C to 100C continuous discharge or up to 250C for pulse power, with 18.26 Wh of energy storage. A two-capacitance model¹¹ of these types of cells was used as a baseline to develop a working model for VL5U cells based on reported data¹². The developed model, shown in Figure 7, is used to design a 270 VDC battery pack consisting of 68 cells in series with an initial cell voltage of 3.9706 V, corresponding to 80% initial state of charge. The model schematic of Figure 7 includes a dynamic load whereby the battery cells are discharged and charged at 20C rate. The resulting load voltage and associated current waveforms are also shown in Figure 7. It can be observed that the load voltage drops by about 4.8 V for 100 A of discharge current, corresponding to an effective battery system resistance of 48 m Ω and a cell resistance of 0.7 m Ω .

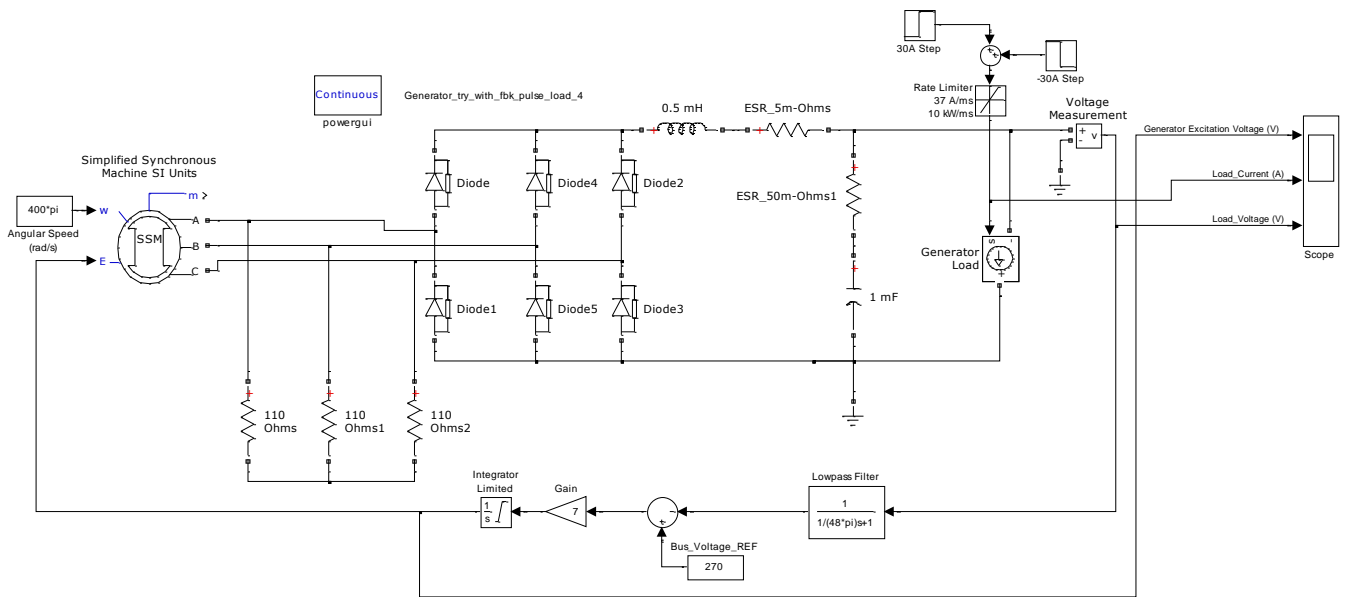


Figure 4: Generator-rectifier system supplying a dynamic load.

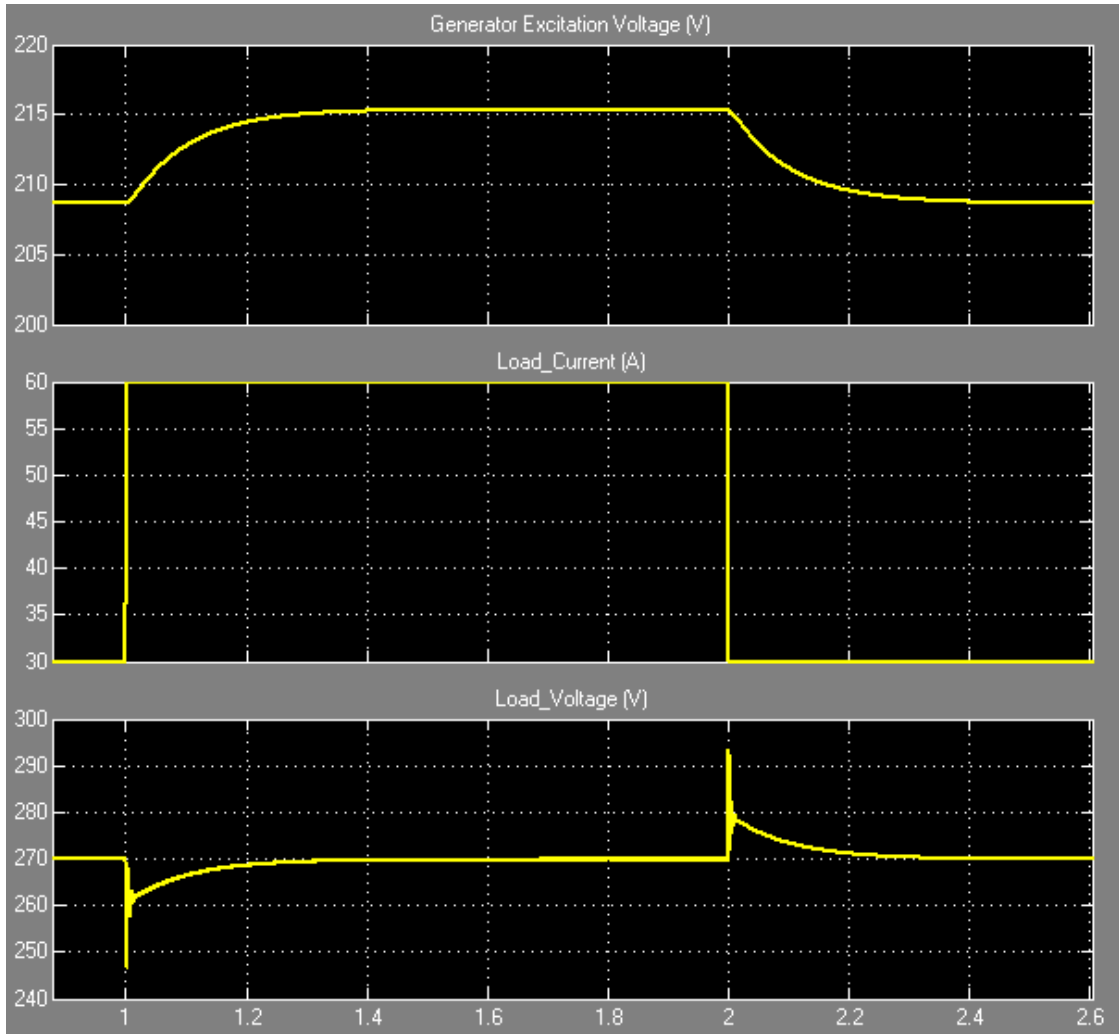


Figure 5: Generator excitation voltage, load current, and load voltage waveforms.

