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SIMULATION FOR VEHICLE-TO-VEHICLE AND VEHICLE-TO-GRID RESOURCE SHARING ANALYSIS

Robert S. Jane
Mechanical Engineering-Engineering Mechanics
Michigan Technological University
Houghton, MI

Gordon G. Parker
Michigan Technological University
Houghton, MI

Wayne W. Weaver
Steven Y. Goldsmith
Michigan Technological University
Houghton, MI

ABSTRACT

A simulation capable of modeling grid-tied electrical systems, vehicle-to-grid (V2G) and vehicle-to-vehicle(V2V) resource sharing was developed within the MATLAB/Simulink environment. Using the steady state admittance matrix approach, the unknown currents and voltages within the network are determined at each time step. This eliminates the need for states associated with the distributed system. Each vehicle has two dynamic states: (1) stored energy and (2) fuel consumed while the generators have only a single fuel consumed state. One of its potential uses is to assess the sensitivity of fuel consumption with respect to the control system parameters used to maintain a vehicle-centric bus voltage under dynamic loading conditions.

INTRODUCTION

A Simulink simulation was developed that allows power throughput and economic impacts of vehicle-to-vehicle (V2V) and vehicle-to-grid (V2G) micro-grids to be evaluated. The vehicles each act as power storage systems, operate their government furnished equipment (GFE) and provide power to the grid. They also allow either export or import of power and discharging or charging of the battery while the vehicle engine is either idling or off. Vehicle communication protocols were included to help size-messaging packets needed for communication between vehicles and the elective-vehicle-supply-equipment (EVSE). The simulation's economic analysis focuses on the amount of fuel used.

The simulation also tracks all power flows including losses incurred by generation resources. AC outputs are monitored via the magnitude and phase of the respective generation resource, enabling power generation and storage analysis possibilities. Two custom graphical user interfaces (GUI) were developed, capable of performing both real time and post processing of the results. The remaining sections of this report will give a brief overview of the model architecture, which includes the five key Simulink systems including (1) the vehicle model, (2) the generator model, (3) the power distribution model, and (4) the control model. After describing these four systems, two example scenarios will be defined and analyzed to highlight the simulations ability to analyze an AC grid network.

MODEL DEFINITION

The simulation is constructed using several models that can accommodate time varying grid topologies. The topology of the micro-grid is constrained by the maximum number of generators, and vehicles specified by the user. The S-Function's input and output port dimensions are determined during model initialization and cannot be altered during model execution. Thus the maximum number of vehicles and generators are fixed during initialization, while not inhibiting run time topology changes.

VEHICLE MODEL

The vehicle model has three components:

- Battery
- Propulsion Systems/(Engine)

- Alternator

When the vehicle engine is off, power can be exported or imported to the vehicle by controlling the voltage difference between the micro-grid bus and the vehicle battery. When the engine is on the battery can be charged by the alternator and power can be used for on board GFE and for export. The battery model uses a single state of charge state as described in [1]. The vehicle engine is the Caterpillar C9 ACERT [2] and a Neihoff [3] alternator, capable of exporting 28 volts at 570 amps, was included. The model also includes a vehicle communication layer. Its packet data is updated based on operating conditions of the vehicle and is available to the EVSE and the vehicles. For a complete list of the vehicle system inputs, outputs, refer to table 1.

Port Name	Type	Unit
Battery Current (I_{Veh})	Input	A
Engine Operation Condition	Input	N/A
GFE Current Draw (I_{GFE})	Input	A
Control2Veh Communication	Input	N/A
State of Charge (SOC)	Output	%
Energy Discharge of Battery (EDB)	Output	W
Open Circuit Voltage (OCV)	Output	V
Vehicle Loss ($Loss$)	Output	W
Vehicle Voltage (V_{Veh})	Output	A
Remaining Fuel (Veh_{Fuel})	Output	Gal
GFE Operation	Output	N/A
Engine Operating	Output	N/A
Engine Operating Speed (ω_e)	Output	Rpm
Veh2Control Communication	Output	N/A

Table 1: Vehicle port specifications.

