EVS24
Stavanger, Norway, May 13-16, 2009

Smart Storage Concept of Grid-connected Electric Vehicle for introducing Renewable Energy to Power System

Yutaka Ota[1], Yoshihiro Hashimoto[2]
[1]*The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku,Tokyo 113-8656, JAPAN, yota@upn.t.u-tokyo.ac.jp*
[2]*Nagoya Institute of Technology, hashimoto@nitech.ac.jp*

Abstract

Renewable energy like photovoltaic and wind power will be introduced into power system with a large percentage of total power generation. Battery energy storage is used for smoothing natural variability of renewable energy in Mega Solar, Wind Park, and Micro Grid. And total capacity of the battery is reduced in Smart Grid because of the grid-wide smoothing effect of renewable energy and the load dispatch by not only battery energy storage but also controllable distributed generator, networked demand equipment, and G2V or V2G of grid-connected EV.

We propose an autonomous distributed "Smart Storage" concept making full use of vehicular battery's high power and fast response features. Smart Storage is able to behave as governor free or spinning reserve for the power system by using modeling technique about battery itself and power system. A central load dispatch center take care of the final load frequency control considering the frequency dependent characteristic of power system generator, load, and Smart Storage.

In this paper, a system structure of intelligent and networked Smart Storage on electric vehicle, battery modeling, power system modeling from demand side power outlet where electric vehicle is plugged-in, and outline of information stream between vehicles and power system, are explained.

Keywords: BEV, PHEV, Battery model, State of Charge, V2G

1 Introduction

In Japan, photovoltaic and wind power will be introduced over 30% of the peak demand (ex. 179TW in 2007 summer) until 2030 shown in Table1[1]. Mega solar, wind park, and Micro Grid require the battery energy storage for smoothing natural variability of renewable energy.

Smart Grid reduce the total capacity of the battery. Because the grid-wide smoothing effect of renewable energy is obtained, and residual power fluctuation is managed to be dispatched by not only battery energy storage but also controllable distributed generator or networked demand equipment.

As a kind of demand response, V2G (Vehicle-to-Grid), in which high power onboard battery of grid-connected EV and PHEV can be used for power grid operation, is investigated and demonstrated[2],[3]. Maximum 40% of Japanese 64 million vehicles will be replaced to the next-generation vehicle including PHEV and EV until 2030. Only 5% grid-connected PHEV and EV with 50kW battery is assumed, total power output for V2G (64000MW) is equals to photovoltaic and wind power (59820MW) shown in Table1.

Table1: Actual achievement and future maximum introducing case of renewable energies and next-generation vehicles in Japan[1]

	actual achievement until 2005	maximum introducing case until 2020	maximum introducing case until 2030
Photovoltaic power	1420 MW	14320 MW	53210 MW
Wind power	1080 MW	4910 MW	6610 MW
Next-generation vehicle	0% of total vehicles	20% of total vehicles	40% of total vehicles
64 million vehicles 50kW battery 5% grid-connected	0 MW	32000 MW	64000 MW

To realize V2G, a battery management based on the battery state estimation is premise for additional charge-discharge cycles by V2G. And simple information exchange between vehicles and power grid is expected for spinning reserve to the sudden supply-demand imbalance and the load frequency control of power grid considering the whole vehicle's behaviour.
We propose an autonomous distributed "Smart Storage" concept realizing V2G with fast response and smart cooperation to the power system. A structure of intelligent and networked Smart Storage is described in this paper. And an outline of the information stream between vehicles and power system and the power system operating method is introduced.

2 Smart Storage Concept

2.1 System Structure

A system structure of Smart Storage concept is summarized in Figure1. EV motor is generally driven at higher voltage than battery voltage in order to reduce the ohmic loss of motor. A DC-DC converter is used as boost chopper, and about 500V AC is supplied through an inverter. These power electronics circuits could be appropriated to the grid-connection.
Each EV's ECU (Electric Control Unit) acquire self battery model by a model identification test. Battery SOC is momentarily estimated based on the acquired model, and battery capacity and internal resistance, which is concerning to battery SOH, is evaluated as model parameters. Concrete procedure of the battery modeling and SOC estimation is described in a chapter 3.
It is well known that supply-demand imbalance cause the frequency deviation all over the power system, which is likened as the scales in Figure2. Therefore, the supply-demand imbalance of the power system is observed from the frequency deviation. PMU (Phasor Measurement Unit)[4],[5] technology enables accurate and synchronized frequency measurement from the power outlet, where EVs are plugged-in. Details of frequency measurement are explained in a chapter 4.
Each grid-connected EV recognize the supply-demand imbalance by measured frequency, and immediately take a charge restraint or an additional G2V or V2G depending on the estimated self SOC and the power system state. This autonomous distributed method shows EV batteries ability to the full, that is high power and fast response. The battery of grid-connected EV, that is called "Smart Storage" in this paper, could effectively contribute the spinning reserve for sudden generator trip and the smoothing the fast natural variability of renewable energy.

