Real-time Simulation of Demand Side Management and Vehicle to Grid Power Flow in a Smart Distribution Grid

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***Abstract*— The price per kilowatt-hour of energy delivered by the electric power utility varies as the total power demand supplied to the region it serves throughout the day. To save money and protect power system equipment, it may be necessary to schedule the energy consumed during these periods of high/critical demand and higher pricing. In this project, a number of demand-side management strategies (DSM) are tested and compared on a modified IEEE 37-bus distribution feeder model in real time using an OPAL-RT real time simulator. This study focuses on the use of battery electric vehicles (BEVs) as energy storage components of a smart-grid. A stochastic model is used to predict the location of BEVs and their state of charge (SOC) over a 24-hour period. During the high demand periods or fault conditions, a number of BEV users may connect to the grid and supply power by using vehicle-to-grid (V2G) power flow. This number depends on the level of consumer interest in participating in V2G service as well as the location and SOC of each vehicle. The results show that a power utility will benefit by offering incentives to consumers with BEVs that are available to supply power to the grid.**

Keywords*— *Demand side management, overload, transmission, distribution, electric vehicles, load shifting, load shedding,

I. Introduction

The local power utility in Pensacola, FL divides each day into three different pricing periods [1]. During the low demand period (P1), the price of energy is 8.3 cents per kilowatt-hour. During the medium demand period (P2), energy cost is 9.6 cents per kWh; and during the high demand period (P3), energy costs 17 cents per kWh. The pricing periods are shown in Fig.1.

May through October

	P_1	P_2	P_3
Weekdays	11 P.M. - 6 A.M.	6 A.M. – 1 P.M. 6 P.M. - 11 P.M.	1 P.M. – 6 P.M.
Weekends	11 P.M. - 6 A.M.	6 A.M. - 11 P.M.	--------

November through April

	P_1	P_2	P_3
Weekdays	11 P.M. - 5 A.M.	5 A.M. - 6 A.M. 10 A.M. - 11 P.M.	6 A.M. - 10 A.M.
Weekends	11 P.M. - 6 A.M.	6 A.M. - 11 P.M.	---------

Fig.1. Pricing periods from Gulf Power, a local electric power utility.

Load shedding is the simplest method of lowering power demand. In load shedding, the customer or the utility disconnects interruptible loads to decrease power demand during high demand periods. Load shifting is a more practical method of saving energy. With load shifting, the customer disconnects any loads that are not necessary during high demand periods and connects them during low demand periods. This method saves on energy costs without significantly affecting the customer's convenience. One possible method of decreasing demand peaks due to concentrated electric vehicle charging loads is V2G power flow. During the high demand periods, any customer that has a charged electric vehicle can use the energy stored in their vehicle to supply power to the grid, lowering the current drawn from the substation transformer. The effectiveness of these DSM strategies on a smart grid was quantified and an optimized level of use for every DSM method was determined [2]. According to [3], level 2 charging is the most practical charging system to implement V2G power flow. These level 2 chargers have a maximum output of 19kW; however, many EV onboard charging systems cannot accept this maximum output. Due to limitations in the charging system used in V2G power flow, this study assumes the standard V2G output to be 5.0 kW.

An electric power grid simulated in real time can be used to test the effectiveness of these DSM techniques and discover new methods to prevent power congestion and overloading of distribution systems. In this research, the authors have attempted to model the distribution grid with BEVs and adopt DSM strategies to study its effect on the grid. The modeling was carried out using MATLAB Simulink and the simulation was run in real time using OPAL-RT simulator. Simulink is a Matlab based simulation software that can simulate many circuit designs with a simple drag-and-drop graphical user interface. Simulink includes a library for power system components and electronic controllers, and any devices not found in the libraries can be modeled using Matlab code. This software and a standard computer are sufficient for general small-scale power flow studies. However, if the model is more complex or stability must be studied, a more powerful computing system is necessary. OPAL-RT is a real time digital simulator that works with a host computer and Matlab

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Simulink. The Matlab code of the model is compiled into C-code and processed at a much faster rate while data monitoring is performed on the host computer. This model allows for the practical digital simulation of large-scale power grids at a time step as small as 10 microseconds. The model described in this paper is executed with a time step of 50 microseconds.

