A VERSATILE SIMULATION TOOL FOR THE DESIGN AND VERIFICATION OF MILITARY VEHICLE POWER SYSTEMS

A Thesis

by

MELISSA ANNE LIPSCOMB

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2005

Major Subject: Electrical Engineering

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ABSTRACT

A Versatile Simulation Tool for the Design and Verification of

Military Vehicle Power Systems. (August 2005)

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The design of the electric platform in military vehicles requires the ability to determine the best combination of power system components that support the desired operational abilities, while minimizing the size, weight, cost, and impact of the overall power system. Because prototypes are both time consuming, rigid, and costly, they have become inadequate for verifying system performance. By using simulations, engineers can best plan for and observe the associations between missions (including modes of operation and system scenarios) and system performance in a dynamic, realistic environment.

This thesis proposes a new tool to analyze and design military vehicle platforms: the Advanced Mobile Integrated Power System (AMPS). This tool is useful for design and design verification of military vehicles due to its unique incorporation of mission-specific functionality. It allows the user ease of design with the ability to customize the vehicle power system architecture and components, while permitting full control over source and load input parameters. Simulation of programmed mission sequences allows the user to ensure that the chosen vehicle architecture can provide all of the electrical power and energy needed to support the mission, thus providing adequate design verification.

The present thesis includes an introduction to vehicle power systems and an outline of the need for simulation, a description of the AMPS project and vehicle specifications, analytical and numerical models of the simulated vehicle, explanation of the power management system, description of the graphical user interface, and a simulation performed with the AMPS tool.

To all of my family, old and new

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Also, I would like to thank my family for the support they provided me through my entire life and in particular, I must acknowledge my fiancé and best friend, Matt, without whose love, encouragement and editing assistance, I would not have finished this thesis.

In conclusion, I recognize that this research would not have been possible without the financial assistance of TACOM (Masrur), and I express my gratitude to this organization.

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CHAPTER I

INTRODUCTION

The U.S army is currently supporting development of software-simulated military vehicle designs with a focus on newer technologies associated with hybrid electric vehicles [1]. The design of the electrical platform of any vehicle requires ascertaining the best combination of power supply components that supports the desired operational abilities while minimizing over-design of the power system. However, the military vehicle drive train design and control are much more complex than those of conventional automobiles. Therefore, the development of techniques for simulation has become crucial for evaluating the performance of the military vehicle electrical platform.

A. Vehicle Power Systems

Electrical system demands of present-day vehicles have increased greatly since their crank-start beginnings. Modern automobile electrical systems have progressed from 100 W ignition and headlight loads to 1 kW loads, consisting of pumps, fans and electric motors, with a projected average power demand increase in the near future to 3 kW and higher [1]. Power needs in military vehicles have followed the same increasing trends, but have power requirements from 3 to 10 times that of automobiles [2]. This

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This dissertation follows the style and format of *IEEE Transactions on Industry Applications.*

increase in power demand on electrical systems has highlighted the importance of improved reliability and necessitated the capability to design and test complex power systems before they are implemented.

1. Commercial Vehicle Power System Requirements

The earliest electrical systems in automobiles incorporated a 6 V battery, providing power for the ignition only. The introduction of new incandescent lamps, and eventually newer engines with higher compression ratios created the need for a more durable and reliable ignition system. This led to the introduction of the current electrical platform, one supported by a 14 V architecture similar to that of Fig. 1. [1]

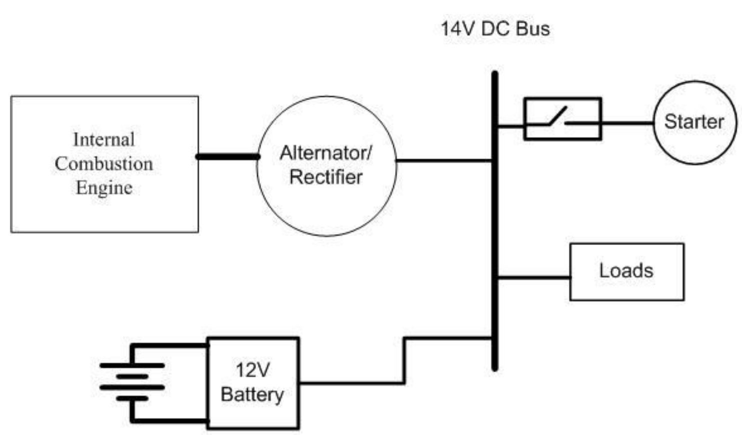

Fig. 1. 14 V vehicle architecture.

Commercial automobiles are required to operate in only two modes of operation, so the complexity of the power sources is minimal. In the first mode of operation, called static consumption, the engine is turned off and the 12 V battery is supplying what few power-consuming loads may be turned on; for instance a radio or the headlights. This mode of operation is used in a very limited capacity. The second and primary mode of operation for automobiles is a normal motoring mode. In the normal motoring mode, the 12 V battery supplies the starter. Once an adequate engine speed is reached, the alternator can power the loads and charge the battery.

In the same way that power demand increases in the 1950's pushed the power system in vehicles from a 6 V to a 14 V system, today the increase in the use of electronics in vehicles is making the way for even higher voltage systems. The application of power electronics to systems that were once mechanically or hydraulically controlled, such as electrical power steering and electrically controlled suspension, has led to a vast increase in electrical loads in the automobile. Although these advancements have increased the level of performance and reliability of automobiles, they are pushing the limits of current vehicle power system capabilities. To meet these increasing power needs, automobile manufacturers are beginning the transition to a 42 V system architecture [3]. Fig. 2 [1] shows an example of this 42 V system, which employs a dual-voltage architecture.

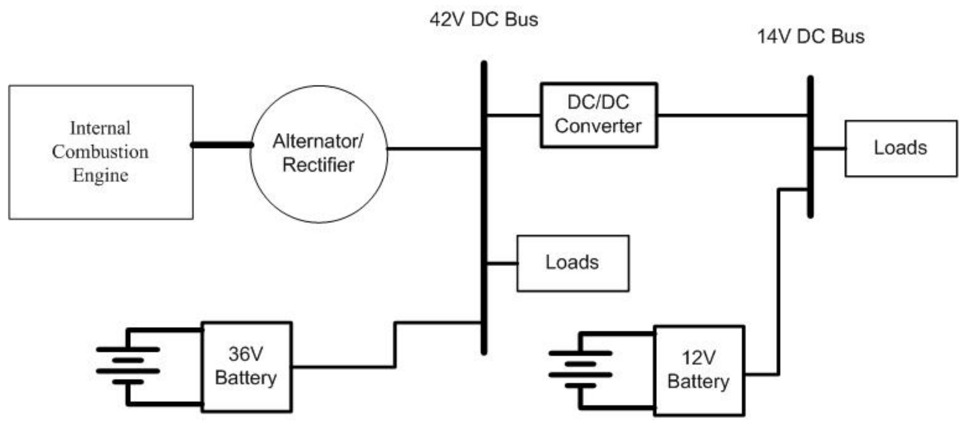

Fig. 2. 14 V/42 V dual voltage architecture.

The necessity for a dual-voltage architecture arises from the economics of transitioning all electrical systems that are currently powered at 14 V to 42 V. A dual-voltage bus makes use of loads that benefit from the higher voltage and maintains currently manufactured loads that operate at the lower voltage. Loads can then be moved to the higher bus voltage as they become available.

2. Military Vehicle Power System Requirements

Military vehicle power systems have followed a similar trend as those seen in commercial automobiles. Because their power needs are relatively higher, military vehicles have been based on a 14/28 V system architecture. Alteration to a 42 V system has led to a 14/28/42 V architecture as opposed to the dual 14/42 V architecture in automobiles. Fig. 3 shows such an architecture, including the additional sources of power and energy storage devices found on some military vehicles.

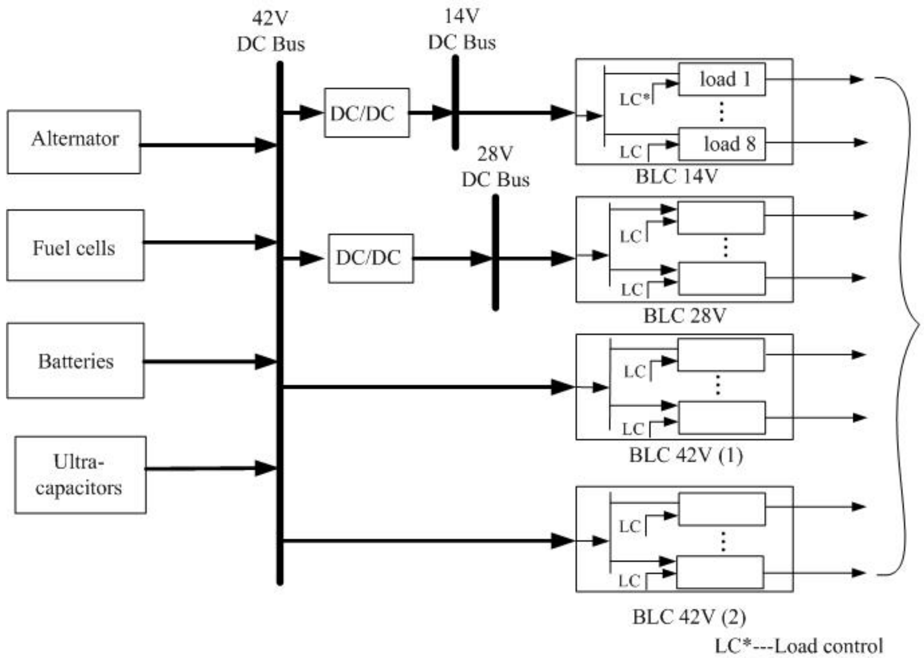

Fig. 3. Triple voltage military vehicle architecture.

The complexity of the power sources in military vehicles arises from the need to operate in a number of modes. Unlike the two distinct modes of operation for commercial vehicles, military vehicles must work in a number of situations with sources and loads in a variety of on/off configurations, all dependent on the mission or task at hand. The number of power sources outside of the alternator/battery combination found in commercial vehicles is due to the unique necessity for military vehicles to provide power to run a significant amount of auxiliary equipment with the engine turned off [2]. Components such as fuel cells and ultracapacitors provide the convenience of having power levels that are independent of temperature and engine speed as well as reducing drain on the battery during prolonged periods where the engine is turned off.

Due to the increase in the number of power sources and energy storage techniques in military vehicles, the conversion to a 42 V power system has a much greater effect on the sizing of power source and energy storage components. The use of fuel cells and ultracapacitors complicates selecting equipment ratings when power available depends solely on the state of charge of each device, and the state of charge is determined by the actions in the previous mode. Simply put, given these numerous variables, it is nearly impossible to calculate and predict the needs of a fully integrated power system for a military vehicle without some form of sophisticated simulation performance analysis. For these reasons, simulation has become critical for evaluating the performance of the electrical platform throughout each mission sequence [4].

B. Advanced Mobile Integrated Power System (AMPS) Tool Concept

Power system design for military vehicles requires the ability to determine the best combination of power source components to support every desired mode of operation. The design engineer must keep in mind how each source will react when modes change and loads are added and removed from the system, as well as be able to predict how well the sources will maintain their loads in situations when battery state-of-charge gets low or fuel cell hydrogen runs out. Designing to meet all of these criteria in such a dynamic environment is extremely difficult and calls for the use of simulations as an aide.

Although simulations of automobiles are extremely common, very few simulations are based on the design of military combat vehicles. Because of the vast difference in the performance requirements of the two, conventional automobile power system simulations do not have the functionality to cover all of the areas of testing or verification needed for military applications. Of the few military vehicle simulations found, most either focused on the reliability of the individual components making up the power system (and not the system as a whole [4]), or failed to include the numerous modes of operation a vehicle would operate in.

The design engineer would prosper from a tool that could simulate the architecture of the military vehicle (including the engine, all sources of power, and loads) given a particular vehicle platform. The freedom to change individual parameters for each of the sources would allow the designer explicit control over components that can be either fully customized, or obtained off-the-shelf. Further, by using and manipulating these customizable components, the designer can observe and fully understand the interrelationships between them, a significant benefit during the vehicle design phase.

Complete manual control over the vehicle operation, such as mode selections and source/load configurations would allow the designer not only the ability to test the vehicle in a number of scenarios, but would allow for the design of missions themselves. Although automatic control over the vehicle, such as the capacity to perform a complete mission simulation, would allow the designer insight into how the power system responds to complex mode changes throughout a mission, creating the ability to fully test missions for the validity of their specifications. Finally, the ability to simulate, and therefore later predict, the state of all the power sources throughout and after a completed mission provides the design engineer with a template for determining future mission predictability. The AMPS Tool provides the functionality of all of the above, and more.

The AMPS tool provides a new method for the analysis and design of hybrid military vehicle platforms. It allows the user ease of design with the ability to customize the vehicle power system architecture and components, while permitting full control over source and load input parameters. Simulation of programmed mission sequences allows the user to ensure that the chosen vehicle architecture can provide all of the electrical power and energy needed to support the mission, thus providing adequate design verification as well.

With the AMPS tool, the user can specify the vehicle platform to be used, select from a variety of different sources to create new vehicle platforms, or enter parameters for each source creating completely new components. Once the vehicle components have been selected, the user can run the simulation automatically by selecting a pre-programmed scenario profile that corresponds to the functioning of the vehicle, or select the modes of operation and sources and load configurations manually for designing.

This tool is also useful in observing the effects of change in one or more of the input variables on the output capabilities of the sources. Observing the differences in the alternator output current in response to load changes by changing parameters such as the alternator field inductance or resistance, the user can easily understand how variables are related to the entire dynamic system.

Cases of over-design of components for a mission can also be easily detected and avoided using this tool. By monitoring outputs throughout the mission sequences, parameters such as hydrogen fuel level can be kept at an optimal level. Also, by using a manual form of operation to select sources for each load configuration, not only can design issues covered up by mission requirements be revealed, but additionally it can lead to uncovering over designed components allowing for smaller, less expensive parts.

C. Research Objectives and Thesis Overview

The primary objective of this thesis project was to develop a versatile design tool for analyzing and verifying the performance of military vehicle power systems. The result was the AMPS Tool. This tool can be used not only during the design process of military vehicles, but also to simulate mission profiles and determine potential limitations of existing power systems. Once the vehicle components have been designed, missions can be thoroughly tested to ensure that the power system designed can support the mission, and verify that the mission specifications were appropriately defined. Finally, mission predictability can be established using automatic simulation control and mission profiles, allowing the tool to be useful long after the design process.

This thesis initially introduces the requirements of a military vehicle simulation, describing the main objectives and the criteria for the vehicle power system simulation and control. The simulation of the vehicle, the general philosophy, architecture, and an explanation of the modeling of each component is outlined in Chapter III. Chapter IV uncovers the necessity of a graphical user interface (GUI), and the advantages of simulation and interface integration. Chapter V discusses the proposed AMPS Tool, how it is designed, and integrated with the simulation for ease of design and analysis, along with a design verification example. Finally, conclusions about the AMPS tool and recommendations for future studies will be offered.

CHAPTER II

REQUIREMENTS OF A MILITARY VEHICLE SIMULATION TOOL

A. Purpose

The purpose of the Advanced Mobile Integrated Power System (AMPS) simulation and graphical user interface (AMPS tool) is to develop a configurable power system that is capable of performing the functions of design verification, mission predictability, and the study of the interrelationship of the vehicle components for design purposes. As mentioned in the previous chapter, designing to meet all of the necessary criteria demanded for in military vehicles is extremely difficult and calls for the use of simulations as an aide. In this chapter, the requirements of a simulation tool useful for military vehicle applications are examined. This chapter also gives a first look at the functionality of the model beyond the scope of the simulation requirements.

The impetus behind the AMPS project was the Army's desire to have a tool capable of not only verifying their complex vehicles before production, but also to use after the vehicle has been constructed to provide simulations of missions before they are executed and predict the state of the power system at all stages throughout the mission. The following examines the necessity for each of the functional requirements demanded of a simulation tool for accurately verifying power systems before and after production.

1. Design Verification

The ability of a simulation tool to incorporate the design engineers' choices of power source components and the configuration thereof within a single mission allows for complete testing of not only the power system design, but the design of the mission itself. Whether run in an automatic mission profile situation, or manually, the designers can ensure that in every mode of operation, the power sources can supply the required load power, and if necessary, charge the energy storage devices without over-sizing any components unnecessarily. The designer may also test the validity of the specifications of the mission (load and source on/off configuration) by observing in each mode if loads or sources are unnecessarily online, or would benefit from being online and are not. If for instance, during the transition from one mode with a low load consumption of power to another such as combat, with a high consumption of power by the loads, the mission requirements specify that only the alternator and battery supply the load power, the designer may find that adjusting the mission requirements to allow for the ultracapacitors to be online can help supply the peaks of power needed due to transients. Because the alternator would have to be oversized to supply these peaks in power demand at low rpm, adjustments such as adding an ultracapacitor to test its impact in these situations can potentially uncover over-designed components and allow for smaller, less expensive parts.

2. Mission Predictability

Mission predictability occurs when a mission has been simulated in many environments, particularly in many different power source states, fully charged to barely charged, and is observed to react in a specific and repeatable manner. The importance of being able to predict the reaction of the vehicle power system throughout a mission sequence must not be overlooked. During certain modes in a mission, especially ones in which the energy storage devices are the primary sources of power, it is important to be able to predict how long the mode can be maintained given the current condition of the power supplies. Silent Watch is one such critical mode of operation where maintaining the loads without using the engine and alternator is necessary for stealth. Because Silent Watch is powered by the battery and fuel cells, the time available to maintain that mode before losing loads due to loss of power, loss of state-of-charge on the battery or depletion of hydrogen for the fuel cell, can be valuable information. Concurrently, being able to simulate, and therefore to later predict, the state of all of the power sources after and even throughout different scenario profiles creates a reference that the vehicle operator can later depend upon. Besides being a critical tool during the development phase of the military vehicle, the ability to simulate how the power components will react throughout the course of a mission makes the simulation tool useful long after the design process.

3. Design Using Vehicle Component Interrelationships

For the purposes of designing vehicle power system structures, a simulation tool can allow the user to fully understand the interrelationships between the vehicle components. The importance of the sizing of the alternator, the effects of changing the ultracapacitor inductance or resistance, or any number of parameters for each of the sources may be analyzed. System and individual sources response to transients can be monitored for a better understanding of their functionality. Because each parameter of the power sources is available to the user to modify, along with the ability to turn on and off sources and loads manually, the simulation can be manipulated in any way the user desires to observe the outcome. These factors are of significant importance to a designer during the design phase, allowing the user to understand the inner workings of the vehicle power system more thoroughly.

B. Model Functionality

Many functions are required of a military vehicle simulation tool outside of the simulation of the vehicle power system. Once the vehicle has been created for simulation, it must be able to perform in the same capacity as the vehicle that will be constructed. Primarily the simulation must also include practical control strategies. All vehicles have, to some degree, a power management scheme. The simulation too, must have a similar ability, and due to its military nature, programmable modes of operation determined by the mission, and other mission-specific functions such as scenarios. These functions added to the vehicle architecture encompass the complete vehicle power system simulation.

1. Modes of Operation

The simulation tool must be able to incorporate all of the modes of operation required by the specific vehicle platform that is being simulated. A military vehicle mode of operation is a description of the configuration of the loads and sources. Each vehicle platform is designed to support specific modes of operation that can vary greatly, but that can all be realized in a given scenario that the vehicle may experience. Because the modes of operation dictate which loads are to be online, and which sources are to be supplying power, each component must be sized to provide all of the electrical power and energy needs to support a particular mission, with modes ranging from high-load modes such as those in combat, to low-load usage in modes like Silent Watch. Since the Simulink vehicle model includes all of the possible power sources and loads that could be used in any given mode, a graphical user interface can be programmed to associate the specific load and source configurations for each available mode of operation. An example of such a grouping of configurations is shown in Table I below.

Table I. Mode of Operation Source Configuration

	Modes of Operation					
Sources	**Off**	**Start**	**Combat**	**Silent Watch**	**Planning**	**Maintenance**
Alternator			x			x
Battery	x	x	x	x	x	x
Fuel Cell				x		
UltraCapacitor		x				

	Modes of Operation					
Sources	**Fording**	**Transit**	**Cold Ops**	**Protection**	**MOPP**	**Sustain**
Alternator	x		x	x	x	
Battery	x	x	x	x	x	x
Fuel Cell						x
UltraCapacitor						

The table shown above can be represented programmatically in the graphical user interface, so that in an automatic run situation the sources will be configured upon entering each mode of operation. Having this functionality in the user interface, as opposed to hard coding it in the simulation itself, leaves the option open for the user to either utilize the mode configurations that are pre-programmed, or override the functionality and set the source configurations manually for mission design.

2. Scenario Profiles

With the available modes of operation programmed as part of the user interface, another functionality of the simulation tool, automatic scenario profile simulations, can be utilized. Military vehicles, throughout the course of one mission, will not typically enter into or remain in just a single mode of operation, but will cycle through several modes. Scenario profiles are descriptions of the particular sequences of modes that the vehicle would enter during a given mission and includes the percentage of overall time that the vehicle would remain in that mode, similar to a drive cycle in automobiles. Table II gives an example of some scenario profiles for the vehicle simulated for the purposes of this project.

Table II. Scenario Profiles

Modes of Operation

Scenarios	Combat	Silent Watch	Planning	Maintenance	Fording
Combat	0.1	0.3	0.1	0.05	0.05
Maintenance	0	0	0.1	0.8	0
Deployment	0.1	0	0	0.15	0

Modes of Operation

Scenarios	Transit	Cold Ops	Protection	MOPP	Sustain
Combat	0	0.15	0.05	0.05	0.15
Maintenance	0	0	0	0	0.1
Deployment	0.65	0	0	0	0.1

From the table above, when running an automatic profile with a Combat Scenario, the vehicle will commence in Combat mode and remain for 10% of the total simulation duration time, then it will move to Silent Watch mode for 25% of the time, and then on to Sustain mode. Modes are not always utilized in every scenario, for example the Transit mode in Combat and Maintenance scenarios is not allotted any time. The data from this table is managed by a Matlab Scenario Profile Data function in the Simulink vehicle model. When run in an automatic mode, and given a profile duration time, the simulation will follow the scenario profile chosen by the user, maintaining each mode of operation for the percentage of time required by the above table. When run manually, the user may choose both the mode of operation sequences as well as the duration time in each of the modes. Many uses can be made of this functionality. The responses of the sources to changes in loads can be monitored, and sources requiring fuel, such as fuel cells with hydrogen tanks can be studied to ensure optimal supply quantities for completing a mission.

3. Power Management

The necessity for power management capabilities of a military vehicle simulation tool is primarily for the purposes of protecting the sources from over-current conditions. Currents supplied by each individual source are monitored in a Power Management routine in Matlab and are compared with continually calculated maximum current capabilities of each source. In the event that any source becomes overtaxed by the load demand, and begins to supply more than its maximum current capacity, loads will begin to be shed. Because some modes in certain missions may have critical loads for operation, priorities must be set for each load in each individual mode of operation. In Silent Watch mode, because the vehicle is in a stationary state with the engine turned off to maintain silence, loads such as the engine controls, or auxiliary power are of less importance than loads such as the crew station power, and will either be taken offline upon entering Silent Watch mode, or will be shed early in case of loss of power due to their low priority. Table III demonstrates, for a sample of the modes of operation, an example priority listing. The priority listing is used in the Power Management routine in Matlab to determine, in the event that load shedding should occur, the order in which the loads are to be shed given the current mode of operation.

Table III. Priority Listing According to Mode of Operation

14V Loads	Combat	Silent Watch	Planning	Maintenance	Fording
Engine Controls	H			M	H
Xmission Controls	H			M	H
Dome Lights	L	L	M	L	
Aux 14V Outlet		L	L	M	
RIU (Brake and Suspension)	H			M	H
RIU (Fuel Control)	H			M	H
Exterior Lighting	L			L	L
Exterior Lighting	L			L	L
28V Loads					
Spare					
Battery Charger			M	M	
Drive Motor Controller	H	L			
Drive Motor Controller	H				
DC/DC Converter	M				
Generator Controller	H			M	H
Engine Control Module	H			M	H
Dissipator Controller	M			L	M
42V Loads					
DC 2 110 AC Conv	M	L	M	M	
Crew Station Power	H	H	H	H	
Integrated Cooling	M		M		
Actuators	H	M			
Battery Charger	L		M	M	
Battery Charger	L		M	M	
Electrolyzer On/Off		H			
Engine Compartment Fan	H				H
42V Loads					
Spare					
Engine Feed Pump	H			M	H
Engine Feed Pump	H			M	H
Water Separator Heater	L	L			
Intra-Tank Transfer Pump	M		L	M	
Intra-Tank Transfer Pump	M		L	M	
Stop Lights	L			L	L
Svc Tail/Head Lamp	L			L	L

H = High Priority
M = Medium Priority
L = Low Priority
Not Prioritized = Off

4. User Defined/Custom Simulation

For the purposes of testing and design of hybrid military vehicle power systems, the ability of the user to customize nearly every portion of the simulation is imperative. Although a simulation tool may have all of the functional capabilities discussed previously for simulating and verifying missions and power system components, the most useful feature may be the flexibility to be customized. Every input parameter of each source should be available to the user to be defined. The vehicle power train should offer inputs to the user such as throttle, engine rated power, vehicle speed and reference voltage. Ultracapacitors should be a collection of inputs including capacitance, inductance, and resistance allowing for full control over each component. Manual control of each source and load should be available in any mode of operation, over-riding any pre-programmed configurations. Without this feature, a military vehicle simulation tool would be appropriate only after the design process for verification, but with this added functionality it becomes, in addition, a useful design tool.

C. Summary

This chapter provides an overview of military vehicle simulation requirements, with an explanation of the purpose and expectations of the AMPS tool. The main features have been identified and the functionalities have been defined. The next chapter will give an in depth description of the simulation of each of the components within the vehicle architecture and the overall management of the vehicle power system.

CHAPTER III

MODELING AND SIMULATION OF THE MILITARY VEHICLE

A. Introduction

As stated in Chapter I, the design of power systems for military vehicles requires the ability to access and alter each parameter of the power source components, and to simulate every desired mode of operation. The last chapter introduced the vehicle system specifications that were used as a basis for the design and simulation of the AMPS tool. In this chapter, the simulation of the vehicle and the modeling and functioning of each component will be discussed. Also the general control the vehicle simulation will be examined along with the management of power flow.

B. Vehicle Specifications

The vehicle power system specifications required for the AMPS project call for four independent sources supplying power for up to 32 loads. Each source and load is to be capable of being taken on or offline at will, with specific power sources used for charging storage components whenever power generation is in excess of consumption. The power system architecture is shown in Fig. 4 below.

