Vehicle-to-Grid System Supplying Flexible Charge/Discharge Capability for House, Building, and Power System

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***Abstract* — Many electric vehicles will be interconnected with the household parking spot in the near future. There is huge potential of electric vehicle as the distributed energy storage because the vehicle is sleeping at the household in most of the day, and he/she have very large capacity battery, 40/62kWh, Nissan Leaf in the laboratory. The electric vehicles connected with the HEMS can contribute self-consumption of rooftop photovoltaic generation, emergency power supply, and the grid-level and distribution-level control, and so on. The authors have proposed a smart inverter control for the electric vehicle, in which active and reactive power is managed as conditions of the power system frequency deviation and the voltage profiles in the distribution feeder. Performance of the proposed smart inverter control was evaluated by the campus HILS (Hardware-In-the-Loop Simulation) facility.**

Keywords-component; Electric Vehicle, Photovoltaic Generation, Energy Management, V2G, V2H, HEMS, Voltage Control, Frequency Control

I. INTRODUCTION

In case of massive integration of rooftop photovoltaic generations (PV), flexible power reserves against variable power output of the photovoltaic generations are required around residential area. Combination of the photovoltaics and battery energy storage brings valuable functions such as self-consumption and emergency power supply for the residence. Electric vehicles (EV) have a huge potential of acting as household energy storage when they are interconnected with the charging spot. Vehicle-to-Grid (V2G) control is also expected because the recent EVs have larger capacity of battery than household energy usage.

An optimization algorithm of HEMS (Home Energy Management System) with a PV, an EV, and household loads based on the model predictive control have been proposed by Nagoya University [1]. Charge or discharge profile of the EV is determined for minimizing the electricity bill of electrical loads and/or maximizing self-consumption of the PV. In this paper, a HEMS controller HILS (Hardware-in-the-loop Simulation) is conducted. The cloud based HEMS is implemented to in Nagoya University, and charge and discharge set point is transferred to the EV and charging facility in Tokyo City University.

As a smart inverter control for the PV and EV, the frequency deviation versus active power droop control [1] and the voltage deviation versus reactive power droop control [2] have been proposed. Control performance of the proposed control was verified through the power HILS. However, it is concerned about interference to the power system dynamics when there are some delays in communication, computation, system response, and so on.

In this paper, we are focusing on communication delay and device response in case of remote control of the EV and charging facility for the HEMS and the power system stabilization. Feasibility of implementation and control performance is evaluated by a controller HILS for the cloud based HEMS and a power HILS for the EV and charging facility.

II. TEST CONDITION

A. ECHONET Lite Communication Protocol

ECHONET Lite [4] is a communication protocol used in HAN (Home Area Network), and uses an IP connection environment such as Ethernet or Wi-Fi. It uses UDP / IP communication, which is popular on Ethernet, and enables air conditioner and lighting control from a smartphone as shown in Fig. 1. There is a gateway PC to communicate with controllable EV charging facility, Smart V2H. In this research, ECHONET Lite communication protocol is used for activating V2G control. Charge or discharge command, frequency/voltage/power measurements, EV state such as SOC (State-Of-Charge) can be exchanged by standardized ECHONET Lite flame as shown in Fig. 2.

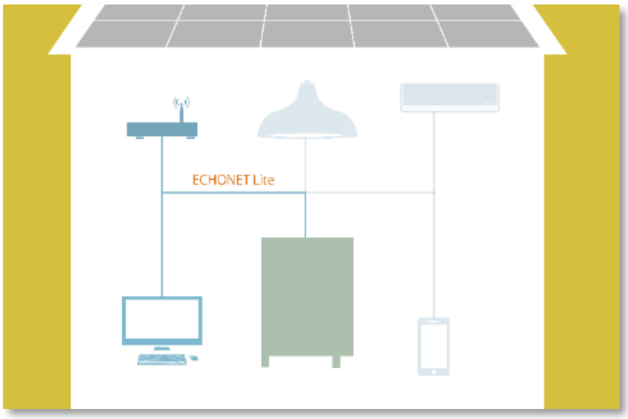


Figure.1 ECHONET Lite.