GENERATOR MODEL

Generators are standalone systems that efficiently produce reliable exportable power to satisfy system loads. Several commercial of-the-shelf (COTS) diesel generators [4] and available for use in the simulation with a power range of 40-310kW at 480V and 60Hz. They are modeled with one fuel consumed state with a power range of 40-3100kW. For a complete list of the generator system inputs, outputs, refer to table 2.

Port Name	Type	Unit
Operating Voltage (V_{Gen})	Input	V
Operating Current (I_{Gen})	Input	A
Control2Gen Communication	Input	N/A
Exported Power (P_{Gen})	Output	kW
Exported Voltage (V_{Gen})	Output	V
Operating Load (L_{Gen})	Output	%
Reaming Fuel(Gen_{Fuel})	Output	Gal
Gen2Control Communication	Output	N/A

Table 2: Generator model port specifications.

POWER DISTRBUTION MODEL

A user defined symmetric, square Boolean topology matrix, shown in equation (1), is used to specify the grid's configuration.

$$\begin{pmatrix} 0 & \cdots & B_{1,N} & B_{1,N+1} & \cdots & B_{1,N+M} & B_{1,N+M+1} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & 0 & B_{N,N+1} & \cdots & B_{N,N+M} & B_{N,N+M+1} \\ 0 & \cdots & 0 & 0 & \cdots & B_{N+1,N+M} & B_{N+1,N+M+1} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & 0 & 0 & \cdots & 0 & B_{N+M,N+M+1} \\ 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \end{pmatrix} \quad (1)$$

Its dimension are governed by the maximum number of vehicles, generators, and loads. The subscripts used in equation (1) indicate which node is connected to all other nodes. Examples of nodal assignments as well as the size of the topology matrix are given in table 3.

Max # of Veh. (N)	Max # of Gen. (N)	Max # of Load (L)	Veh. Nodes	Gen. Nodes	Load Nodes	Topology Matrix Dim.
1	1	1	1	2	3	[3x3]
2	2	1	1-2	3-4	5	[5x5]
3	3	1	1-3	4-6	7	[7x7]
4	4	1	1-4	5-8	9	[9x9]
5	5	1	1-5	6-10	11	[11x11]
10	10	1	1-10	11-20	21	[21x21]
20	20	1	1-20	21-40	41	[41x41]
30	30	1	1-30	31-60	61	[61x61]
40	40	1	1-40	41-80	81	[81x81]
50	50	1	1-50	51-100	101	[100x100]

Table 3: Topology matrix nodal assignments used to size and structure the nodal admittance matrix used to define grid architecture.

An example of a generic topology matrix for a system which is composed of three vehicles and generators and one load is given in equation (2). An example grid architecture is given in figure 1 which corresponds to the topology matrix given in equation (3).

$$\begin{pmatrix} 0 & B_{1,2} & B_{1,3} & B_{1,4} & B_{1,5} & B_{1,6} & B_{1,7} \\ 0 & 0 & B_{2,3} & B_{2,4} & B_{2,5} & B_{2,6} & B_{2,7} \\ 0 & 0 & 0 & B_{3,4} & B_{3,5} & B_{3,6} & B_{3,7} \\ 0 & 0 & 0 & 0 & B_{4,5} & B_{4,6} & B_{4,7} \\ 0 & 0 & 0 & 0 & 0 & B_{5,6} & B_{5,7} \\ 0 & 0 & 0 & 0 & 0 & 0 & B_{6,7} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{2}$$

