Autonomous Voltage and Frequency Control by Smart Inverters of Photovoltaic Generation and Electric Vehicle

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Abstract — **Voltage fluctuation and frequency fluctuation is to be significant issue in case of large-scale interconnection of photovoltaic generation and electric vehicle into the power system. In this paper, smart inverter control of interconnection inverter system of PV and EV is proposed as a countermeasure against the power quality issue. Effectiveness of the proposed control is verified through the HIL tests modifying the system wide frequency fluctuations and local voltage violation in the local distribution power system with massive PV and EV, simulated inverters of PV and EV. Two smart inverters of PV and EV is actually interconnected with the HIL simulator in which characteristics of multiple inverters are modified.**

Keywords-component; electric vehicle, photovoltaic generation, distribution power systems, smart inverter control, voltage management, frequency management.

I. INTRODUCTION

With the increase in interconnection of photovoltaic power generation (PV) and electric vehicle (EV) to the distribution power system, voltage fluctuation would be issued caused by the complicated power flow on the distribution lines. Sudden supply and demand imbalance would cause frequency fluctuation on the power system level. In order to evaluate effectiveness of PV and EV smart inverter connected to distribution feeder, simulation considering both voltage and frequency and test using actual machines are required.

One of the countermeasures against the voltage fluctuation, smart inverter control of the PV has been proposed [1]. An autonomous Watt&Volt/Var control is confirmed to be effective for massive PVs integration environment [2]. In this paper, the Watt&Volt/Var control is modified to the PVs and EVs. Furthermore, autonomous smart inverter control that suppresses both voltage fluctuation and frequency fluctuation is proposed by implementing Freq-Volt/Watt control in EV inverter.

When inverter connected to the distribution feeder is used to adjust frequency fluctuation, it is necessary to consider both voltage and frequency. Furthermore, in order for multiple inverters to autonomously active and reactive power control at the same time, it is necessary to consider interference and transient instable phenomena of the inverter control loop and between the inverters.

We have constructed HIL(Hardware In the Loop) consisted by a real-time power system simulator in which voltage and power flow profile on the distribution feeder with massive PVs and EVs and frequency fluctuation by demand and supply calculation are assumed, two power amplifiers, and two smart inverter system flexibly controlling active and reactive power output. Then, we have verified effectiveness of the proposed control method using HIL.

II. TEST CONDITION

A. Power System Model

Demand and supply calculation model [3] composed of thermal power generation model, photovoltaic power generation models, electric power demands and electric vehicles are shown in Fig.1. We assumed a microgrid (Kanagawa prefecture) in which the frequency fluctuation is significant with massive photovoltaic generation integration into the microgrid. Governor Free Control (GF), Load Frequency Control (LFC), Economic load Dispatching Control (EDC), are supplied by an aggregated thermal power generator. Large-scale power fluctuation of photovoltaic generation is assumed without consideration of their smoothing effect. Electricity demand is based on 16.7% proportional division of historical data of TEPCO (Tokyo Electric Power Company).The number of passenger vehicles in Kanagawa prefecture is 3 million. Considering EV possessing rate of 16% in 2030, 480 thousand electric vehicles are interconnected with the power system. Charging and discharging capability for each EV is 3 kW. It is assumed that all the EVs are interconnected with the same SOC (State-of-Charge) in this paper.

B. Disribution System Model

A distribution feeder model is shown in Fig.4. R/X values of distribution lines and transformers are summarized in Table

1. Nominal value of secondary voltage of distribution substation is 6600V, and length of high-voltage distribution line is 5km. Five nodes are assumed on the distribution line, and 144 customers are connected to a node through a pole transformer and low-voltage distribution lines. Total number of the customers is 720. Nominal values of voltage, power demand, PV generation power, and EV charging power at the customer is 200V, 0.5kW, 6.0kW, 6.0kW, respectively. Grid frequency is calculated by use of the power system model described in the previous section.