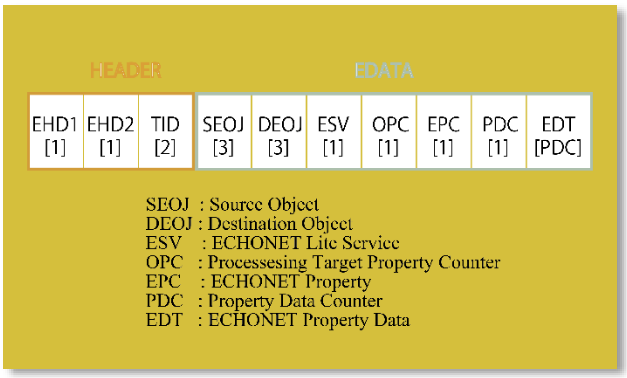


Figure.2 ECHONET Lite flame.

B. *Configuration of HILS*

Fig.3. shows overview of the HILS. The cloud based HEMS server is located on Nagoya University, and the gateway PC is in Tokyo City University. Controller HILS via VPN network is executed by data exchange between the site.

In this research, a bulletin board type data exchange is established between the site. Status of the EV and charging facility in Tokyo City University is transferred to the HEMS server, then the HEMS server in Nagoya University returns EV charge and discharge profile till 24 hours ahead. Dataset is sequentially saved in JSON type file, as shown in Fig. 4, which is easy to treated by Python.

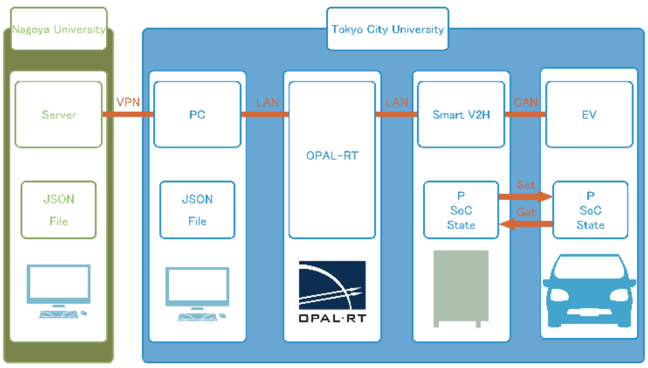
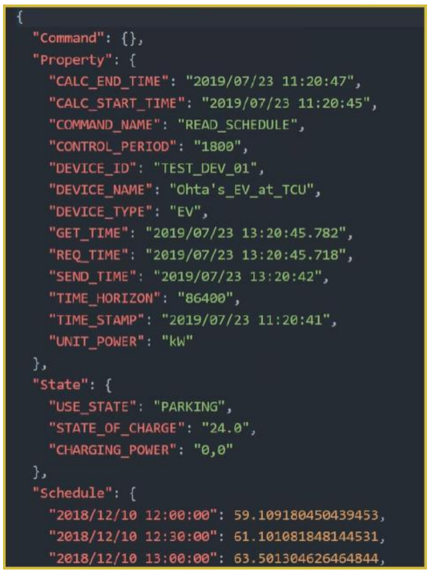


Figure.3 Structure of HILS.