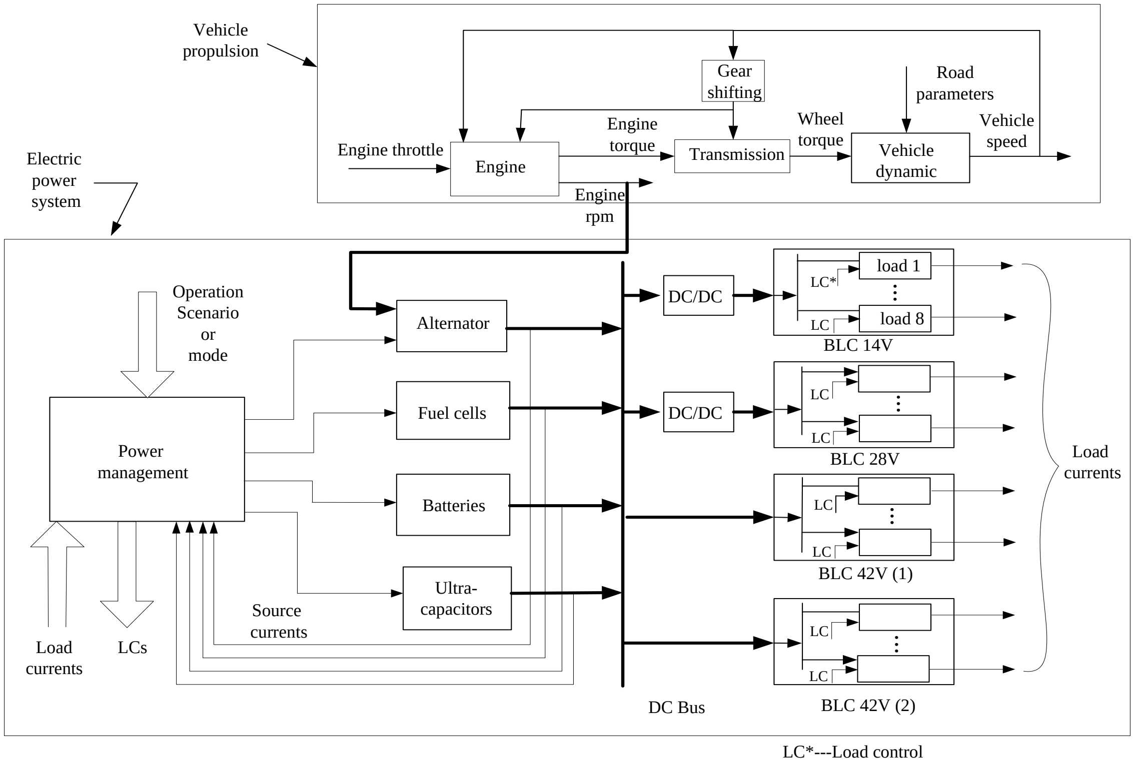

Fig. 4. Power management network.

Four sources are employed to maintain power throughout the various stages of the mission, an engine-driven alternator, batteries, a fuel cell system, and ultracapacitors. These four power sources are connected in parallel to the DC bus designed to be 42 V. The loads of the system include four branches with rated voltages of 14 V, 28 V and 42 V, with each load branch consisting of eight individual loads. Of the 32 loads that are connected to the vehicle, there are two main types, fully resistive, and a combination of resistive and motor loads. The 14 V and 28 V load branches are connected to the DC bus through two DC/DC converters with the two 42 V branches connected directly to the DC bus.

The alternator is the primary source of power when operating while the engine is running. Only in modes where the engine is turned off for the purposes of testing, performing maintenance, or to provide stealth, is the alternator not online. The batteries are a consistent back up source of power that are kept on in all modes for either providing power during shortages, or for charging. The configuration of the vehicle used for the purposes of this thesis utilize the ultracapacitors only for engine starting to provide back-up power to the batteries in case of cold-start conditions. Though not specified for the function of the particular vehicle simulated, the ultracapacitors could also be used in times of mode transitions where the addition of heavy loads can cause power transients that are ideal for the ultracapacitor to supply. The final source specified for this vehicle is the fuel cell system. Fuel cells are used in this vehicle solely for the purpose of supplying power to very light loads for a prolonged period of time, thereby relieving the battery from potential depletion.

C. Component Modeling

The following is a detailed description of the modeling of each component and includes the equations governing the functions of the models. Four sources are modeled, an alternator, fuel cells, battery and ultracapacitors.

1. Alternator Model

The alternator model is a three-phase AC model. It includes an armature, field, and a voltage regulator and rectifier shown in Fig. 5. The Simulink model of the alternator is shown in Fig. 6 and contains three sub-blocks, one to generate the phase voltages and create a rectified open circuit voltage, one block for simulating the armature circuit, and the last to simulate the field circuit and voltage regulator.

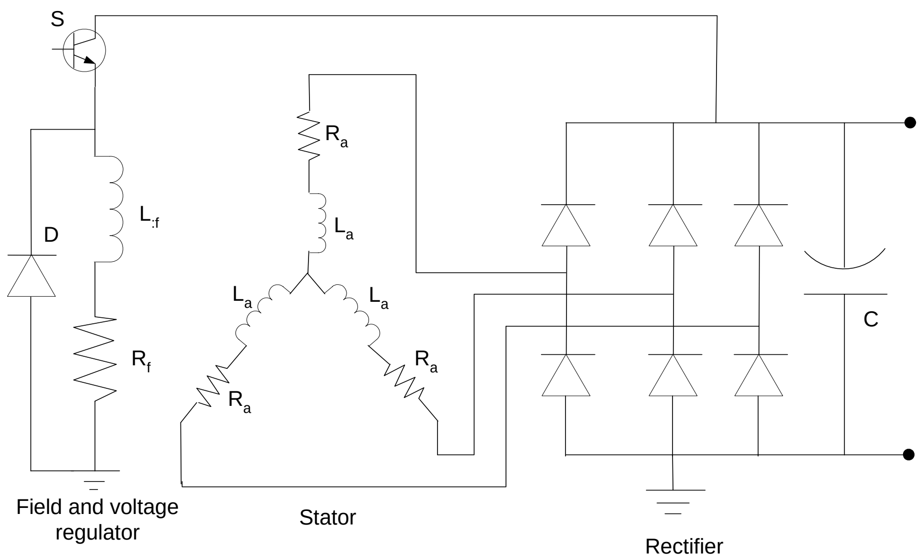

Fig. 5. Alternator model.

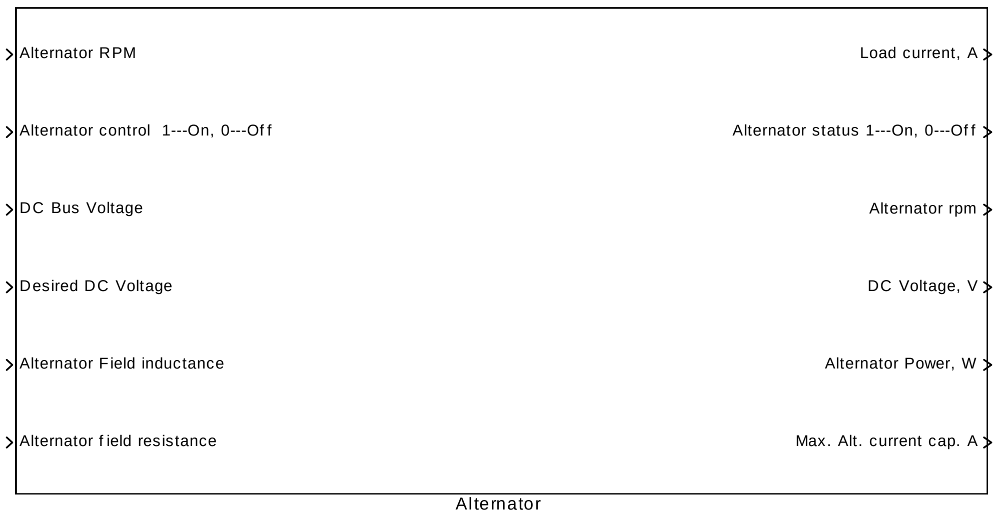

Fig. 6. Simulink alternator model block.

The first sub-block, is used to generate the phase voltage, calculate the line-to-line voltage, and to rectify the open circuit voltage. The input DC voltage is the magnitude of the phase voltage (back emf), which is expressed as:

$$Vb = k_{\phi}\phi\omega \qquad (1)$$

where

k_{ϕ} = constant

ϕ = field

ω = alternator angular velocity

The alternator angular velocity is calculated in the vehicle power train model from the engine speed, k_{ϕ} is generated in the armature circuit sub-block, and ϕ is generated in the field circuit sub-block. The armature circuit sub-block simulates the armature circuit shown in Fig. 7.

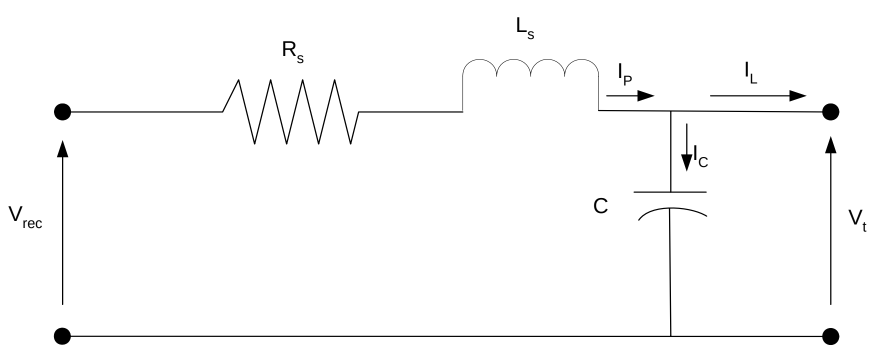

Fig. 7. Armature circuit.

The differential equations describing the armature circuit are:

$$(V_{rec} - V_t) = I_P R_s + L_s \frac{dI_p}{dt} \tag{2}$$

$$I_c = C \frac{dV_t}{dt} \tag{3}$$

$$I_L = I_P - I_c \tag{4}$$

In this block, k_ϕ is generated and is proportional to the inductance of the armature, that is, $k_\phi = AL_s$, where A is a constant.

The last sub-block of the alternator simulates the field circuit, Fig. 8, and the voltage regulator.

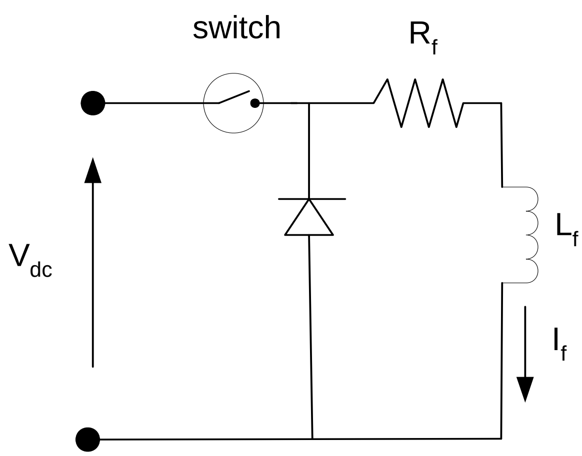

Fig. 8. Field circuit.

The switch is used for regulating the voltage, when the terminal voltage is higher than desired, the switch is open, and likewise it is closed when the terminal voltage is lower than desired. The differential equations describing the field circuit are:

$$V_{dc} = I_f R_f + L_f \frac{dI_f}{dt} \text{ when the switch is closed,} \tag{5}$$

$$0 = I_f R_f + L_f \frac{dI_f}{dt} \text{ when the switch is open.} \tag{6}$$

This sub-block solves the above equations to obtain the field current I_f and ϕ. ϕ is assumed to be proportional to the field current, I_f, and the field inductance L_f. From this complete model the alternator current, voltage, and maximum current capacity can be monitored.

2. Fuel Cell Model

The fuel cell model is based on a proton exchange membrane fuel cell. The input parameters include two design parameters of rated power and rated voltage, and four operating parameters including fuel cell on/off control, DC bus voltage, fuel cell fuel level and hydrogen capacity, as seen in Fig. 9.

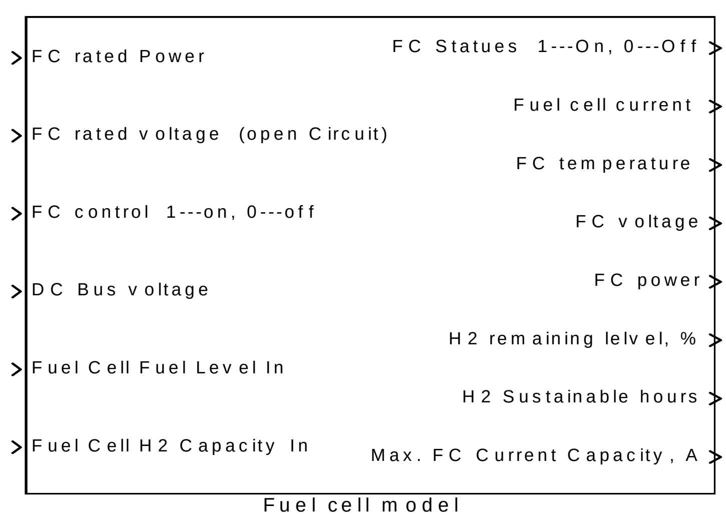

Fig. 9. Simulink fuel cell model block.

The fuel cell system modeled has the structure shown in Fig. 10, which includes the fuel cell stacks and the hydrogen and air supply. The dual stack is a series of single cells connected together serially shown in Fig. 10.

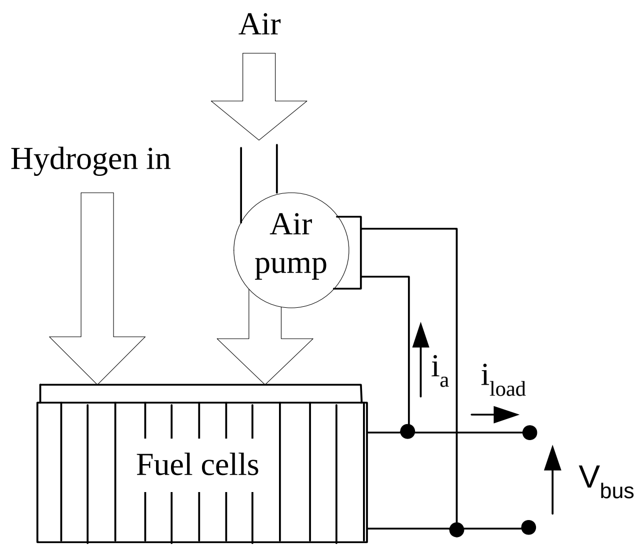

Fig. 10. Fuel cell stack.

The terminal voltages at various cell currents describe the cell characteristics. According to the fuel cell document supplied by Joel D. King, Alion Science and Technology [5], the cell voltage-current relationship can be expressed as:

$$V_{fc-cell} = 0.9619 I_A^3 + 1.327 I_A^2 - 0.8999 I_A + 0.9587 \tag{7}$$

where I_A is the current density of the fuel cell in A/cm^2. The cell voltage versus current density is shown in Fig. 11.

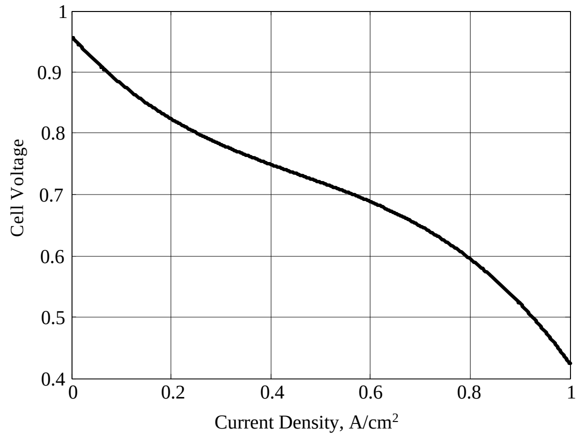

Fig. 11. Cell voltage as a function of current density.

The number of cells in the fuel cell stack can be obtained from:

$$N_{fc} = \frac{V_{rated}}{V_{fc-cell-open}} \tag{8}$$

where

V_{rated} = rated voltage of the fuel cell stack in an open circuit condition

$V_{fc\text{-}cell\text{-}open}$= cell voltage in open circuit (0.9587)

The rated cell current density, with which the rated power of the fuel cell stack is designed, is assumed to be the current density at which the cell has 70% of the open-circuit voltage, and can be expressed as:

$$I_{rated} = \frac{P}{0.7V_{rated}} \tag{9}$$

and the active area of the fuel cell can be expressed as:

$$A = \frac{I_{rated}}{I_{d-rated}} \tag{10}$$

where $I_{d\text{-}rated}$ is the rated current density of the fuel cell at 70% of open circuit voltage, which is calculated with the function of F(z)=0. The fuel cell stack is initially modeled as a function of V=f(I), where *V* is the stack terminal voltage and *I* is the current flowing to the DC bus. Then using the *F(z)=0* function, simulink solves for the current *I* at a given DC bus voltage to fit the system model.

The hydrogen-consuming rate (g/s) is proportional to the total fuel cell current and can be expressed by:

$$H_f = \frac{2.016}{2 \times 96495} I \tag{11}$$

where

I = total current from the fuel cell stack

The airflow rate is proportional to the hydrogen flow rate, and can be expressed by:

$$A_f = 34.21 \lambda H_f \tag{12}$$

where

λ = equivalence (fuel/air) ratio

The power consumed in compressing the air can be expressed by:

$$P_{air-com} = \frac{\gamma}{\gamma - 1} \frac{R\ T\ A_f}{28.96} \left[\left(\frac{p_1}{p_0} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \frac{1}{0.6} \tag{13}$$

where

γ = specific heat of air

R = gas constant (287.1 J/kg K)

T = inlet temperature (Kelvin)

p_1 = outlet pressure

p_0 = inlet pressure

The number 28.96 comes from the molecular weight of the air, and 0.6 is the efficiency of the air compressor including the motor drive. The stack current is then calculated as the summation of the load current and the current used to compress the air.

3. Battery Model

The battery model is an electrical equivalence model, as shown in Fig. 12. *E* is the back EMF of the battery produced by the chemical reaction, which is a function of the battery state-of-charge (SOC). The model also includes two internal resistances; one caused by the chemical reaction (over potential), R_{ch}, and the other by internal conductor resistance (ohm resistance) R_{ohm}. R_{ch} depends on the battery SOC, and the discharging and charging process shown in Fig. 13.

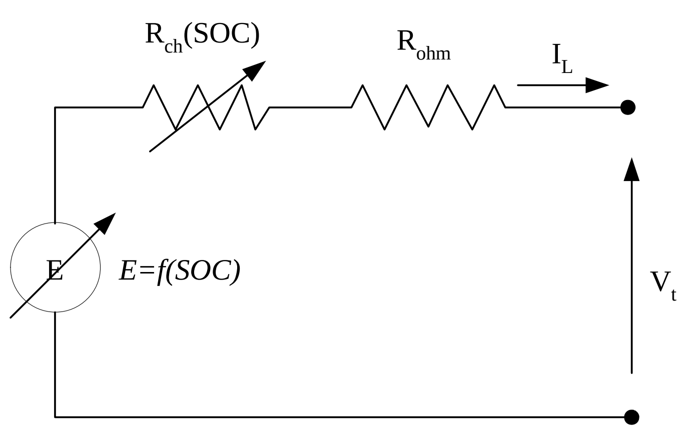

Fig. 12. Battery model.

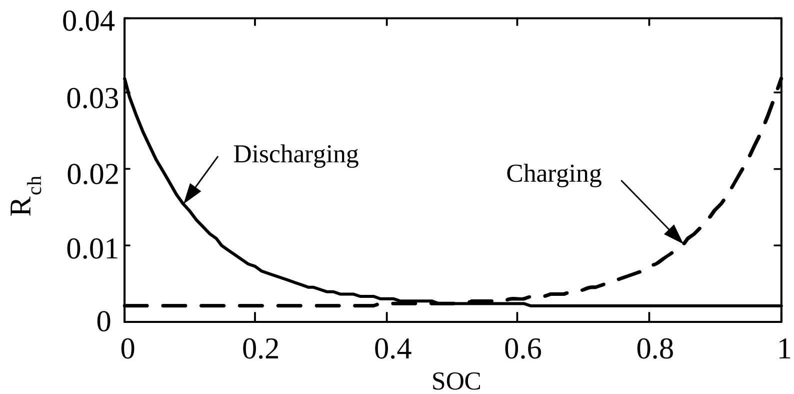

Fig. 13. Discharging and charging process.

The terminal voltage of the battery is expressed by:

$$V_t = E(SOC) - (R_{ch}(SOC) + R_{ohm})I_L \qquad (14)$$

where I_L is the battery current, positive in discharging and negative in charging, and the cell ohm resistance, R_{ohm}=2.0×10^{-3} Ω.

The cell back EMF, E, is expressed by:

$$E = 2.0 + 0.03\,SOC \qquad (15)$$

The cell chemical resistance R_{ch} is expressed by:

$$R_{ch} = k_1 e^{k_2(1-SOC)} \text{ when discharging, and} \qquad (16)$$

$$R_{ch} = k_1 e^{k_2(SOC)} \text{ when charging} \qquad (17)$$

Above, k_1=4.5×10^{-6}, and k_2=8.8.

The cell number is determined by:

$$N_{bc}=\frac{V_{sta-rated}}{V_{cell-rated}} \tag{18}$$

where

$S_{sta-rated}$ = battery pack rated voltage

$V_{cell-rated}$ = cell rated voltage

The battery current SOC can be expressed as:

$$SOC = SOC_0 - \frac{1}{Q}\int_0^t I_L dt \tag{19}$$

where

SOC_0 = initial *SOC* of the battery at *t*=0

Q = battery current capacity in *Ah*

The battery model described by Equation (14) has the load current I_L as the input and terminal voltage V_t as the output. To fit the system model (V_t=DC bus voltage), the *F(z)=0* function in simulink is used to change the model as $I_L=f(V_t)$, that is, terminal voltage V_t (DC Bus voltage) as the input and load current I_L as the output.

The sustainable time that the batteries can support the system's operating can be estimated by:

$$T = \frac{Q(SOC - SOC_{\min})}{i_{bd}} \tag{20}$$

where SOC_{min} is the minimum SOC below which the batteries cannot deliver enough power to the system, and i_{bd} is the instantaneous battery discharging current.

The battery model block illustrating battery model inputs and outputs in Simulink is shown in Fig. 14.

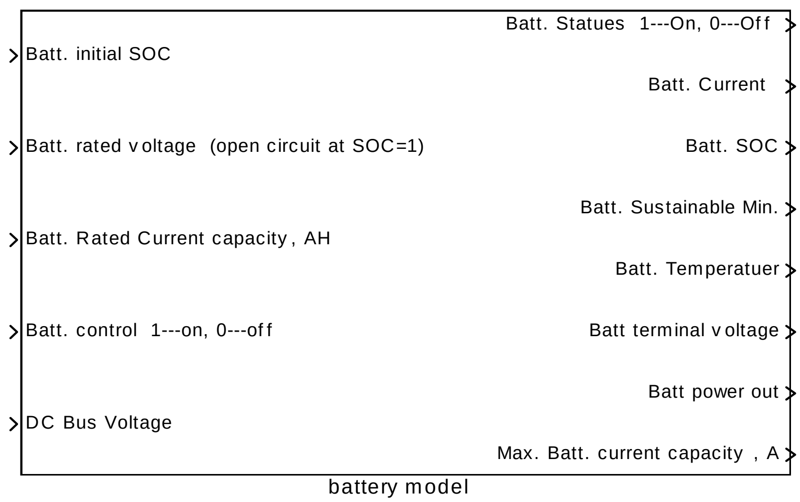

Fig. 14. Simulink battery model block.

4. Ultracapacitor Model

The ultracapacitor model is also an electrically equivalent model as shown in Fig. 15. An ideal capacitor is connected in parallel to a resistor R_p representing the current leakage effect, and then in series to a resistor, R_s, which represents the internal series resistance.

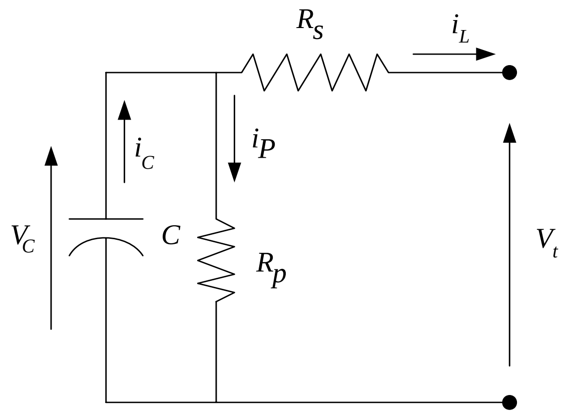

Fig. 15. Ultracapacitor equivalent circuit.

The ultracapacitor model equations are as follows:

$$i_C = i_L + i_P \tag{21}$$

$$i_L = \frac{V_C - V_t}{R_s} \tag{22}$$

$$i_P = \frac{V_C}{R_P} \tag{23}$$

$$V_c = V_{C0} - \frac{1}{C}\int_0^t i_C \, dt \tag{24}$$

where

i_C = the current from the ideal capacitor

i_L = the output current from the ultra capacitor

i_P = the leakage current through the dielectric

V_C = the voltage across the ideal capacitor

V_{C0} = the initial voltage of the ultracapacitor at t=0

The sustainable time (T_{sus}) that the ultracapacitor can support the operation of the system can be expressed by:

$$T_{sus} = \frac{E_{Avail}}{P_{Cd}} \tag{25}$$

where

E_{avail} = the available energy stored in the ultracapacitors

P_{Cd} = the instantaneous discharging power of the ultracapacitors

The available energy stored in the ultracapacitors can be expressed by:

$$E_{avail} = \frac{1}{2}C(V_{C-full}^2 - V_{C-\min}^2), \tag{26}$$

where

V_{C-full} = capacitor voltage at full charge

$V_{C-\min}$ = capacitor minimum voltage

In the ultracapacitor model, the State-of-Energy (SOE) is defined as

$$SOE = \frac{E_c}{E_{c-full}} = \frac{V_c^2}{V_{c-full}^2}, \tag{27}$$

where

E_c = instantaneous energy stored in the ultracapacitor

V_c = instantaneous voltage of the ultracapacitor.

The ultracapacitor model block illustrating ultracapacitor model inputs and outputs in Simulink is shown in Fig. 16.

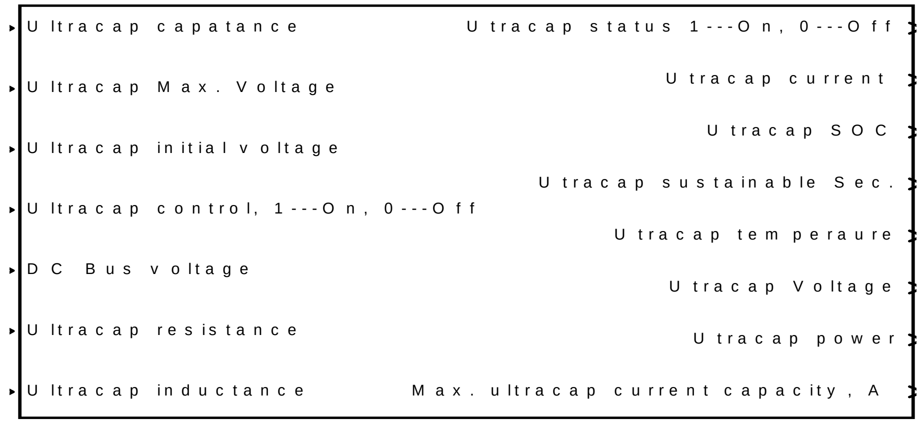

Fig. 16. Simulink ultracapacitor model block.

5. Load Model

According to the specification of the system simulated, the loads fall into two categories, one a resistive load and the other an electric motor load.

a. Resistive load

The resistive loads are modeled by:

$$I = \frac{V}{R} \tag{28}$$

where

R = load resistance

V = voltage acting on the load

I = current flowing through the load.

b. Motor load

Strictly speaking, the electric motor is not an energy sink, but an energy converter. In this project, the energy sink of the electric motor is assumed to be a fan or pump, as shown in Fig. 17.

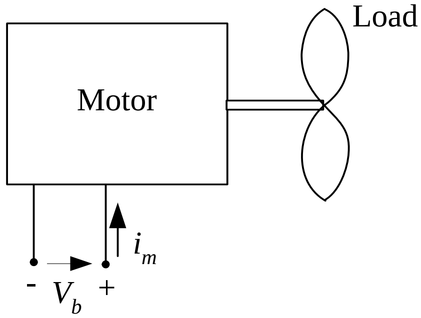

Fig. 17. Motor and load.