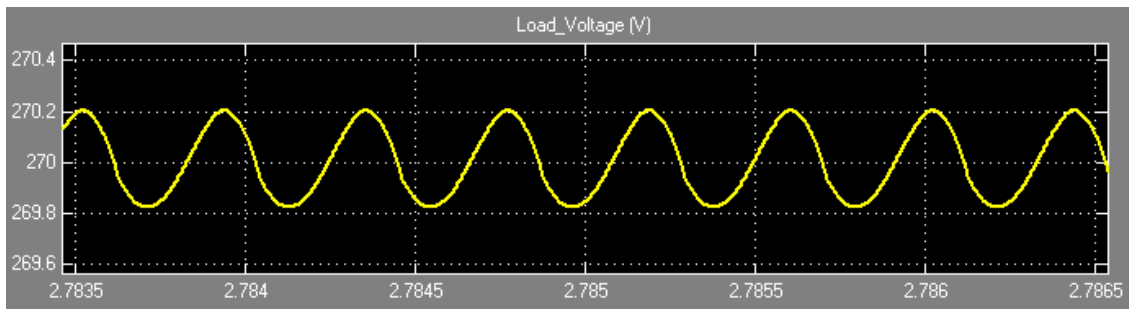
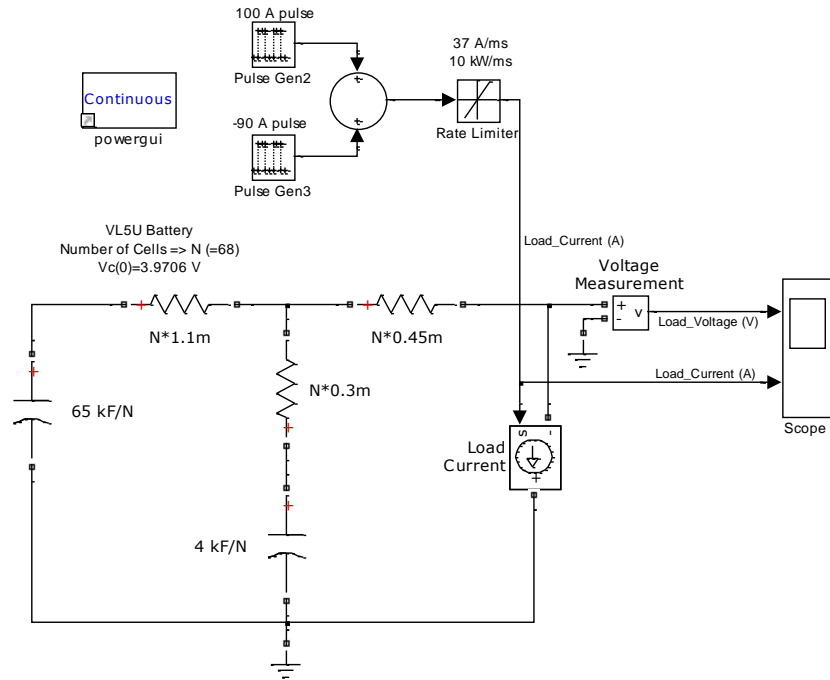
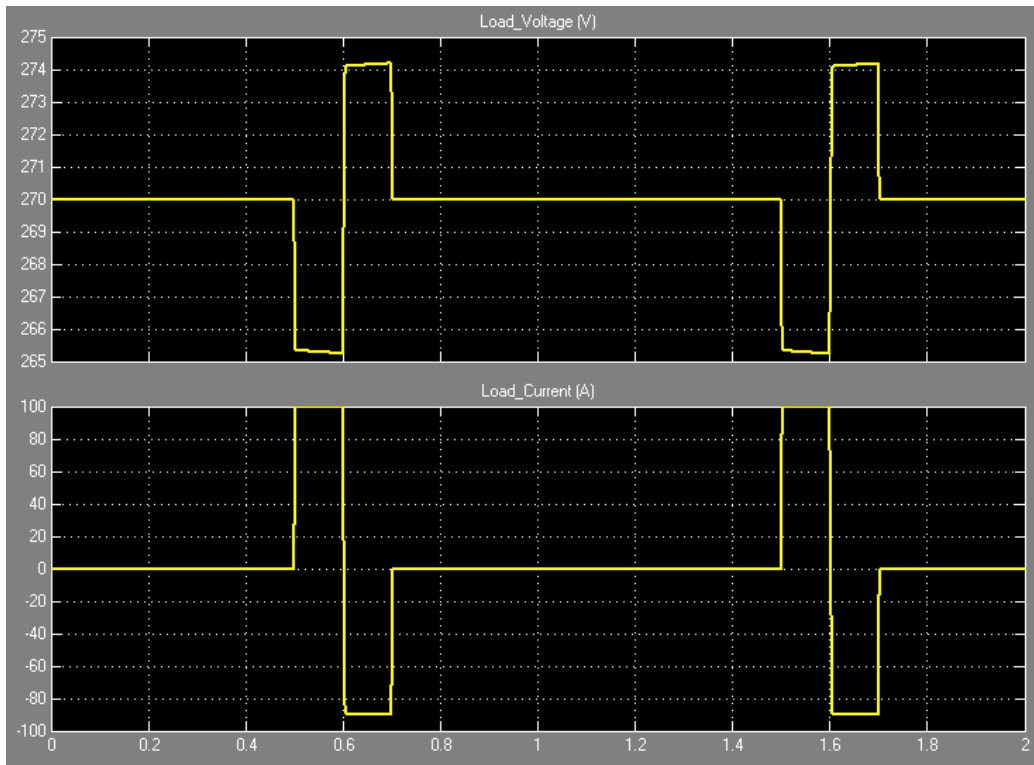


Figure 6: 2.4 kHz ripple on the 270 VDC bus supported by the generator.



(a) Two capacitance Li-Ion battery model



(b) Load voltage and load current waveforms supplied by a 270 VDC Li-Ion battery pack

Figure 7: Li-Ion battery model and associated waveforms for a 270 VDC load.

HESS Configurations

The following four HESS configurations, shown in Figure 8, were investigated as part of this study.

- Generator-Ultracapacitor bank
- Generator-Battery pack
- Generator-Ultracapacitor bank-Battery pack
- Generator-Battery pack (with dc-dc power converter)

