2011 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
VEHICLE ELECTRONICS AND ARCHITECTURE (VEA) MINI-SYMPOSIUM
AUGUST 9-11 DEARBORN, MICHIGAN

Microgrid Modeling and Control to Investigate the Stability Impact of Hybrid Vehicle Loads and Renewable Sources

Kyle Bordeau
Gordon Parker
Department of Mechanical Engineering
Michigan Technological University
Houghton, MI

Gregory Vosters
Wayne Weaver
Department of Electrical & Computer Engineering
Michigan Technological University
Houghton, MI

David Wilson
Rush D. Robinett III
Sandia National Laboratories
Albuquerque, NM

ABSTRACT

This paper explores the effect dispatchable loads have on microgrids with a high penetration of renewable sources. For this study, the dispatchable loads are electric vehicles whose state of charge must be maintained on a 24 hour cycle. Simulation and optimization tools are utilized in MATLAB to optimize a grid design with 50% renewable energy sources in the form of a photovoltaic solar array. The findings of this study are that the electric vehicle dispatchable loads can be used to stabilize a microgrid against unpredictable losses in renewable generation.

INTRODUCTION

Attaining defined levels of safety, reliability, security, sustainability and cost for energy needs is the focus of the concept called energy surety[1]. A wide range of technologies and approaches are being considered to facilitate energy surety including renewable power sources and vehicle electrification with a microgrid architecture[2]. The U.S. DoD has a particular interest in decreasing fossil fuel usage and dependence on civilian energy sources at military installations. Renewable energy sources help to ease the supply line for a forward operating base (FOB) by decreasing fossil fuel consumption used for power generation and also provide silent generation capability in the case of solar energy. Electrification of U.S. Army non-tactical vehicles (NTVs) could impact the effectiveness of military base microgrids. This impact could be positive or negative depending on the level of upfront design implemented to ensure efficient and harmonious integration of technologies. For example, renewable power sources tend to destabilize microgrids at high penetration levels[3] due to disturbances in sunlight or variable winds. Similarly, renewable sources such as solar and wind power suffer from being non-dispatchable, meaning they cannot be simply turned on or off like a diesel generator. However, the destabilizing effects of renewable sources can be overcome by using distributed energy resources, in the form of NTV fleets, through scheduling of charging loads and potential vehicle-to-grid source capability[2, 4, 5].

Analysis and design tools are needed to optimize the charging and discharging of electric vehicles, sizing of a traditional energy storage system (ESS) and stabilizing the power demands in a microgrid with high penetration renewable sources. This work uses an example to illustrate possible effects that an NTV fleet can have on a microgrid with 50% renewable generation.

An idealized microgrid, consisting of PV and fixed generation sources, energy storage, primary loads, and an NTV fleet is designed for several different NTV fleet sizes. For each optimal design, the effect of reducing the expected PV power by 50% is calculated in terms of the percent of time the primary loads are missed and the state of charge of the PV fleet. As the NTV fleet size increases, the effect of a 50% reduction in PV generation on primary load satisfaction is decreased. The per vehicle state of charge of the NTV fleet also decreases. This allows the calculation of the excess vehicle capacity needed in order to meet both fleet state of charge requirements and primary load satisfaction in the presence of reduced PV generation.

This study uses many simplifying assumptions regarding the microgrid operation and does not consider transient behavior. Stability defined in this study is the ability of the grid to meet the load demand at all times.

The remainder of the paper is organized as follows. The microgrid and operational scenario is presented first. This is followed by an overview of the optimal design approach used to size microgrid components for each NTV fleet size considered. The results of the optimal designs and the effect of reduced PV generation are presented next. Conclusions and a significant list of future work topics are then discussed.

MICROGRID MODEL & SIMULATION

This study focuses on how the design of a microgrid changes performance in response to an NTV fleet and forecasted PV generation when PV penetration is fixed at 50%. The microgrid and operational scenarios description are thus divided into features that are constant for each scenario and features that can be manipulated during the design.