2.2 Cooperation with Power System

Central load dispatch center grasp the state of Smart Storage. Time interval of information gathering might be relatively late, for example fifteen minutes. Because battery behaviour can be predicted by the battery model and battery SOC at the beginning of gathering interval. Therefore, the model parameters, for example, battery capacity, internal resistance, and so on, are collected in addition to the estimated battery SOC.
Finally, a load frequency control of the power system is operated considering the frequency dependent characteristics of power system generator, load, and Smart Storage. The frequency dependent characteristics of Smart Storage are acquired by accumulating the product of measured frequency deviation and appropriate preset control gain of each Smart Storage. The control gain are dominated by the battery SOC.

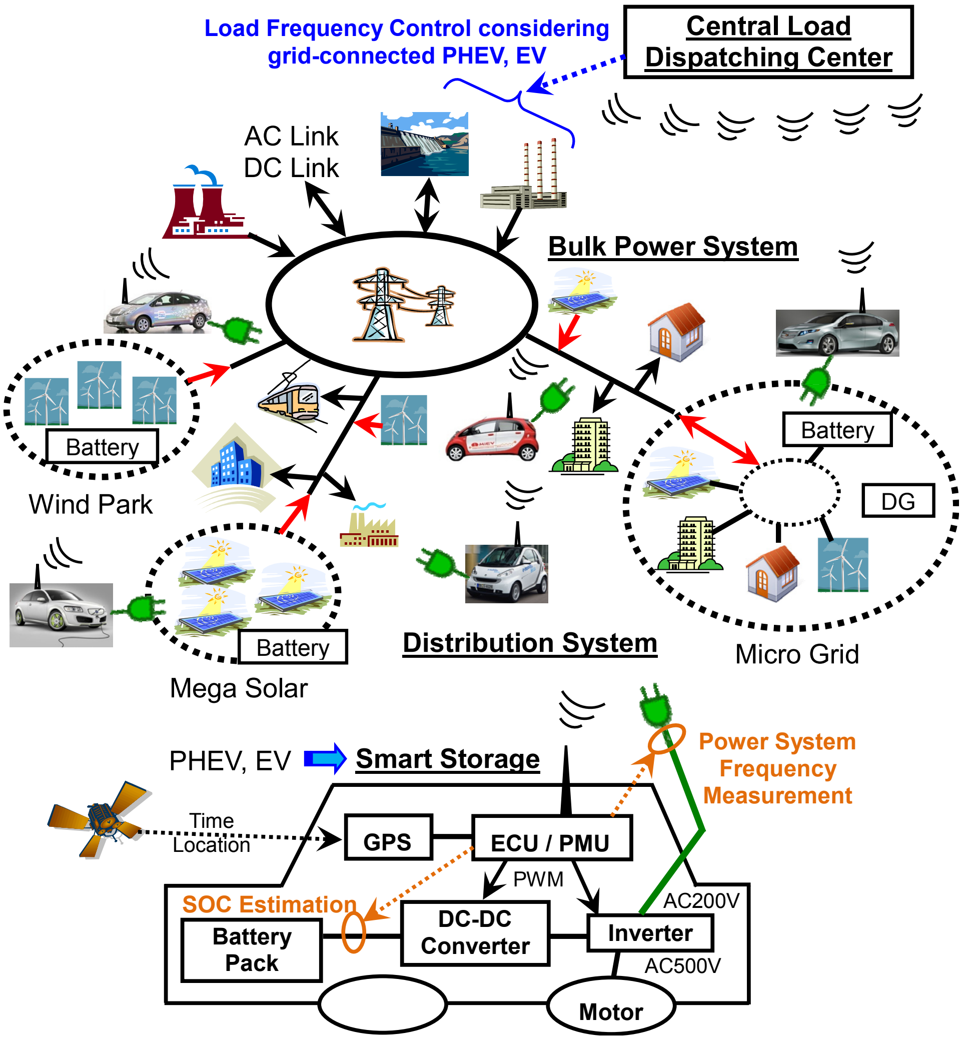


Figure1: Smart Storage concept for grid-connected electric vehicles

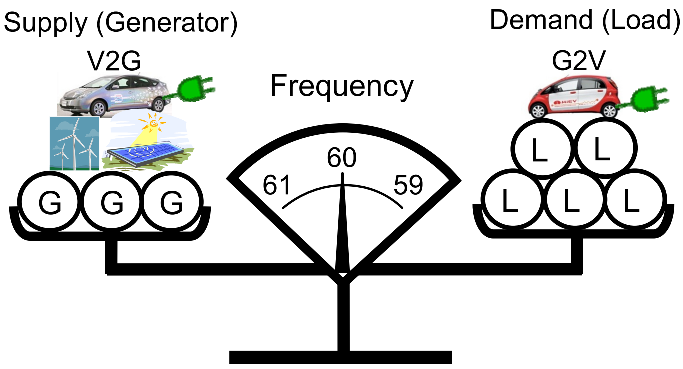


Figure2: The scales characteristics between supply-demand balance and power system frequency

3 Battery Modeling[6]

3.1 Model Structure

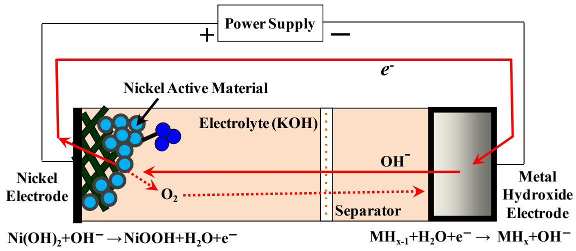
Battery SOC is generally estimated by coulomb counting. As charge and discharge cycle is increased, estimation error is accumulated by calibration error of current sensor, side reaction and self discharge of the battery, and so on. Therefore the relationship between OCV (Open Circuit Voltage) and SOC, which is based on Nernst equation, is used in combination. However voltage hysteresis[7],[8],[9] and relaxation make the measurement of OCV difficult. Measured OCV after charge (discharge) is higher (lower) than estimated