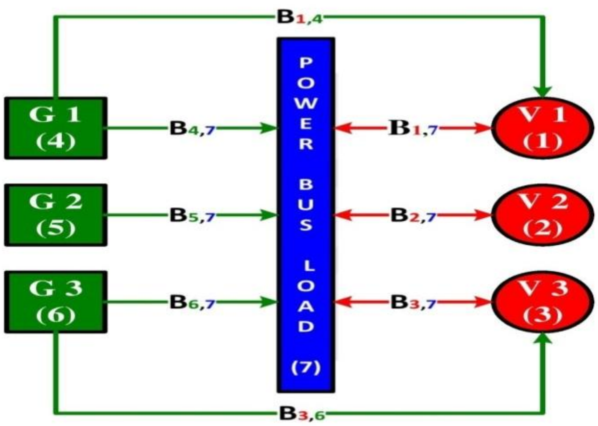

Figure 1: Example grid topology

$$\begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{3}$$

The colored subscripts are used to distinguish between different source connections. Common colored subscripts represent interconnection between similar sources, while dissimilar colored subscripts represent interconnections between dissimilar sources.

Once the topology matrix is defined the topology matrix is converted into a complex nodal admittance matrix [5] denoted as Y_{Bus}, using the resistance and inductance values of the transmission lines. If the topology matrix is altered during a simulation run, indicating a vehicle or a generator has become disconnected or connected, the topology matrix changes, leading to voltage and current changes within the micro-grid. In general, a subset of nodal voltage, V, and currents, I are unknown. The model rearranges the steady state, AC current and voltage relationships of equation (4) and solves for the unknowns at each time step.

$$I = [Y_{Bus}]V \tag{4}$$

CONTROL MODEL

A control system was developed that maintains the bus voltage when the load is time varying. Vehicles such as the JLTV[6] and the MRAP [7] export 75kW and 30kW respectively. However vehicles are less efficient than generators at supplying exportable power. For this reason the control methodology uses weighting factors to blend the power across all assets. The weighting methodology directly relates to the number of active generation resources available as well as what type of generation resources are available. The control law is derived from the final row of the admittance matrix (load row), and is shown in equation (5),

$$0 = \sum_{i=1}^{N} V_{Veh_i} Y_{Veh_i} + \sum_{i=1}^{M} V_{Gen_i} Y_{Gen_i} - V_{Bus}\left(\sum_{i=1}^{N} Y_{Veh_i} + \sum_{i=1}^{M} Y_{Gen_i} + Y_{Load}\right) \tag{5}$$

where V_{Veh_i} is the i_{th} vehicle's voltage, V_{Gen_i} is the i_{th} generator's voltage and Y_{Veh_i}, and Y_{Gen_i} are the net admittances of the vehicles and generators. The quantity Y_{Load} is the load admittance. Weighting constants α_i and β_i for the vehicles and generators are coupled with a common voltage V which require $V_{Veh_i} = \alpha_i V$ and $V_{Gen_i} = \beta_i V$, the scalar voltage V can be computed as shown in equation (6) and is used to set the V_{Veh_i} and V_{Gen_i}.

$$V = \frac{V_{Bus}\left(\sum_{i=1}^{N} Y_{Veh_i} + \sum_{i=1}^{M} Y_{Gen_i} + Y_{Load}\right)}{\sum_{i=1}^{N} \alpha_i Y_{Veh_i} + \sum_{i=1}^{M} \beta_i Y_{Gen_i}} \tag{6}$$

Simply put, equation (6) represents a ratio between the current at the bus and the total impedance of the transmission paths. For a complete list of the control system inputs, outputs, refer to table 4.

Port Name	Type	Unit
Admittance Matrix	Input	Ω
Bus Voltages	Input	N/A
Vehicle Communication Data	Input	N/A
Generator Communication Data	Input	N/A
Admittance Matrix	Output	Ω
Vehicle Controlled Voltages	Output	V
Generator Control Voltages	Output	V
Vehicle Communication Data	Output	N/A
Generator Communication Data	Output	N/A

Table 4: Control model port specifications.

EXAMPLE SIMULATION 1 DEFINITION

In this first example, we will analyze a system who's grid architecture is composed of two 40kW generators connected directly to the main power bus, as shown in figure 2. The system topology will remain fixed through the duration of the simulation, which is to last six hours. Results obtained from the simulation can be seen in figures 3-5.