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{
  "Command": {},
  "Property": {
    "CALC_END_TIME": "2019/07/23 11:20:47",
    "CALC_START_TIME": "2019/07/23 11:20:45",
    "COMMAND_NAME": "READ_SCHEDULE",
    "CONTROL_PERIOD": "1800",
    "DEVICE_ID": "TEST_DEV_01",
    "DEVICE_NAME": "Ohta's_EV_at_TCU",
    "DEVICE_TYPE": "EV",
    "GET_TIME": "2019/07/23 13:20:45.782",
    "REQ_TIME": "2019/07/23 13:20:45.718",
    "SEND_TIME": "2019/07/23 13:20:42",
    "TIME_HORIZON": "86400",
    "TIME_STAMP": "2019/07/23 11:20:41",
    "UNIT_POWER": "kW"
  },
  "State": {
    "USE_STATE": "PARKING",
    "STATE_OF_CHARGE": "24.0",
    "CHARGING_POWER": "0,0"
  },
  "Schedule": {
    "2018/12/10 12:00:00": 59.109180450439453,
    "2018/12/10 12:30:00": 61.101081848144531,
    "2018/12/10 13:00:00": 63.501304626464844,
```


Figure.4 Shared data between the universities.

Real time power system digital simulator, Opal-RT, have two roles, ECHONET Lite gateway and the power system emulation. Opal-RT communicates with Smart V2H by use of standard ECHONET Lite frame, and evaluate response of communication and calculation accurately. CHAdeMO protocol over CAN communication is used for realizing V2G function coordinating the EV and the charging facility.

The power system model and the distribution feeder model, details are shown in the next section, are installed into Opal-RT. Opal-RT can emulate not only the EV charge and discharge profile received from the cloud based HEMS but also the power system stabilizing control for the EVs.

Emulated frequency and voltage deviations at each node in the power system simulator are implemented to the two power amplifiers, AMETEK MX15 and TriphaseNV PM15. And two charging facilities, Mitsubishi Electric Smart V2H and TriphaseNV PK5, are interconnected with the power amplifiers. Measurements of active and reactive power output of the charging facilities are returned to Opal-RT, then closed-loop power system frequency and voltage deviations considering the EV control can be generated as a power HILS. Configuration of the power HILS at Tokyo City University is summarized in Fig. 5. Power output of the charging facility is 3kW, and capacity of EV battery is 64kWh, Nissan Leaf e+.