II. THE MODEL

The model described in this paper is a simulation of the IEEE 37-bus 4.8kV distribution feeder [4]. This data set provides the details of a real unbalanced three-phase power grid in California including line impedance parameters, regulator data, spot load data for every bus, and transformer data. A schematic of the 37-bus feeder is shown in Fig.2. The system was modified to have a symmetrical base load.

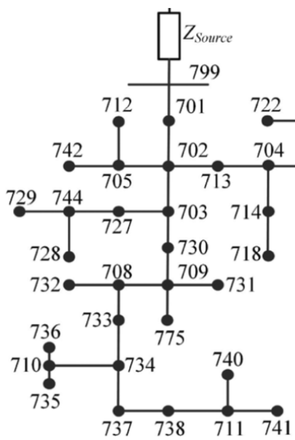

Fig.2. Schematic of IEEE 37-bus distribution feeder.

The Simulink and OPAL-RT blocks used to model the micro-grid are described below:

A. Matlab data files

Matlab data files and "OPfromfile" blocks are used frequently in this model. They are Matlab arrays containing two rows. The first row is the time array. The time array is a row of time values each equally separated by a time step that is not necessarily equal to the time step size of the simulation model. The second row is the data series, containing the data value for every time array value. As the simulation progresses, the OPfromfile block will change its output to the next data value when the simulation timer meets the next time series value. They can be written to any resolution, but the difference from any time value to the previous value must be constant throughout the file. For the model described in this paper, all Matlab date file resolutions must be consistent throughout the model. For some parts of the model, it is necessary to enable the linear interpolation feature of the respective OPfromfile block. This feature will estimate a line between each data point of the data file, allowing for smoother variations between data points and an estimated data point for every time step. An example of the OPfromfile block and its inputs is shown in Fig.3.

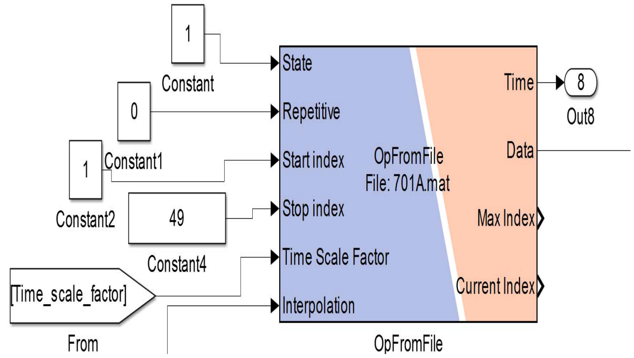

Fig.3. OPfromfile block and inputs, supplying data to the load on phase-A of bus 701.

B. Transmission lines

Transmission lines are modeled using the "Artemis Distributed Parameters Line" block. This block allows for the input of the following parameters: number of phases, frequency, impedance values per kilometer, and the length of the line. An example of the DPL block supplying the load at bus 731 is shown in Fig.4.

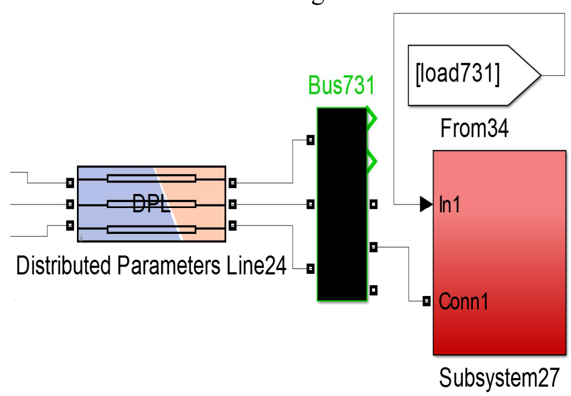

Fig.4. Distributed Parameters Line example.

C. Spot loads

The "three-phase dynamic load" block is used to model varying three-phase loads and varying single-phase loads. The values for the spot load data provided in the IEEE data set were assumed to be the typical peak demand of each load. These values were set as the maximum power drawn by their respective loads. Using the data in [5], the load for a typical summer day in Tampa, Florida was normalized by dividing every power demand data point by the maximum power demand value in the data set. This normalized input from a Matlab data file is multiplied by the maximum spot load value and the product is used to supply a scaled power demand signal input to the dynamic load block. For a balanced three-phase load, the block is connected to the grid by all three phases. For a single-phase load, the loaded phase is connected and the remaining phases are grounded. An example of a single-phase dynamic load is shown in Fig.5.