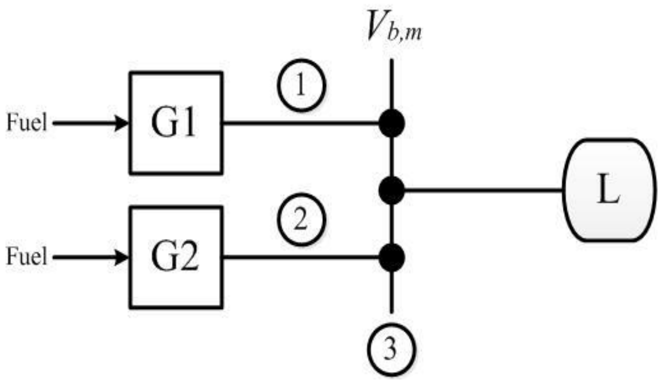

Figure 2: Example simulation grid topology architecture for ($0 \le T \le 6$)Hr.

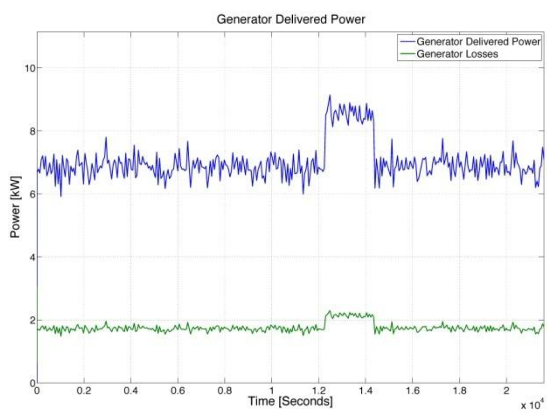

Figure 3: Generated power and corresponding power generation losses.

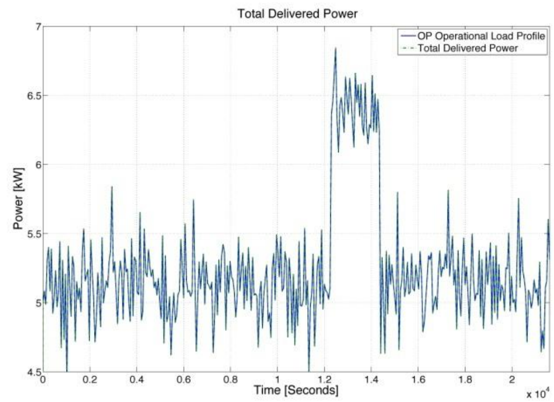

Figure 4: OP Load Vs. Generator Delivered Power.

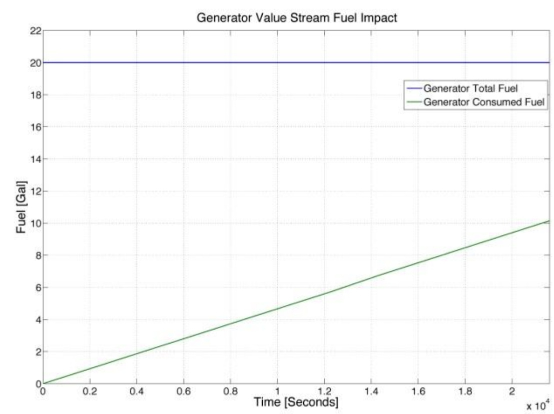

Figure 5: Total Fuel Value Stream Impact.

EXAMPLE SIMULATION 1 ANALYSIS

Analysis of figure 4 reveals that the generators are able to supply adequate amounts of power to supply the base's operational load profile. The economic impact of operating the two generators for 6 hours which produced an average of 7kW of power is around 10 gallons of diesel fuel, out of a possible 20 gallons available which is shown in figure 5. The main purpose of this example is to act as a control simulation, which can be used to compare results obtained from varying the topology of the system, as shown in the second simulation example.