The fixed aspects for each design scenario are the primary, or non-NTV, loads, shown in Figure 1, the schedule when the NTV fleet is plugged into the grid, shown in Figure 2, and the shape of the PV source profile, shown in Figure 3. The primary load has a constant power component at $P_{fix} = 20\ kW$ and a varying component that ramps up between 0600 and 0700. It holds constant at 60 kW and then ramps down between 1600 and 2400. The PV profile ramps up between 0600 and 1100, holds constant for one hour and then ramps down between 1300 and 1700. Its maximum output is denoted P_{PVmax} which scales the size of the PV array and is one of the microgrid design variables addressed below. The NTV fleet is plugged into the grid between 1100 and 1300 and between 1800 and 0600. While plugged in, the NTV fleet has the ability to draw up to $P_{VehIn} = 1.1\ kW$ per vehicle. The vehicles discharge at the same rate, $P_{VehOut} = P_{VehIn}$, when not plugged in.

The variable aspects for each design are the size of the energy storage system, $E_{stormax}$, its state of charge at 0600, $E_{storinit}$, and the size of the PV array, P_{PVmax}.

A set of parameters, an example of which is shown in Table 1, uniquely defines a microgrid design and its operational scenario. The system can be modeled with two states, E_{stor} and E_{NTV}, which are the storage system and NTV fleet states of charge respectively shown in Eq. 1. A simulation was constructed in MATLAB to solve

$$\dot{E}_{stor} = P_{stornet}$$
$$\dot{E}_{NTV} = P_{NTVnet} \qquad (1)$$

where $P_{stornet}$ and P_{NTVnet} are nonlinear functions that are dependent on several factors, including available energy and vehicle plug-in state. The simulation uses Euler integration

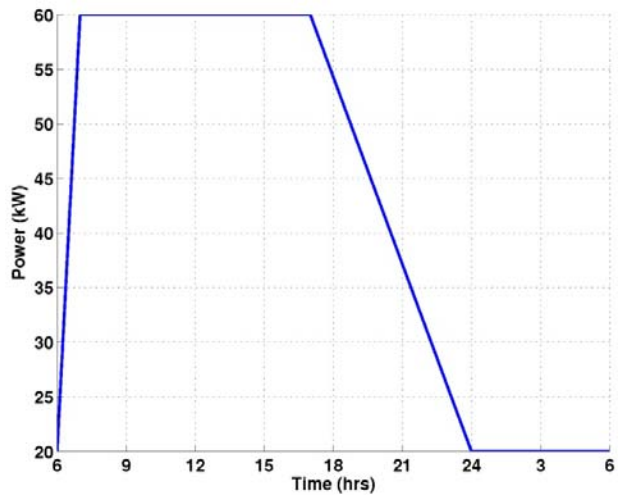

Figure 1: Primary load profile, fixed throughout study

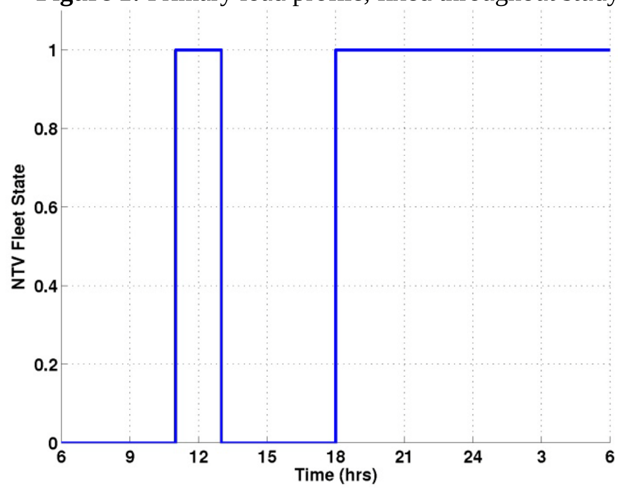

Figure 2: NTV use schedule (0=use, 1=plugged into grid)