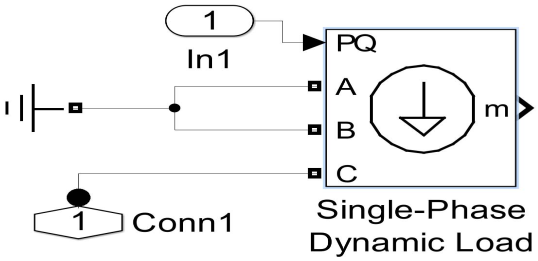

Fig.5. Single-phase Dynamic Load block example.

D. *Feeder source*

The power utility source to the grid is modeled by an ideal three-phase voltage source with the impedance of the transformer given in the data set. This block acts as a swing bus for the grid, supplying any power that the renewable sources, generators, and V2G cannot provide. The power flowing through this bus is monitored and recorded. The feeder source and the OpWriteFile block used to record data is shown in Fig.6.

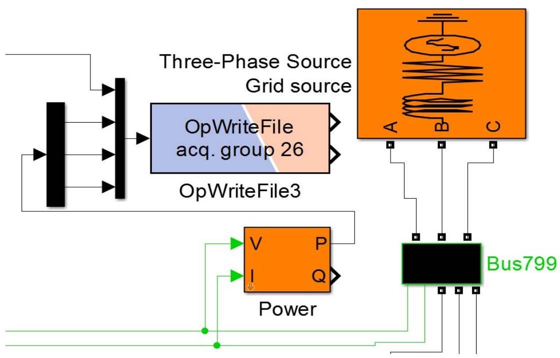

Fig.6. Ideal Feeder Source and OpWriteFile block example.

E. *Generators*

Generator models are based on the "controlled current source" blocks. The block is set to type "AC". An ideal three phase voltage source was used as the signal to drive the voltage controlled current sources. The voltage source was measured with a "three-phase measurement" block, and the output of the measurement block is multiplied with a scaling factor. The new signal is connected to the input of the controlled current source block. To vary the generator's output over time, the scaling factor must be fed with a Matlab data file. The schematic of the generator model is shown in Fig.7.

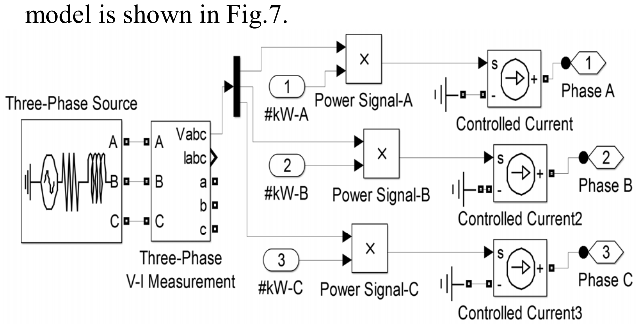

Fig.7. Generator model schematic.

F. *Electric vehicle charging load and vehicle-to-grid power flow model*

The electric vehicle load portion of the model is very similar to the spot load model. Instead of a normalized input, the Matlab data file supplies the number of vehicles charging in the area at that time interval. This value is multiplied with the power drawn by one charging vehicle (assumed 6.6kW). The vehicle-to-grid (V2G) power flow portion of the model is very similar to the generator models. A Matlab data file supplies the number of active V2G suppliers, and that value is multiplied by the typical power that can be sourced by an electric vehicle in V2G mode (assumed 5kW). The data values in the Matlab file are generated by the stochastic model developed in [6]. An EV charging and V2G model is shown in Fig.8.

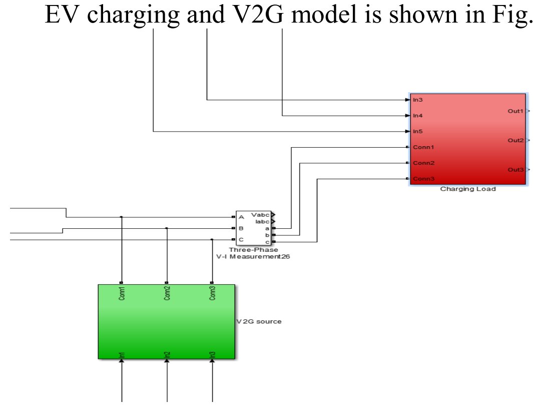

Fig.8. EV charging and V2G model.