The electric motor is modeled as a DC model with the electric circuit shown in Fig. 18.

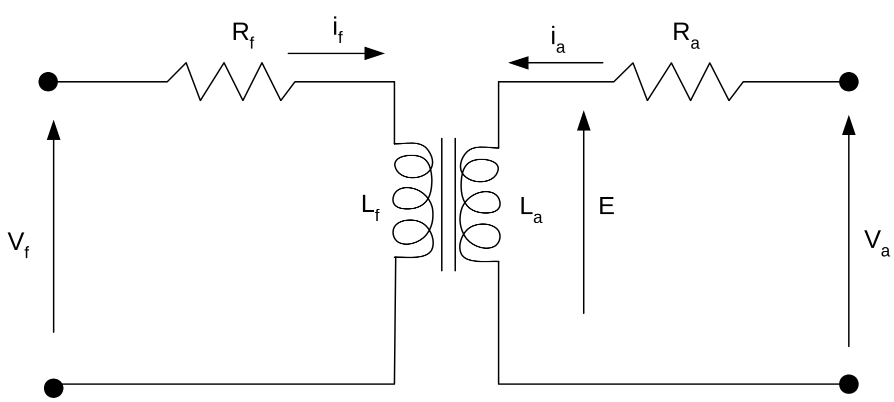

Fig. 18. Armature and field circuit of a DC motor.

The field is described by

$$V_f - R_f i_f = L_f \frac{di_f}{dt} \tag{29}$$

where V_f is the source voltage, and is equal to the armature voltage V_a (bus voltage), and i_f is the exciting current.

The field produced by the field circuit is

$$\phi_f = k_f L_f i_f \ , \tag{30}$$

where, k_f is a constant.

The armature is described by the equations:

$$V_a - R_a i_a = E \tag{31}$$

$$E = \phi_f \omega_m \ , \tag{32}$$

$$T = \phi_f i_a \ , \tag{33}$$

where

R_a = armature resistance

i_a = armature current

ω_m = motor speed

T = motor torque

ϕ_f = field constant

V_a = armature voltage

E = back EMF (air gap voltage)

The load of the motor is a fan, which is described as

$$T_L = C\omega_m^2 + B\omega_m \tag{34}$$

where *C* and *B* are constants.

The total current flowing to the electric motor is the summation of the armature and field currents. Fig. 19 and Fig. 20 show one of the four load branches along with an individual load model.

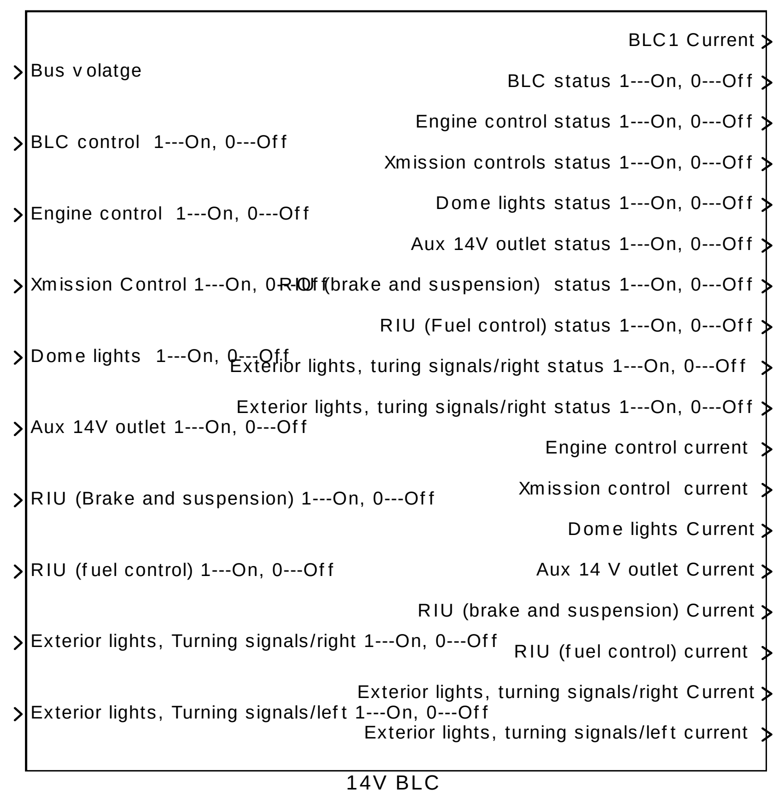

Fig. 19. 14V Load branch block.

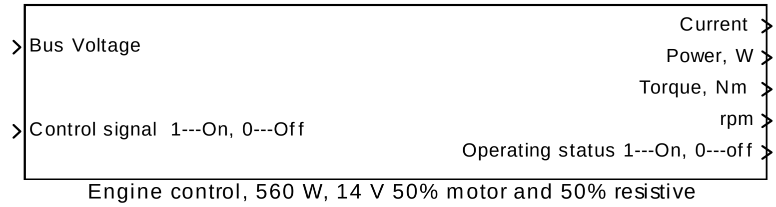

Fig. 20. Engine control load block.

6. DC/DC Converter

Two DC/DC converters are used to convert the 42 V DC bus voltage into 14 V and 28 V needed to support the 14 V and 28 V load branches. The DC/DC converter is modeled with ideal switches, e.g. the output and input have the same power as shown in Fig. 21 and are expressed by Equation (35).

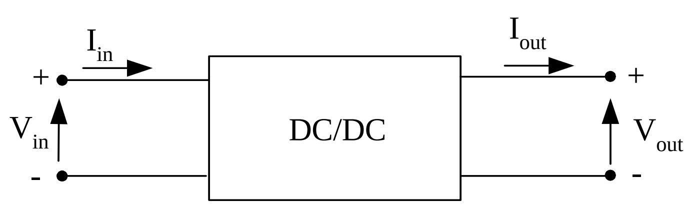

Fig. 21. DC/DC converter.

$$P_{DC/DC} = I_{in}V_{in} = I_{out}V_{out} . \tag{35}$$

The current from the DC bus can be expressed by:

$$I_{load} = \frac{P_{load}}{V_{bus}} \tag{36}$$

where V_{bus} is the DC bus voltage.

D. Power Source Current Calculation

As shown in Fig. 5, all the power sources and loads are directly connected to the DC bus. Except for the on/off controls of all the power sources and loads, there is no active control for the power flow, thus the power delivered by each power source is a natural response to load requirements, and depends on its voltage-current characteristics.

In the calculation of power source current, one constraint is that the summation of the power source currents should be always equal to the total load current, with their terminal voltages remaining the same and equal to the bus voltage. This constraint can be mathematically described by the following two equations:

$$I_{alt} + I_{fc} + I_{batt} + I_{uc} = I_{load} \tag{37}$$

$$V_{alt} = V_{fc} = V_{batt} = V_{uc} = V_{bus} \tag{38}$$

where

I_{alt} = alternator current

I_{fc} = fuel cell current

I_{batt} = battery current

I_{uc} = ultracapacitor current

V_{alt} = alternator voltage

V_{fc} = fuel cell voltage

V_{batt} = battery voltage

V_{uc} = ultracapacitor voltage

Equations (37) and (38) are depicted in Fig. 22.

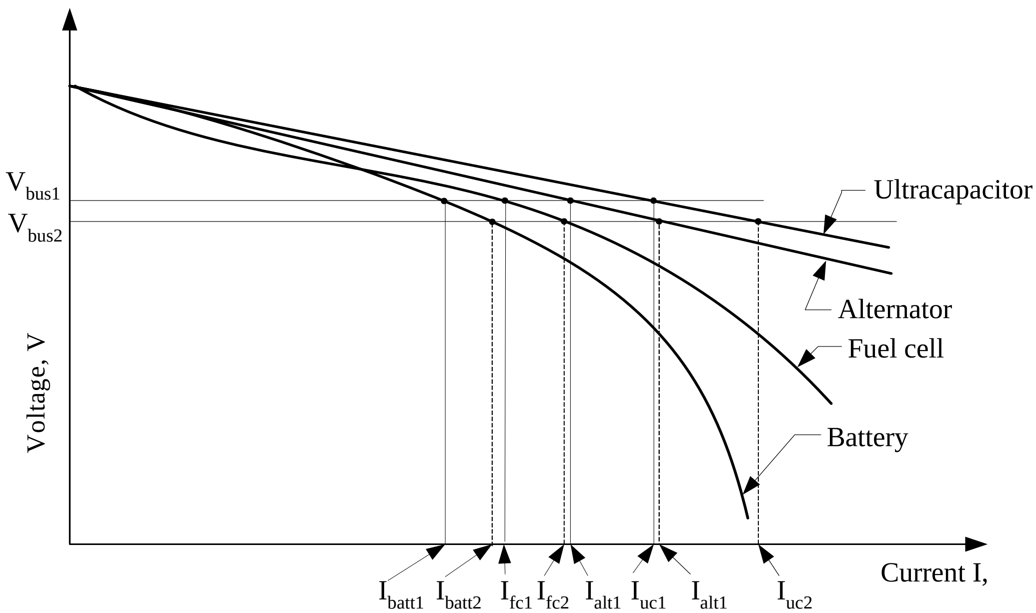

Fig. 22. Power source current and bus voltage at given total load current.

Due to the complicated model-defined functions of the power source characteristics, it is difficult to get explicit solution for Equations (37) and (38) (obtaining the power source currents and bus voltage at a given load current). This problem is solved in the Simulink by using a PID function as shown in Fig. 23. The drawback of this method is the slow operation.

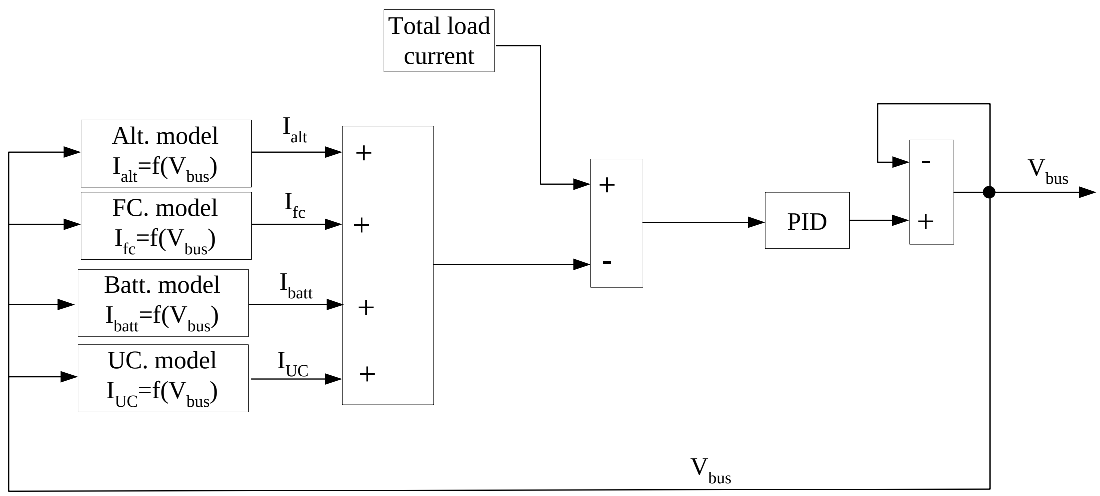

Fig. 23. Block solving for the power source currents and bus voltage.

E. Simulation Control

Because one of the main purposes of the AMPS tool is for design verification, the ability to operate the vehicle in simulation exactly as it will be operated in practice is key. To this end, there must be more to the simulation than development of the power source and load components alone. The complete simulated vehicle power system consists of three basic subsystems, or sub-blocks, developed to control the simulation and imitate the behavior of an actual military vehicle. These subsystems include a Scenario Profile Data system, a Power Management system, and a previously discussed Vehicle Component system, Fig. 24.

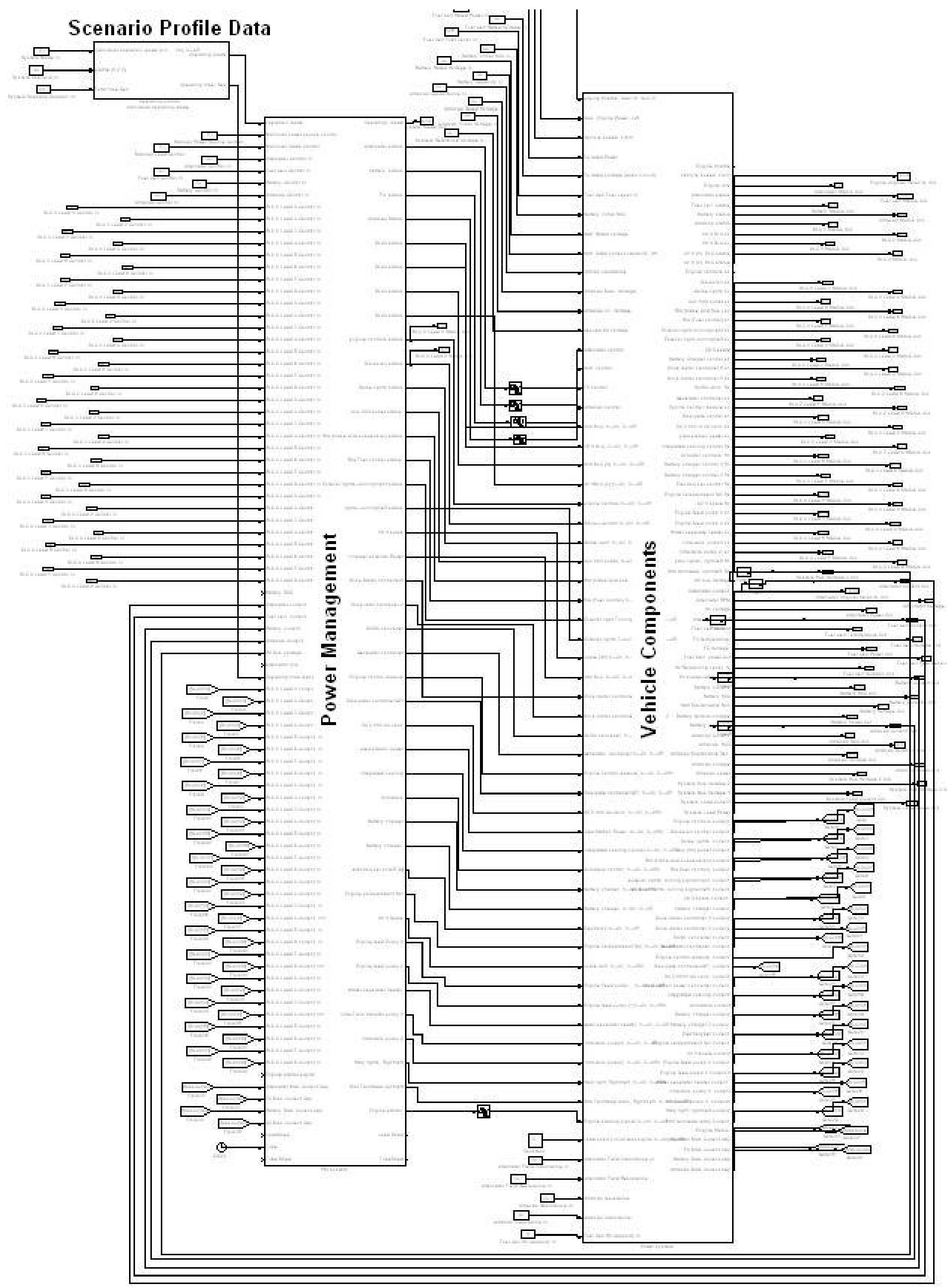

Fig. 24. Simulated vehicle power system.

1. Scenario Profile Data

In the Scenario Profile Data sub-block Fig. 25, different operation scenarios and modes are managed.

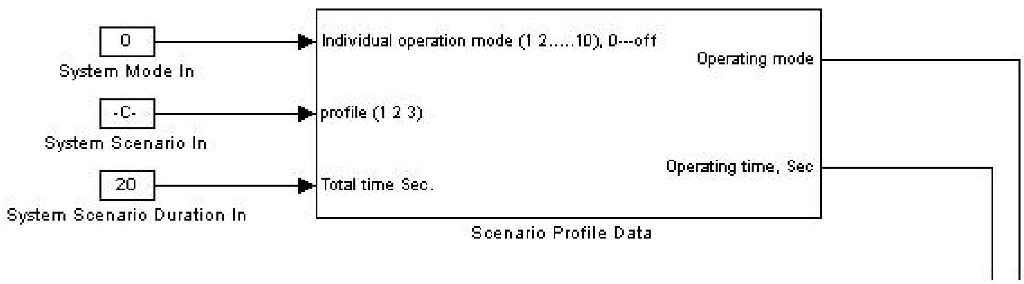

Fig. 25. Scenario profile data.

In the vehicle used for the purposes of this thesis, there are three mission scenario profiles, namely, (1) Combat Mission Profile, (2) Maintenance Profile, and (3) Deployment Profile. Each scenario includes a particular combination of the modes of operation. These operation modes are classified into two categories of Crew Selectable Modes and Vehicle Configuration Modes. The Crew Selectable Modes consists of (1) Combat, (2) Silent Watch, (3) Planning, (4) Maintenance, and (5) Fording modes. The Vehicle Configuration Modes consists of (6) Transit, (7) Cold Operation, (8) Protect, (9) MOPP, and (10) Sustain modes. Table IV provides the profiles for each scenario, with the percentage of time spent in each mode of operation before passing to the next mode.

Table IV. Scenario Profile Data

Modes of Operation

Scenarios	Combat	Silent Watch	Planning	Maintenance	Fording
Combat	0.1	0.3	0.1	0.05	0.05
Maintenance	0	0	0.1	0.8	0
Deployment	0.1	0	0	0.15	0

Modes of Operation

Scenarios	Transit	Cold Ops	Protection	MOPP	Sustain
Combat	0	0.15	0.05	0.05	0.15
Maintenance	0	0	0	0	0.1
Deployment	0.65	0	0	0	0.1

The Scenario profile Data sub-block takes inputs from the user as to system mode in, or scenario in and scenario duration time in. Two types of operation can be maintained with these inputs. If the user chooses to control the simulation manually and select the modes of operation at will, then the mode in selection (1-10) can be made, and each mode is maintained until the user selects a new mode. If the user chooses to run an automatic profile however, the mode is chosen to be off (0) which indicates that a scenario profile is to be employed. The user then chooses the profile he wishes to follow, and enter a simulation duration time that the simulation will use to calculate the total time allotted for each mode of operation. The current operating mode and simulation time are then outputs to the power management sub-block to be processed and fed to the vehicle components.

2. Power Management

The power management functionality is performed in the Simulink model as a Matlab function and has several features; it provides the simulation with information regarding the load configurations for each mode, it reads in the source configurations for each given mode, and it compares data from each of the source currents to calculated data of the source maximum currents to determine whether load shedding should occur, and if so, what order loads should be shed. The block diagram of the power management system is shown in Fig. 26.

In this system, there are a total of 32 loads, which are grouped into four branches as indicated by 12 V BLC, 28 V BLC 42 V BLC and 42 V BLC. Each individual load is assigned a priority number based on its importance in each of the operation modes. The primary function of the power management is to manage (turn on/off) the power source and loads, depending on the power source capability, required load power, and load priority. A flowchart of the power management algorithm is shown in Fig. 27.

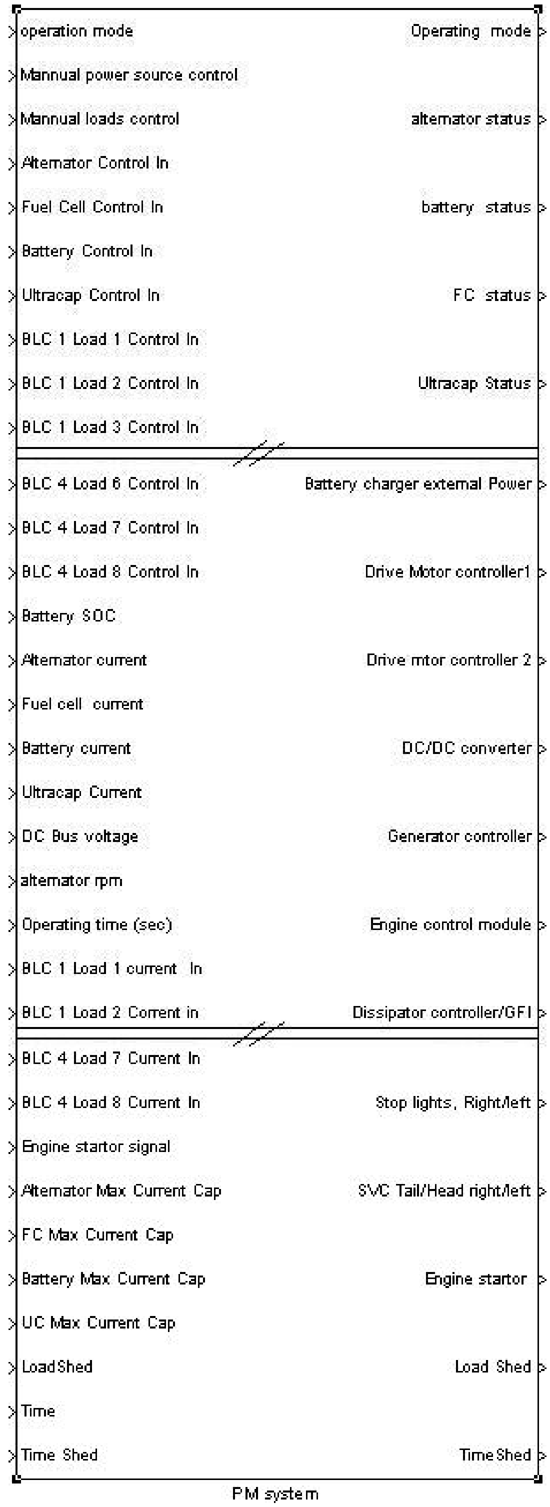

Fig. 26. Power management block diagram.

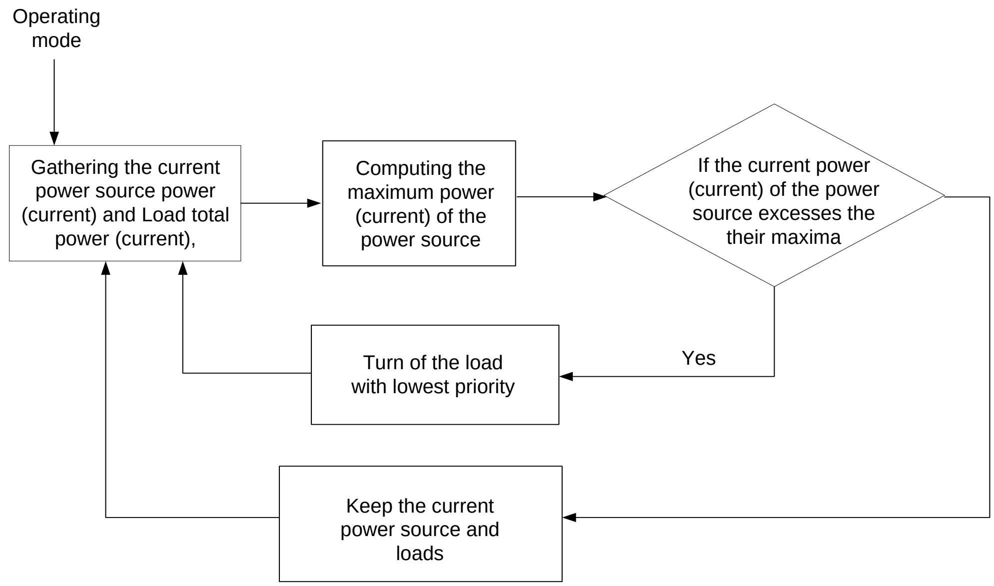

Fig. 27. Flowchart of power management.

The most important feature of the power management system is the load-shedding capability. The inputs of source currents, alternator, battery, fuel cell, and ultracapacitor, are monitored by the power management system and compared against a computation of the maximum current capabilities of each individual source. In the event that any source is providing more than its maximum current, loads begin to be shed to reduce the power demand. The order in which the loads are shed depends upon which mode of operation the vehicle is currently in. Matrices of load priorities for each mode of operation are programmed into the power management system, allowing for a very specific load-shedding profile. Table V shows an example of how the load priorities were selected for each mode.

Table V. Load Shedding Priority

Modes of Operation

14V Loads	Combat	Silent Watch	Planning	Maintenance	Fording
Engine Controls	H			M	H
Xmission Controls	H			M	H
Dome Lights	L	L	M	L	
Aux 14V Outlet		L	L	M	
RIU (Brake and Suspension)	H			M	H
RIU (Fuel Control)	H			M	H
Exterior Lighting	L			L	L
Exterior Lighting	L			L	L
28V Loads					
Spare					
Battery Charger			M	M	
Drive Motor Controller	H	L			
Drive Motor Controller	H				
DC/DC Converter	M				
Generator Controller	H			M	H
Engine Control Module	H			M	H
Dissipator Controller	M			L	M
42V Loads					
DC 2 110 AC Conv	M	L	M	M	
Crew Station Power	H	H	H	H	
Integrated Cooling	M		M		
Actuators	H	M			
Battery Charger	L		M	M	
Battery Charger	L		M	M	
Electrolyzer On/Off		H			
Engine Compartment Fan	H				H
42V Loads					
Spare					
Engine Feed Pump	H			M	H
Engine Feed Pump	H			M	H
Water Separator Heater	L	L			
Intra-Tank Transfer Pump	M		L	M	
Intra-Tank Transfer Pump	M		L	M	
Stop Lights	L			L	L
Svc Tail/Head Lamp	L			L	L

H = High Priority
M = Medium Priority
L = Low Priority

During simulation, the power management sub-block will receive the mode status from the Scenario Profile Data sub-block. This mode will be used in the Matlab routine, to find the proper load configuration. If the mode is different than the last mode, then a new load configuration must be found corresponding to that mode of operation. If the mode is the same as the last run through of the routine, then the load configurations are maintained and source currents are monitored for over-current conditions. If load shedding should occur in one mode, the load-shed priorities are obtained for that mode, and load statuses are changed dynamically as the loads are shed. The outputs of the power management system are load and source on/off configurations that are sent to the vehicle component sub-block for the vehicle configuration. With the previously discussed mode or scenario profile inputs, and source configurations, the loads can automatically be selected and a successful vehicle simulation can be obtained with the addition of the basic source parameter inputs to the simulation in the vehicle component sub-blocks. Although this method of configuring all of the inputs to the vehicle for simulation will provide the user with an accurate description and simulation of the military vehicle, the use of a graphical user interface can greatly simplify the task.

F. Summary

This chapter presented a detailed description of the modeling of each of the vehicle components including their characteristics and equations governing their operation. This chapter also discussed the functionality of the vehicle simulation as a whole from the overall control of the vehicle throughout the simulation, to the regulation of power flow to each component. Although the feasibility of using the simulation alone for design and verification of military vehicles has been presented here, the next chapter will present arguments for implementing a user interface with the simulation making the complete package a useable and beneficial tool.

CHAPTER IV

INTERFACE BETWEEN SIMULATION AND USER

A. Introduction

The primary function of a graphical user interface is to allow the user ease of access to important input and output parameters, while maintaining a stable system safe from over-configuring. Chapter I introduced the idea of being able to access and alter parameters of the power source components, the vehicle configuration, and overall mission specifications. Chapter II proposed expectations of the AMPS tool and briefly examined how these expectations were met and exceeded. The previous chapter disclosed the modeling and simulation of each component of the vehicle and gave a description of the power management scheme and the general control of the power flow utilized. The present chapter provides an examination of the need for and advantages of having a graphical user interface (GUI) in a vehicle simulation such as this. Also an exploration of the differences in functionality between the GUI and Simulink simulation will be discussed.