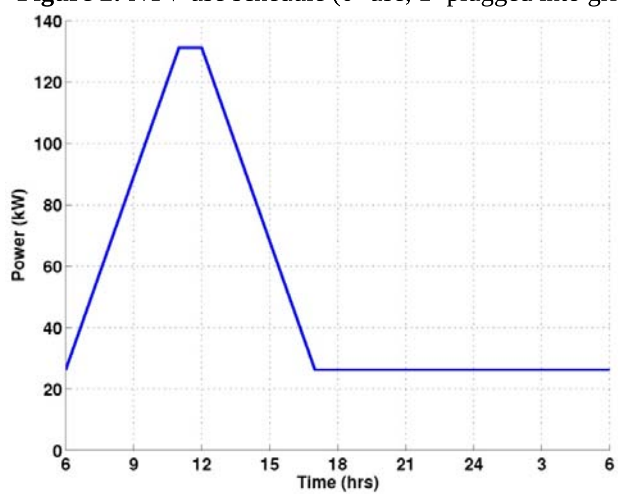

Figure 3: Scalable source profile with 50% penetration PV generation

with a one second time step and its flowchart is shown in Figure 4.

Fleet Size	*20*
P_{PVmax} ***(W)***	1.00E+05
$E_{stormax}$ ***(J)***	8.07E+08
$E_{storinit}$ ***(J)***	2.21E+07

Table 1: Simulation parameters

The simulation first determines if excess power is available on the grid after satisfying the primary loads of Figure 1 using any combination of the PV, constant source, or the storage system. If there is not enough source power, then the mismatched load is computed. If there is excess source and stored energy, and the NTV fleet is plugged in, then the excess power is used to charge the NTV fleet if the fleet has excess capacity. After charging the NTV fleet, any excess power is used to charge the storage system if it has excess capacity. If there is no place to put the excess energy, then it is shed. When the NTV fleet is not plugged in, it has a constant discharge rate as described earlier.

A sample storage system and NTV fleet energy state time history is shown in Figure 5 for the parameters of Table 1. At the beginning of the simulation the NTV decreases at a constant rate since it is not plugged into the grid. The storage system has a relatively low initial charge which depletes in the first 90 minutes. At which time the storage energy remains zero and all loads are missed until the PV generation can make up the primary loads. The storage system charges in-step with the PV source over the day with some extra capacity to charge the NTV fleet when it is plugged in for the day. At about 1400 the storage maximum is reached and there is shed energy for about an hour until PV generation drops. At about 2200 the storage system is once again depleted, but the excess fixed generation allows the NTV fleet to charge, however not back to 100% by the end of the 24 hour period. There is not enough power generated to charge the battery, so its final state is depleted.