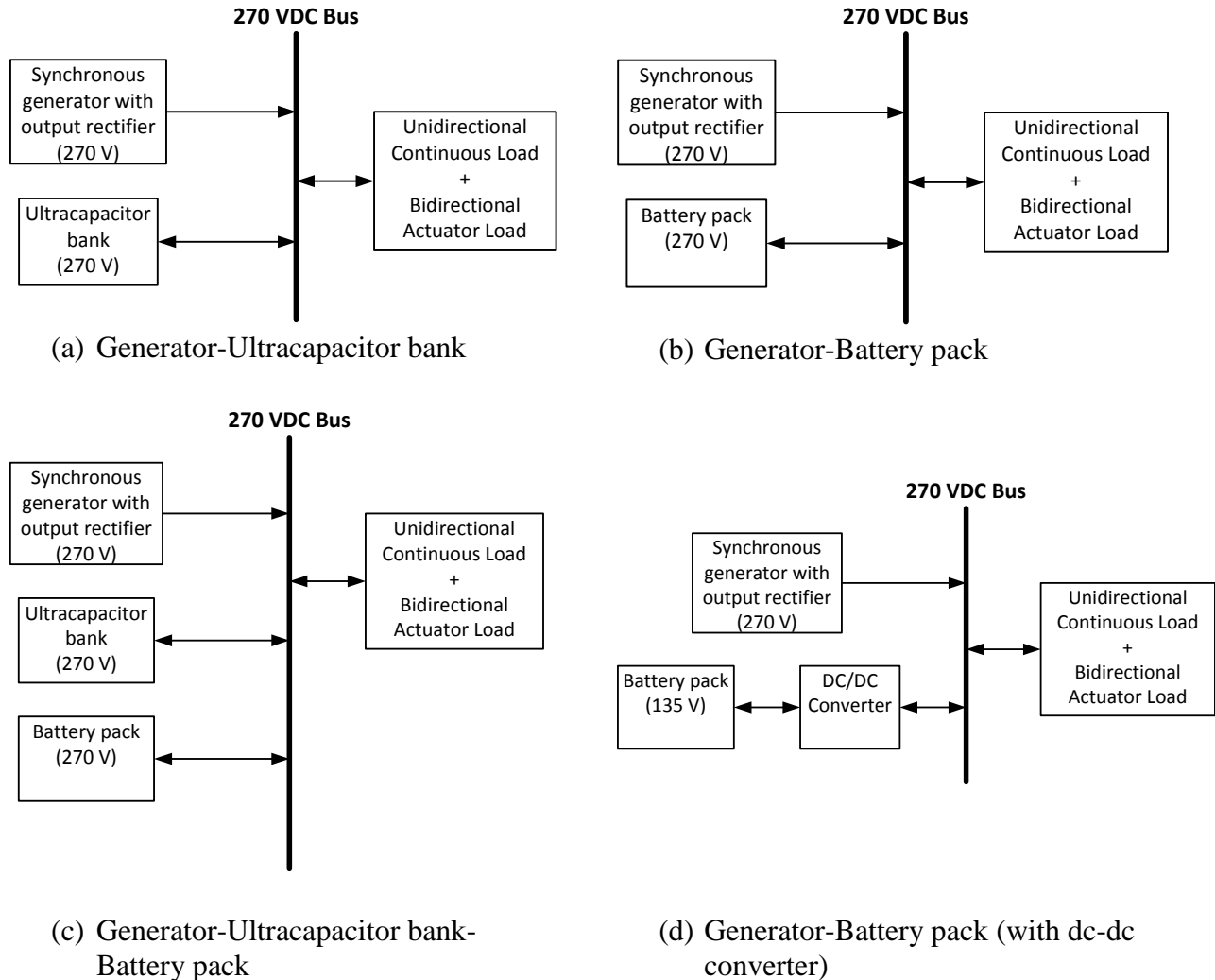


Figure 8: Various HESS configurations simulated for this study.

Generator-Ultracapacitor configuration

The simulation schematic is shown in Figure 9. The actuator load on the 270 VDC bus is supplied primarily by the bus-connected 270 V capacitor bank consisting of 110 cells of 1200 F/2.7 V ultracapacitors in series. The generator supplies a constant load of 8.1 kW whereas the ultracapacitor bank supplies most of the 27 kW of actuator dynamic load.

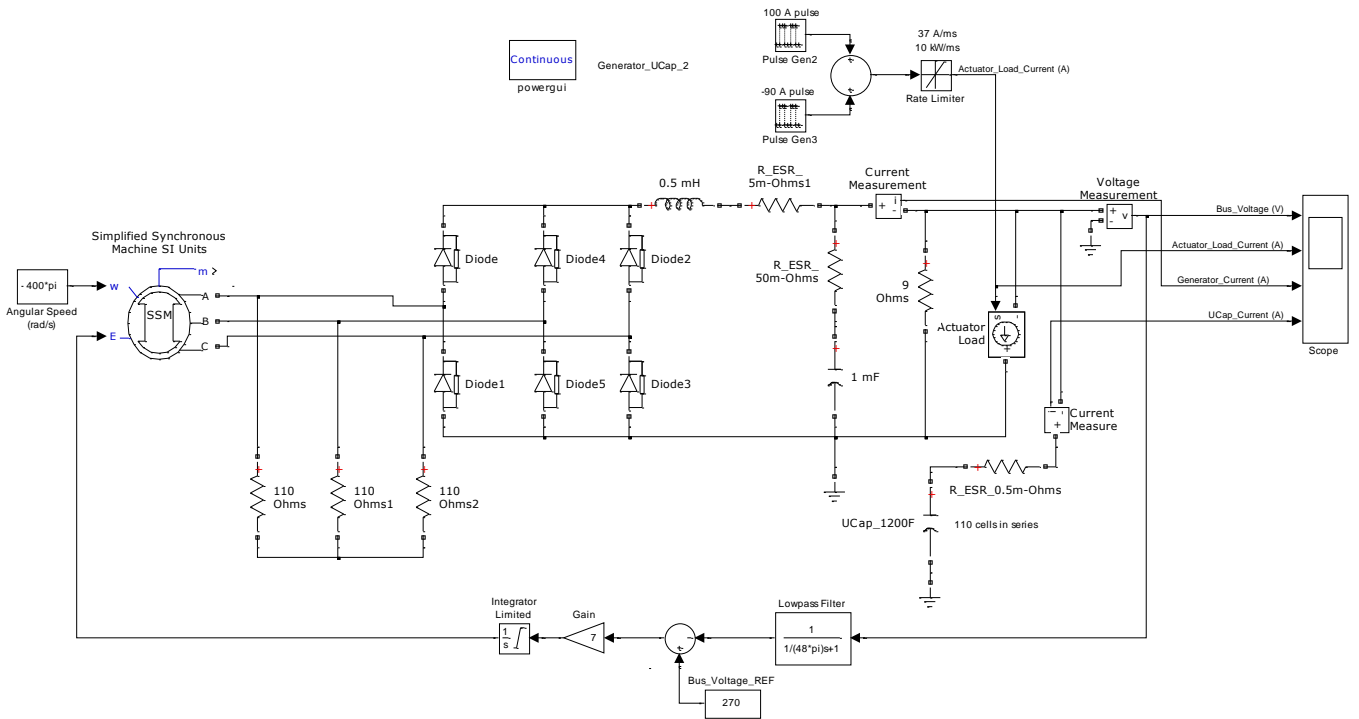


Figure 9: Generator-Ultracapacitor HESS supplying a 270 VDC actuator load.

The simulated waveforms for the generator-ultracapacitor bank system are shown in Figure 10. It can be observed that the 270 VDC bus is well regulated and it drops during the discharging mode and increases during the charging mode by only about 5 V. The ultracapacitor supplies more than 80% of the actuator load while the generator supplies the rest of the dynamic load. Additionally, the generator supplies the constant load on the system bus.