EXAMPLE SIMULATION 2 DEFINITION

In this second example, we will analyze a grid which has several topology changes and is composed of the same 40kW generators used in the first simulation, and four vehicles which have exportable power capabilities. During the time interval $(0 \le T < 2)Hr$ the grid topology will be that of the two generators and one vehicle which is primarily acting as a secondary load, which is shown in figure 6. At $T \quad 2Hr$, three additional vehicles will become connected to the grid, and each vehicles engine will be brought online to export power, as shown in figure 7. At $T \quad 2.2Hr$ the generates will be disconnected from the grid and all vehicles will be forced to supply the grid with adequate power to satisfy the bases operational load profile, the topology is shown in figure 8. At $T \quad 4.2Hr$ the generators will be brought back online as shown in figure 9. The final topology change will take place when $T \quad 4.4Hr$, all vehicles will become disconnected from the grid and the generators will be forced to supply the bases operational load profile, which is shown in figure 10. Results obtained from the simulation can be seen in figures 11-15.

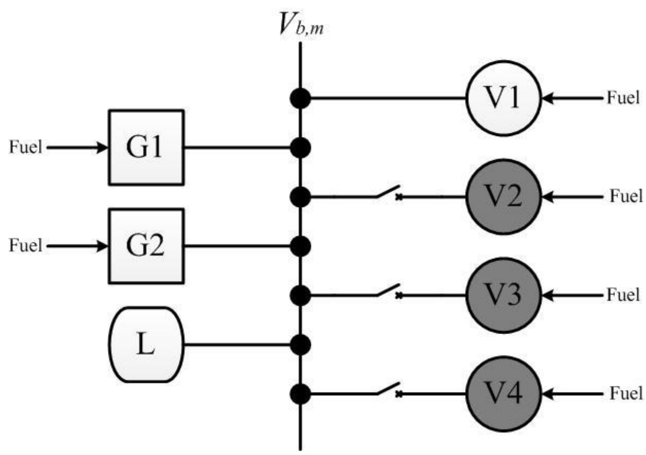

Figure 6: Example grid architecture during $(0 \leq T < 2)Hr$.

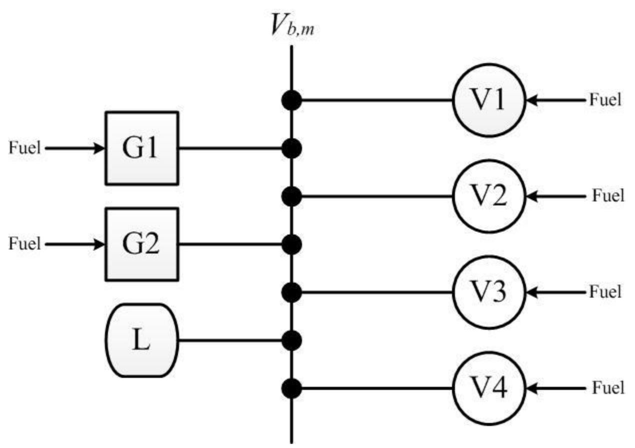

Figure 7: Example grid architecture during $(2 \leq T < 2.2)Hr$.

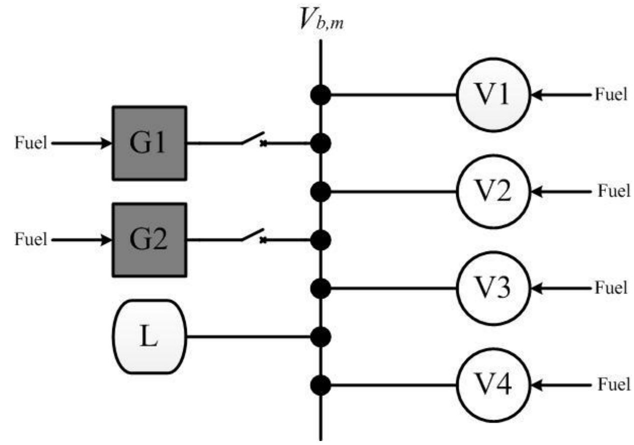

Figure 8: Example grid architecture during $(2.2 \leq T < 4.2)Hr$.