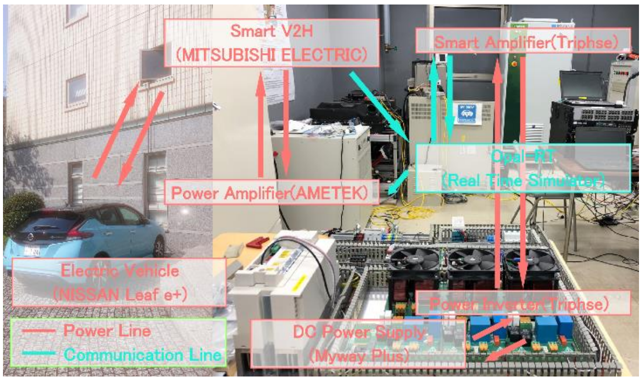


Figure.5 Configuration of power HILS.

C. *Coupled Model of Power System and Distribution Feeder*

Fig. 6 shows a power system model [2] consisted by a thermal power generation, a photovoltaic generation, an aggregated electricity demand, and EVs. For electricity demand, hysterical data supplied by Tokyo Electric Power Company is reduced as a prefecture level Microgrid. Maximum electricity demand is about 8.3GW. Economic dispatching control and load frequency control is supplied by an aggregated thermal generator with a typical turbine and governor dynamics. The installed capacity of the photovoltaic power generation is 20% against the peak electricity demand, and typical generation curve in a cloudy day is assumed. The number of installed EV is assumed as 48000, which is 16% of ownership rate of passenger cars in this Microgrid region.

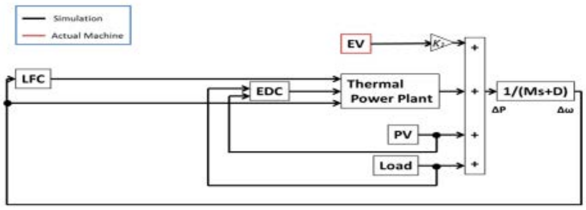


Figure.6 Power system model.

Fig. 7 shows the distribution feeder model [3] emulating local voltage distribution around the residences. The secondary voltage of the distribution substation was 6600V, and the frequency of the voltage source at the distribution substation is as frequency deviation calculated by the power system model explained in the previous section. The length of the distribution line is 5km, the number of residences in the distribution feeder is 720, and the residences are divided to five nodes. All the residence has 0.5kW load, 6kW rooftop PV, and the EV. The power amplifiers are interconnected with top and end node of the distribution feeder considering with gain for aggregated 144 residences in a node. As for the EV V2G control, gain for the Microgrid is also considered.

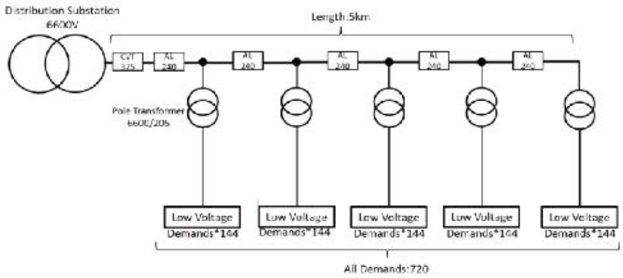


Figure.7 Distribution feeder model.

III. RESULT OF HIL TEST

A. *Step Response of Single EV*