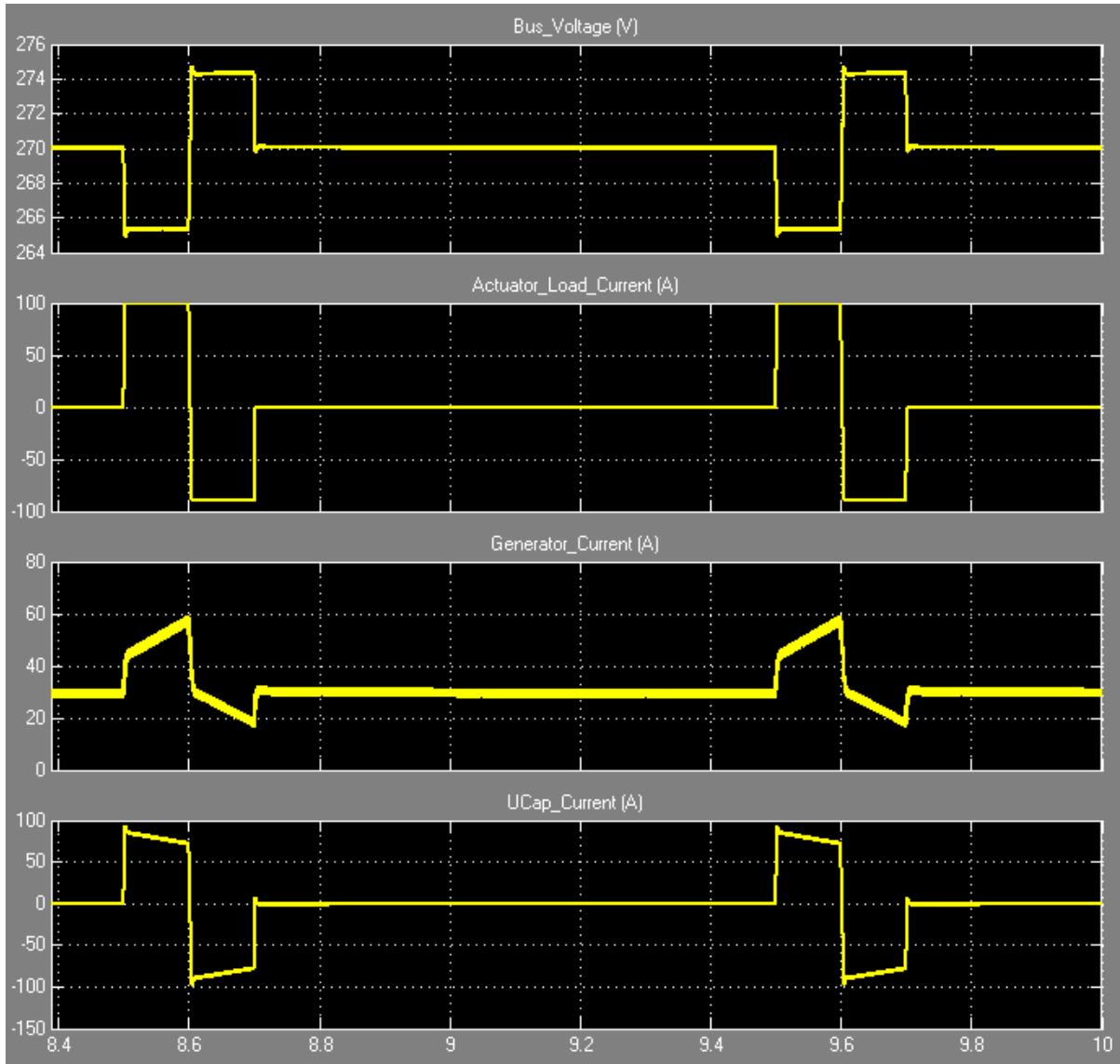


Figure 10: Voltage and current waveforms for the generator-ultracapacitor HESS.

Generator-Battery configuration

The simulation schematic of a generator-battery pack system is shown in Figure 11. The 270 VDC battery pack consists of 68 VL5U Li-Ion cells in series at 80% initial state of charge. Again in this configuration, the generator supplies the constant load on the bus while the battery pack supplies most of the dynamic actuator load.

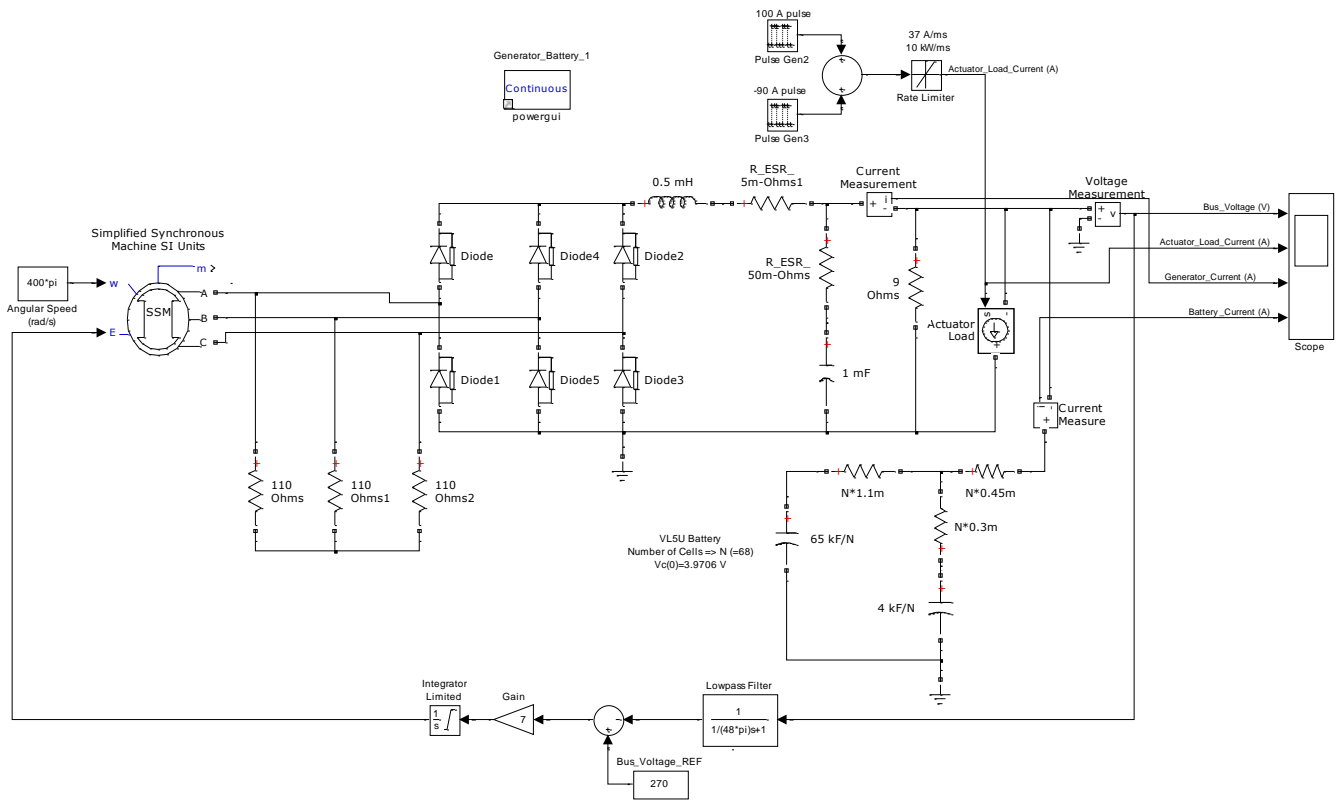


Figure 11: Generator-Battery HESS supplying a 270 VDC actuator load.

The simulation waveforms for the generator-battery pack configuration are shown in Figure 12. It can be observed that more than 80% of the actuator load is supplied by the battery bank while the generator supplies the remaining actuator load plus the constant load on the bus. The voltage regulation is $\pm 4\text{V}$ for the 270 VDC bus, well within the acceptable range.