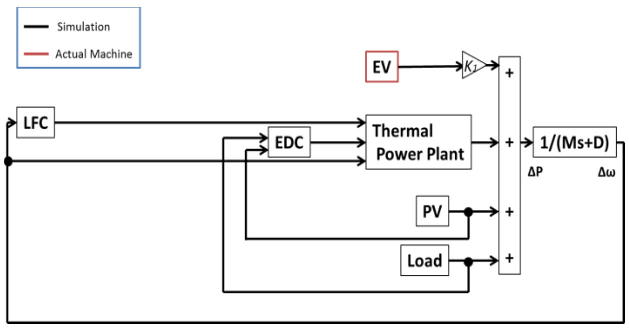


Figure.1 Power system model

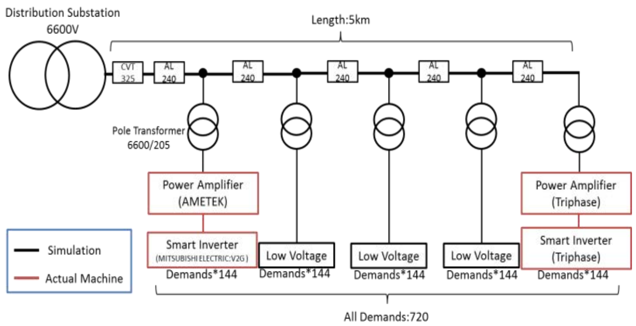


Figure.2 Distribution system model

Table.1 R/X values

	Resistance R[Ω/km]	Reactance X[Ω/km]
CVT325	0.0762	0.0954
AL240	0.126	0.309
ALOE120	0.253	0.268
DV2.3	2.3	0.094
Pole Transformer	0.0186	0.0328

C. Conditions of HIL Test

In the real-time power system simulator (Opal-RT: OP5600), multiple smart inverter of PVs and EVs are modified as ideal current source, and active and reactive current injected as the voltage phase angle detected by the PLL. Instantaneous values of a terminal voltage can be emulated by use of two different power amplifiers (AMETEK: MX15-1pi, TriphaseNV: PM15). Two different rapid prototyping inverters (TriphaseNV: PK5, MITSUBISHI ELECTRIC: Smart V2G) is interconnected with the power amplifiers, respectively. Actual inverter systems have a high-speed ACR within a second time response, and active and reactive power is controlled by the APR and the AQR block according to measured voltage and power output at interconnection point.

Power HIL is realized by controlling active and reactive power as voltage, frequency and active power measurements, and active and reactive power measurements are returned to the real-time simulator. Laboratory setup of the HIL is shown in Fig. 3.

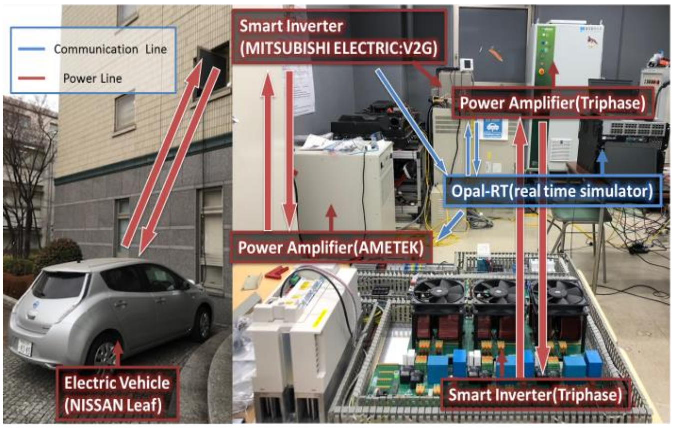


Figure.3 Setup of the HIL

III. Control Method

A. Reactive Power Control (Watt&Volt/Var)

Reactive power of smart inverters is autonomously controlled according to both active power output (charging power) of the PV (EV) and voltage at interconnection point [1]. The reactive power control scheme is summarized in Fig, 4, and voltage and power factor droop is shown in Fig.5. Reference value of interconnection point voltage is 202V with tolerant range between 190V to 214V, and limit between 188V to 222V. The lowest value of power factor (cos *θ*) is assumed as 85%.

B. Active Power Control (Freq-Volt/Watt)

Active power of smart inverters is autonomously controlled according to the frequency. Furthermore, when the voltage fluctuation becomes large, additional control mitigating local voltage impact is considered. The proposed active power control scheme is summarized in Fig. 6. Frequency and active power droop, and voltage and active power droop are shown in Fig.7.