OCV by Nernst equation, and is slowly relaxed with time constant from few minutes to few hours. This voltage hysteresis has been modeled by adding simple voltage modification term to Nernst equation[10],[11], by using a SOC-dependent voltage source including hysteresis[12],[13].

In this paper, to express voltage hysteresis and relaxation of NiMH battery, which is in commercial use as a HEV battery, three layers model concerning Nickel active materials is proposed. Figure3 shows a schematic diagram of NiMH battery and a proposed model during charge. A voltage gap between surface and inside of Nickel active materials is introduced, and voltage hysteresis is modeled as surface partial battery decides OCV of the whole battery. Voltage relaxation is also expressed as equalization between surface layer and relaxation layer with higher internal resistance. After charge-discharge, internal charge exchange flows according to potential difference between surface layer and relaxation layer.

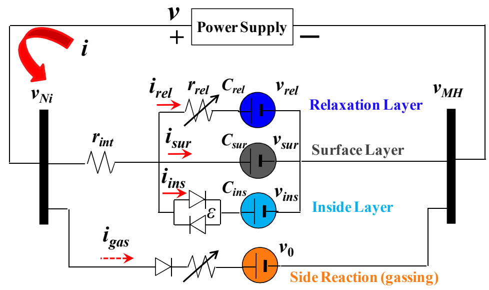
3.2 Experimental Validation

Proposed model is applied to the experimental results of 7.2V 6.5Ah NiMH battery module. In advance, the model parameters, capacitor ratio of three layers, two internal resistances, and forward voltage of diode, are carefully decided through a model identification test. Then an initial state of the model is adjusted by using EKF (Extended Kalman Filter).

The voltage hysteresis and relaxation in each SOC range and its dynamical behaviours are confirmed to be modeled as shown in Fiure4. Internal state including battery SOC can be estimated by proposed model. And information about battery SOH is also evaluated by periodical model identification test.