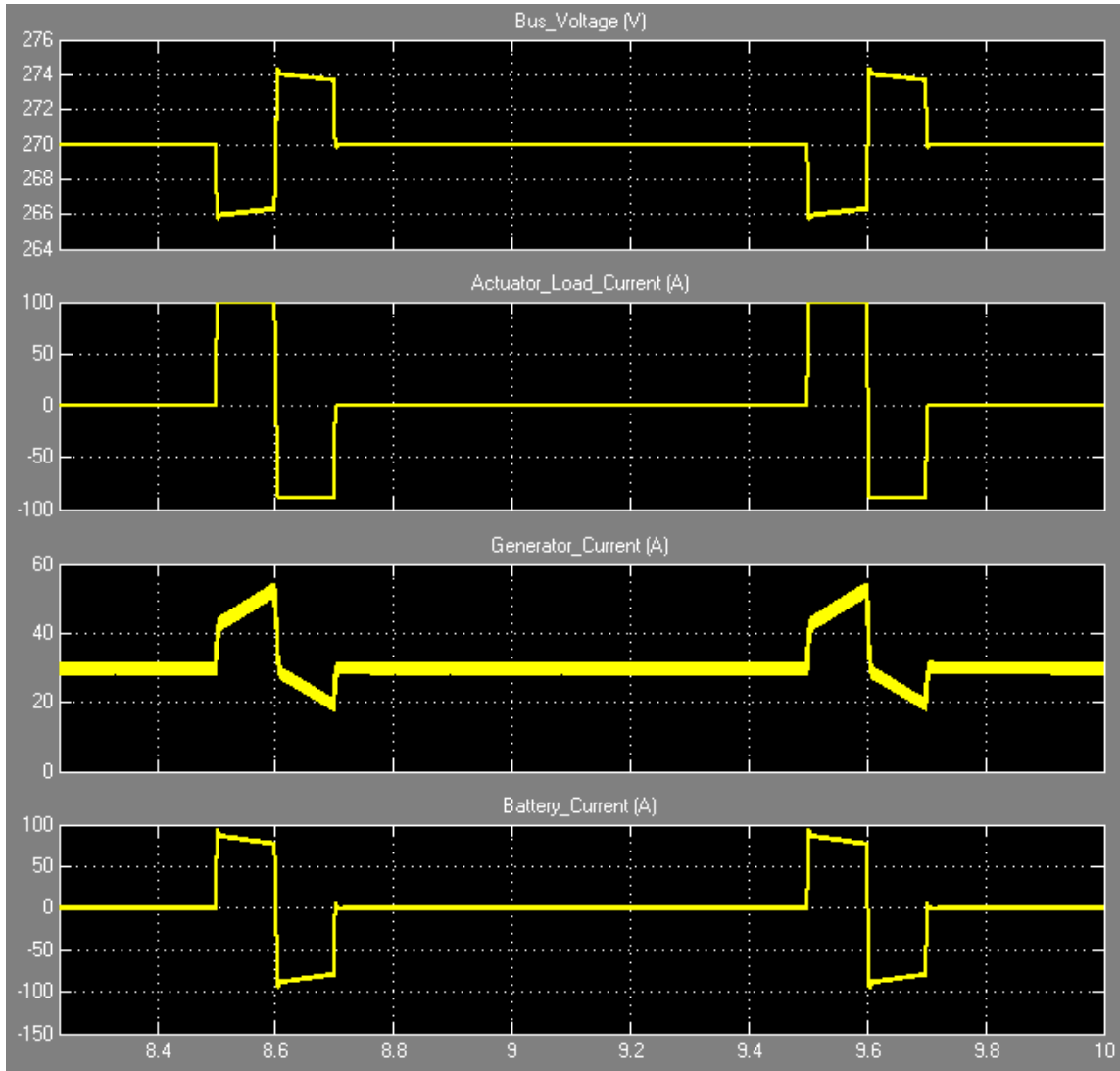


Figure 12: Voltage and current waveforms for the generator-battery HESS.

Generator-Ultracapacitor-Battery configuration

In this configuration shown in Figure 13, both the ultracapacitor bank and the battery pack contribute to sourcing and sinking the actuator load while the generator primarily supplies the constant load on the bus. The relevant simulated waveforms for this system are shown in Figure 14. The bus regulation has improved to $\pm 2\text{V}$ since the actuator load is shared between the battery pack and the ultracapacitor bank. The battery pack, ultracapacitor bank, and the generator carry about 50%, 40% and 10% of the actuator load, respectively. Based on the voltage regulation data, it is evident that this system is oversized and there is room for reduction in the system's energy storage capability as well as mass and volume.

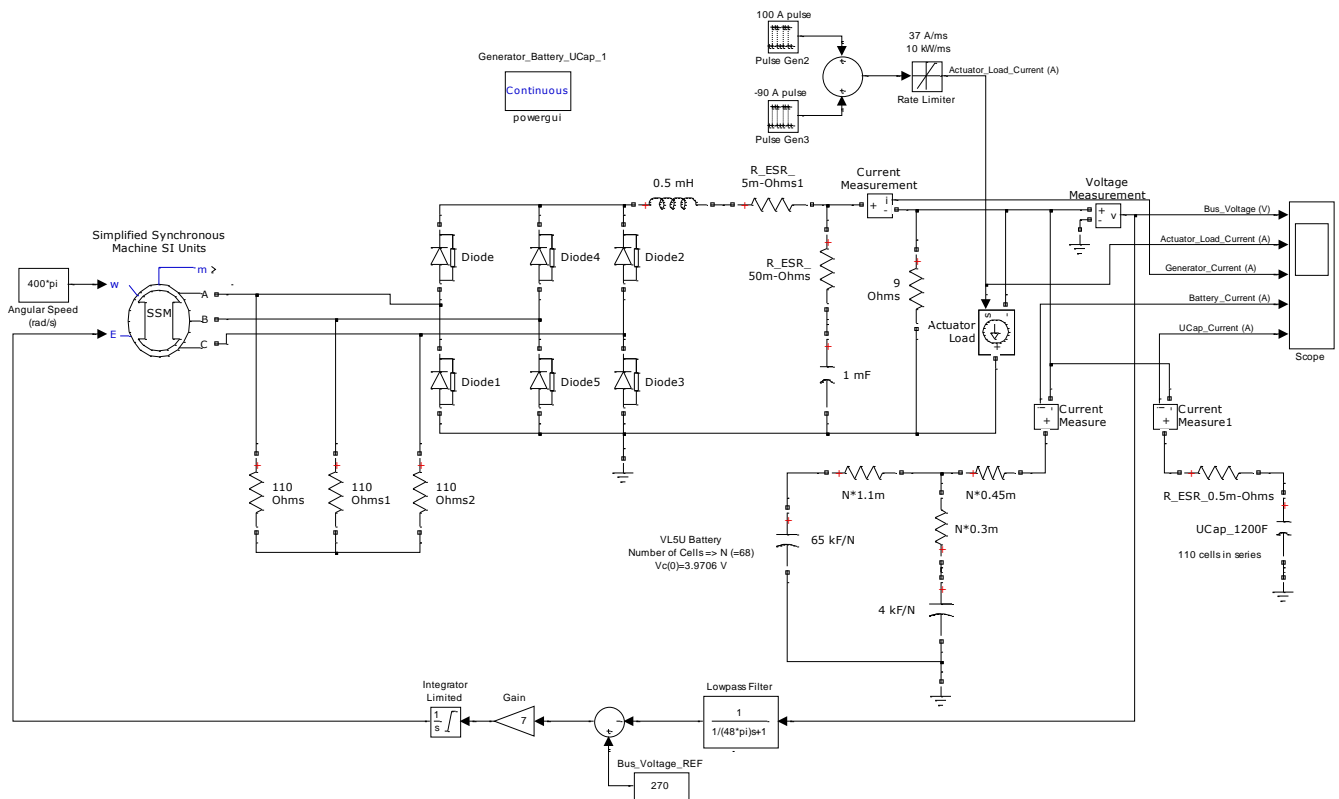


Figure 13: Generator-Ultracapacitor-Battery HESS supplying a 270 VDC actuator load.