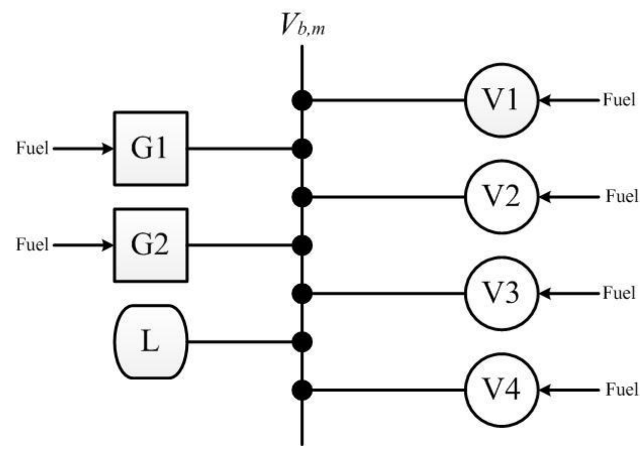

Figure 9: Example grid architecture during $(4.2 \leq T < 4.4)Hr$.

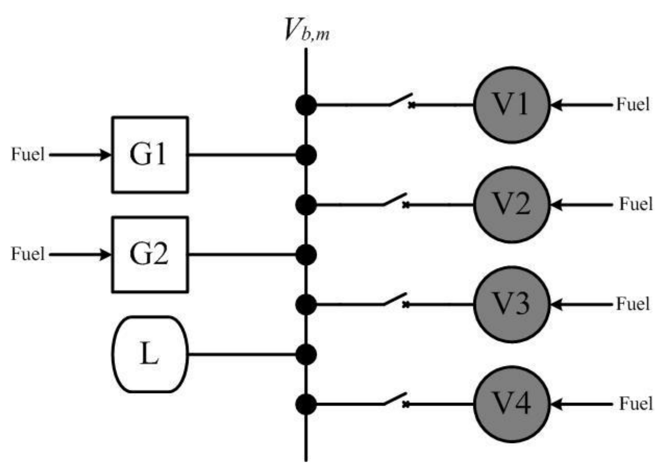

Figure 10: Example grid architecture during

$(4.4 \leq T < 6)Hr$.

Figure 11: Generator Power Value Stream Impact.

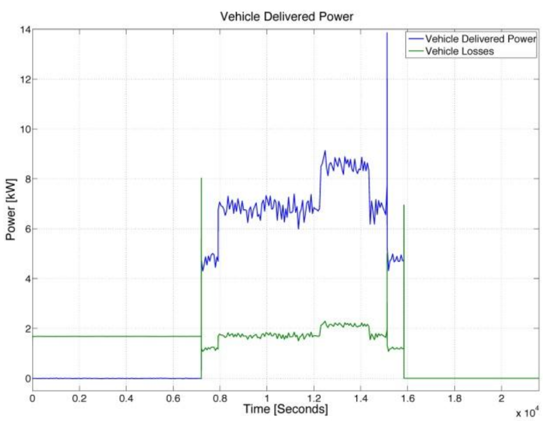

Figure 12: Vehicle Power Value Stream Impact.

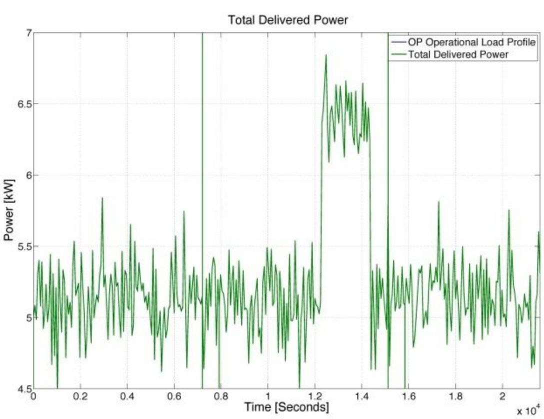

Figure 13: Total Power Value Stream Impact.