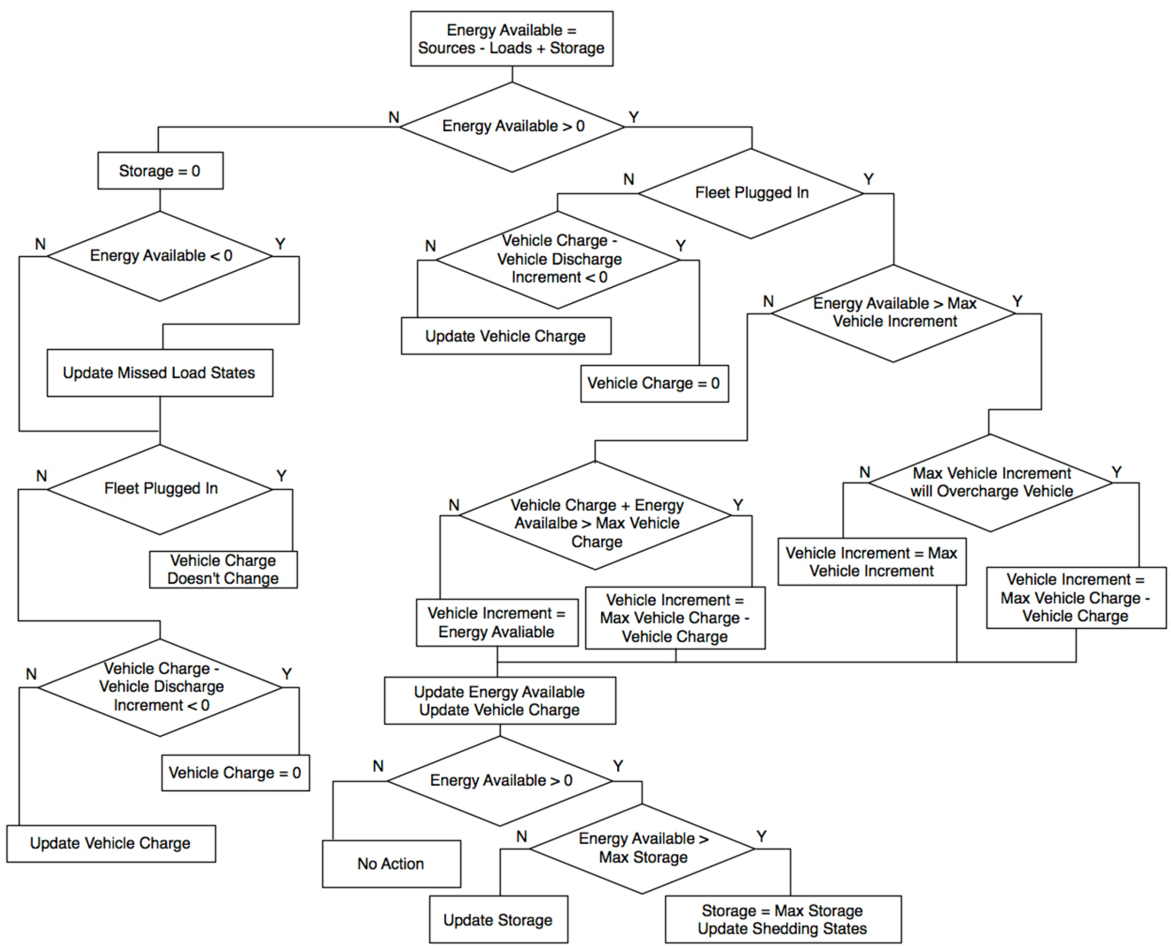

Figure 4: Simulation flow chart

The model and operational scenario assumptions are summarized as:

1. There are no losses in the grid
2. Energy can flow freely to or from storage as demand necessitates
3. The entire NTV fleet operates as a single unit, either charging or discharging together
4. The NTV fleet is in use and discharging whenever not connected to the grid

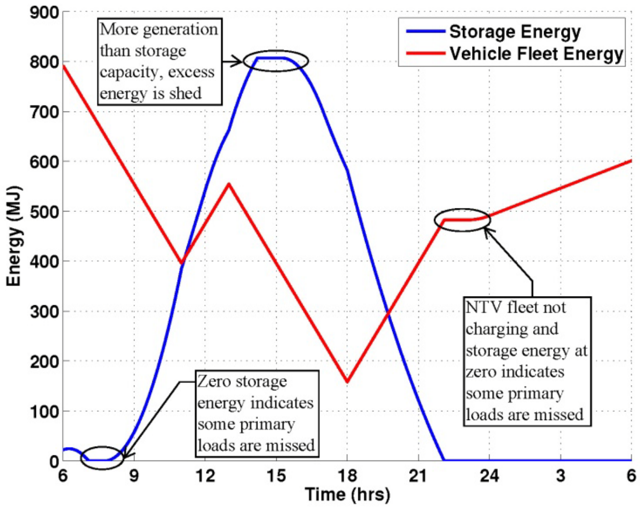

Figure 5: Storage and NTV fleet energy states for a 20-vehicle grid, not optimized