G. *Reactive Power Control Systems*

Reactive power control systems are modeled with a "Three-phase Dynamic Load" block and a simple control system. This model subtracts the measured RMS voltage from the desired RMS voltage at a bus. The difference is multiplied by a scaling factor and added to the previous reactive power value. This model continuously adjusts the injected reactive power in order to correct power factor and voltage deviation. An example of a capacitor bank model is shown in Fig.9.

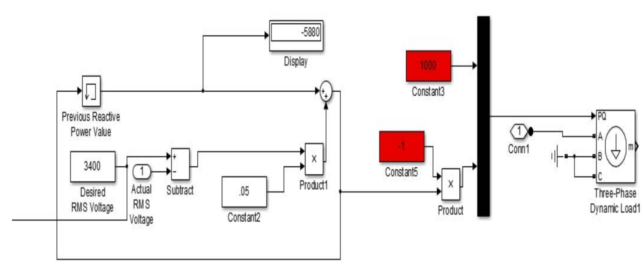

Fig.9. Example of reactive power control system model.

H. *Wind farm and photovoltaic array*

The wind farm and solar plant is based on the "controlled current source" blocks. The block is set to type "AC". An ideal three phase voltage source was used as the signal to drive the voltage controlled current sources. The voltage source was measured with a "three-phase measurement" block, and the output of the measurement block is multiplied with the power signal. The power signal is formed by multiplying the normalized output of an OPfromfile block with the constant block containing the maximum power output of the modeled source. The product of the AC signal and the power signal are fed to the current sources determine the current in each phase at each time interval. The renewable source model is shown in Fig.10.

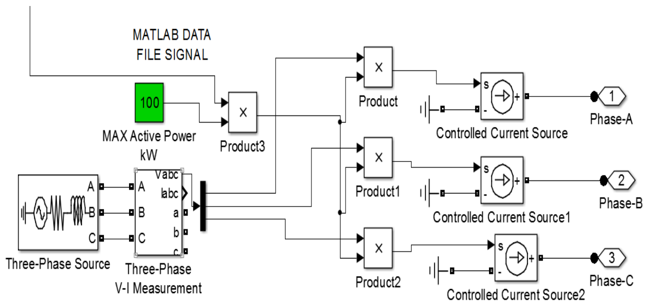

Fig.10. Example of renewable source model.

III. TEST SCENARIOS

The distribution grid serves a base residential load as well as 600 EVs that charge or supply power to the grid according to a stochastic model. The system is loaded the point where the 2.5MVA substation transformer is critically loaded at the daily demand peak due to EV charging loads. In order to reduce the daily demand peak to 90% of the transformers MVA rating, the following methods are considered:

- Load shed: Loads are simply disconnected by the utility when desired. Total demand on system during high price and critical load period is reduced by 10%
- 10% load shift: Consumers choose to disconnect their loads during the high demand period and connect them at another time. 10% of the total demand during high price and critical load period is shifted to lower demand periods.
- V2G: Available charged EVs can be used to supply power to the grid during the high price and critical load period. The number of active participants is determined by the stochastic model and a consumer participation factor.

First, all three DSM techniques are compared at 100% V2G participation. Then, the level of V2G participation is varied and the effects on the demand profile are observed.

IV. RESULTS

10% Load Shed:
In this case, the demand during the high/critical demand period is reduced by 10%. This is the ideal condition; however, it is highly unlikely to occur.

10% Load Shift:
In this case, the high/critical demand is reduced by 10%, but the load is then connected during a lower demand period. This results in a flatter load profile which is desired by the power utility.

100% V2G Participation:
When assuming every available V2G user participates in supplying power during the high demand period, the peak demand was reduced by 18.2%.