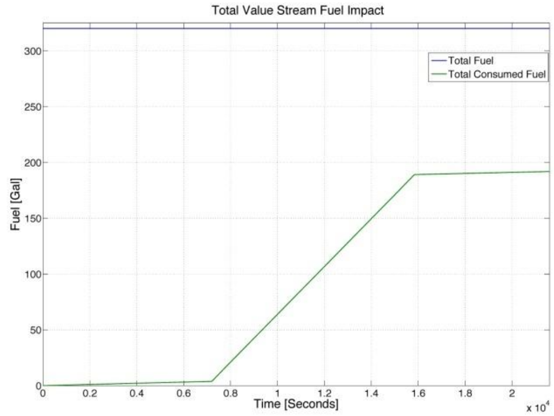

Figure 14: Total Fuel Value Stream Impact.

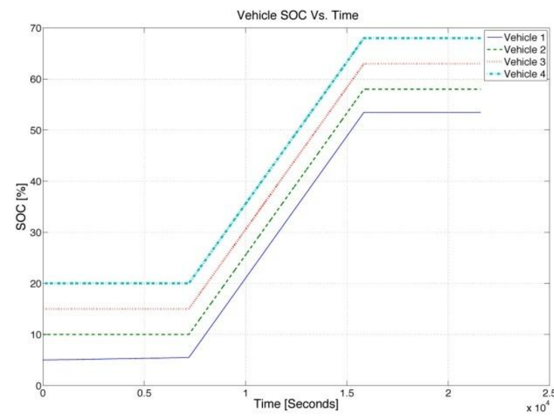

Figure 15: Vehicle State of Charge Value Stream Impact.

EXAMPLE SIMULATION 2 ANALYSIS

Analysis of figures 11 - 15 indicates that the system composed of two generators and four vehicles with various topology changes was able to satisfy the base operational load profile. Specifically figure 11 shows the generators ability to provide adequate amounts of power to satisfy the bases operational load profile. During the periods when the vehicle were not supplying any power the generators supplied enough power to meet the base's power demands. Analysis of figure 13 reveals that varying the topology of the system ultimately did not affect the vehicles and generators ability to supply the bases with enough power to satisfy the bases operational load profile. During the time in which the vehicles were actively supplying power, the amount of fuel consumed drastically rose. By the end of the simulation, some 200 gallons of fuel was consumed, which is shown in figure 14 When compared to example 1, this is 200% increase in fuel required to satisfy the same operational load profile used in example 1, indicating that varying the topology caused the system to operate less efficiently. During the simulation, specifically when the vehicles engines were active the alternator was used to supply the bulk of the exportable power, while a small portion of this power was used to charge the vehicles battery, which can be observed in figure 15.

CLOSING REMARKS

Through the use of the steady state nodal admittance matrix, a MATLAB/Simulink simulation was developed that allows grid-tied electrical systems, V2G, and V2V micro-grids to be modeled and analyzed. Specifically the systems composed within the simulation are capable of providing a thorough power throughput assessment for either the main micro-grid or individual systems included within the grid architecture. In addition to the power throughput analysis, the simulation is capable of monitoring and displaying the value stream impact in terms of both fuel consumption and state of charge. The examples provided within this report have demonstrated the simulations ability to define an analyze a micro-grids architecture which is capable of allowing V2G and V2V resources sharing.

While the simulation provides a useful tool which aids itself in defining and analyzing a micro-grids architecture, the simulation currently lacks the ability to provide information related to the communication aspect of a any of the grid-tied electrical systems or vehicles included within the simulation architecture. In order to effectively implement a tool which is capable of modeling grid-tied electrical systems, V2G and V2V resource sharing the communication aspect must be considered. In order to facilitate communication between the individual components within the simulation environment it has been determined that the simulation will be updated to include communication protocols which will help to expand the current simulation's versatility in defining and analyzing a micro-grid.

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