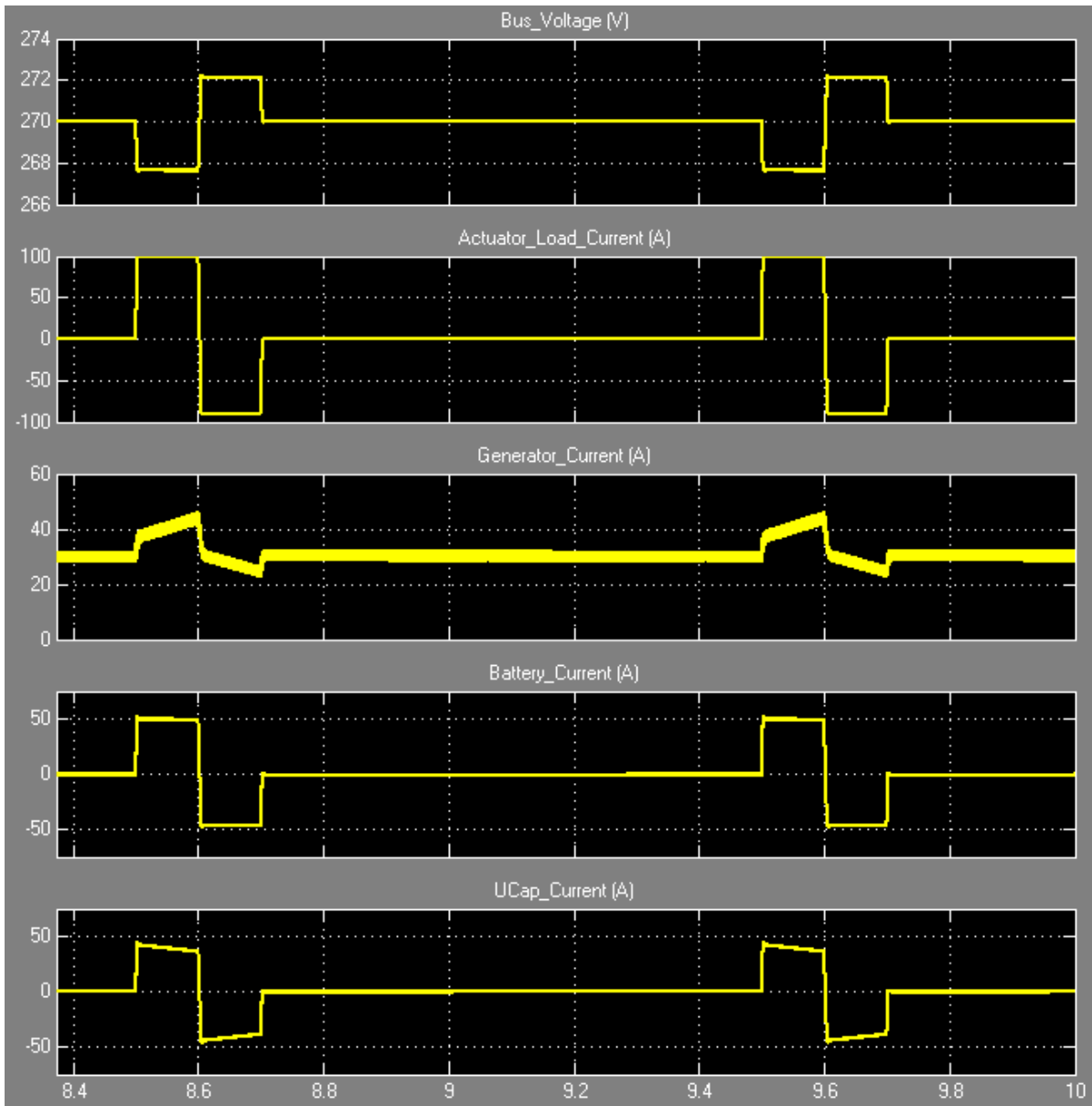


Figure 14: Voltage and current waveforms for the generator-ultracapacitor-battery HESS.

Generator-Battery (with dc-dc power converter) configuration

In this configuration a dc-dc power converter is used to avoid excess energy storage due to direct bus connection of battery pack. Instead of using 68 cells for 270 V direct bus connection, a 135 V battery pack consisting of 34 cells in series is connected to the bus via a bidirectional dc-dc synchronous buck/boost converter. The system schematic shown in Figure 15 uses a 100 kHz dc-dc converter to interface the battery pack to the 270 VDC bus. In this configuration, the bus voltage is regulated by the generator controller whereas the dc-dc converter controller regulates the current contributed by the battery pack via the converter. By design, the battery converter sources 90% of the actuator load during the discharging mode and sinks 100% of the actuator load during the charging mode to be able to maintain a stable battery state of charge.

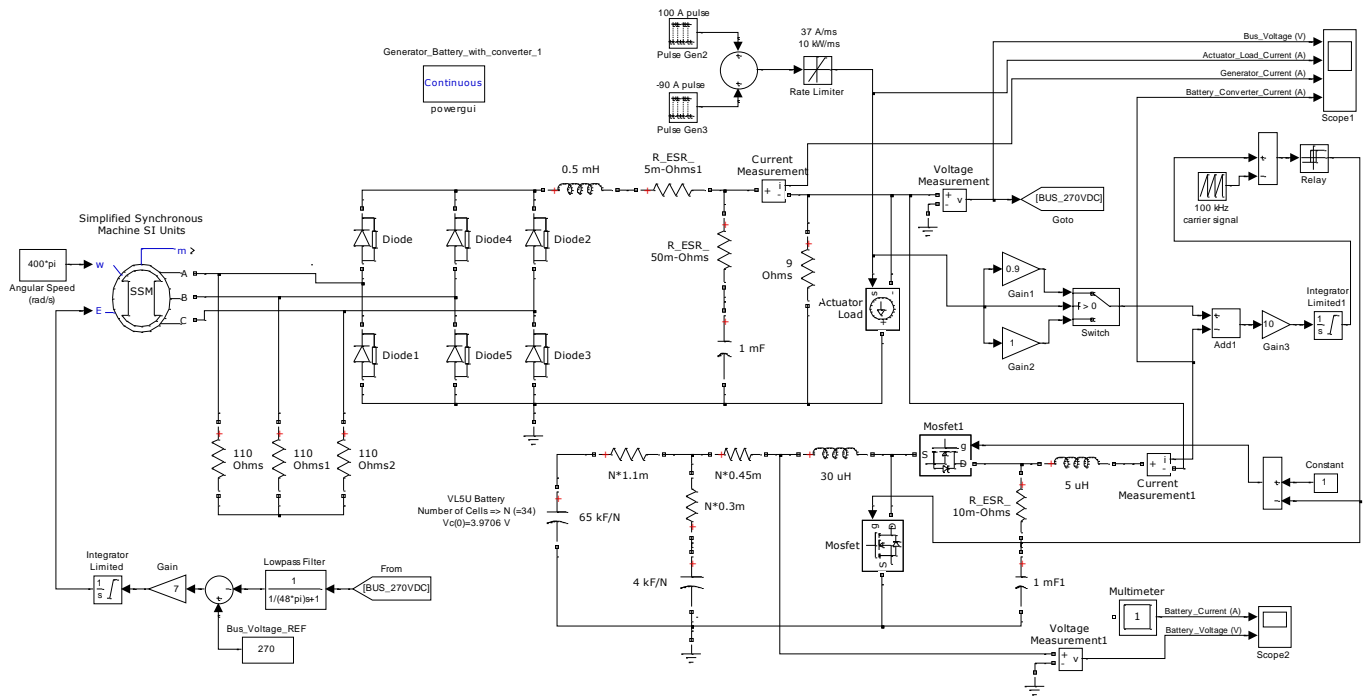


Figure 15: Generator-Battery with dc-dc converter HESS supplying a 270 VDC actuator load.