B. Necessity for a Graphical User Interface

There are a number of needs for providing an interface to a simulation, especially the more complex the simulation becomes. Although a simulation created by an engineer may be fairly straightforward for that particular engineer to manipulate, sharing the functionality with others, even other engineers, can prove very difficult. Only the design engineer of the particular piece of software is truly knowledgeable about maintaining the software in its intended form, and can distinguish between useful input and output data.

1. Inputs

Maintenance of the software, or simulation, simply relates to the parameters or constants basic to the proper functioning of the model, but not required to be accessible for normal simulation operation. Although it is natural for the designer to be able to distinguish between these necessary default parameters and changeable model inputs, the same is not necessarily true for any other user, and both would benefit from an interface that would be capable of hiding unnecessary parameters, revealing, and showcasing only those needed for a proper simulation trial. The vehicle simulated for this thesis includes hundreds of parameters inherent in each of the components derived from equations that govern the operation of each component. These values, once established by the simulation designer, need not, and often must not, be changed. After developing the simulation, these constants are not necessary for inclusion into any display used in controlling or manipulating the simulation. The diesel engine model of Fig. 28 shows how changeable inputs and fixed parameters can easily be confused and unintentionally altered.

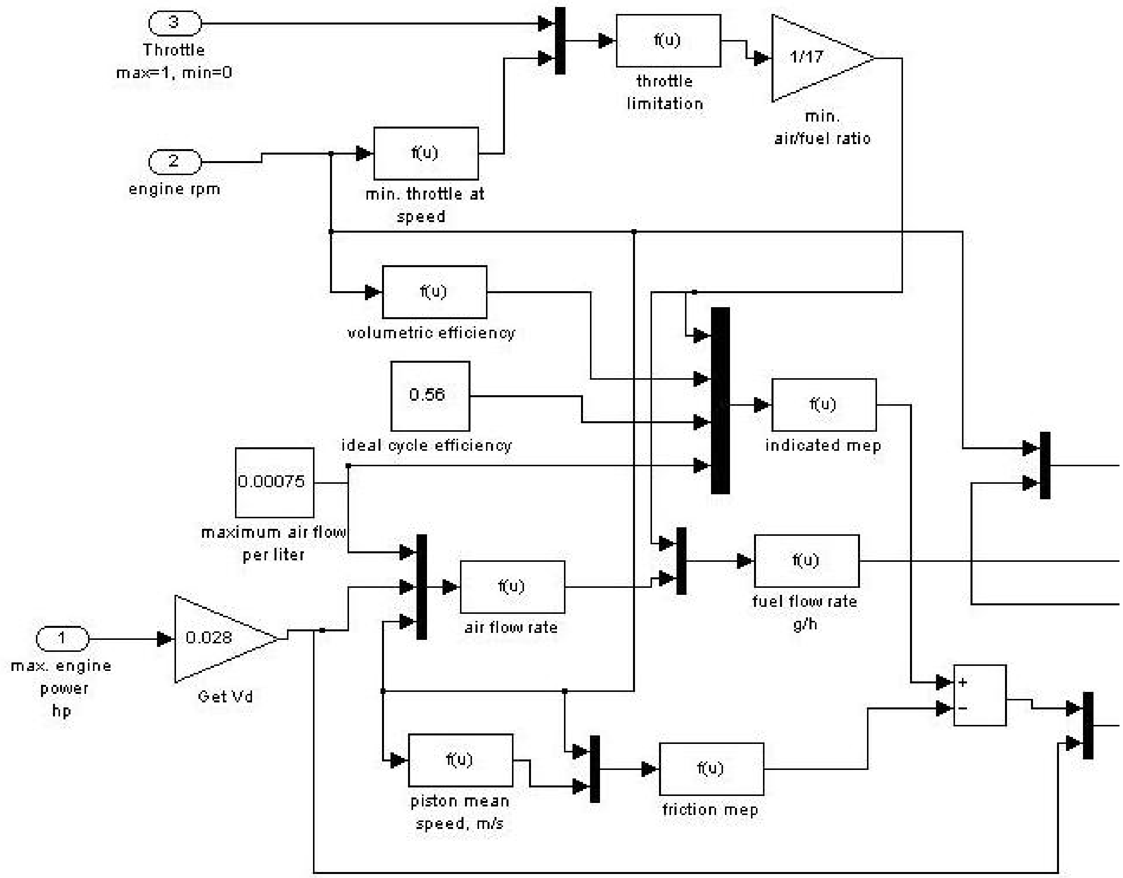

Fig. 28. Diesel engine model.

The model of the diesel engine above gives an indication of the number of parameters that are available to be altered in just one small sub-block of the simulated vehicle. In this sub-block, the parameters that are intended for manipulation by the user are to the left and labeled 1-max engine power, 2-engine rpm, and 3-throttle. Simply clicking on each of these inputs allows the user to change the value; however, the process is just as simple for changing important functional constants such as the air flow rate, cycle efficiency, and air fuel ratio, constants that are specifically chosen to accurately model the engine properly. A user interface can prevent the inadvertent destruction of a model by transforming the jumbled array of accessible parameters shown in Fig. 28, to a clearly defined set of changeable inputs as shown in Fig. 29.

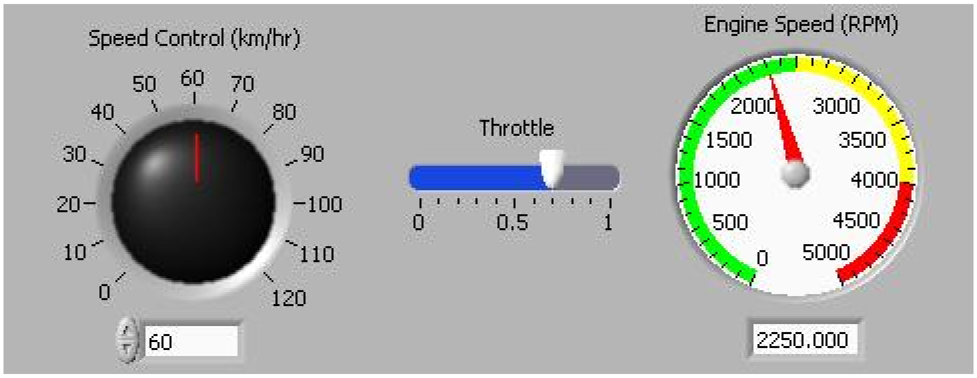

Fig. 29. Changeable inputs.

Fig. 29 shows a graphical user interface display of the inputs to the diesel engine. The ease of use due to the easily readable input slides and knobs allows the user to know at all times the selected input values, without the confusion of sorting through unnecessary constants. In this capacity, a user interface makes inputs easy to manipulate, and keeps the user confined to the boundaries of the simulation.

2. Outputs

The abundance of inputs and constants in simulations are not the only overwhelming characteristics that must be overcome to accurately control and acquire useful data. The number of outputs available to be monitored in such complex systems is also daunting. Fig. 30 shows a small portion of the outputs containing beneficial information to the user, describing the state of the vehicle and specifics of power flow.

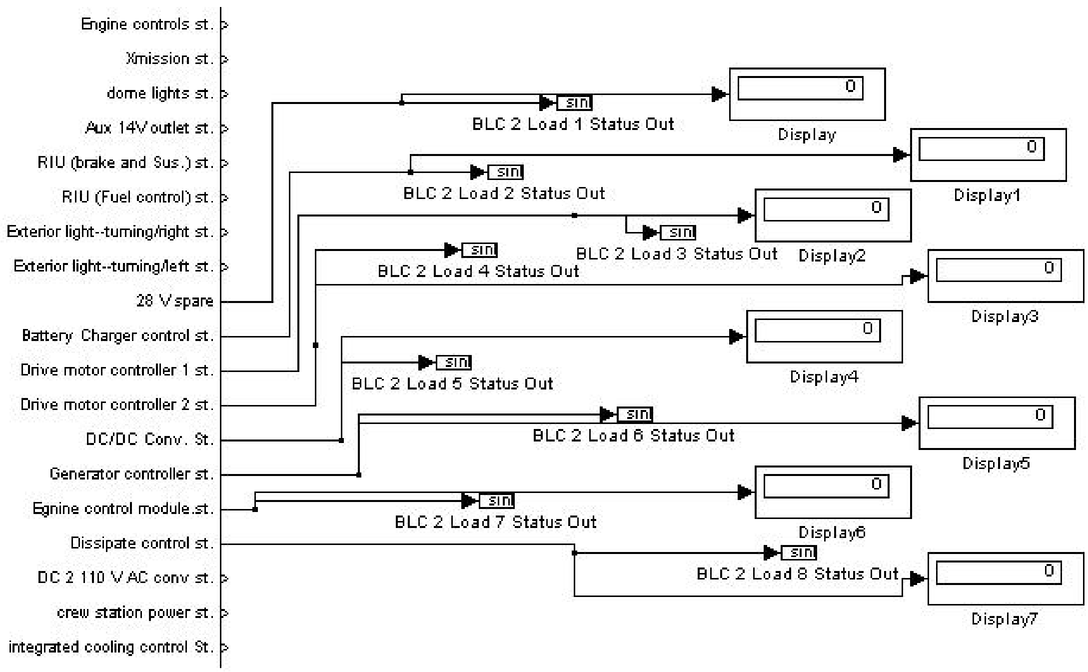

Fig. 30. Load status outputs.

If a user were relying solely on the Simulink model without an interface, monitoring outputs would be a difficult task and would involve sorting through the above sample of outputs. Fig. 30 demonstrates how eight of the 32 loads in this vehicle are monitored for on and off states. Because loads have been defined to display a 1 when on, and a 0 when off, digital displays can be used easily show the on/off status. As can be seen above, digital displays can quickly become a jumbled mess of their own, creating tedious work of viewing outputs, when one would prefer to see easily and quickly how loads are being added or shed. A graphical user interface accomplishes this by assigning LED indicators to outputs such as those for load status, so that a simple lit or extinguished indicator can quickly provide the same information in a user-friendly format (Fig. 31).

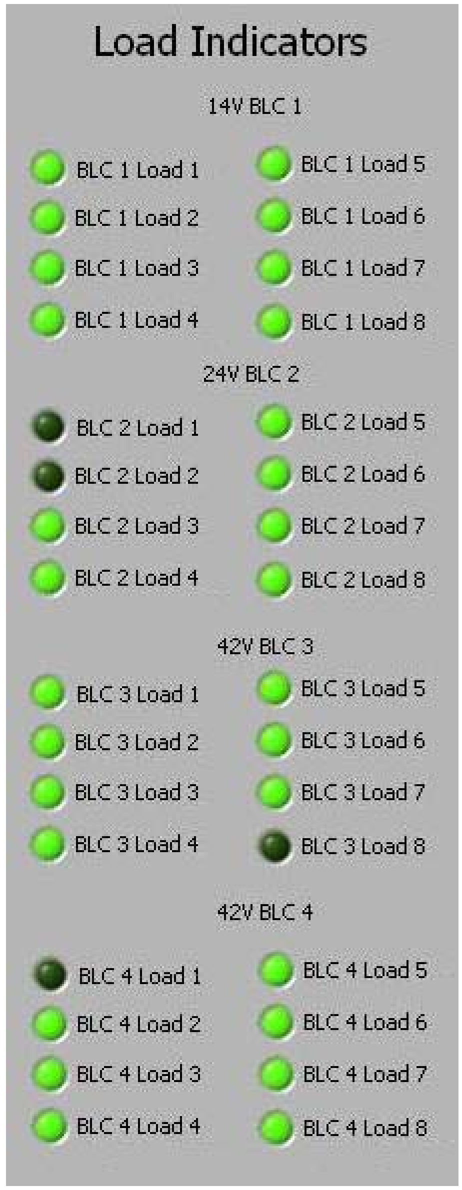

Fig. 31. LED load status outputs.

More complex however than viewing on and off states of loads or sources even, is monitoring trends throughout the vehicle mission, such as the source currents. Similar to viewing the load outputs, scopes must be established throughout the model (shown in Figs. 32 and 33) wherever trends or changes need to be examined.

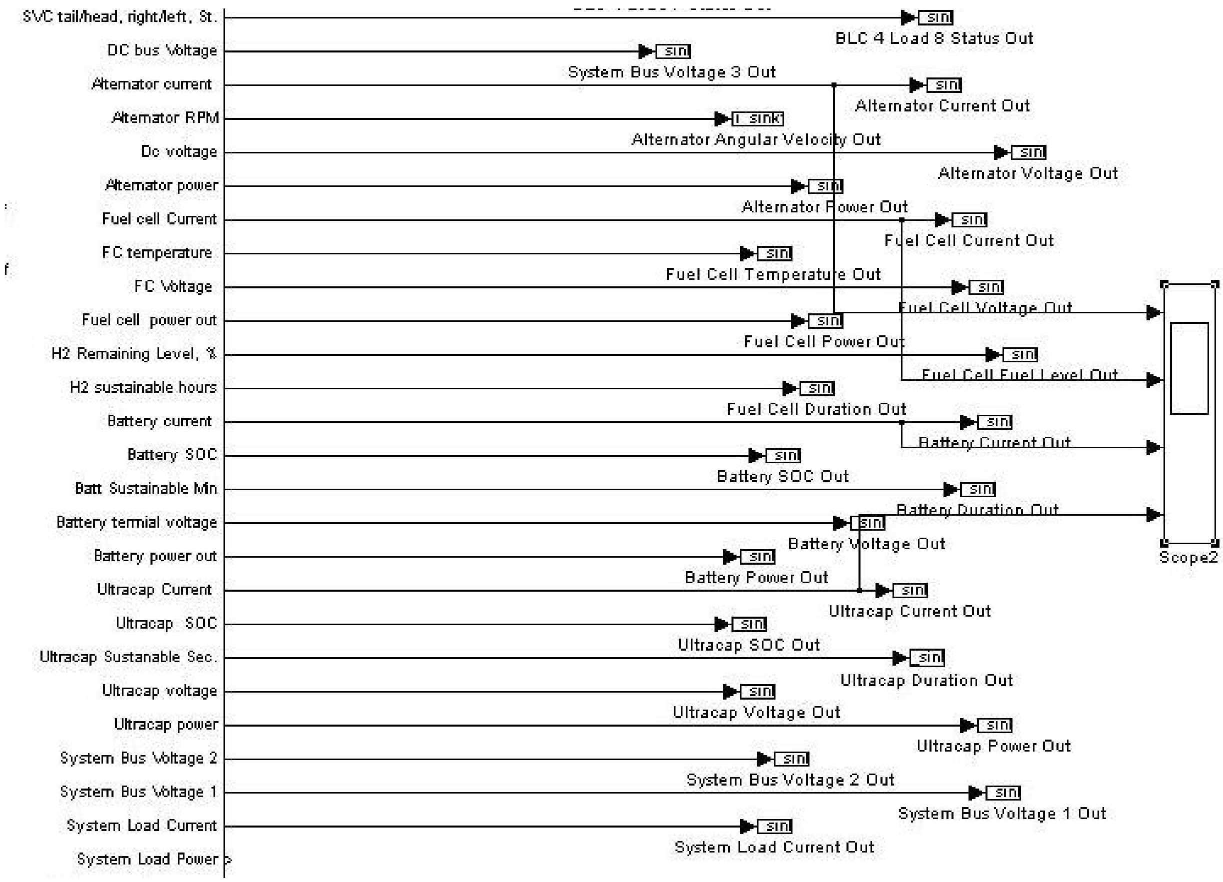

Fig. 32. Source current outputs.

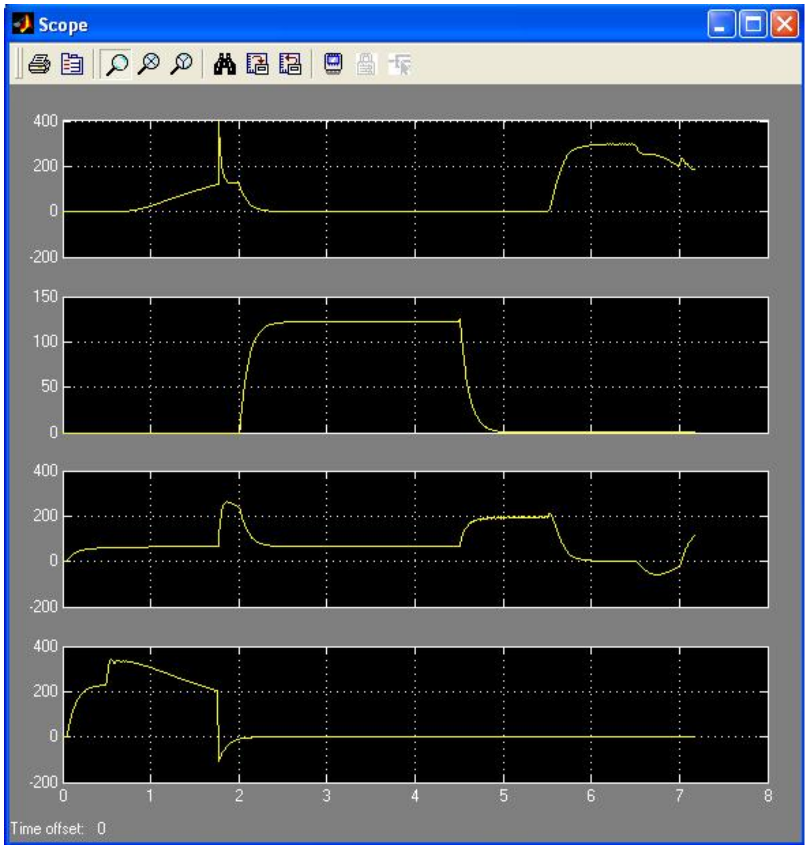

Fig. 33. Scope of source current outputs.

Figures 32 and 33 demonstrate the steps necessary to display the output of the four source currents in a manner that allows for comparison. Although the source current data is viewable, the interactions between other parameter changes on the system, such as load changes or mode changes are difficult to examine concurrently.

Studying the changes in the power system due to changes in load configurations or mode changes is one of the most important functions of a tool used for designing and verifying vehicle power system performance. A user interface can arrange data in a manner that makes it easy to compare with other data, or view reactions to other changes in the system. Fig. 34 demonstrates how a user interface can eliminate useless information and create a screen that displays data in a manner that is easier for comparison purposes.

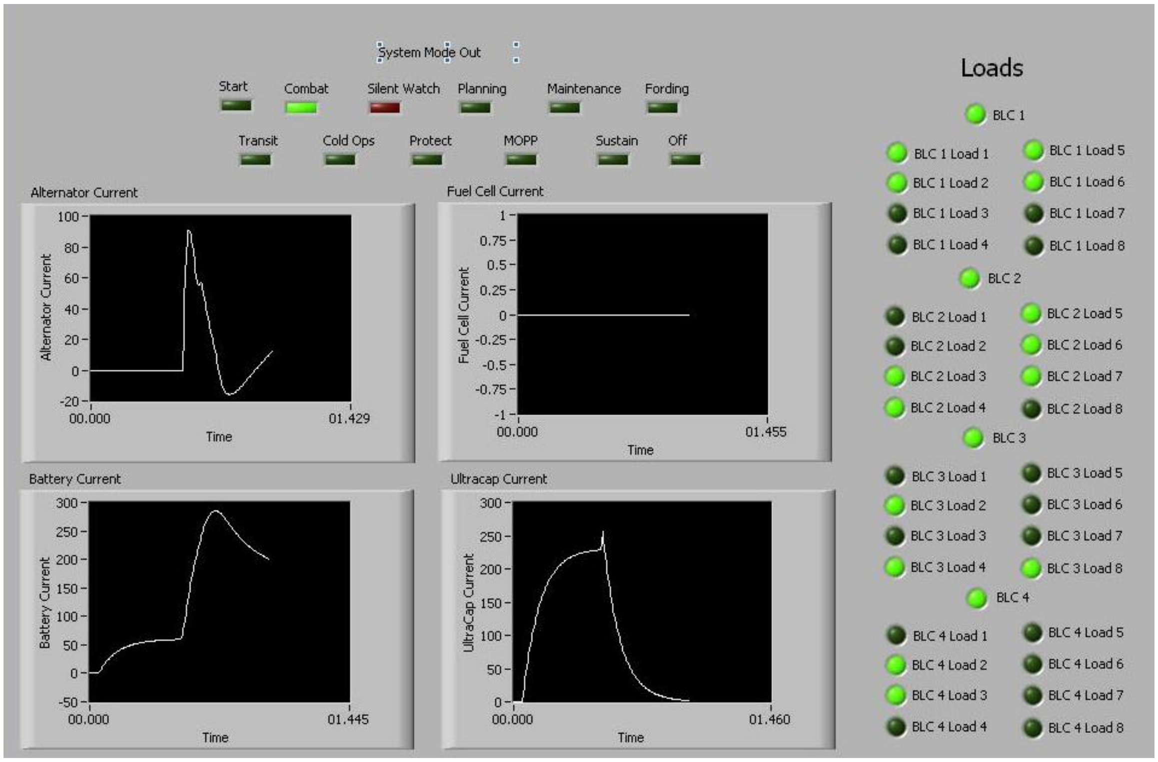

Fig. 34. User interface output screen.

The user interface above demonstrates the ability to compare the currents of each source along with allowing the user to easily examine reactions in the source current profiles upon entering a new mode of operation, or when a load change occurs.

C. Advantages of a Graphical User Interface

Besides the obvious advantages of having a user friendly interface addressing the needs mentioned previously, there are many added advantages to having an interface separate from the simulation itself. Many added features can be realized by moving direct control of the simulation to a slightly more indirect and buffered method. Commands from the user can be made to accomplish much more than individual parameter value changes. Because commands from the user are evaluated by the user interface before being processed by the simulation, two very unique and novel functions can be achieved: Multiple control schemes such as manual and automatic control of the simulation can be obtained and the utilization of pre-programmed vehicle components and even complete vehicle platforms can be accomplished.

1. Automatic/Manual Simulation Control

The most important feature of a GUI is its ability to create for the simulation, the operational environment that is encountered by the actual vehicle. As has been discussed in previous chapters, the simulation has been equipped with both scenario control that allows for the automatic cycling through of modes by the vehicle, as well as a power management scheme that not only establishes the proper load configuration for each mode, but also provides load shedding in low-power situations. Although these simulation features are programmed into the simulation itself they will not run without the mode source configuration programmed as part of the GUI. Even though the simulation alone contains some functionality that allows for automatic control, without the functionality embedded only in the GUI, automatic control is not obtainable.

For automatic simulations, the user can simply set the source parameters as desired, and choose a scenario to run along with a simulation duration time, and the user interface handles the rest. The interface sends all of the necessary inputs to the simulation and allows the simulation to automatically run through the modes according to the scenario profile chosen. The simulation, upon entering each new mode of operation, signals the user interface of a mode change, and re-configures the source selections and loads according to the mission requirements. The user interface then sends this new configuration back to the simulation where it maintains the selections until a new mode is entered and change is again prompted by the user interface. Throughout this process, loads are configured automatically (when the user interface load selection is set to automatic control) by the simulation power management routine. An example automatic simulation run is demonstrated at the end of this chapter.

The user interface also allows for the use of manual control over the entire simulation as well. Loads can be controlled manually by selecting to turn off the power management routine through the GUI. Overall, when run manually, upon entering each new mode of operation, the power management will set up the default load settings for that mode, but will allow the user to change the configuration at any time by utilizing the on/off control buttons provided in the GUI. The power management system in a manual situation will not be able to control the loads for the purposes of load shedding. When a load has been changed using the on/off buttons, the user interface signals the change to the simulation, over-riding power management load defaults, and once the change is made, the simulation sends a command back to the user interface LED's to denote the new configuration.

Sources can be modified manually as well, even throughout a scenario cycle. Though the scenario will automatically select the sources to be online in each mode, the user has the option of removing a source, or adding a source at any time. No manual or automatic selections need to be made for these changes, or for manually configuring any other part of the simulation, as opposed to the load situation, the user interface will always put user commands ahead of and in place of automatic settings. Manual or automatic control must be specified in the selection of loads simply to keep the load shedding functionality.

Because manual and automatic control can become confusing to the user and cause control difficulties between the simulation and interface, the interface has been designed specifically to control and check the functioning of the simulation. Every selection button on the user interface is a request that is sent to the simulation. Each request is then sent back from the simulation to the interface when it has been processed in the form of an indicator typically an LED. With this feature, the user is always cognizant of the controls that are driving the vehicle simulation and the current configuration of the vehicle.

2. Programmable Simulation Components

Another added feature gained by implementing a user interface is the ability to lump component information together to create programmed components, such as sources and even entire vehicle platforms. For example, the most basic inputs needed for the simulation are the parameters for the drive train and each of the sources (Fig. 35).

Fig. 35. Drive train and source parameter inputs.

Once these are chosen, a scenario can be selected and the simulation can be run. Although a designer may appreciate the flexibility of choosing the input parameters at will, from a design verification standpoint, there will be a specific and limited number of actual sources that are manufactured and available for use. The user in this case would probably prefer not to be prompted for every parameter of the alternator every time he wished to use it. Having a pull down menu selection with these parameters pre-programmed for each alternator type would make continual testing much easier. A graphical user interface can be designed specifically for design verification purposes meeting these needs as shown on Fig. 36.

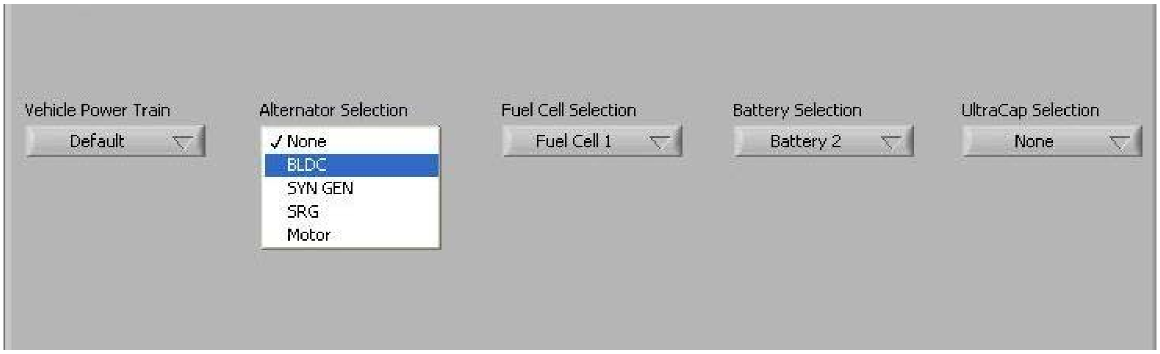

Fig. 36. Pull down menu source selection.

If the user chooses to implement pre-defined alternators, batteries, fuel cells or ultracapacitors, they can simply be selected from a pull-down menu. Once the source has been chosen, the user can verify, if necessary, his choice by returning to a parameter input portion of the graphical user interface and reading the parameters for each of the sources that was selected (Fig. 37).

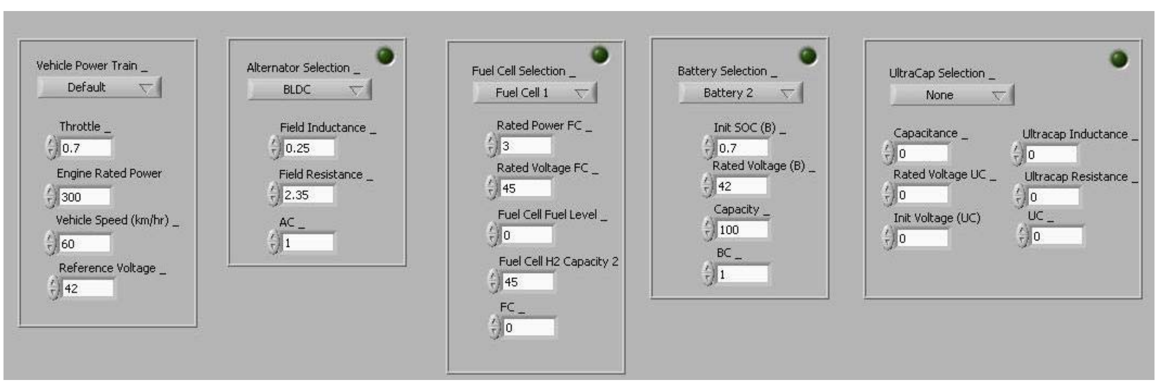

Fig. 37. Parameter input selection.