OPTIMIZATION

Using a gradient-based optimization approach (MATLAB's *fmincon* function) in the simulation, the PV array and storage system were sized. Also, the storage system's initial state of charge for a specified number of vehicles in the NTV fleet between 15 and 25 was set. The cost function minimized was the weighted sum of the PV array size and the storage system to reflect the total cost of the system. The constraints, imposed using an additional penalty term in the cost function, were:

1. $E_{storinit} = E_{storfinal}$
2. $E_{NTVfinal} = 100\%$
3. $E_{missed} = 0$
4. $E_{shed} = 0$

The optimal solution for a grid with a 20 vehicle NTV fleet is shown in Table 2 and Figure 6. There are three key features to note about the optimized solution in Figure 6 over the simulation shown in Figure 5. First, after about 90 minutes the storage dips down to zero but the PV generation increases enough at that time to charge the storage supply and avoid any missed loads. Second, when the state of the storage system reaches its peak, it does not saturate and so there is no shed energy. Third, the storage again dips back to zero toward the end of the day while the vehicles are charging, but there is enough energy to fully charge the fleet and to replenish the storage supply to its initial state. Also note that although the storage is at zero, there are no missed loads because the NTV fleet is charging at a slower rate to accommodate the energy state of the system.

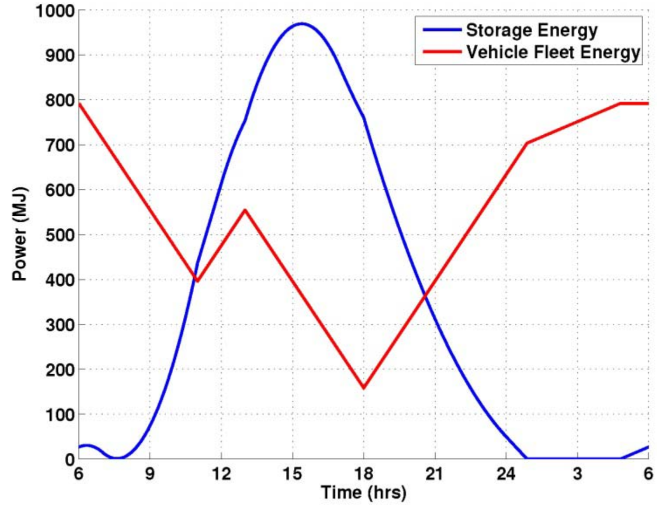

Figure 6: Storage and NTV fleet energy states for optimized 20-vehicle grid

Optimal solutions are found for grids with 15 to 25 vehicle fleets. To further investigate the effect of the fleet size on the grid, each optimal solution is run through the simulation with 50% PV power production to represent a decrease in renewable source output.

RESULTS

Eleven optimal designs were created corresponding to NTV fleet sizes of 15 to 25 vehicles. Integrating the load profile gives the total energy demand from the primary loads throughout the day of 3744 MJ. The total energy required from the vehicle fleet is determined by the number of vehicles and the maximum for each individual vehicle, which is 39.6 MJ. For a 15 vehicle grid the total energy demand is 594 MJ and for a 25 vehicle grid the total is 990 MJ. Since the primary load profile is constant throughout all simulations and because NTV fleet energy demand changes linearly with the size of the fleet, the ratio of NTV load penetration increases linearly from 0.137 for 15 vehicles to 0.209 for 25 vehicles.

Table 2 and Figure 7 show the optimal parameter results for each vehicle case considered. The trends for all three optimization parameters are linear as a function of vehicle number. For all results, the 20-vehicle optimized grid is used as the benchmark to normalize the other results for comparison.