The simulated waveforms for this system are shown in Figures 16-19. Bus voltage regulation can be seen in Figure 16 along with the load sharing between the generator and the battery converter. It can be seen that during the discharging mode, the generator and battery converter supply 10% and 90% of the actuator load, respectively. And during the charging mode, the battery accepts 100% of the actuator current. The constant load of 30 A on the 270 VDC bus is supplied by the generator.

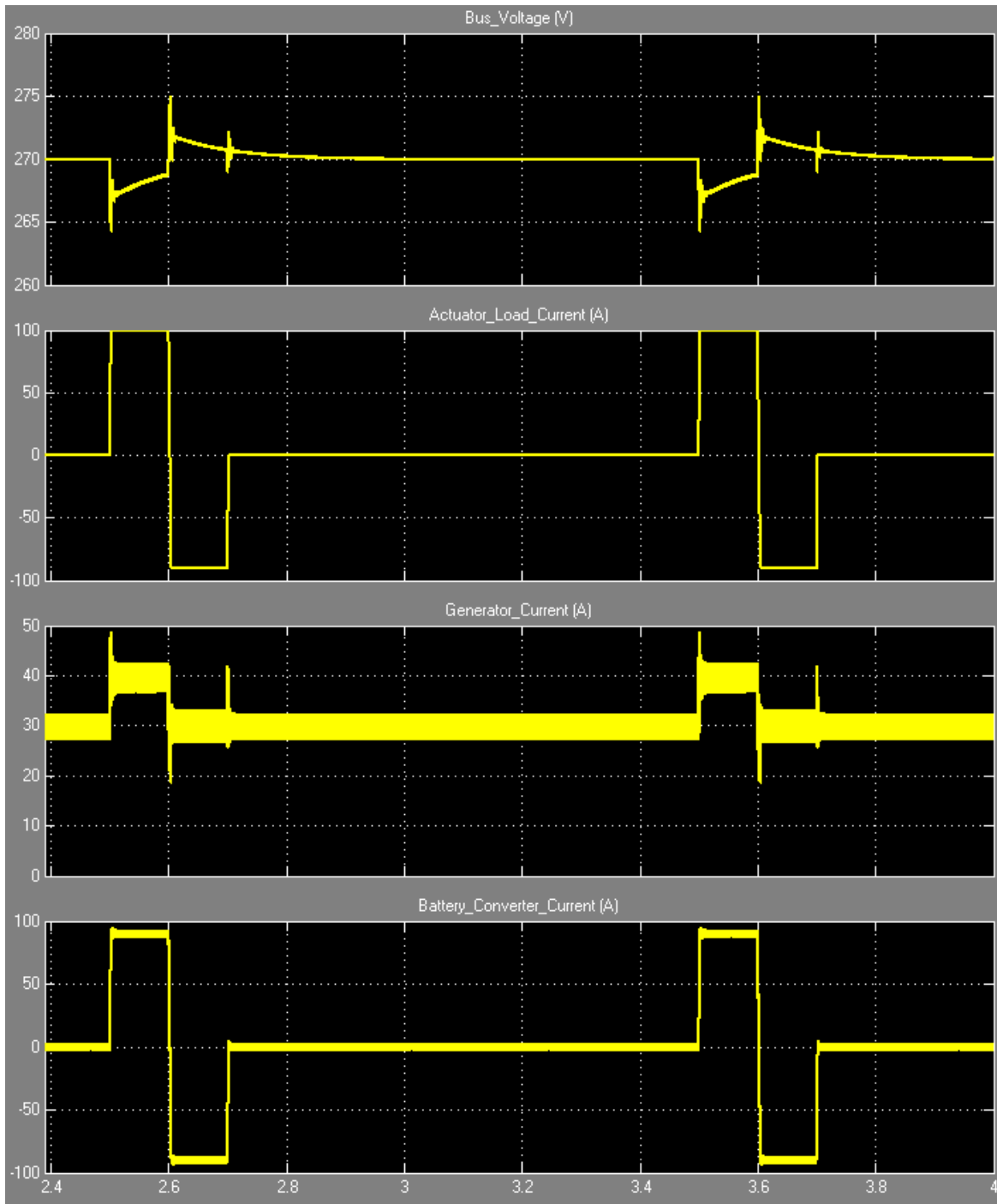


Figure 16: Voltage and current waveforms for the generator-battery with dc-dc converter HESS.

The battery current and voltage waveforms are shown in Figure 17. The battery sources slightly more current than it sinks since its voltage is about 130 V during the discharging mode compared to 139 V during the charging mode. Significant high frequency ripple can be observed in the generator and battery converter currents (Figure 16) and battery current and voltage (Figure 17) waveforms. These 2.4 kHz and 100 kHz ripples shown in Figures 18 and 19, respectively, are contributed by the generator/rectifier circuit and the switching dc-dc power converter. The 2.4 kHz peak-to-peak ripple in the generator current and the battery converter current are about 5 A and within the acceptable level. Similarly, the 100 kHz ripple in the battery current is about 22 A and about 0.5 V in the battery voltage, and are deemed acceptable. If further reduction in ripple voltages and currents is necessary, additional filtering can be incorporated into the design.

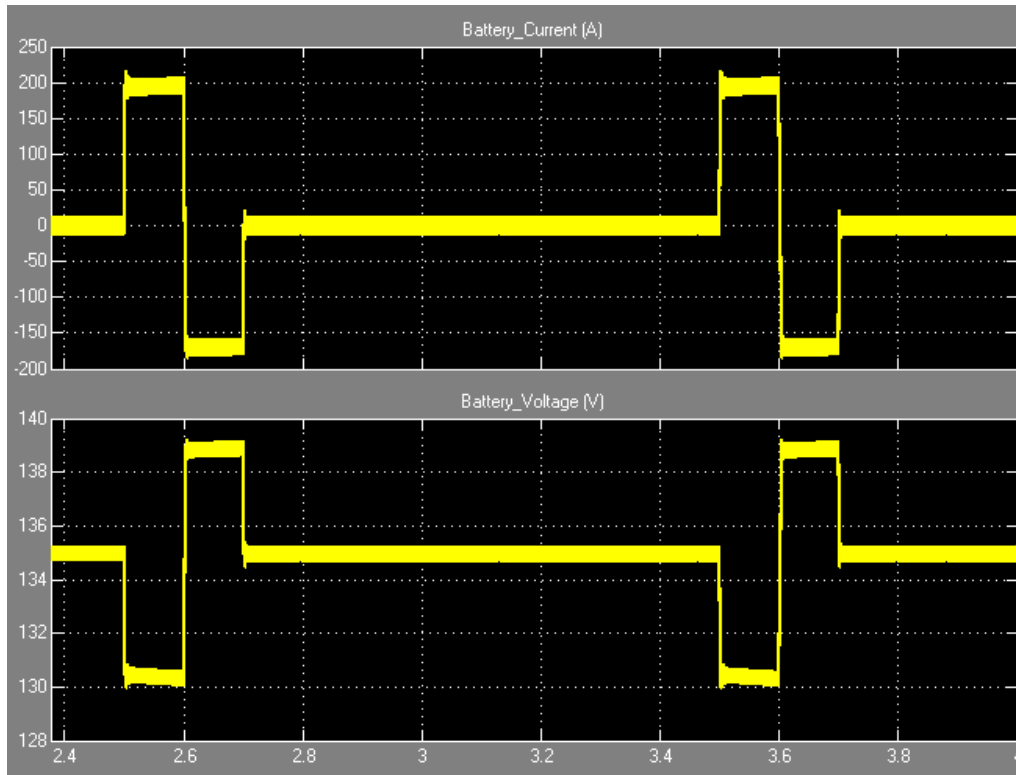


Figure 17: Battery current/voltage waveforms for the generator-battery/dc-dc converter HESS.