Delay of internet communication between the site can be evaluated from time difference of "REQ_TIME" and "GET_TIME in the shared JSON file shown in Fig. 4. The delay of internet communication was 0.064 second. Opal-RT receives active power command for single EV from the gateway PC, and communicate with Smart V2H by use of ECHONET Lite frame. Then measurements of actual power output are returned to Opal-RT. Fig. 8 shows measurement results of a step response in Opal-RT. The system response including local communication, response of the charging facility and EV, and power measurement is found to be about 0.3 second.

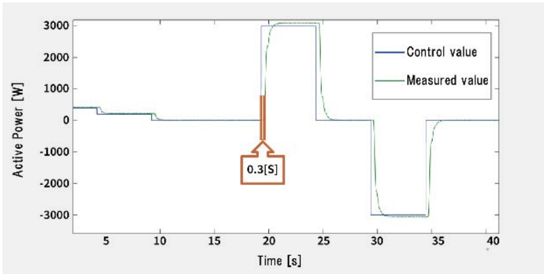


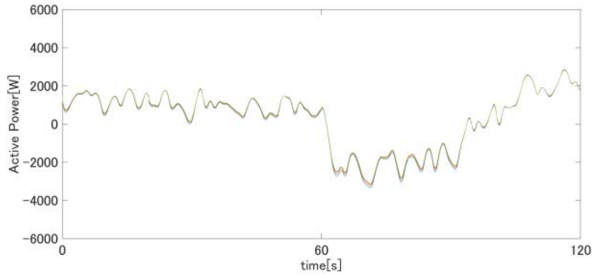
Figure.8 Step response of active power control.

B. *HILS for Frequency Control*

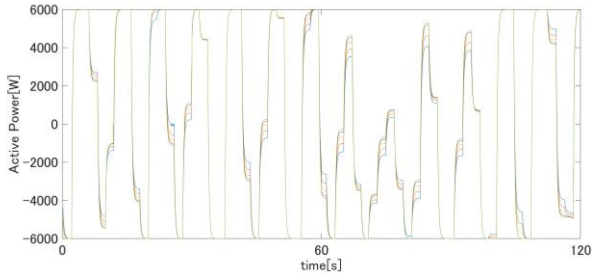
In case of the power system stabilizing control, system response might be critical because an aggregator integrate state of multiple EVs and determine charge and discharge profiles for multiple EVs. In this research, variation of dead-time in communication, control, and measurement is assumed in the emulated EVs in the HILS. Variation of the dead-time is set as 0.0 (fast), 0.5, 0.8, 1.0, 1.2, 1.5, and 2.0 (slow) seconds.

Active power outputs of EVs and resulted frequency deviations under variable dead-time situation are summarized in Fig. 9 and Fig. 10, respectively. It is confirmed that frequency control is successfully achieved by fast response EVs. On the other hands, there are oscillations on the frequency if dead-time is significant. Interference between the dynamics of conventional generator and the system response of the EVs would be occurred.

Absolute values of maximum frequency deviations are summarized in Fig. 11. EV active power control is found to be effective when dead-time is within 0.8[s]. Frequency is unstable when dead-time is larger than 2.0[s].

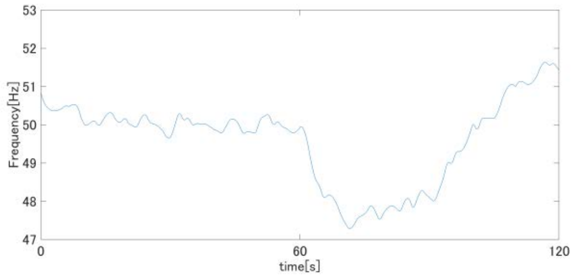


(a) Dead-time 0.0[s] (Fast)

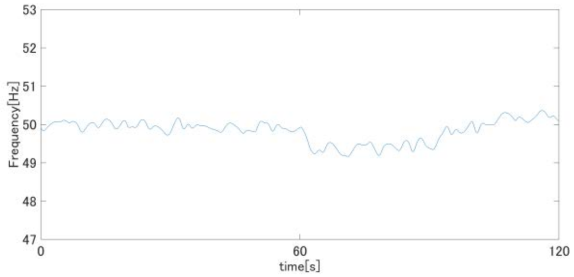


(b) Dead-Time 2.0[s] (Slow)

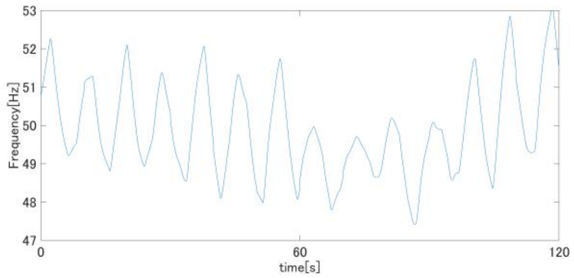
Figure. 9 Active power outputs of EVs.



(a) Without EV control



(b) Dead-Time 0.0[s] (Fast)



(c) Dead-Time 2.0[s] (Slow)

Figure.10 Frequency deviations.