Fleet Size	P_{PVmax} *(W)*	$E_{stormax}$ *(J)*	$E_{storinit}$ *(J)*	*Cost*
15	1.004E+05	8.866E+08	3.714E+07	18.908
16	1.013E+05	9.038E+08	3.574E+07	19.173
17	1.022E+05	9.191E+08	3.245E+07	19.416
18	1.032E+05	9.355E+08	3.024E+07	19.672
19	1.041E+05	9.519E+08	2.790E+07	19.927
20	1.050E+05	9.693E+08	2.659E+07	20.194
21	1.059E+05	9.850E+08	2.349E+07	20.442
22	1.068E+05	1.002E+09	2.140E+07	20.701
23	1.077E+05	1.019E+09	1.960E+07	20.964
24	1.087E+05	1.036E+09	1.734E+07	21.222
25	1.096E+05	1.053E+09	1.617E+07	21.775

Table 2: Optimized simulation parameters and cost

To examine the effect of reduced PV power, for each design of Table 3, the simulation was run with P_{PVmax} reduced by 50%. This resulted in times where the primary loads were missed, and also in reduced NTV fleet state of charge on a per vehicle basis. Figure 8 shows the amount of time where primary loads were missed and Figure 9 shows the reduction in NTV fleet state of charge at the end of the 24 hour simulation. As the number of vehicles increases, the amount of missed primary load decreases. This occurs because the primary load size is constant across all vehicle scenarios. As the number of vehicles increases, the generation increases and the percent contribution of the primary loads to the total capacity of the system decreases. Although the missed time at 50% PV output decreases as the NTV fleet size increases, the final energy state (percent of maximum) of the vehicle fleet decreases with more vehicles because they become a larger fraction of the total load.

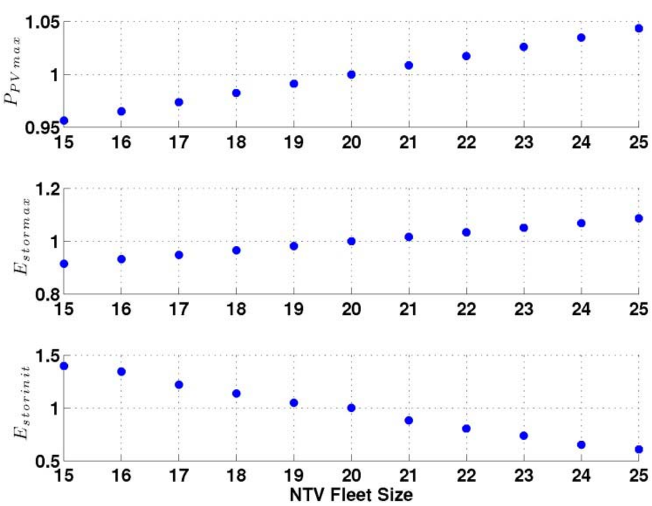

Figure 7: Optimized simulation parameters normalized to the 20-vehicle grid solution

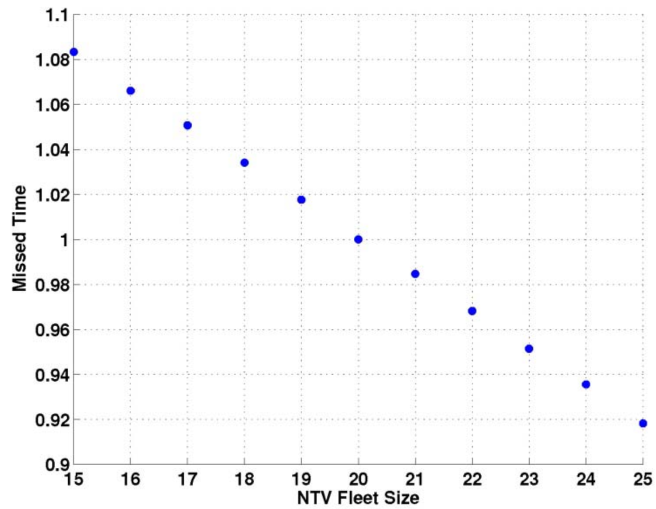

Figure 8: Missed energy time in optimized grids for 50% loss in PV output, missed time is 36476 seconds for 20-vehicle case