For every source change made by the user, the fields for each of the parameters above will be automatically changed to reflect the new source parameters. The user can still fill in each parameter individually if he chooses, and the changes will be made to the simulation.

Although selecting pre-configured sources is a valuable time saver for the user, some experiments will involve using the same vehicle over again, especially in situations where design verification is being performed. Another characteristic of the user interface allows for the pre-configuring of the complete vehicle platform, providing the data to the simulation regarding which of the pre-configured sources for the alternator, fuel cell, battery, and ultracapacitor will make-up the vehicle to be examined. Fig. 38 shows an example of how vehicle platform selections can automatically choose the power system components corresponding to the selected vehicle.

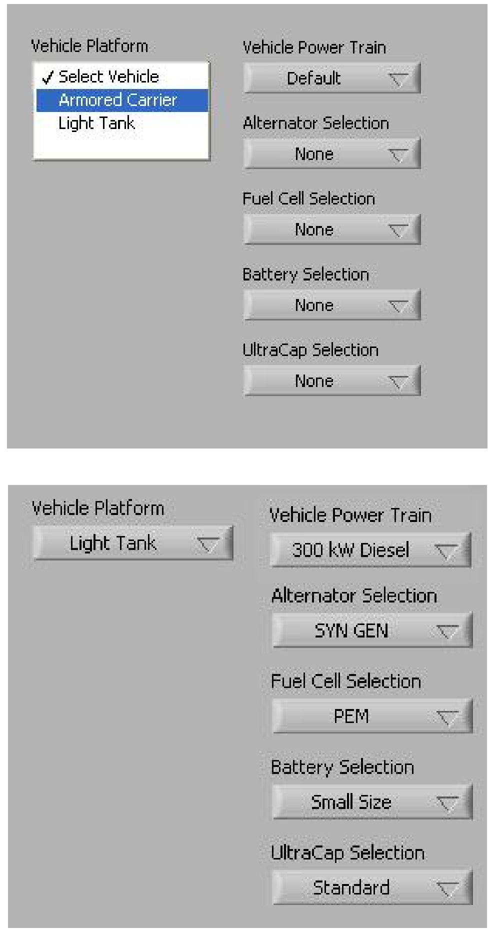

Fig. 38. Vehicle platform selections.

With this functionality, several vehicles can be simulated at any time with minimal set-up on one tool, and the user can run simulations for design verification of a single vehicle with great ease. Again, the specific parameter values corresponding to each of the source components can be transferred to the simulation, and represented on the graphical user interface as in Fig. 37.

The use of a graphical user interface for simulations is certainly helpful for providing easily accessible inputs and readable outputs, but the advantages demonstrated above are what allow the AMPS tool its definition as a tool. They allow not only ease of use for the design engineer during the design phase, with limitless control over every individual parameter, source and load configuration, but offer considerably beneficial techniques to the end user as a design verification and mission testing tool with its unique mission and vehicle programmability.

D. Summary

Although the use of a graphical user interface for simulations provides easily accessible inputs and readable outputs, the advantages demonstrated above make the AMPS tool a tool. They allow not only ease-of-use for the design engineer during the design phase, with limitless control over every individual parameter, but offers considerable benefits to the end user as a design verification and mission-testing tool with the unique mission and vehicle programmability offered through the user interface. The next chapter will introduce the AMPS tool providing details on the implementation of the program as well as a design verification simulation to support claims made in this and previous chapters.

CHAPTER V

PROPOSED AMPS TOOL AND DESIGN VERIFICATION EXAMPLE

A. Introduction

The previous chapter introduced the concept of integrating a graphical user interface with a vehicle simulation, thereby expanding the functionality of the simulation. Although the simulation itself can provide a useable vehicle model, it lacks the vital information necessary to turn the complicated simulated vehicle into an easy-to-use mission-oriented military vehicle tool. The AMPS tool, as a package, provides the overall functionality specified in Chapter II for military vehicle design and verification, as well as incorporating all of the advantages of a graphical user interface mentioned in Chapter IV. In this chapter, the actual software tool will be discussed with explanations of the user interface screens and functions. Finally, a design verification simulation will be performed to show the flexibility of the tool and support the claims in earlier chapters.

B. User Interface

Every input and output of the Simulink simulation is connected through a data port to LabVIEW, and displayed on controls and indicators on a customized interface screen. Two interface screens were developed for the purpose of this thesis; the

Design/Testing page (Figure 39) provides the engineer with full access to every input parameter to the vehicle and complete manual control, whereas the User Verification page is a tool for post design verification testing.

1. Design/Testing Page

Fig. 39. Design/Testing page.

The design page consists of three main sections, Parameter (source component) Inputs, Load Controls, and Outputs. The parameter input section is where the design engineer has the flexibility to construct the sources on the vehicle in any way desired (Fig. 40).

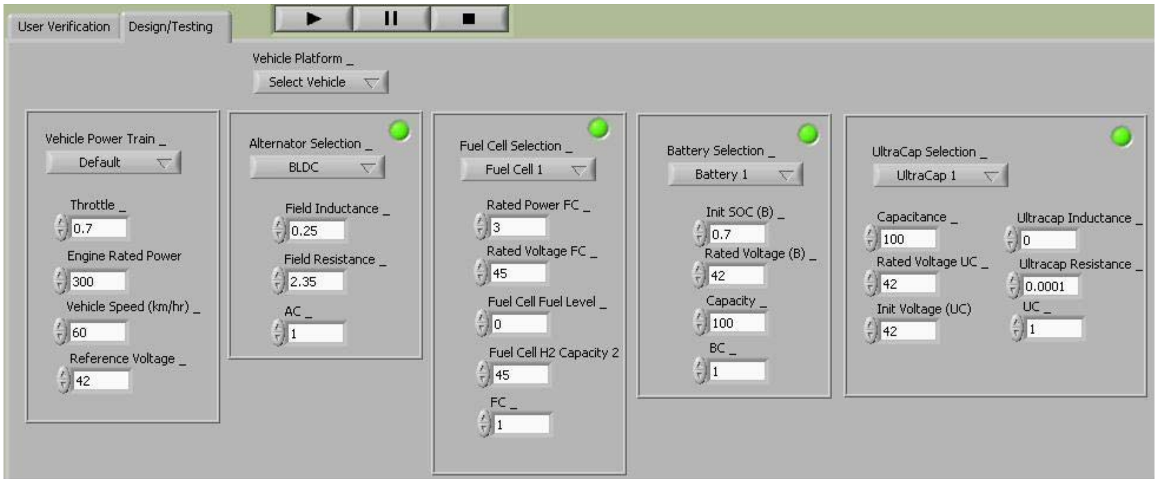

Fig. 40. Parameter inputs.

In this section, the designer can input any parameter he wishes into the displays for each vehicle component. The choice is also available to use preset components from pull-down menus above each input control. For example, if the designer chooses to use a brushless dc motor (BLDC) as the alternator, the pull down menu can be activated and the appropriate parameters corresponding to that component will be entered into the fields below. If the designer chooses to change one of the parameters of the alternator, say the field resistance, he may do so, and a change will result in a strikeout through the name of the Alternator Selection menu indicating that that alternator is no longer being used, and a customized component is being employed (Fig. 41).

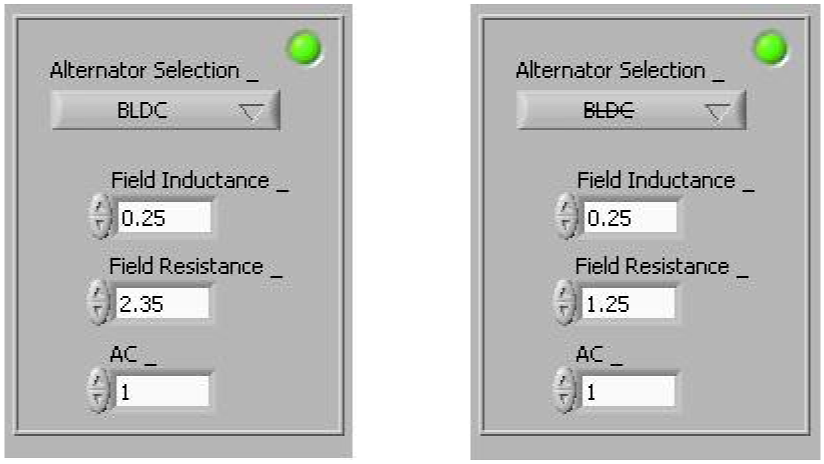

Fig. 41. Alternator selection.

Turning on and off sources is less intuitive on the design page, but is controlled by the last input field in each of the source sections. In Fig. 41, the field labeled AC controls whether the component is part of the vehicle system (a 1 in the input field), or offline (0 in the input field). The LED indicators to the top right of each component let the designer know which sources are actually being used by the simulation, a check to ensure that the simulation properly interprets the 1 or 0 in the field. The designer also has use of the pre-configured vehicle platforms as well. He may choose to employ a particular vehicle, and similar to the functioning of the preset sources, each source will be automatically configured with the correct parameters. Fig. 42 demonstrates the selection of the Vehicle Platform as Armored Carrier, and shows the automatic configuration of the sources corresponding to that vehicle.

Fig. 42. Automatic configuration of sources.

If any source parameter is changed, the changed source will indicate a strikethrough to avoid confusion, and the vehicle selection will return to a default Select Vehicle label.

The load control section allows the designer full control over the load configuration throughout the simulation as well (Fig. 43).

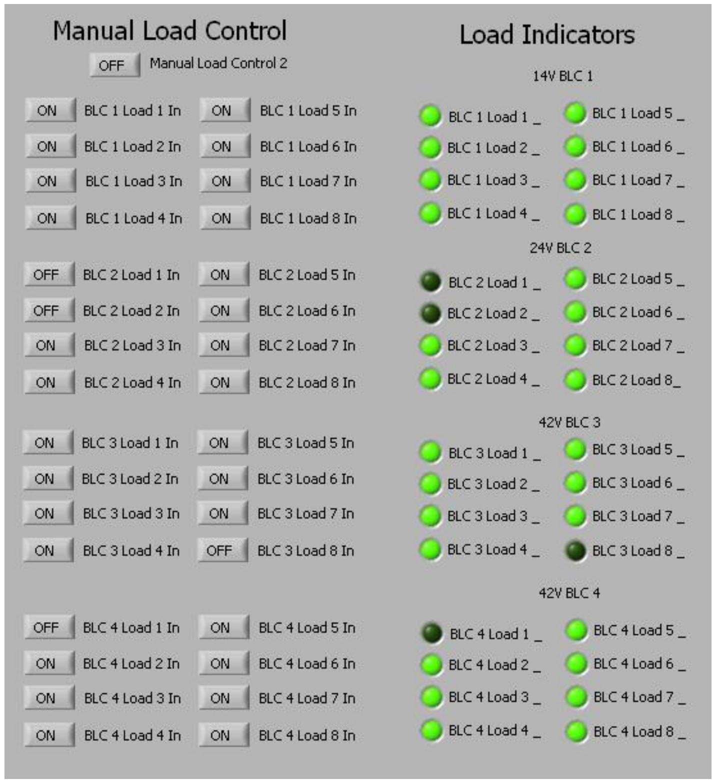

Fig. 43. Load control section.

When the Manual Load Control Button is set to OFF, as shown above, the loads are configured according to preset load configurations according to the mission and mode of operation the vehicle is currently in. When set to ON, the designer has full control over applying and removing loads from the system by simply turning them ON or OFF using the corresponding buttons. The buttons are signals from the GUI to the simulation, and the indicators are sent from the simulation once the commands have been processed. Indicators allow for instantly observing load shedding should it occur.

The final section of the designer page displays the observable outputs (Fig. 44).

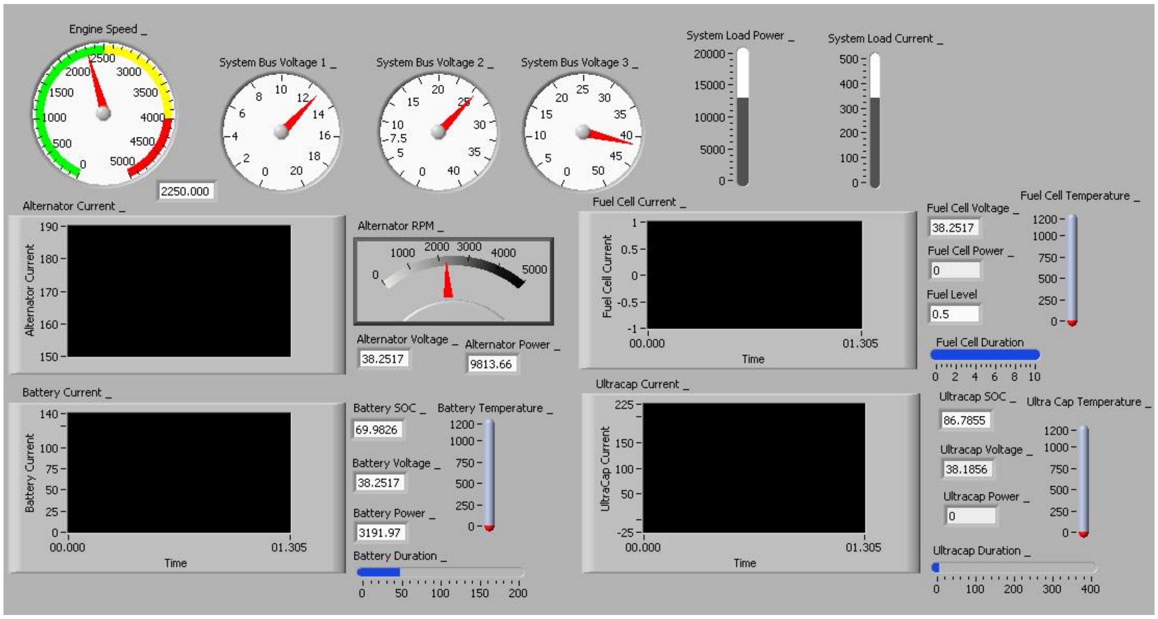

Fig. 44. Observable outputs.

These outputs come directly from the simulation through a data port, and are displayed in a well-arranged manner. With this GUI display, outputs can more easily be monitored with respect to what is happening to the entire vehicle power system. With the load configurations and shedding within view, and bus voltages and source currents all on one screen, changes in the vehicle system with respect to load or source changes are easily observed and designed around.

2. User Verification Page

The User Verification page of the GUI contains nearly all of the same functions of the Designer page, with the exception of specific source parameter input selections (Fig. 45).

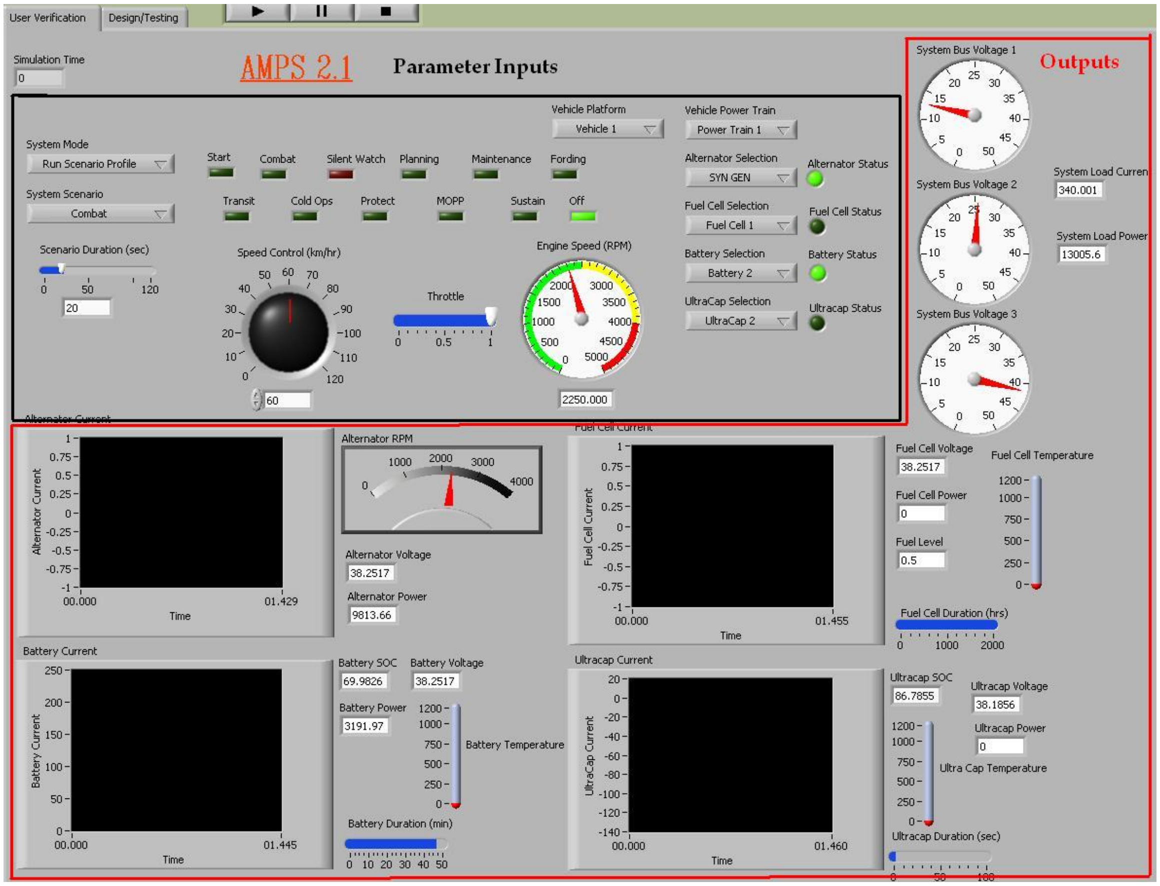

Fig. 45. User verification page.

The displayed outputs are identical to those found on the Designer page, and include the load input/output section exactly as shown in Fig. 43 for automatic or manual control of loads. The Vehicle/Mission Set-up section is intended for the purposes of design verification due to the lack of the user's ability to specifically select individual source parameter inputs. The user can however access inputs typical to a vehicle user, such as throttle and vehicle speed (Fig. 46).

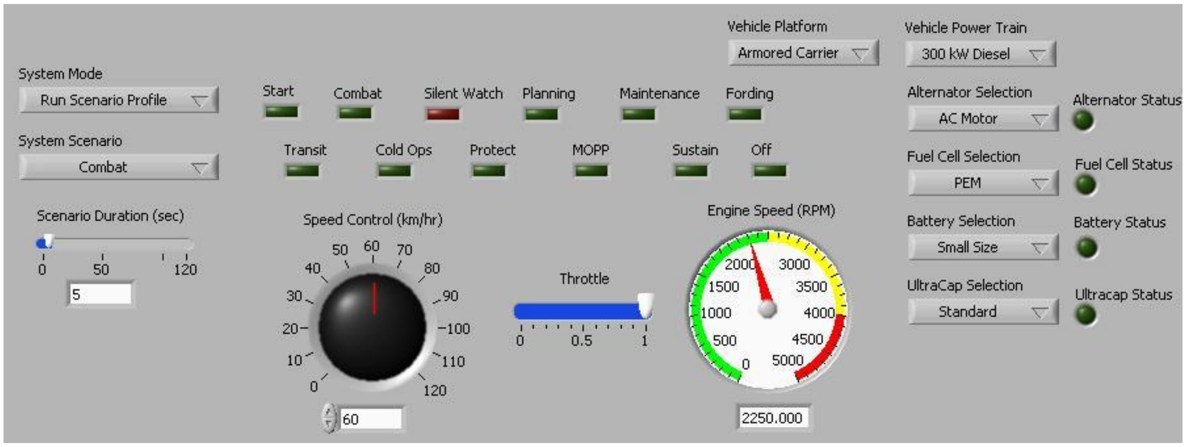

Fig. 46. Vehicle/Mission set-up.

Sources and vehicles are pre configured and are selected using pull down menus, for instance, the vehicle platform shown in Fig. 46, Armored Carrier, will automatically set up the sources associated with it, the 300 kW Diesel power train, an AC Motor for an alternator, a Proton Exchange Membrane fuel cell, and so on. The user can also choose source configurations that are not programmed into the Vehicle Platform by selecting each source individually from the pull-down menus. Similar to that of the Design page, if the user selects a vehicle, Armored Carrier, and changes the Alternator Selection to BLDC instead of AC Motor, the Vehicle Platform will change back to Select Vehicle to indicate that the Armored Carrier vehicle is no longer being simulated and a customized vehicle has been chosen (Fig. 47).

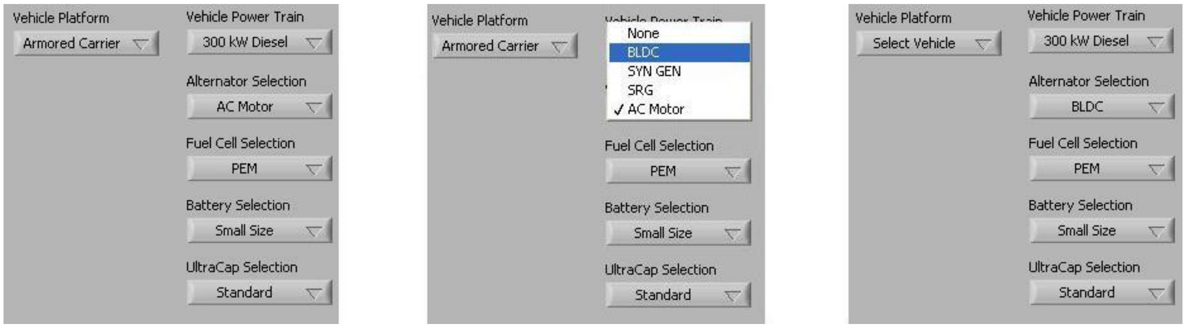

Fig. 47. Individual source selection.

Once the inputs have been established, the simulation can be run either manually, or using scenarios by selecting from the System Mode and System Scenario pull down menus (Fig. 48).

Fig. 48. System scenario/system mode selections.

The selection shown above, Run Scenario Profile, initiates the simulation to automatically cycle through modes according to the Scenario chosen according to Table VI.

Table VI. Combat Scenario Profile

Modes of Operation

Scenarios	Combat	Silent Watch	Planning	Maintenance	Fording
Combat	0.1	0.3	0.1	0.05	0.05
Maintenance	0	0	0.1	0.8	0
Deployment	0.1	0	0	0.15	0

Modes of Operation

Scenarios	Transit	Cold Ops	Protection	MOPP	Sustain
Combat	0	0.15	0.05	0.05	0.15
Maintenance	0	0	0	0	0.1
Deployment	0.65	0	0	0	0.1

Because Combat is the scenario chosen, the simulation will cycle through the modes, remaining in each mode for the percentage of the total simulation time allotted by the above table. Upon entering a new mode of operation, the simulation will send a signal to the GUI illuminating the LED's to indicate the current mode. Upon entering each mode, the GUI also controls the sources that are online and offline, according to Table VII.

Table VII. Mode Source Selections

Modes of Operation

Sources	Off	Start	Combat	Silent Watch	Planning	Maintenance
Alternator			x			x
Battery	x	x	x	x	x	x
Fuel Cell				x		
UltraCapacitor		x				

Modes of Operation

Sources	Fording	Transit	Cold Ops	Protection	MOPP	Sustain
Alternator	x		x	x	x	
Battery	x	x	x	x	x	x
Fuel Cell						x
UltraCapacitor						

Modes can be selected manually as well. If the user chooses to select a random assortment of modes to cycle through, the System Mode can be set to any mode the user chooses, and a simulation duration time is unnecessary (Fig. 49).

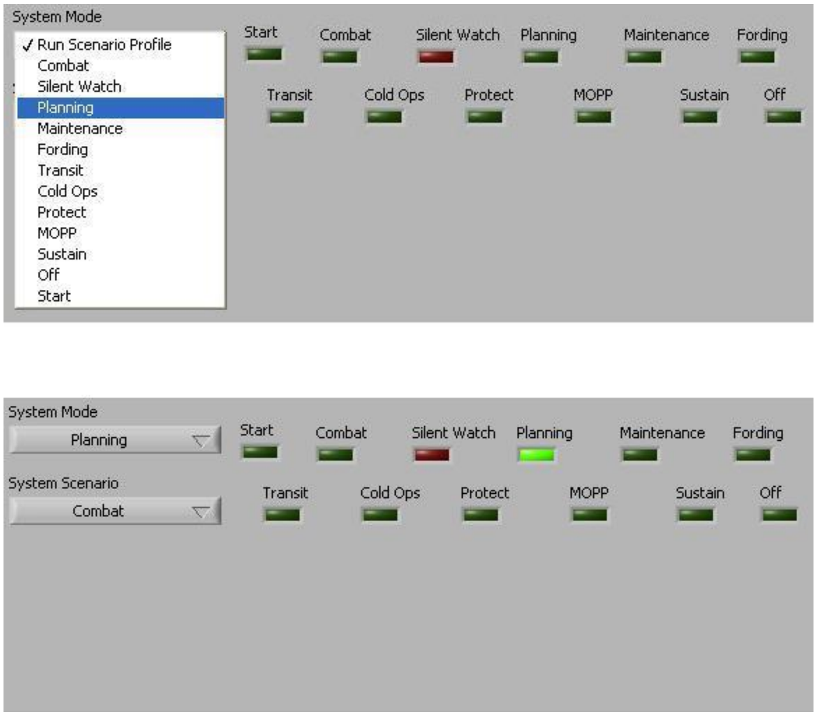

Fig. 49. Manual mode selection.

Once the user chooses a mode, the simulation is prompted to change modes. Once the mode change has occurred, the GUI mode LED is lit to indicate the current mode of operation.

Sources can also be controlled manually by selecting from the Source Selection pull-down menu. For example, if the vehicle is in Combat mode, the Alternator is originally specified to be online. If the user chooses to take it offline, he can select None from the Alternator Selection menu and the alternator will be removed (Fig. 50).

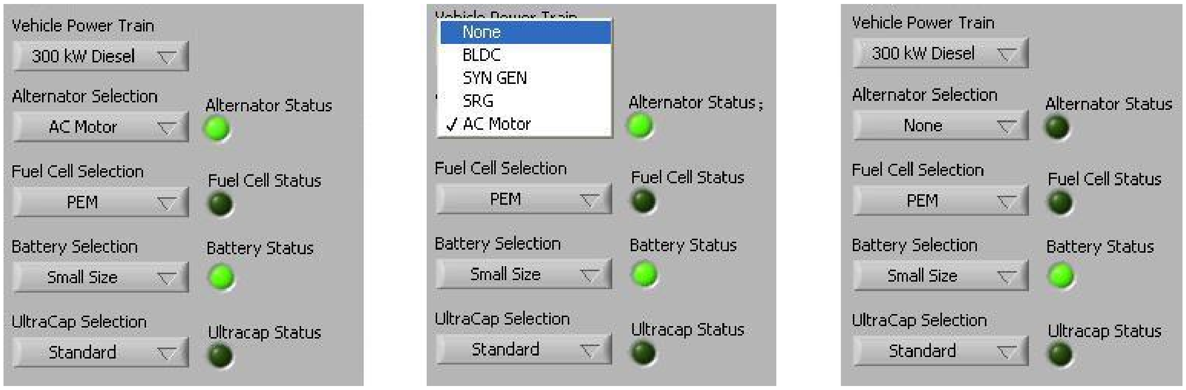

Fig. 50. Manual source control.