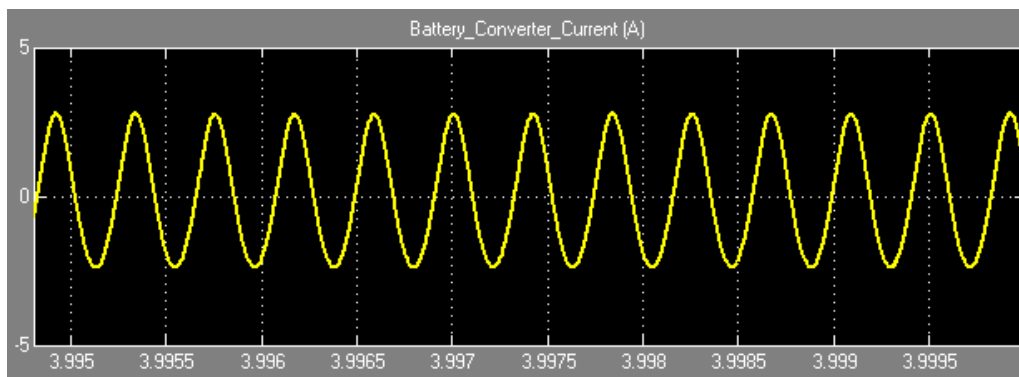


Figure 18: 2.4 kHz ripple in the battery converter output current.

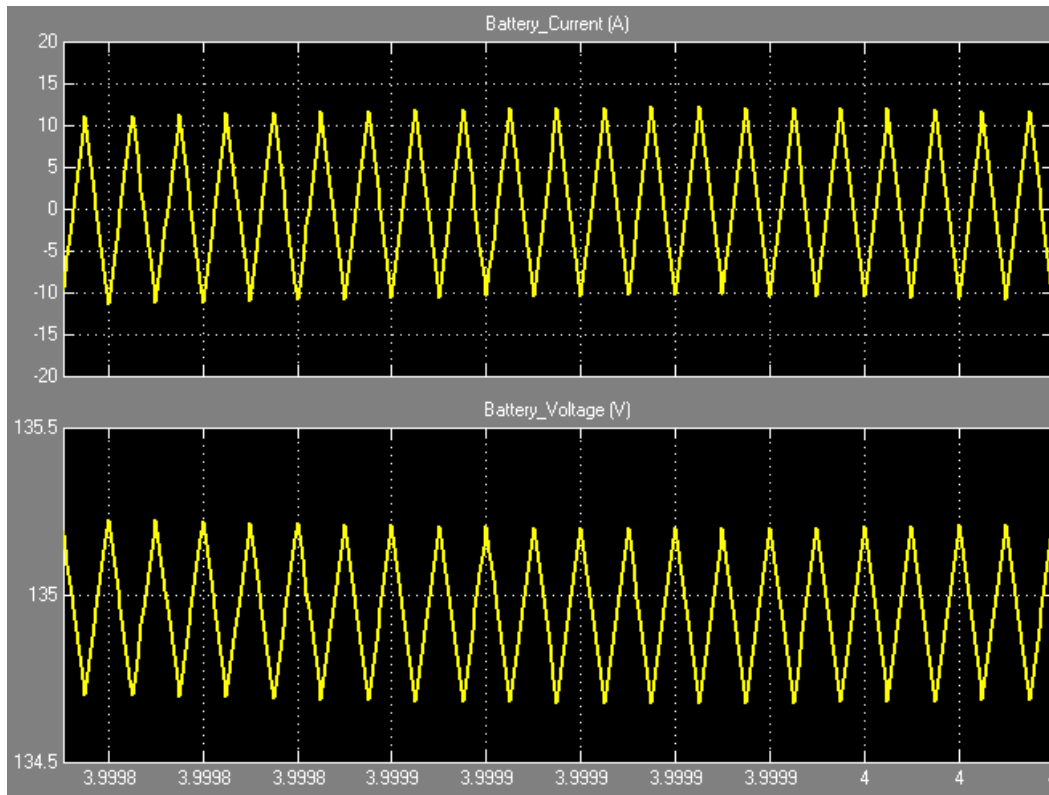


Figure 19: 100 kHz ripple in battery current and voltage.

Discussion

Simulation results from various HESM configurations indicate that energy storage devices (ultracapacitors and Li-Ion batteries) are capable of supporting bidirectional actuator load while the generator mostly supports the steady load on the power bus. Also, direct connection of energy storage devices onto the power bus may be preferable from reliability point of view but doing so will likely result in overdesign in terms of bus voltage regulation and/or energy storage requirement. Use of dc-dc converters to interface energy storage devices to the power bus provides an opportunity for the designer to optimize the overall system by reducing the effective voltage level of the energy storage banks/packs, thereby reducing the number of cells in the energy storage bank/pack. This in turn will help optimize the overall system in terms of electrical performance as well as mass and volume. Use of dc-dc converters also helps to match the number of energy storage elements in the bank/pack to the system required energy storage amount. Additionally, by using dc-dc converters, the bus voltage can be regulated by the generator controller whereas the converter controllers can be used to control the current sourced/sunk by energy storage banks/packs.

In a HESS with defined energy storage requirement in addition to bus regulation against bidirectional dynamic actuator load, direct bus connected power-dense ultracapacitors are the device of choice to support the actuator load while energy-dense Li-Ion batteries can be used to meet the energy storage requirement. Since this stored energy will likely be used for emergency situations, a dc-dc converter will be needed to regulate the dc bus while the generator is offline.

Such a system configuration is shown in Figure 20. Using the power-dense ultracapacitors for dynamic actuator load and energy-dense batteries for energy storage opens up opportunities to optimize the system in terms of electrical performance, thermal performance, mass, and volume.

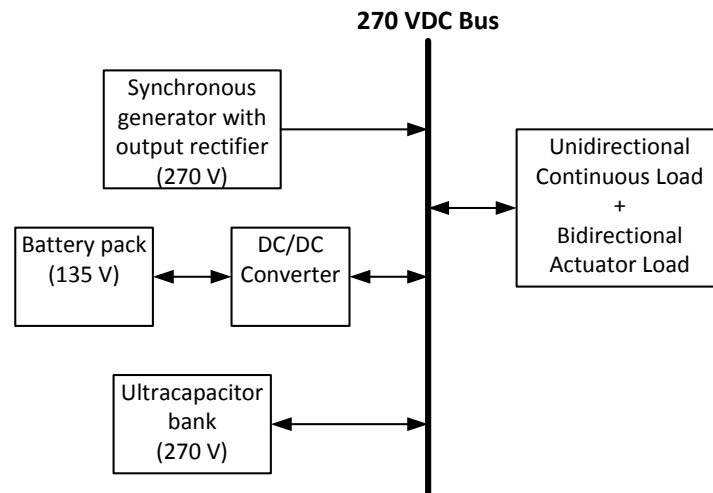


Figure 20: A high-performance HESS configuration utilizing energy-dense batteries and power-dense ultracapacitors.

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