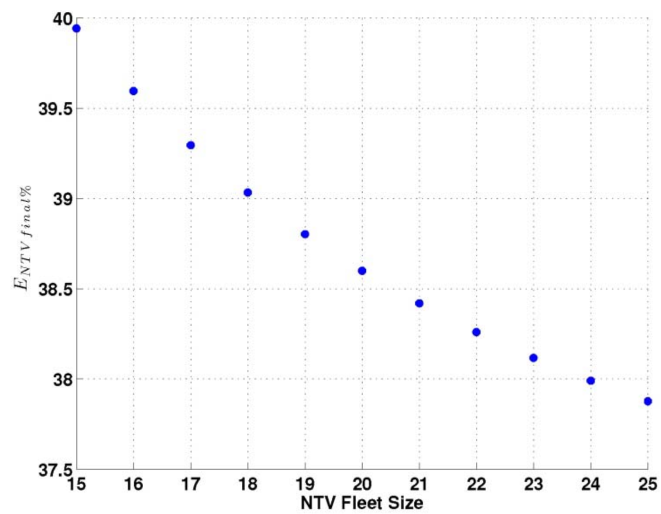

Figure 9: Vehicle fleet final energy state with 50% PV output

CONCLUSIONS

The goal of this paper is to demonstrate that dispatchable NTV loads can be used to stabilize microgrids with high penetration renewable sources, and the results shown in Figure 8 support this claim. Optimizing the grid for a dispatchable fleet decreases the missed energy time from an unpredictable drop in renewable sources. Furthermore, the missed time decreases as the size of the vehicle fleet increases. Thus, for sufficiently large vehicle fleets, all the primary loads can still be met when sources drop. This would be possible only when the NTV load is at a much higher penetration level than was explored here.

One negative consequence is that the vehicles will not have the desired energy state at the end of the day. Additionally, vehicles will have a lower percentage of their total energy level as the number of vehicles increases.

FUTURE WORK

The findings of this study demonstrate that there is some relevance in additionally studying similar microgrid architectures. The work done here could be extended to explore further renewable penetration levels, more diverse grid architecture, and larger NTV fleets among other possible scenarios.

Other future investigations into this subject should consider different renewable sources, as well as real world data. The transient, dynamic behavior of the grid could be incorporated to show the losses in the system and yield a more realistic model as could a different approach to the NTV fleet that tracks the individual vehicles and allows for vehicles to have different use schedules. In addition, these optimization profiles can be used as ideal open-loop profiles and by merging with closed-loop control architecture[6] designs, one can then start to develop robust systems to accommodate the transient behavior and identify more specifically, the storage device dynamic requirements, such as power, energy, and frequency responses.

ACKNOWLEDGEMENTS

This work was supported in part by the John and Cathi Drake Professorship of Mechanical Engineering at Michigan Technological
University.

Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DEAC04-94AL85000.

REFERENCES

[1] J. Davis, et al., "Multi-domain Surety Modeling and Analysis for High Assurance Systems," in IEEE Conference and Workshop on Engineering of Computer-Based Systems, 1999, pp. 254-260.

[2] J. Ehnberg and M. Bollen, "Generation Reliability for Small Isolated Power Systems Entirely Based on Renewable Sources," in IEEE Power Engineering Society General Meeting, 2004, pp. 2322-2327.

[3] D. Halamay, et al., "Reserve Requirement Impacts of Large-Scale Integration of Wind, Solar, and Ocean Wave Power Generation," IEEE Transactions on Sustainable Energy, vol. 2, pp. 321-328, 2011.

[4] W. Lachs, et al., "Power System Control in the Next Century," IEEE Transactions on Power Systems, vol. 11, pp. 11-18, 1996.

[5] W. Kempton and J. Tomic, "Vehicle-to-Grid Power Implementation: From Stabilizing the Grid to Supporting Large-scale Renewable Energy," Journal of Power Sources, vol. 144, pp. 208-294, 2005.

[6] R.D. Robinett III and D.G. Wilson, Nonlinear Power Flow Control: Utilizing Exergy, Entropy, Static and Dynamic Stablity, and Lyapunov Analysis, Springer-Verlag London Limited 2011, Chapter 10.