Fig.11 displays the graph comparing the daily load profile using the three DSM techniques compared to the base load profile including BEV charging loads. Fig.12 shows the different load profiles for varying levels of V2G participation during the high/critical load period. The results show that widespread V2G participation can significantly reduce power demand peaks and flatten a substation transformer's load profile when necessary. A power utility and its consumers could benefit greatly by offering incentives to BEV owners to participate in scheduled V2G implementation. The results show that if just 50% of already available BEV users participate during high/critical demand periods, the high/critical load during that period is reduced by 10.2%. This would provide the same benefits of an ideal 10% load shed but without potentially inconveniencing any customers. This study assumes that the standard output for V2G equipment is 5kW, a conservative assumption. Potential benefits could be even more significant as V2G equipment performance increases.

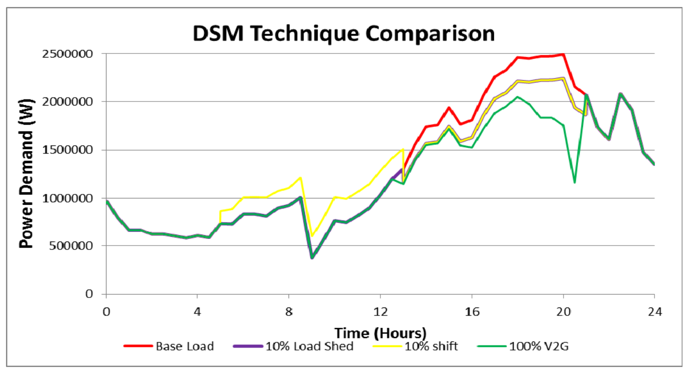

Fig.10. Load Profile Comparison of DSM Techniques

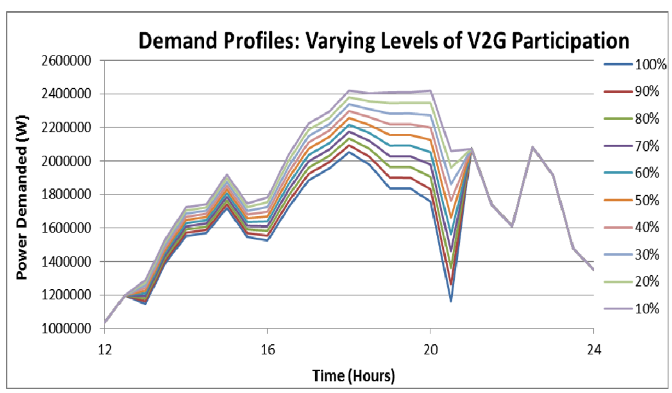

Fig.11. Load Profiles from Different Levels of V2G Participation

V. CONCLUSION

This paper presents the integration of a real-time 37-bus distribution grid simulation with a stochastic model that predicts the location, state of charge, and charging status of every electric vehicle in a given area. The simulation and model are used to record and compare the substation transformer load profiles produced by implementing standard DSM strategies and widespread V2G power flow participation. Future research in this area could include using V2G capabilities to increase reliability of a smart grid during fault conditions. For example, instead of rerouting all current through an already heavily loaded line during a fault, V2G power flow could be used to reduce the current drawn from the heavily loaded line. Also, this study does not consider scheduled charging as a method for load shifting. Offering incentives to participate in scheduled charging and V2G power supply will enable a power utility to preserve its equipment and avoid new installations.

REFERENCES

[1] Residential Service Variable Pricing, Gulf Power, 2015. (online) available at: http://www.gulfpower.com/pdf/rates/rsvp.pdf

[2] M.A. López, S. de la Torre, S. Martín, J.A. Aguado, “Demand-side management in smart grid operation considering electric vehicles load shifting and vehicle-to-grid support”, in Electrical Power and Energy Systems, August 2014.

[3] U.S. Department of Energy, "Vehicle-to-Grid Power Flow" Idaho National Laboratory, 2009.

[4] 37-bus feeder. (online) available at: http://ewh.ieee.org/soc/pes/dsacom/testfeeders/

[5] U. S. D. O. Energy, Office of Energy Efficiency & Renewable Energy, “The Residential Energy Consumption Survey,” 2013.

[6] A. Keyhani, “Stochastic Modeling Of Battery Electric Vehicles For Predicting Power Demand,” Poster presented at the Power and Energy Conference at Illinois 2017