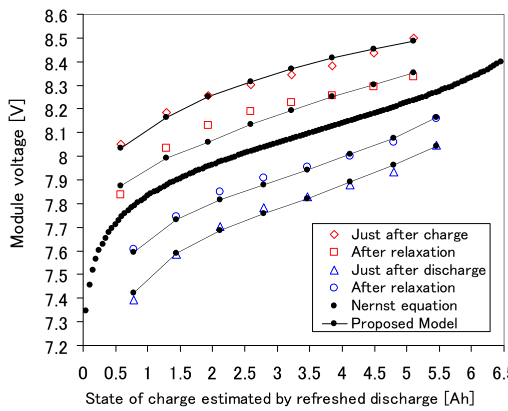


(a) Schematic diagram of NiMH battery

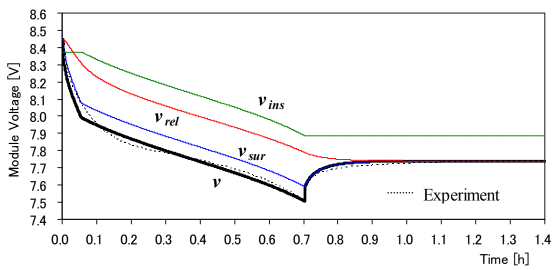


(b) Equivalent three layers model

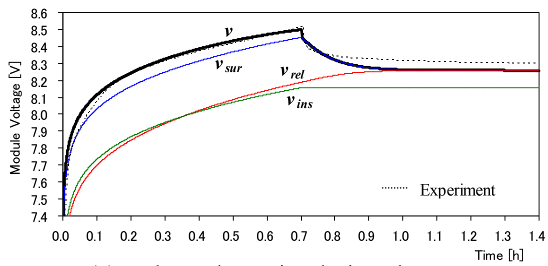
Figure3: NiMH battery model



(a) Voltage hysteresis and relaxation



(b) Voltage dynamics during discharge



(c) Voltage dynamics during charge

Figure4: Modeling of battery voltage

4 Power System Modeling

PMU is in the spotlight as a key technology of WAMS (Wide-Area Measurement System), and some applications making use of a merit that synchrophasor shows the snapshot of power system state have been developed for world-wide power systems[5]. Recently, PMU/WAMS network is spread into lower voltage power outlet at distribution level. The power system frequency is used for evaluating power system event such as a sudden generator trip and power system modeling[14],[15].

We believe that these distributed level PMU technology have a great potential. Very huge constituents of future Smart Grid, that are distributed generators, demand side equipments, and grid-connected Smart Storages proposed in this paper, can understand the power system state at self interconnected terminal with synchronism. These "Smart Grid devices" contribute the power system operation such as governor free, spinning reserve, and demand response by taking the power system frequency by PMU as a common index. Of course, synchronizing action is easily accomplished at the same time.

Authors have been developed Campus PMU/WAMS[16] for another research project as shown in Figure5. Figure6 show the grid-wide synchronized frequency measurements when a sudden generator trip occurred. Common tendency of frequency drop is confirmed as shown in Figure6.

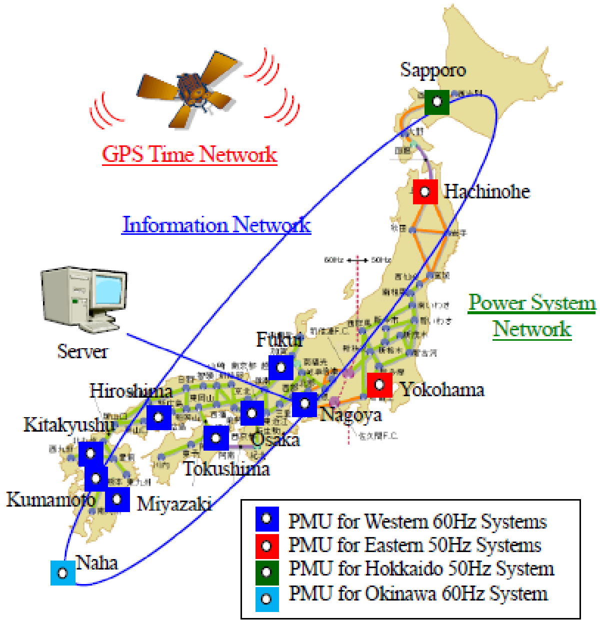


Figure5: Campus PMU/WAMS at distribution level

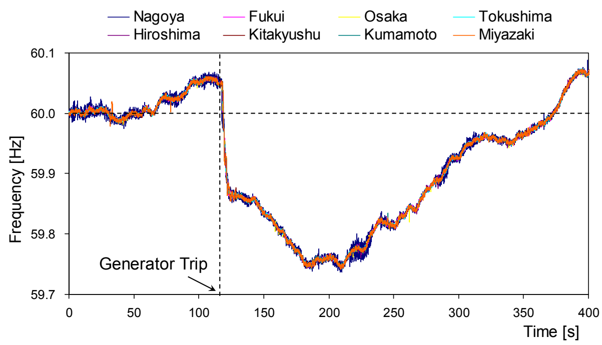


Figure6: An example of grid-wide frequency measurements

5 Conclusion

In this paper, a system structure of autonomous distributed Smart Storage concept for grid-connected electric vehicle is proposed. Each Smart Storage understand the power system state from synchronized frequency measurement at self interconnected terminal. On the other hands, the power system understand the aggregated behaviour of Smart Storage from a simple information about battery model and SOC.