Once the user chooses the Alternator Selection, the simulation is prompted of either the input parameter changes, or if None is selected, as in Fig. 50, the simulation takes the source offline and the change is indicated by the LED turning off.

The output section of the user verification page is identical to that of the design page discussed previously. Every output can be observed on one screen, while monitoring the progression of the simulation through the various modes of operation. To demonstrate the usefulness of the user verification page and the fully automatic simulation features, a design verification example will be presented. Screen captures displaying the progression of the simulation emphasize the ease of evaluation of the system as a whole, and allow for a full verification of the vehicle components and mission specifications.

C. Design Verification Example

Verification of a design with the AMPS tool encompasses more than observing and verifying component reactions. Although potential design issues with components may be observed and resolved during a design verification, the overall operation of the vehicle as a unit can be monitored, and more importantly, an entire vehicle platform and mission can be verified. Sizes of power sources can easily by monitored throughout a mission sequence to determine their effectiveness, and items such as fuel levels for fuel cells can be monitored to ensure that a mission can be completed without the loss of necessary power due to inadequate supplies. It is also important for the engineer to be mindful that even though a vehicle may be observed to operate as required by design specifications or mission specifications, the mission specifications themselves may be suspect as well. The designer of the mode source specifications may not be able to realize the full potential of the vehicle before simulation, and may therefore have over or under anticipated the necessity of sources in a given mode of operation. Design verification therefore is a critical tool for proving reliability of the vehicle power system, and supporting acceptable mission requirements.

The design verification that will be performed will feature the fully automated simulation, using pre-programmed vehicle platforms, automatic load and source configurations, and mode cycling using a scenario profile, as described in the User Verification section above. The scenario profile chosen for this simulation is a Combat profile with a duration of 10 seconds, and follows the time duration percentage shown in Table VIII.

Table VIII. Combat Profile

Modes of Operation

Scenario	Combat	Silent Watch	Planning	Maintenance	Fording
Combat	0.15	0.25	0.1	0.1	0.05

Scenario	Transit	Cold Ops	Protection	MOPP	Sustain
Combat	0	0.05	0.05	0.05	0.2

The simulation will follow the mode cycles shown in Table VIII above, with the addition of 0.5 seconds to the total simulation time spent in Start mode. The simulation time breakdown is shown in Table IX.

Table IX. Simulation Mode Duration

Simulation Time	Mode
0 - 0.5	Start
0.5 - 2.0	Combat
2.0 - 4.5	Silent Watch
4.5 - 5.5	Planning
5.5 - 6.5	Maintenance
6.5 - 7.0	Fording
7.0 - 7.5	Cold Ops
7.5 - 8.0	Protection
8.0 - 8.5	MOPP
8.5 - 10.5	Sustain

The vehicle platform chosen for this simulation is the Armored Carrier Vehicle, which is configured to include a 300 kW diesel engine, a three phase ac motor alternator, a 42 volt battery, proton exchange membrane fuel cell, and standard ultracapacitors. The source configurations for each mode of operation follow the specifications of Table VII, and the load configuration and load shedding priorities are as shown in Table V. The selected vehicle, scenario and simulation duration are chosen as described above and shown on the User Verification page of Fig. 51.

The simulation is now set up to be run, and monitored for power supply and consumption, load shedding, fuel levels, or whatever else is desired. The following figures 52-54 will display the data obtained in each mode of operation as the simulation cycles through the combat scenario. During testing of the specifications given for the purposes of this project, a potential source configuration specification during the transition from start to combat mode was uncovered, and will be discussed as it appears in the simulation. A brief discussion of the overall simulation will follow the resulting data.

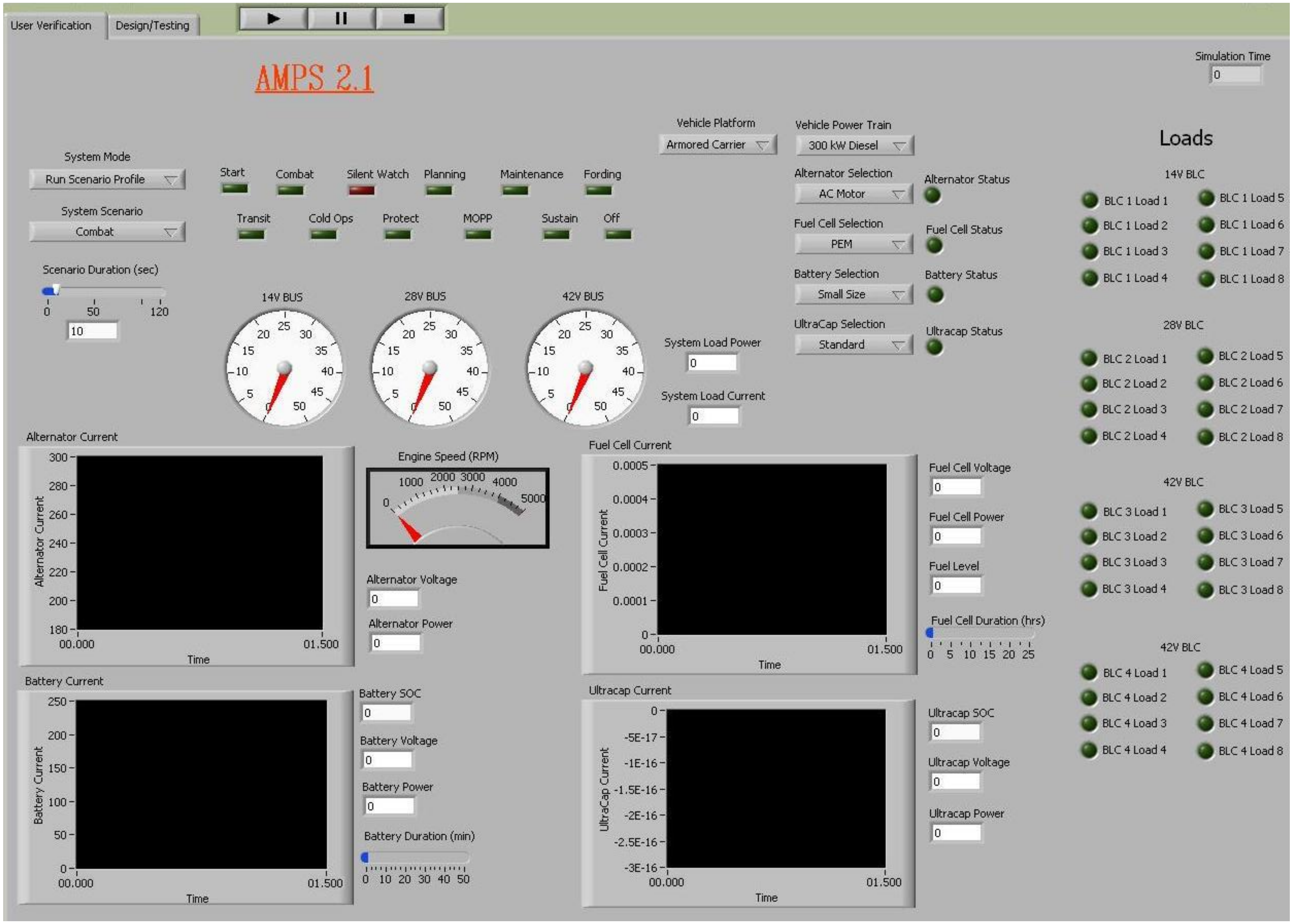

Fig. 51. Vehicle simulation set-up.

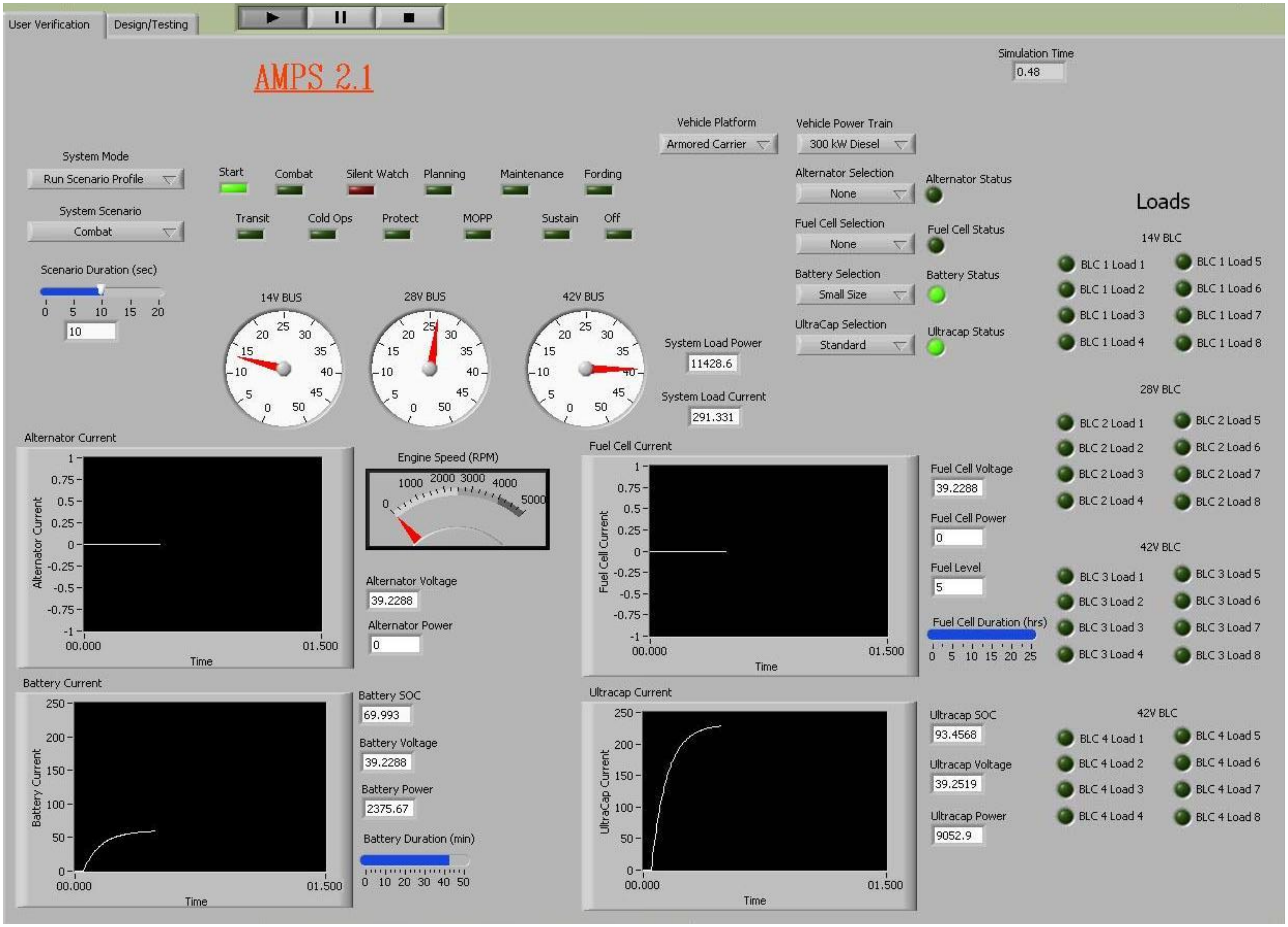

Fig. 52. Start mode.

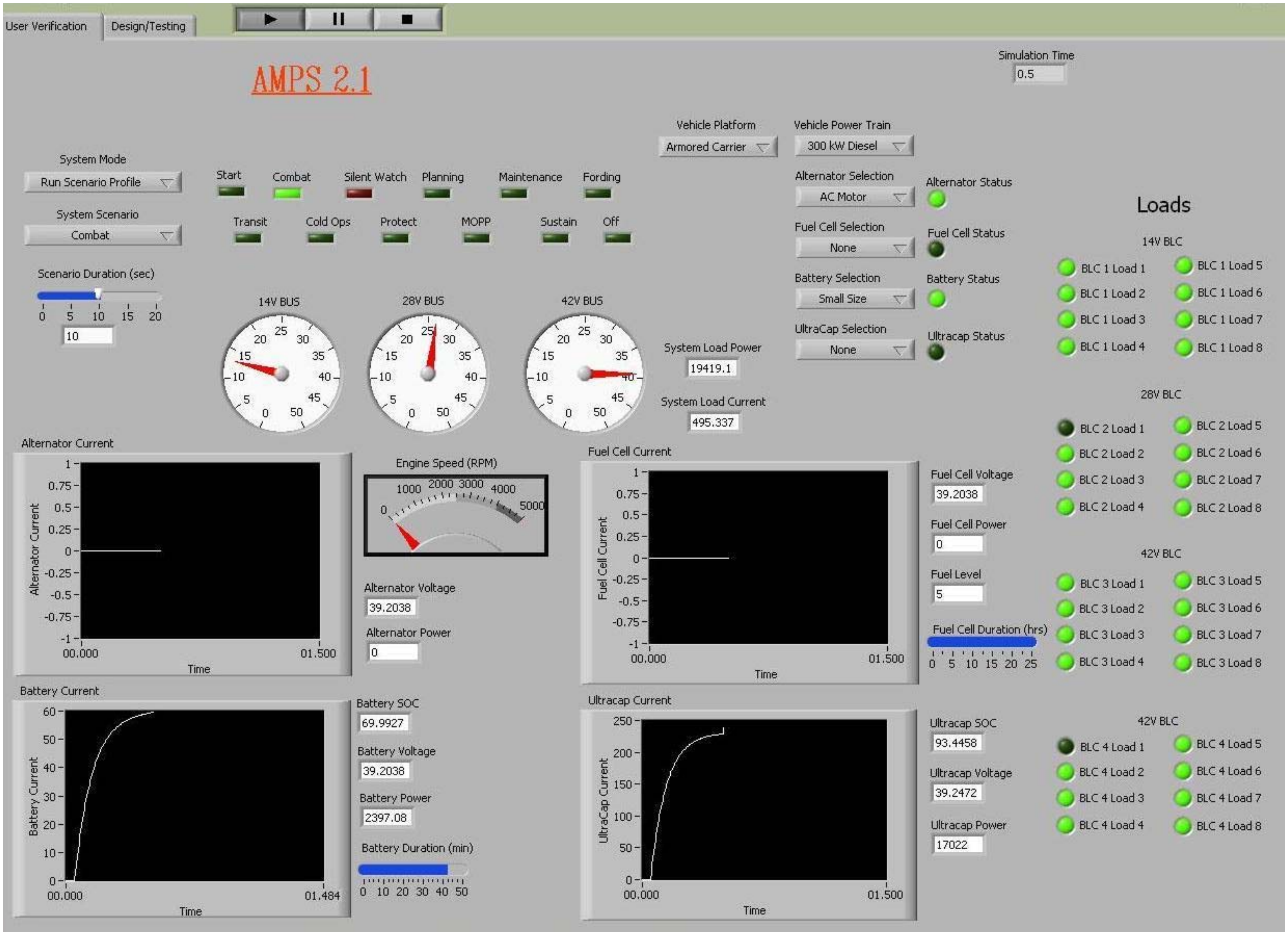

Fig. 53. Combat mode.

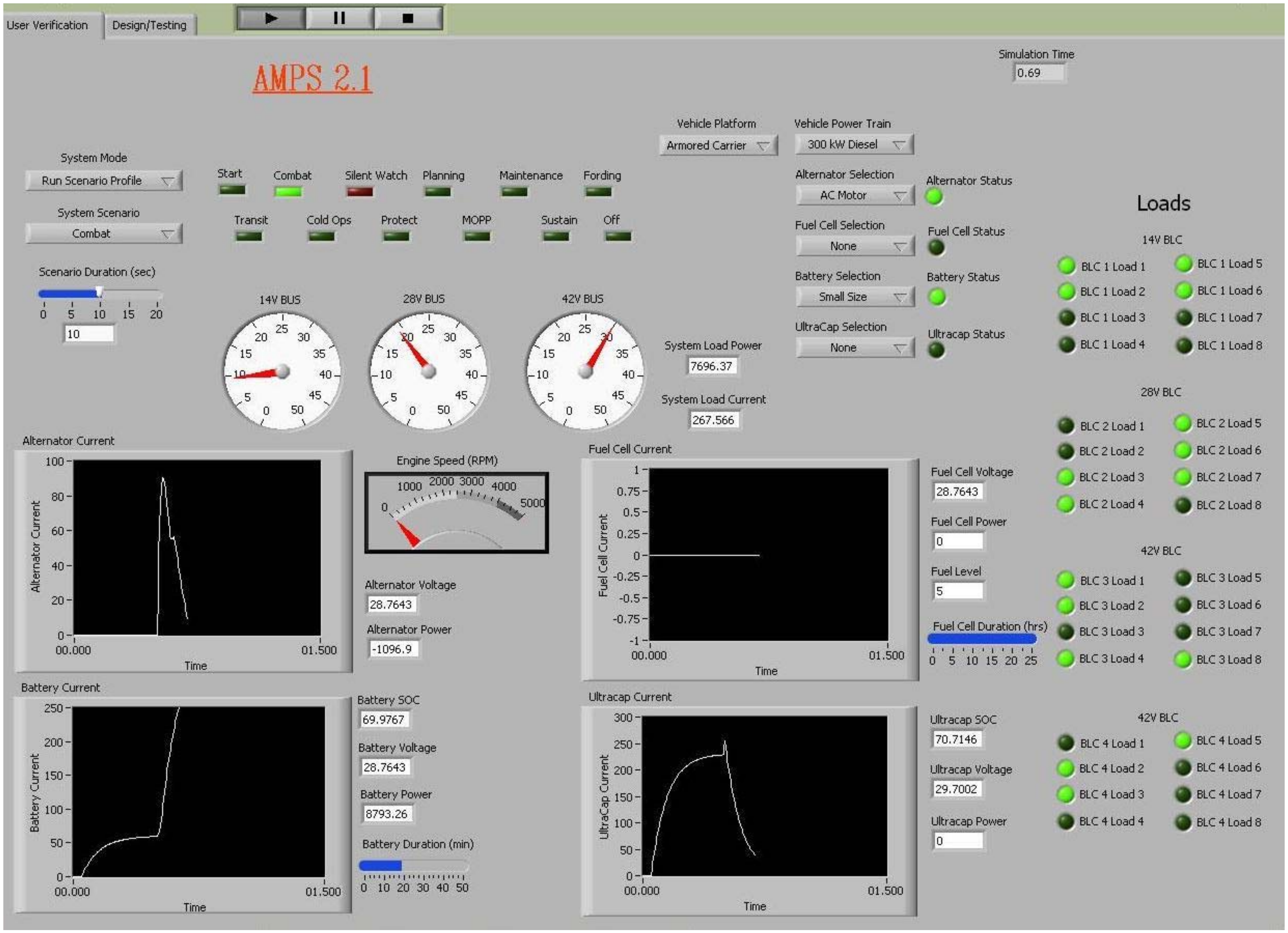

Fig. 54. Combat mode – load shedding.

Observing the load configurations during combat mode in Figures 53 and 54, it is apparent that loads are being shed. This occurs because the battery current is exceeding the maximum current capacity and the alternator is incapable of supplying the necessary current instantaneously. This is a situation where mission specifications were found to be lacking. The specifications for this particular mission require that only the alternator and battery supply the power necessary when turning on the numerous motor loads while in combat mode. The alternator cannot supply transients formed from the addition of such heavy motor loads, and thus loads are being shed instantly. Once the designer sees this quick shedding of loads, he can determine whether the alternator needs to be resized to accommodate the heavy load addition, or another source should be added to the specifications during combat mode to accommodate the load addition. Because the ultracapacitors are not being utilized otherwise in combat mode, their addition at the beginning of the mode change could spare loads from being shed unnecessarily as well as save money on over-sizing the alternator without need.

Figures 55 through 68 resume the simulation at the beginning of combat mode, with a change in the mission specifications to allow for the addition of the ultracapacitors online for the duration of combat mode.

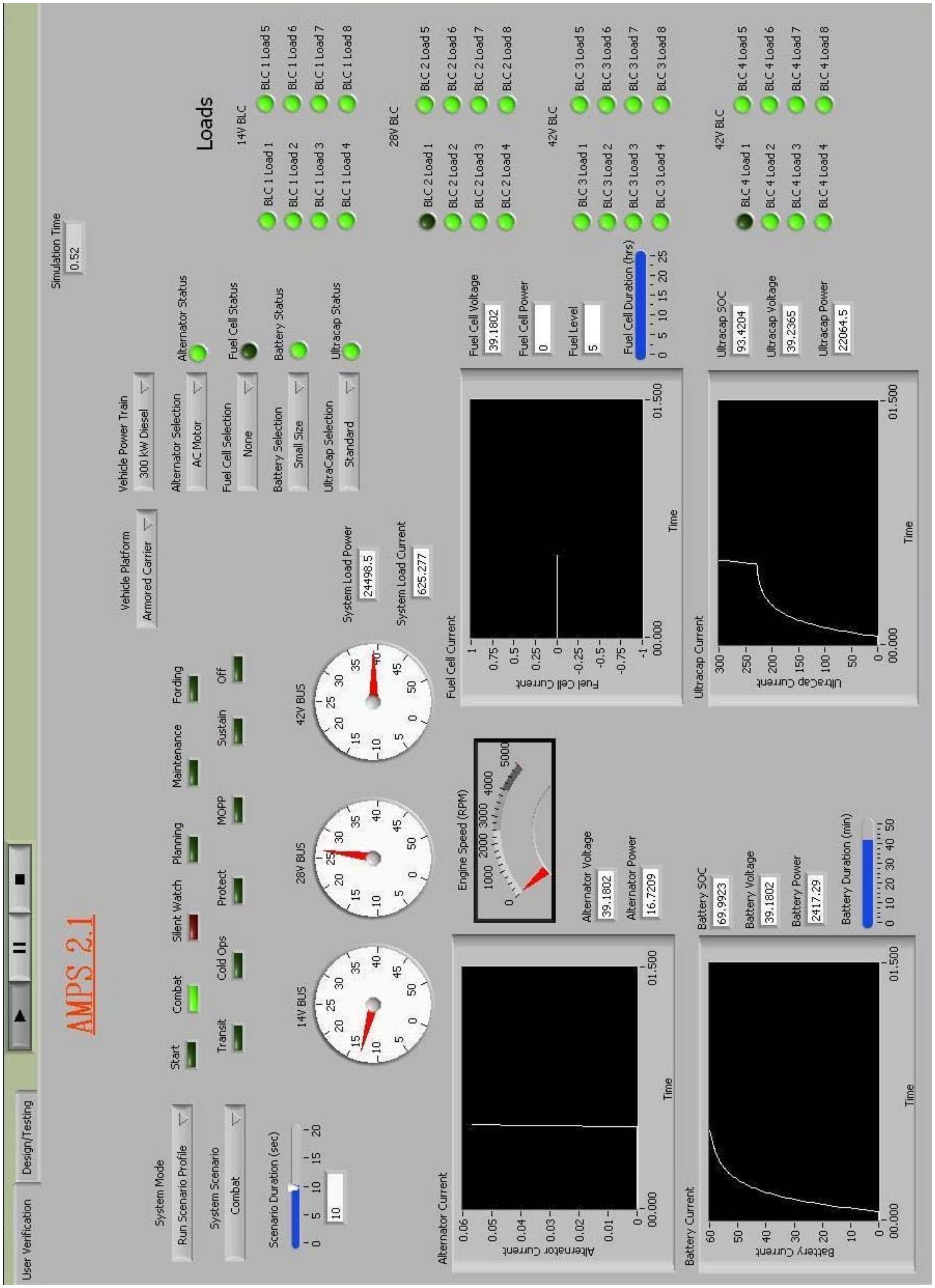

Fig. 55. Start of combat mode.

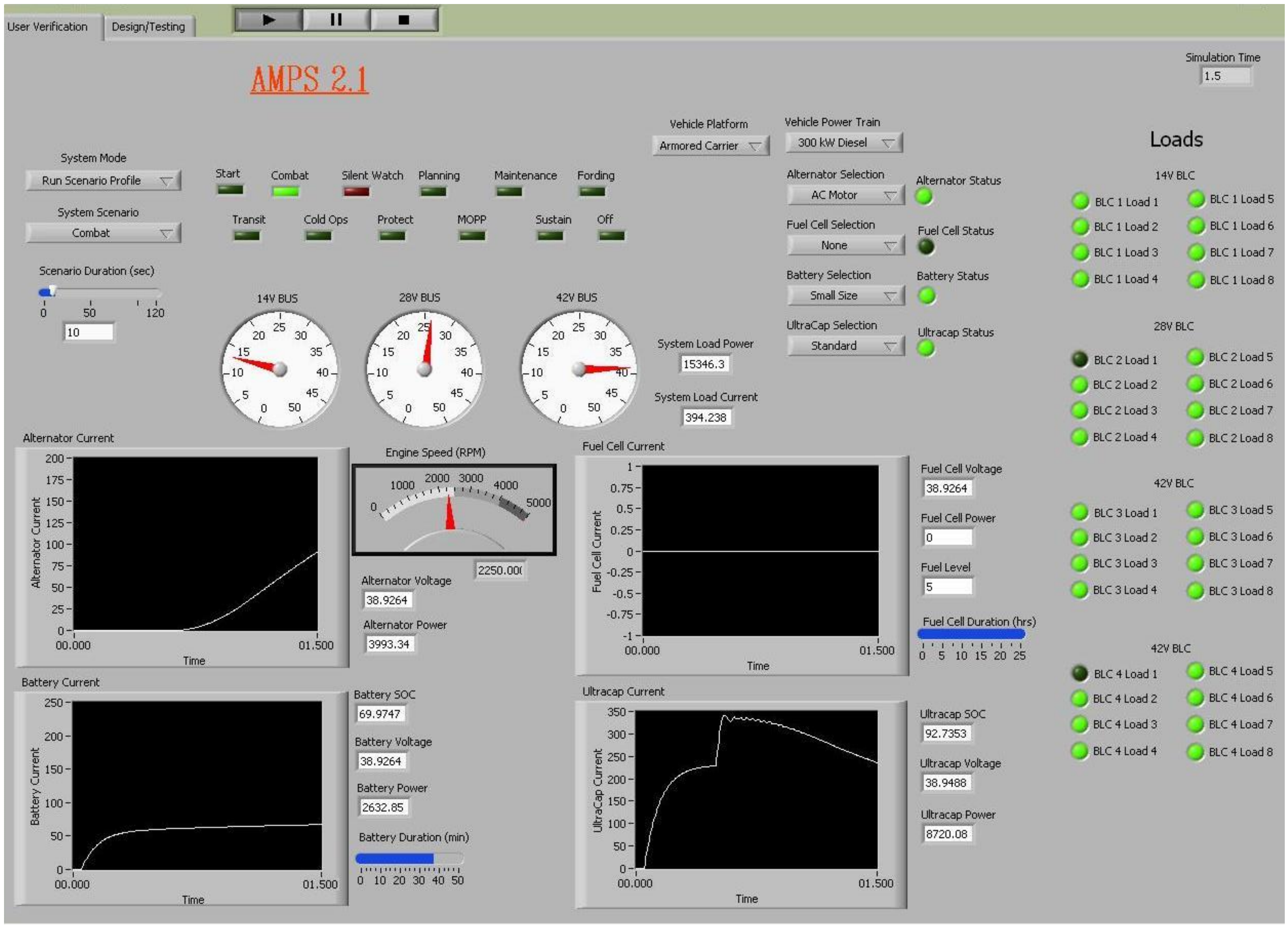

Fig. 56. Combat mode with ultracapacitor.