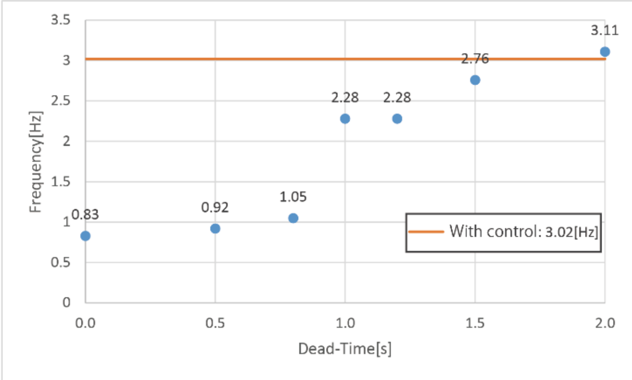
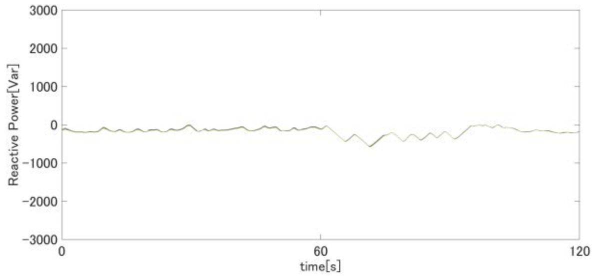


Figure. 11 Impact of dead-time on frequency control.

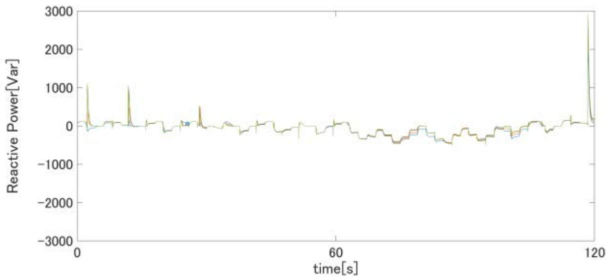
C. *HILS for Voltage Control*

Reactive power outputs of EVs and resulted voltage deviations under variable dead-time situation are summarized in Fig. 12 and Fig. 13, respectively. It is confirmed that voltage control is successfully achieved by fast response EVs. On the other hands, there are oscillations on the voltage if dead-time is significant. Interference between the EVs and the local voltage distribution would be occurred.

Absolute values of maximum voltage deviations are summarized in Fig. 14. EV reactive power control is found to be effective when dead-time is within 0.8[s], same as the frequency control.

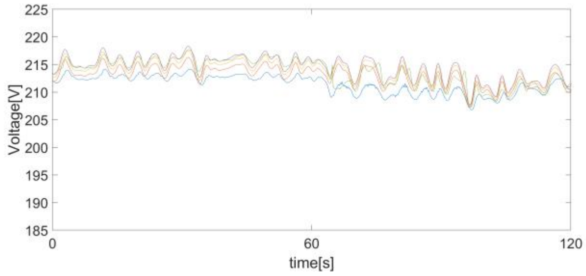


(a) Dead-Time 0.0[s] (Fast)

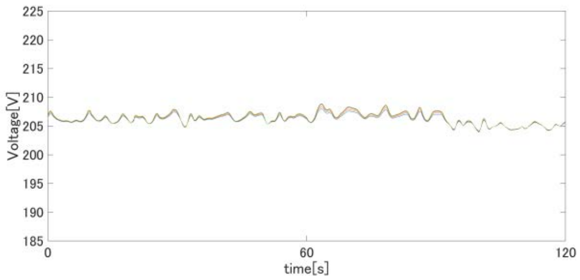


(b) Dead-Time 2.0[s] (Slow)

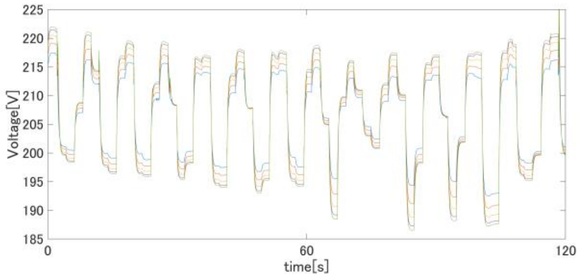
Figure. 12 Reactive power outputs of EVs



(a) Without EV control



(b) Dead-Time 0.0[s] (Fast)



(c) Dead-Time 2.0[s] (Slow)

Figure.13 Voltage deviations.

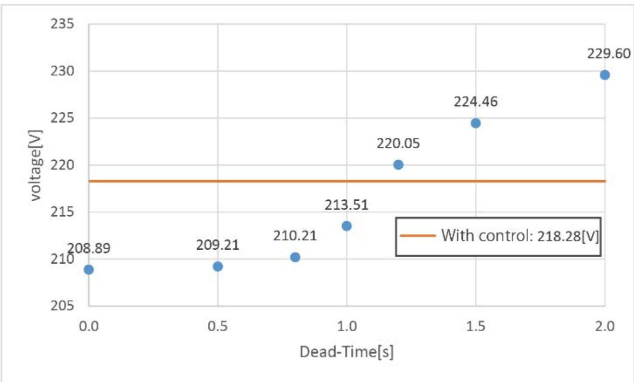


Figure.14 Impact of dead-time on voltage control

IV. Conclusion

In this paper, the controller HILS targeting the cloud based HEMS was constructed based on VPN network between Nagoya University and Tokyo City University. The power HILS consisted by a power system real time simulator, EV fleet, and the charging facilities is also conducted in Tokyo City University campus.

System response controlling single EV is small enough, 0.3 second. Communication delay between the universities is also small in this time. However, it is concerned that the power system oscillations on the frequency and voltage would be occurred because of slow response of the EV control. On the power system and distribution feeder model assumed in the paper, 0.8 second was a threshold value of the dead-time.

This research was supported by JSPS KAKENHI 17K06316 and JST CREST JPMJCR15K3.

References

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