Fast response of vehicular battery realize smoothing of fast natural variability of renewable energy. And information stream between vehicles and power system would be simplified for future Smart Grid.

Future work is a battery modeling of lithium ion battery by the proposed three layers model and a battery SOH evaluation by the model parameters. Numerical simulations are necessary for the power system load frequency control considering Smart Storage.

Acknowledgments

This research was partially supported by 1) Japan Power Academy, 2) the Naito Science & Engineering Foundation, and 3) the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (A) 18206028.

The authors gratefully acknowledge these supports.

References

[1] "Long-term energy supply-demand forecast", Ministry of Economy, Trade and Industry, http://www.enecho.meti.go.jp/topics/080523b.pdf (in Japanese) (2008)

[2] MAGICC (Mid-Atlantic Grid Interactive Cars Consortium), http://www.magicconsortium.org, accessed on 2009-04-13

[3] M.Duvall, "Plug-in Hybrid and Electric Vehicles", SAE Hybrid Technology Symposium (2009)

[4] K.E.Martin et al, "Exploring the IEEE Standard C37.118–2005 Synchrophasors for Power Systems", IEEE Trans. Power Delivery, Vol.23, No.4, pp.1805-1811 (2008)

[5] A.G.Phadke et al, "The Wide World of Wide-Area Measurement", IEEE Power & Engineering Magazine, September/October, pp.52-65 (2008)

[6] Y.Ota et al, "Modeling of Voltage Hysteresis and Relaxation of HEV NiMH Battery", Proc. 16th IFAC World Congress (2008)

[7] K.P.Ta and J.Newman, "Proton Intercalation Hysteresis in Charging and Discharging Nickel Hydroxide Electrodes", J. The Electrochemical Society, Vol.146, No.8, pp.2769-2779 (1999)

[8] V.Srinivasan, J.W.Weidner, and J.Newman, "Hysteresis during Cycling of Nickel Hydroxide Active Material", J. The Electrochemical Society, Vol.148, No.9, pp.A969-A980 (2001)

[9] C.G.Motloch et al, "Implications of NiMH Hysteresis on HEV Battery Testing and Performance", Proc. The 19th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exposition (2002)

[10] Y.H.Pan, V.Srinivasan, and C.Y.Wang, "An Experimental and Modeling Study of Isothermal Charge/Discharge Behavior of Commercial Ni-MH Cells", J. Power Sources, Vol.112, pp.298-306 (2002)

[11] M.Verbrugge and E.Tate, "Adaptive State of Charge Algorithm for Nickel Metal Hydride Batteries Including Hysteresis Phenomena", J. Power Sources, Vol.126, pp.236-249 (2004)

[12] M. Thele et al, "Impedance-based Modeling of Electrochemical Energy Storage Devices – A Successful Implementation for NiMH Batteries used in Design Tools for Hybrid Electric Vehicles", Proc. The 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exposition (2006)

[13] O. Bohlen et al, "Robust Algorithms for a Reliable Battery Diagnosis -Managing Batteries in Hybrid Electric Vehicles", Proc. The 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exposition (2006)

[14] O.Samuelsson et al, "Monitoring of Power System Events at Transmission and Distribution Level", IEEE Trans. Power Systems, Vol.21, No.2, pp.1007-1008 (2006)

[15] J.Dong et al, " Monitoring power system disturbances at the distribution level", Proc. IEEE PES General Meeting, pp.1-8 (2008)

[16] Y.Ota et al, "Monitoring of Interconnected Power System Parameters using PMU based WAMS", Proc. IEEE PowerTech Conference, pp.1718-1722 (2007)

Authors

Yutaka Ota received the Ph.D. degrees in engineering from Nagoya Institute of Technology in 2003. He researched about PMU/WAMS for power system monitoring, protection, and control and about battery management for HEV as a Assistant Professor of Nagoya Institute of Technology. He is currently a Project Assistant Professor of the University of Tokyo. Research project is about Ubiquitous Power Grid and Smart Grid including PHEV and EV.

Yoshihiro Hashimoto received the Ph.D. degrees in engineering from Kyoto University in 1986. He is currently a Professor of Nagoya Institute of Technology. His research interest is about process system control and nonlinear system control.