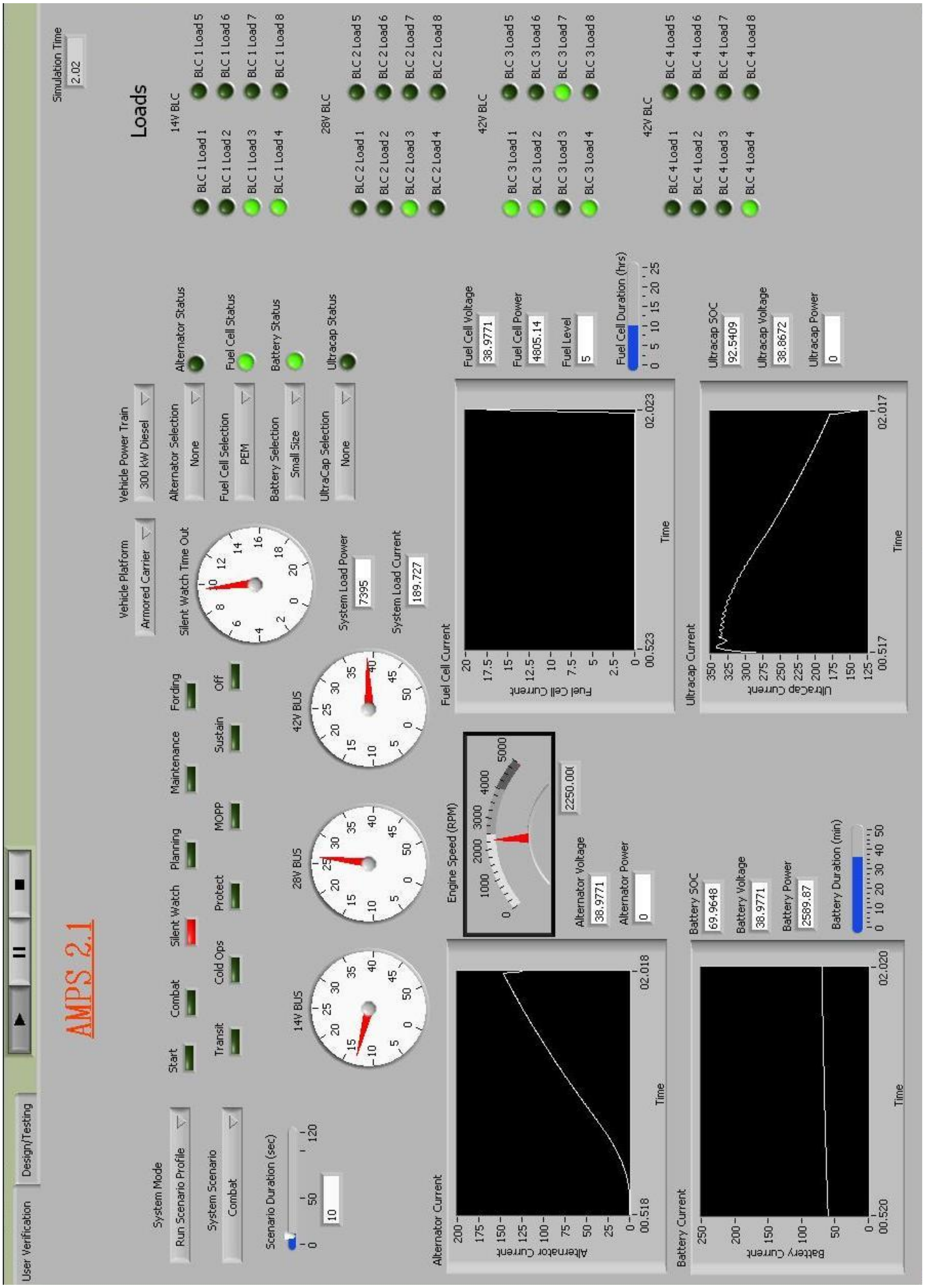

Fig. 57. Transition from combat to silent watch.

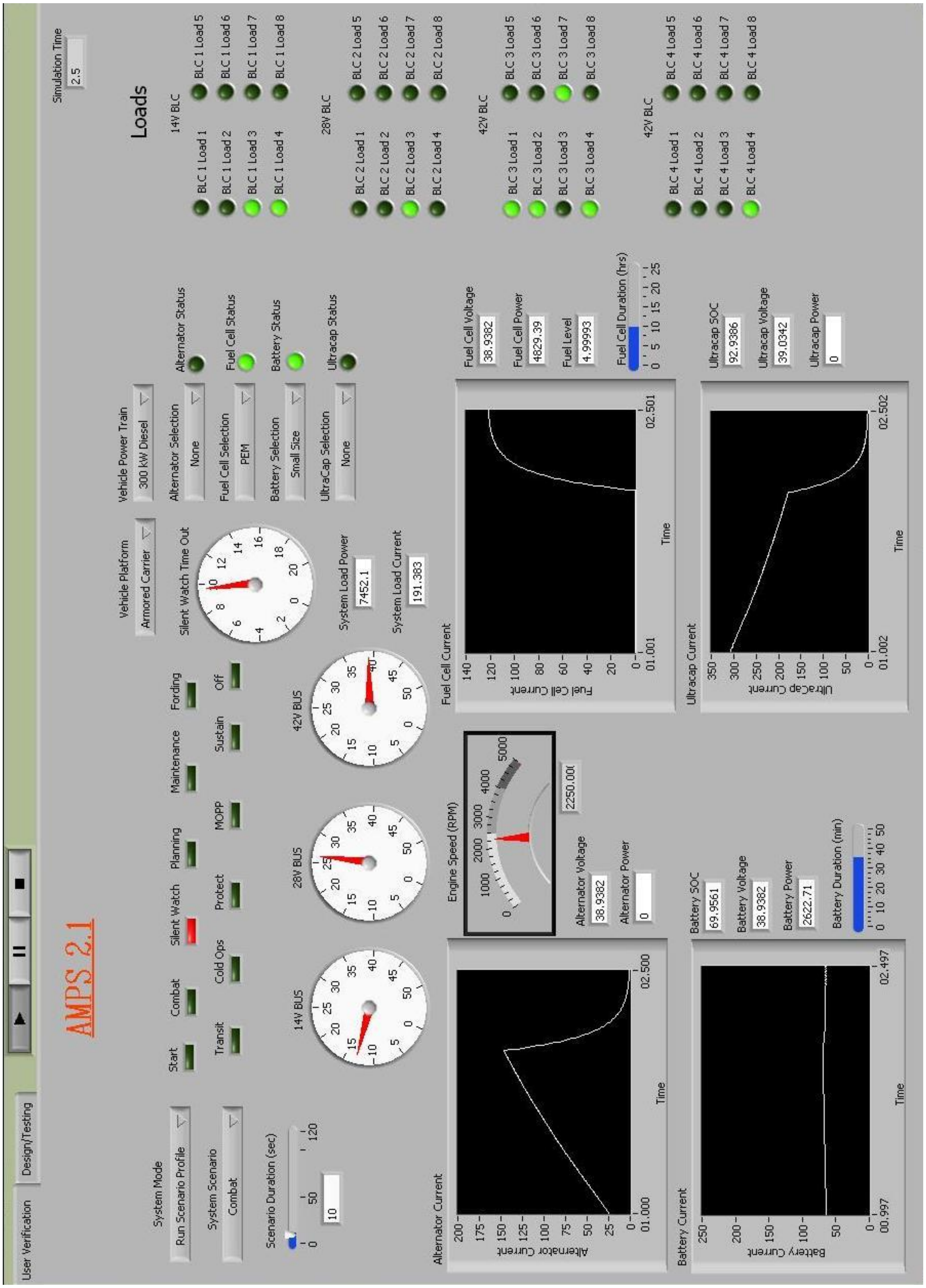

Fig. 58. Silent watch mode.

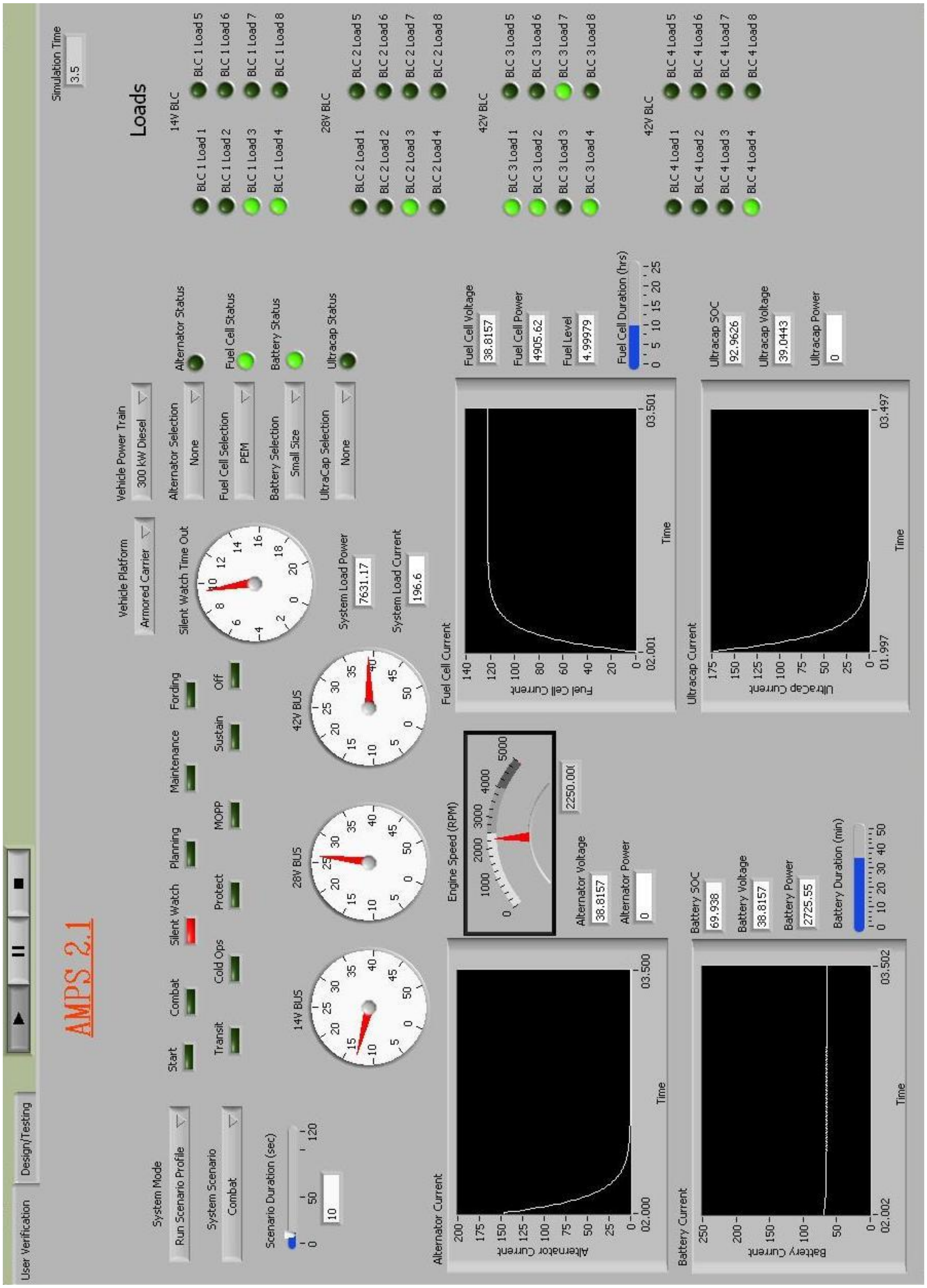

Fig. 59. Silent watch continued.

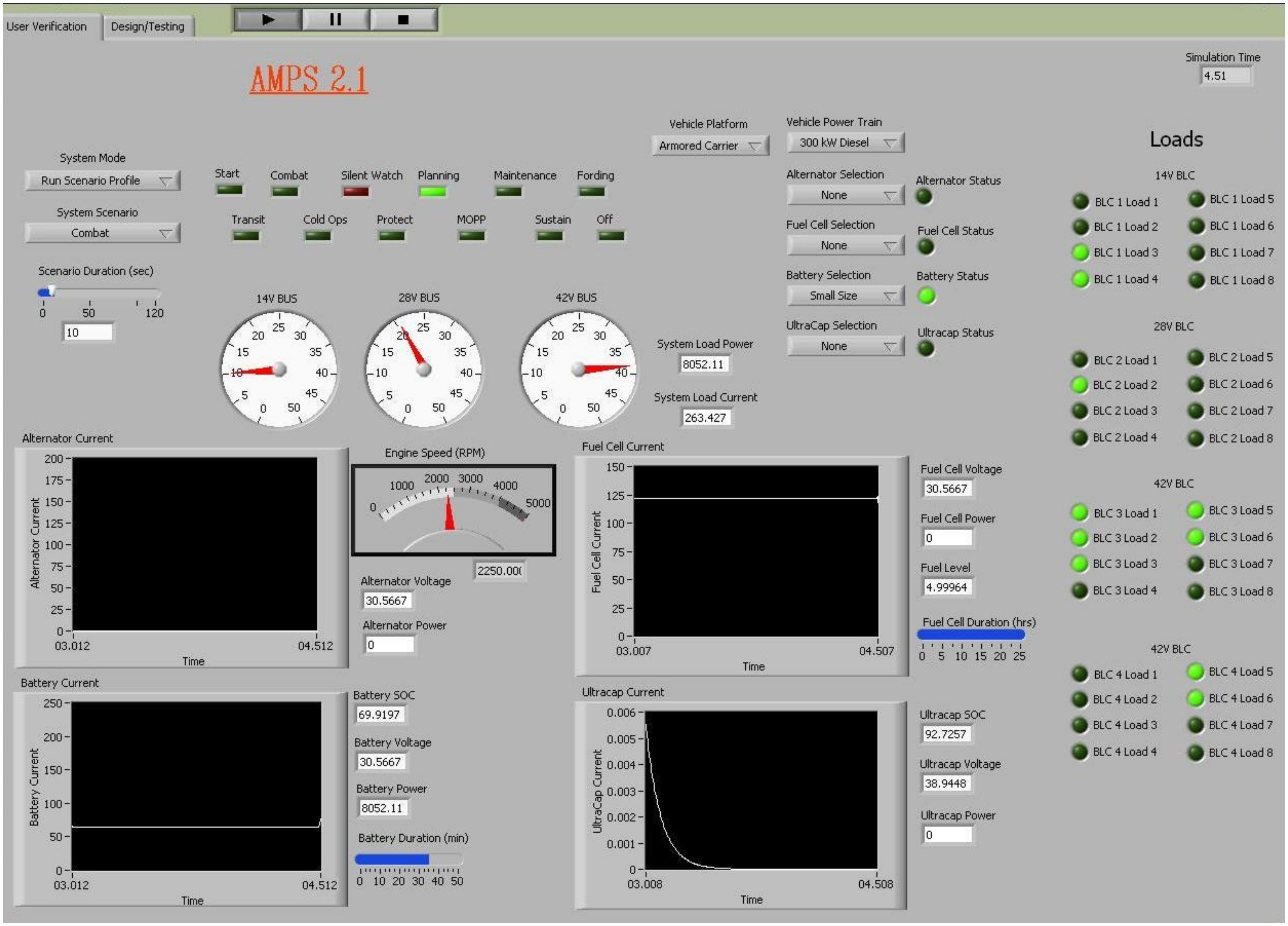

Fig. 60. Transition from silent watch to planning.

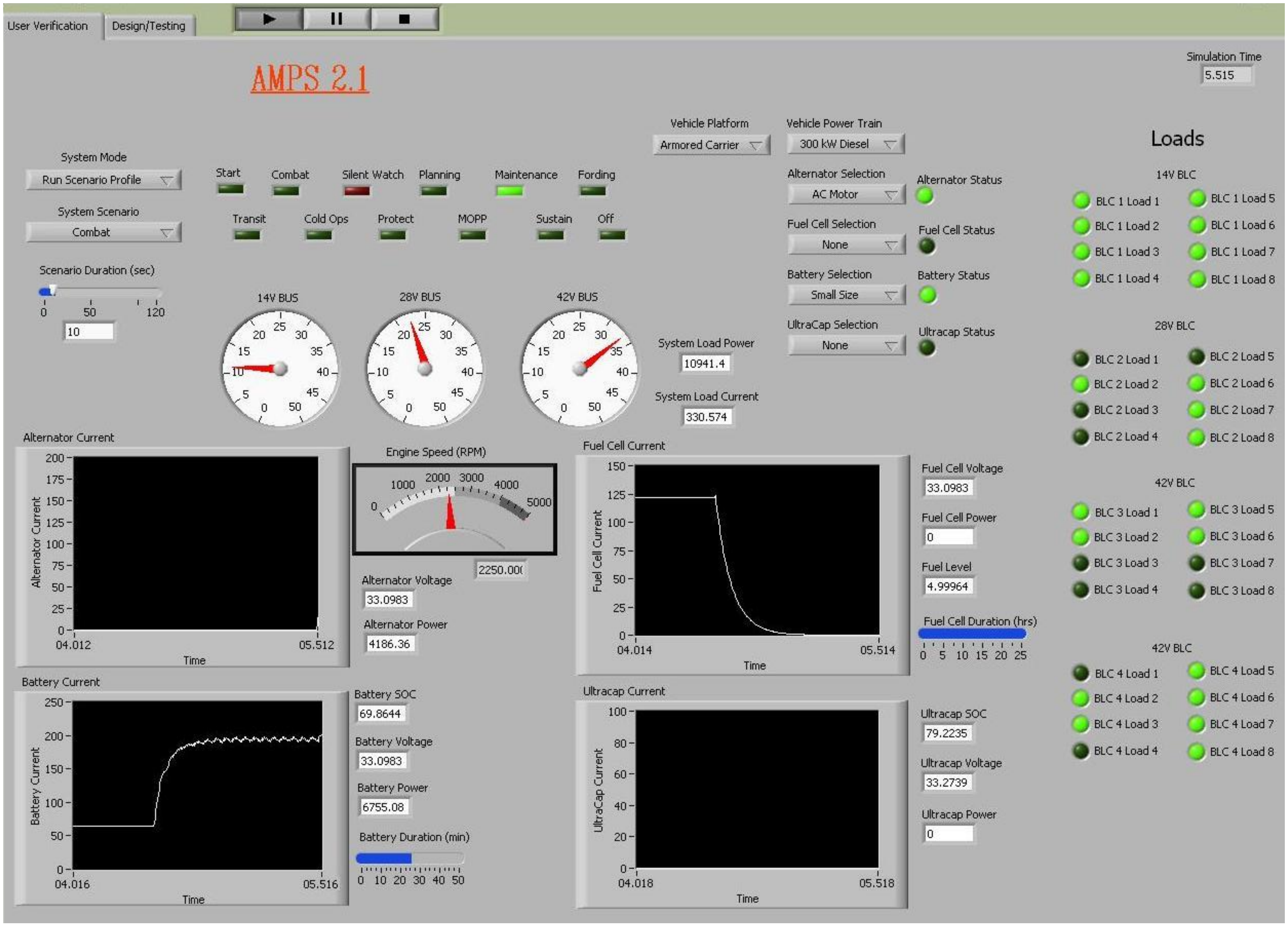

Fig. 61. Transition from planning to maintenance.

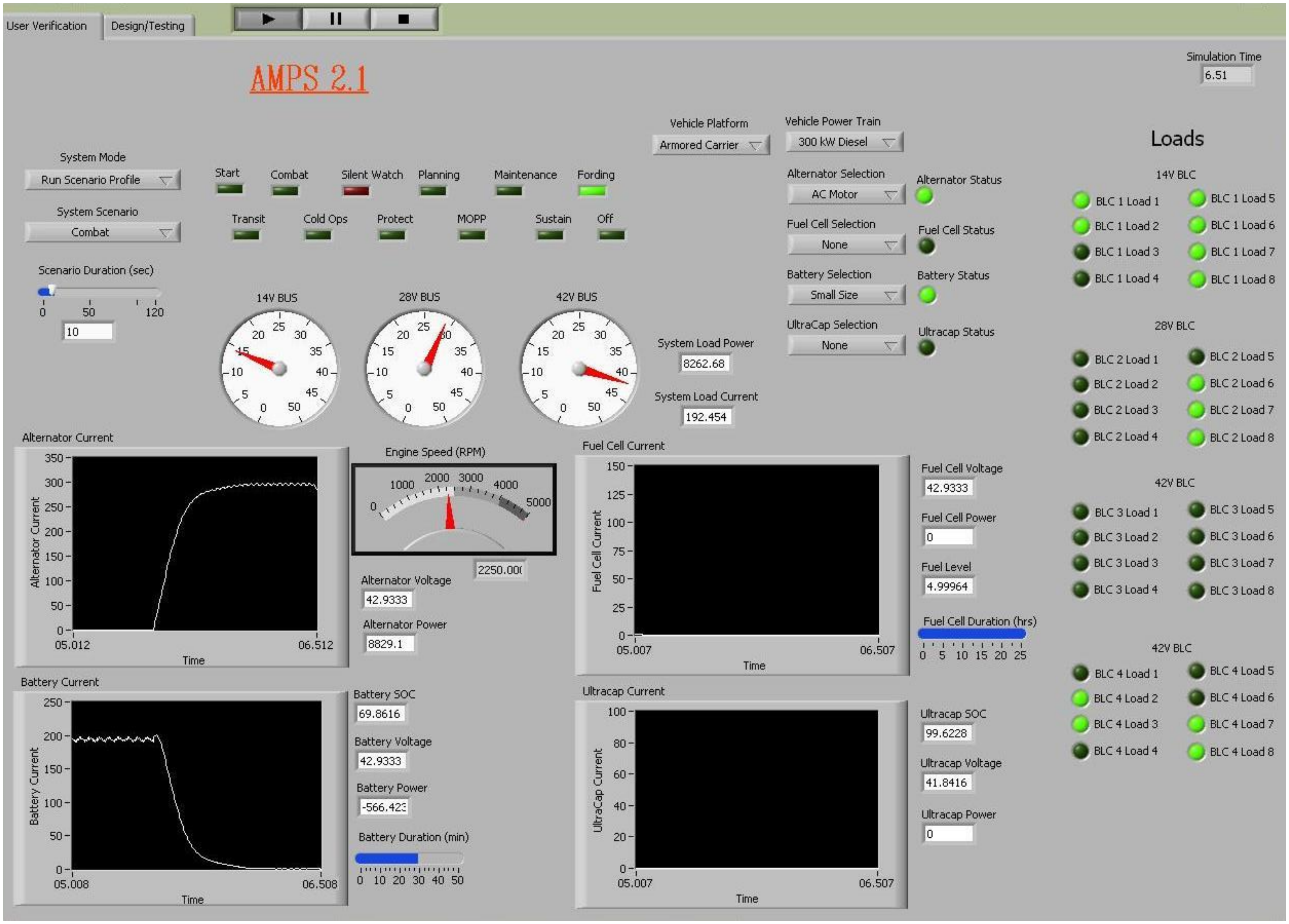

Fig. 62. Transition from maintenance to fording.

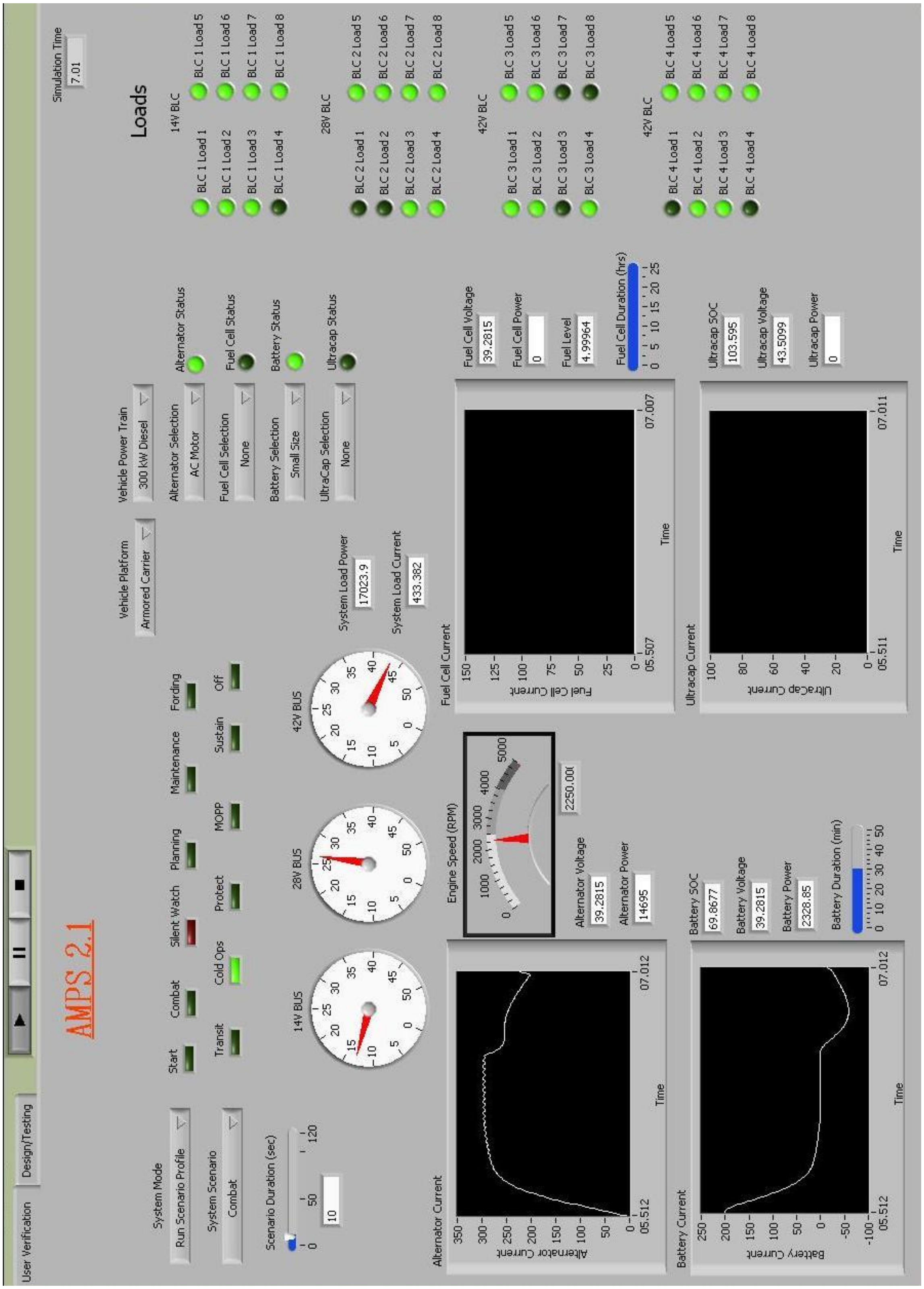

Fig. 63. Transition from fording to cold ops.

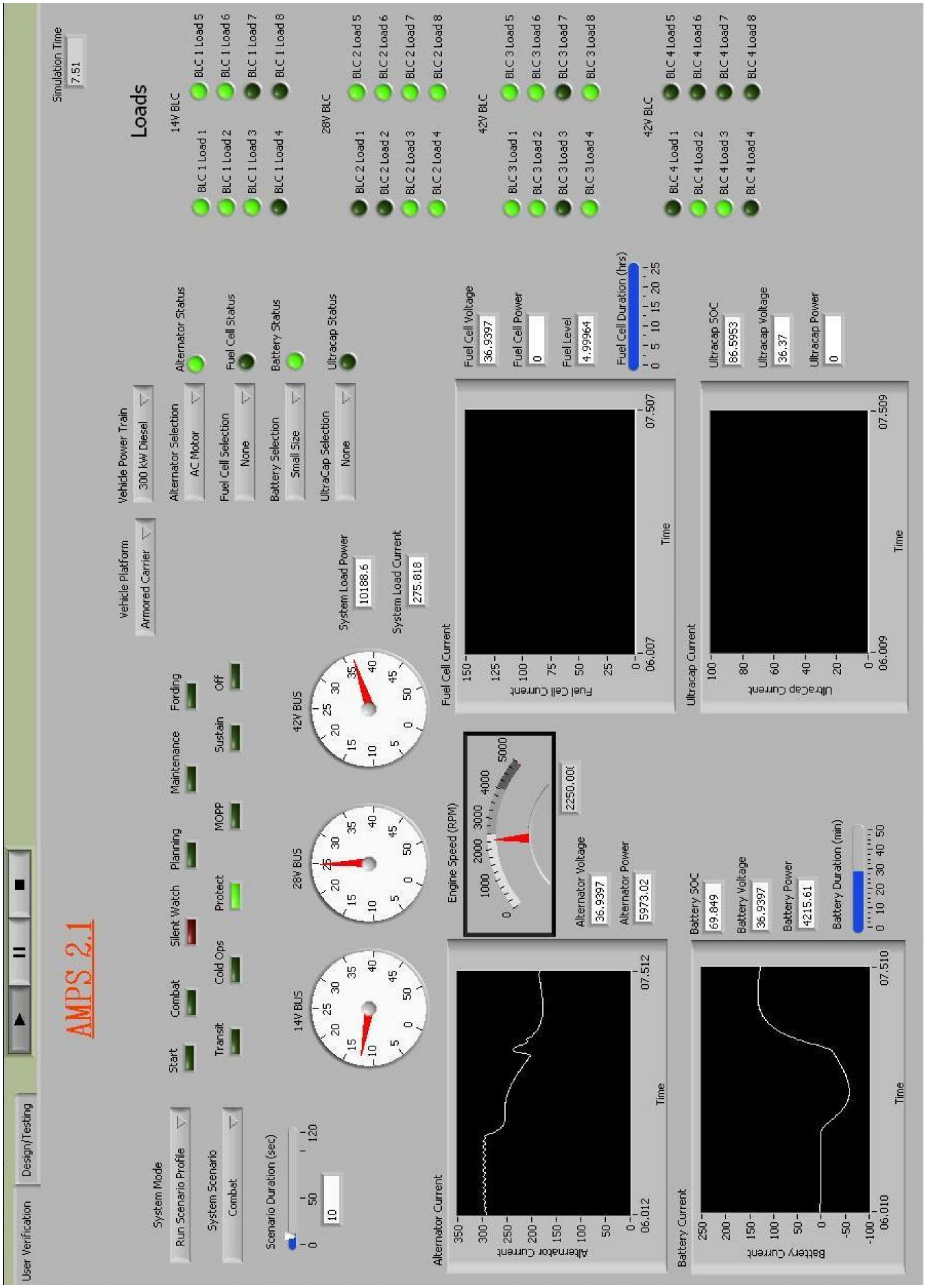

Fig. 64. Transition from cold ops to protect.

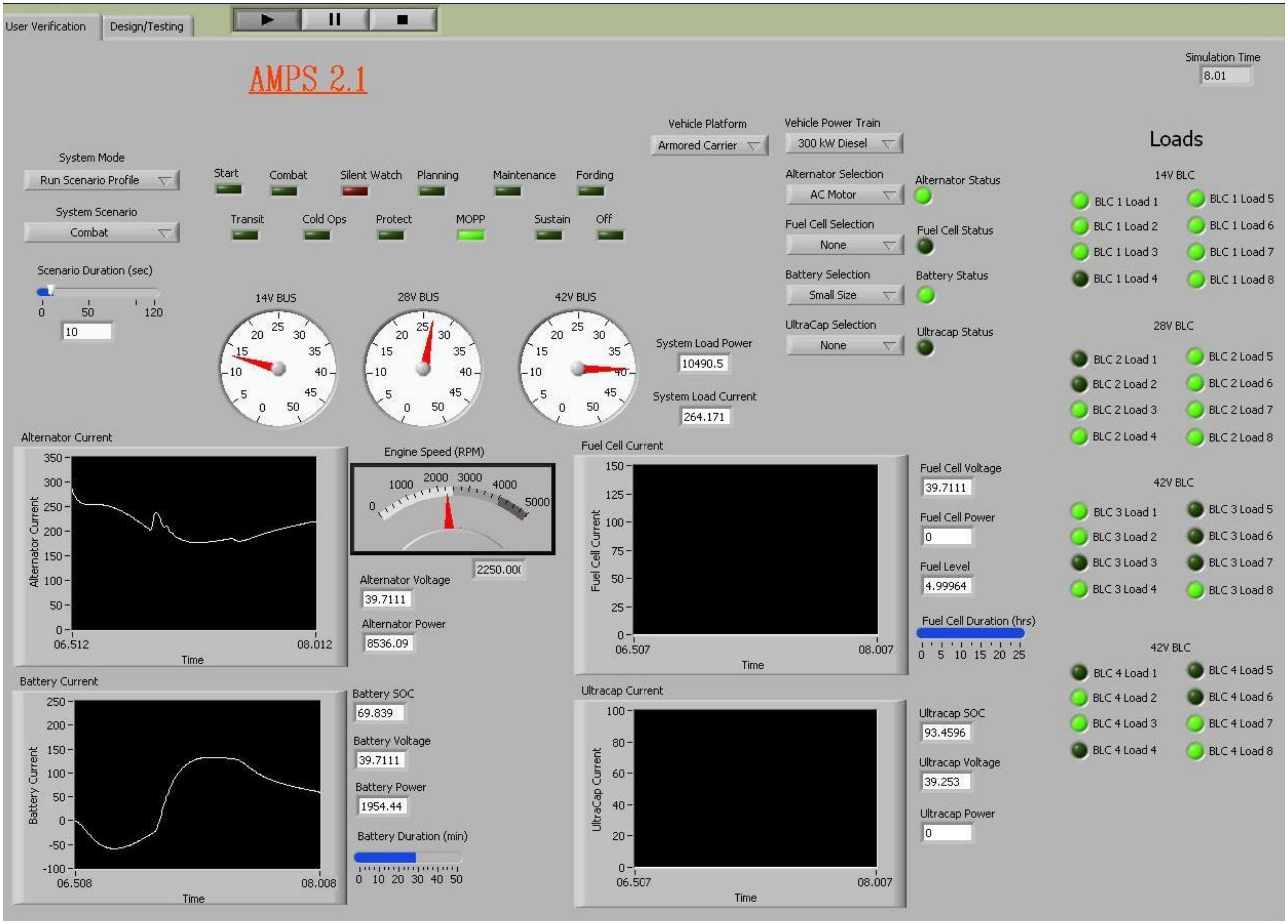

Fig. 65. Transition from protect to MOPP.

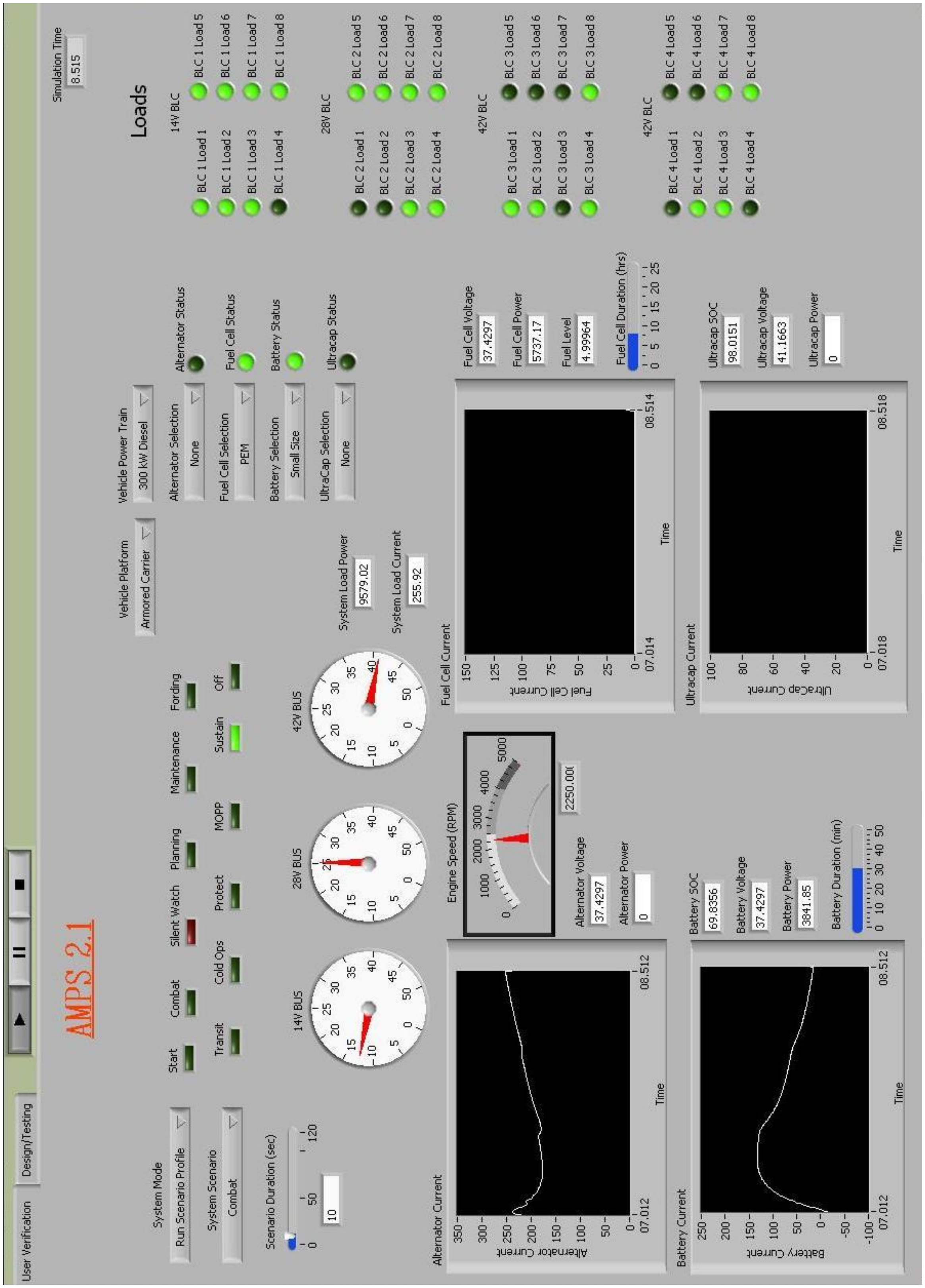

Fig. 66. Transition from MOPP to sustain mode.

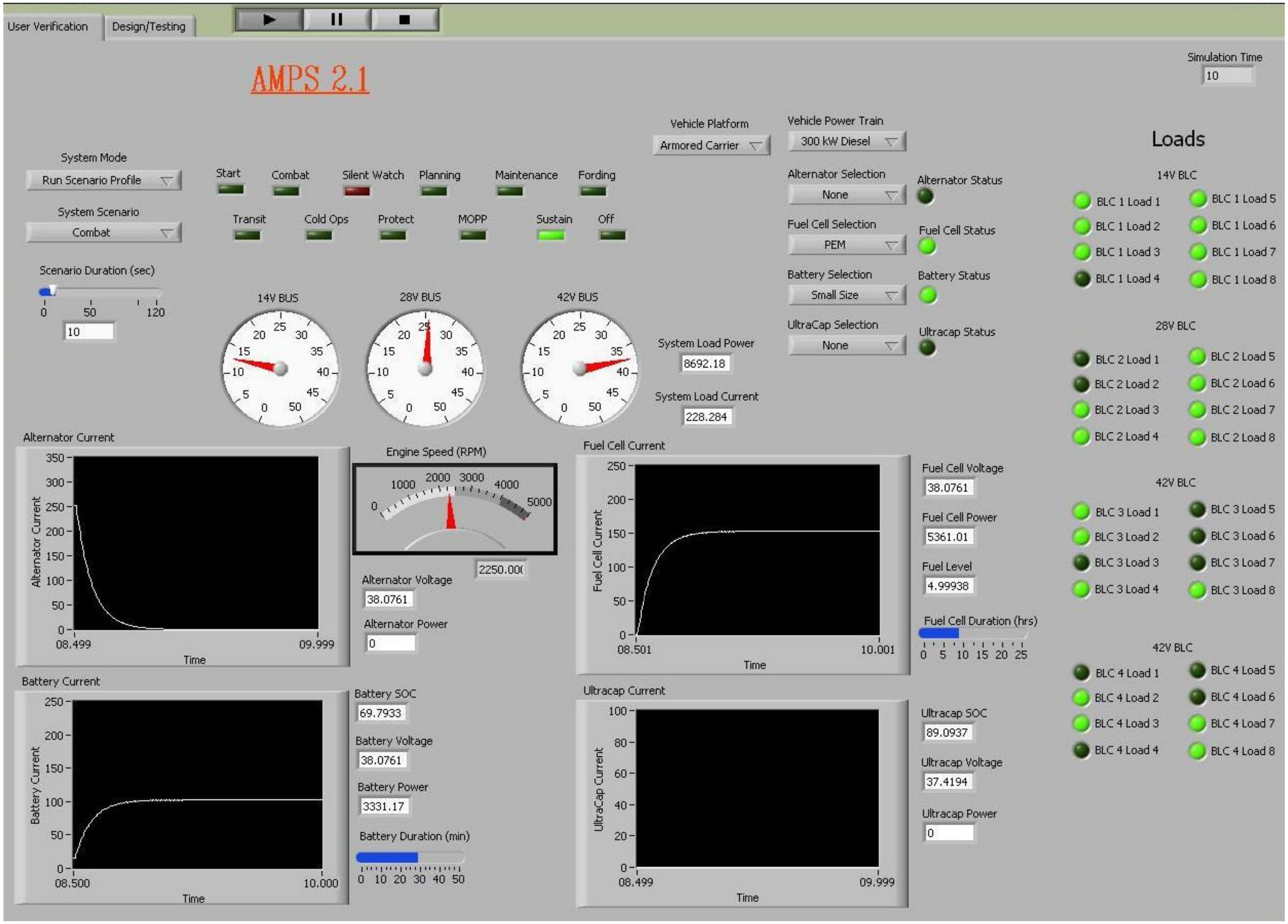

Fig. 67. Sustain mode.

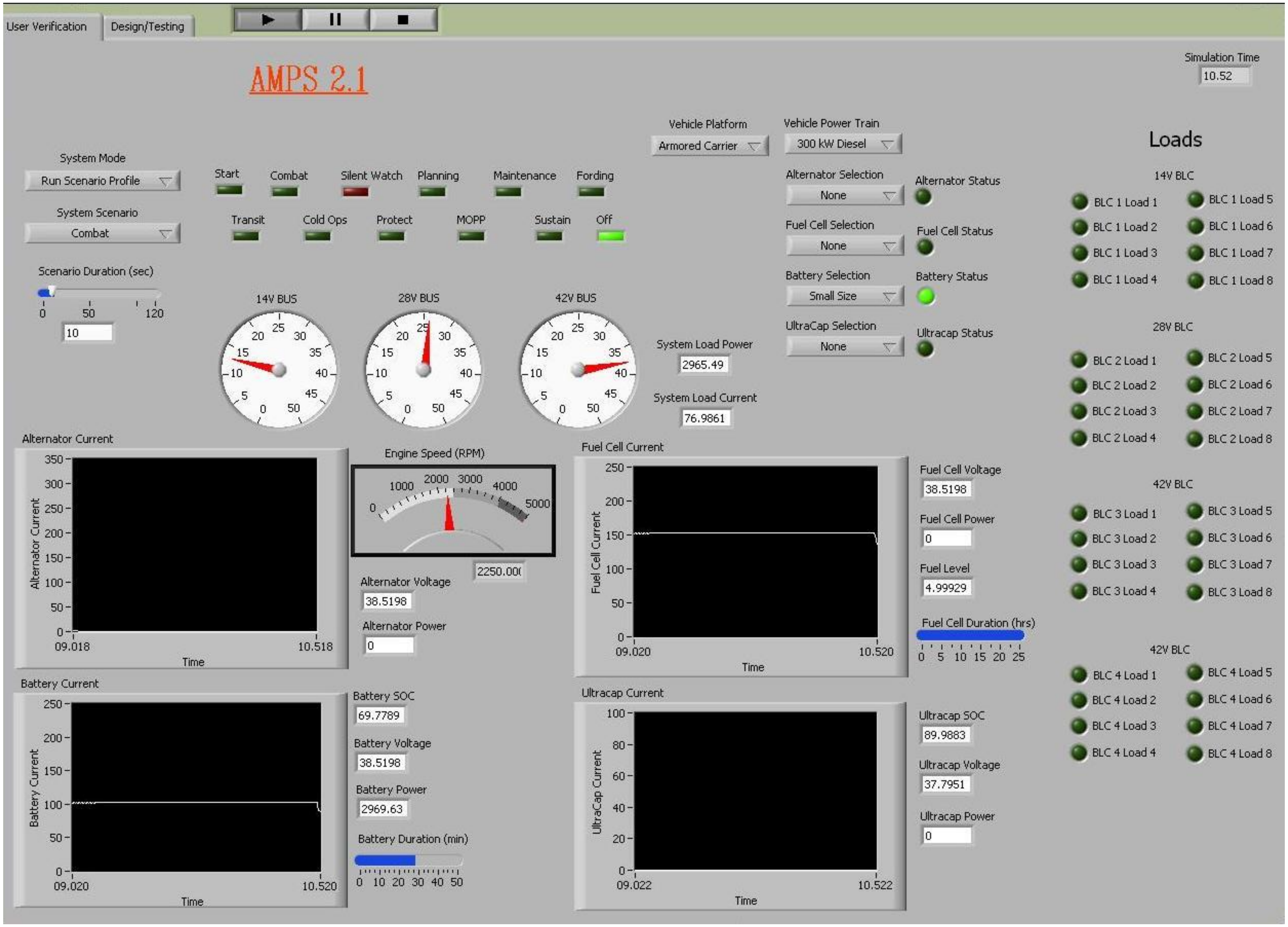

Fig. 68. Transition from sustain to off mode.

Figures 55 through 68 complete the Combat Scenario simulation. With the redefining of the specifications for transitioning from Start to Combat mode allowing for the addition of the ultracapacitor to aid the alternator and the battery in supplying power, it can be observed in Figures 55 and 56 that combat mode is now capable of being maintained without the loss of any loads.

After 2 seconds of simulation time, the vehicle transitions from combat mode to silent watch mode. Fig. 57 shows the source and load configurations upon entering Silent Watch mode, and as displayed, the only sources of power in this mode are the fuel cells and battery. The alternator is specifically not used in this mode to maintain stealth. Critical also to this mode is the duration of time that the vehicle can remain in this stealth-like state. To monitor this critical time, an additional output has been added to the screen, for this mode only, called Silent Watch Time Out. This "clock" indicates the amount of time left to support the present load configuration with respect to the remaining hydrogen fuel supply. As can be seen from Figures 58 and 59, the hydrogen supply and battery SOC (state-of-charge) are both adequate to maintain the mode for the specified time period.

At 4.5 seconds, the vehicle is transitioning into and residing in Planning mode, where it can be seen from Fig. 60 that only the battery is supplying power. In this mode the battery state of charge and duration are important outputs to monitor, as they will indicate whether the present loads demands can be met, and for how long. The simulated vehicle can meet these demands, and as can be seen between 4.5 seconds and

5.5 seconds in Fig. 61 the battery state-of-charge and duration decrease only minimally throughout the mode.

The next transition occurs at 5.5 seconds entering into Maintenance mode and employing once again (as from start to combat) the alternator and battery combination for the power supply, the load configuration is however different (Fig. 61). Throughout the duration of the Maintenance mode (5.5 seconds to 6.5 seconds) it can be seen in Fig. 62 that the alternator current reacts very differently to the load additions compared when entering combat mode. It can be seen in Fig. 54 that the alternator has a dramatic response to the transients induced by the addition of the heavy motor loads, in turn creating more demand on the battery, which resulted in load shedding. In this transition to Maintenance mode, however, fewer motor loads are being added to the vehicle and it can be seen in Fig. 62 that the alternator can meet the power demands of the loads allowing the battery current to drop to near zero.

At 6.5 seconds, the simulation transitions to the Fording mode. Although the alternator and battery are again maintained as the sources of power, numerous loads have been removed from the vehicle (Fig. 62). This significant loss of loads greatly decreases the current demand from the alternator and as can be seen in the 6.5 second to 7.0 second Fording mode period of Fig. 63, excess current from the alternator is being used to charge the battery.

Cold Ops mode begins 7.0 seconds into the simulation and again has the same source configurations, but different load configurations shown in Fig. 63. Fig. 64, from 7.0 seconds to 7.5 seconds, indicates that this new load configuration is drawing more current than the last and requiring some power output from the batteries. The exact same is true for both Protect mode and MOPP mode, Figures 64 through 66.

Sustain mode begins at 8.5 seconds and is configured with the fuel cells and battery as the sources and the load configuration shown in Fig. 66. Figures 67 and 68, between 8.5 seconds and 10.5 seconds, show the current profiles throughout the duration of sustain mode, and indicate steady operation with minimal impact on the battery state-of-charge and fuel cell hydrogen fuel level.

Finally, at 10.5 seconds, the simulation returns to the Off mode, removing all loads from the vehicle and maintaining only the battery (Fig. 68).

D. Summary

This chapter provided a detailed description of the AMPS tool along with the inherent functionality. The development of the AMPS tool was shown to have implemented the theories discussed in earlier chapters and the design verification example showcased the flexibility and usefulness of the AMPS tool.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

This chapter presents the summary of the work accomplished during the course of this research. Suggestions for future research work in this area will also be presented.

A. Summary of the Work

The primary objective of this thesis was to introduce a new method for military vehicle electrical system design and verification, and to implement this design and verification tool such that it meets the needs of military vehicles with the control strategies and power management techniques similar to those found in the actual vehicles themselves.

Chapter I presented a review of the progression of power systems in both commercial and military vehicles over the years with an introduction to the architectures and power system requirements of present-day vehicles. It explains that although numerous simulations currently exist for commercial vehicles, the complexity of the architecture and functionality of military vehicles prohibits their use for accurately modeling and verifying vehicles for military purposes. Additionally, an explanation of how present military vehicle simulations fall short of fully modeling all of the functionality of the vehicle create a need for a new method of simulation and verification.

In Chapter II, the requirements of a military vehicle simulation tool useful for military vehicle applications were examined. The necessity for designing and testing vehicle power systems and additionally implementing checks for design verification and mission predictability on the system is examined. This chapter also gives a first look at the functionality of the model beyond the scope of the simulation requirements, including an examination of the performance requirements of military vehicles such as operating modes, scenarios, and power management techniques.

In Chapter III, a detailed description of the Simulink modeling of each of the vehicle components including their characteristics and equations governing their operation was presented. The functionality of the vehicle simulation as a whole from the overall control of the vehicle throughout the simulation, to the regulation of power flow to each component was also discussed.

Chapter IV provided an examination of the need for and advantages of having a graphical user interface (GUI) incorporated into a vehicle simulation such as this. An exploration of the differences in functionality between the GUI and Simulink simulation were discussed and it was concluded that, although it is feasible to use the simulation alone for design and verification of military vehicles, implementing a user interface with the simulation makes the complete package a more useable and beneficial tool.

In Chapter V, the proposed AMPS tool was discussed with explanations of each of the user interface screens and functions therein. Finally, a design verification simulation was performed to show the flexibility of the tool and support the claims made in previous chapters. The AMPS tool was shown to have implemented the theories discussed in earlier chapters and the design verification example showcased the flexibility and usefulness of the AMPS tool.

B. Contributions of the Research

This research mainly focused on developing a tool for the analysis and design of hybrid military vehicle electric platforms. The major contributions of the research work can be summarized as follows.

- A new method for military vehicle power system modeling is developed. By studying the available simulation and modeling techniques for commercial and military vehicles, it has been discovered that present modeling falls short of providing accurate simulations and descriptions of vehicles used for military platforms. The new method presented meets the needs of military vehicles with control strategies and power management techniques similar to those used in actual vehicles
- A versatile design tool has been developed using the above method for analyzing and verifying the performance of military vehicle power systems. This design tool provides the designer not only with the ease of conceptual vehicle design, but includes the functional capabilities that allow the designer the ability to test and verify designs based on the platform and mission specifications of the vehicle.
- The work in this thesis not only advances design studies for military combat vehicle electric platforms but also provides an adequate method for performing design

verification and mission predictability, establishing the usefulness of the tool long after the design process.

C. Future Research Work

In this thesis, a new tool for military vehicle electrical system design and verification was presented. Although the AMPS tool meets all of the criteria for military vehicle design, there are certain areas that can be improved upon, and require further research. Major suggestions for future research are summarized as follows.

- At present, only the electric power system is included in the modeling and simulation. In the future, the vehicle propulsion section could be included for completeness of the overall system.
- Except for the on/off controls of all the power sources and loads, there is no active control for the flow of power. The power delivered by each power sources is a natural response to load requirement, and depends on its voltage-current characteristics. The power management routine could be extended to monitor and control power flow from the sources.
- An extension of the simulation allowing for more general control over the vehicle architecture, such as parallel/series configurations, dc bus voltages, load types, would make the tool applicable to any number of vehicle platforms.
- Allowing the user to input and save scenario profiles, customized modes of operation and load configurations and priorities as well as saving source parameter data or

vehicle platform data rather than selecting from pre-configured selections or using a completely manual selection would provide more flexibility for the user.

- Permitting the user to save input or output data from a simulation for later viewing could aid in the design verification and mission predictability, allowing the user to view previously saved data without running a simulation over again.
- Many courses of action could be taken to increase the overall speed of the simulation tool. Bringing the tool into a real-time environment could save the design engineer valuable time and allow for more accurate evaluation of the performance of the vehicle.

REFERENCES

[1] A. Emadi, M. Ehsani and J.M. Miller, *Vehicular Electric Power Systems – Land, Sea, Air and Space Vehicles*, NewYork: Marcel Dekker, Inc., 2003.

[2] M.A. Masrur, J. Monroe, R. Patel, V.K. Garg, "42-Volt Electrical Power System for Military Vehicles - Comparison with Commercial Automotive Systems", in *Proc. of the IEEE Vehicular Technology Conference*, vol. 3, 24-28 Sept. 2002 pp.1846 – 1850.

[3] "Transitioning to 42-Volt Electrical System", in *SAE 2000,* Paper # 2000-01-3050.

[4] S. Fish, and T.B. Savoie, "Simulation-Based Optimal Sizing of Hybrid Electric Vehicle Components for Specific Combat Missions," *IEEE Transactions on Magnetics*, vol. 37, no. 1, pp. 485-488, January 2001.

[5] M. Ehsani, Y. Gao, S. Gay and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles – Fundamentals, Theory and Design*, Boca Raton, Florida: CRC Press, 2005.

[6] S.R. Parker, "Combat Vehicle Reliability Assessment Simulation Model (CVRASM)**",** in *Proc. Simulation Conference*, 8-11 Dec. 1991, pp.491 – 498.

VITA

Melissa Anne Lipscomb received her B.S. degree in electrical engineering from Texas A&M University, College Station, Texas, in 2000. From 2000 to 2003 she worked with the Department of Energy at the Bettis Atomic Power Laboratory in Pittsburgh, Pennsylvania, where she conducted research and development for the Naval Nuclear Propulsion Program. In 2003, she joined the master's program at Texas A&M University where she taught power electronics and motor drives labs, as well as furthering the development of an introductory level electronics lab. She can be reached at 95 Kimberly Ct., Atlantic Beach, Florida 32233.