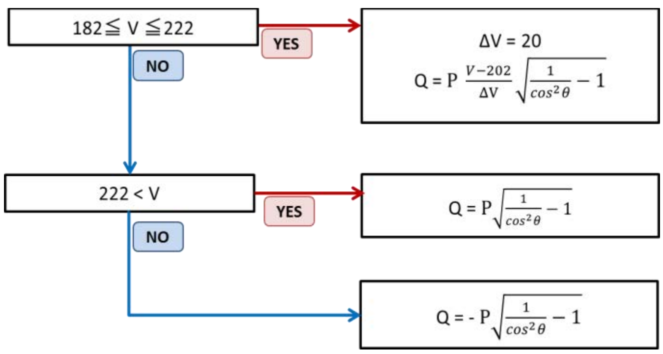


Figure.4 Flowchart of reactive power control

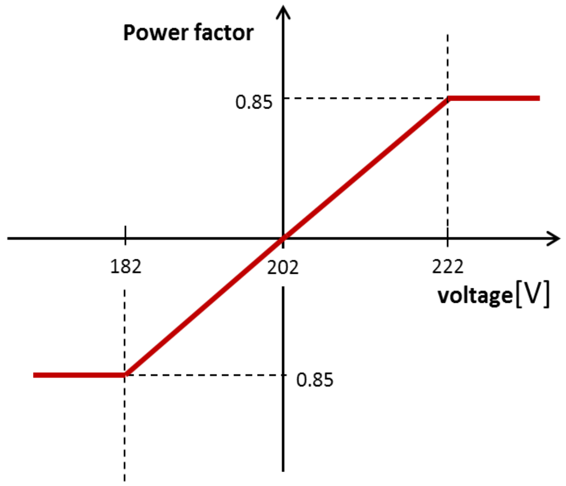


Figure.5 Voltage and power factor droop

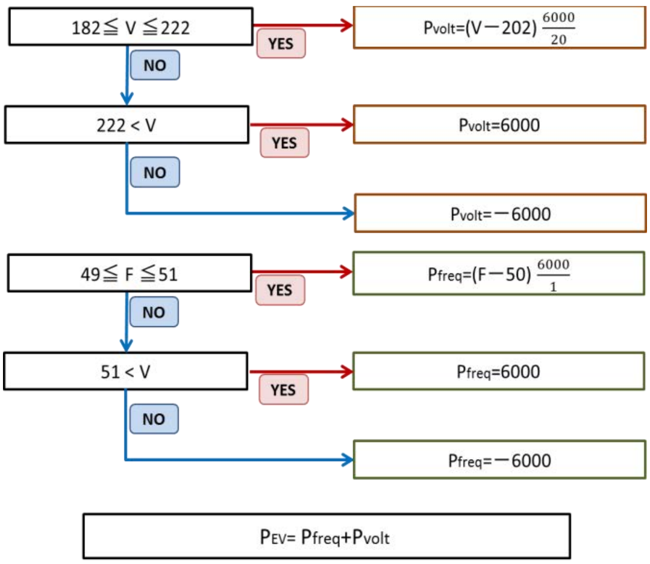
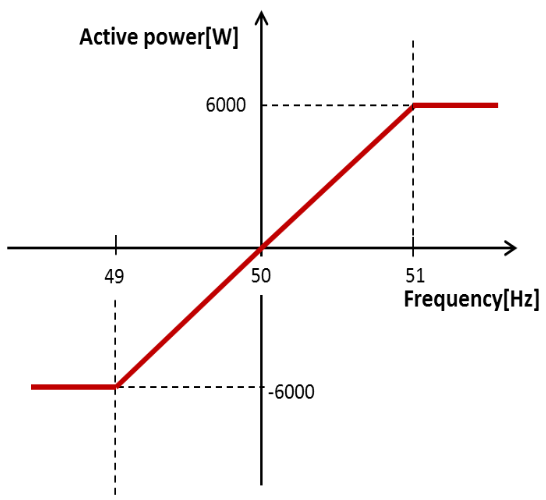
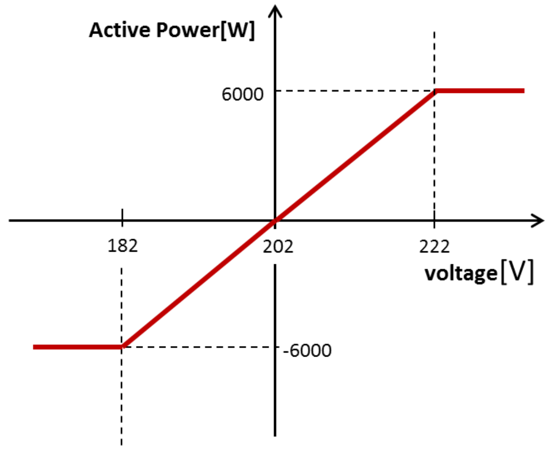


Figure.6 Flowchart of active power control



(a) Frequency and active power droop



(b) Voltage and active power droop

Figure.7 Frequency-voltage and active power droop

IV. RESULT OF HIL TEST

A. Preparation of verification

MITSUBISHI ELECTRIC: Smart V2G is connected to near the distribution substation (node1) and TriphaseNV: PK5 is connected to terminal (node5). Both smart inverters are modified as EV. Other PVs and EVs in each node were installed in the real-time simulator using ACR with 0.2 sec dead time and first-order lag, in which time constant is 0.15 [s], modifying the response of actual inverter.

Fig. 8 is showing a step response test with step frequency change from 50[Hz] to 50.5[Hz] to verify active power control. It is confirmed that smart inverter model in the simulator is similar response of the actual inverter system (TriphaseNV: PM15).

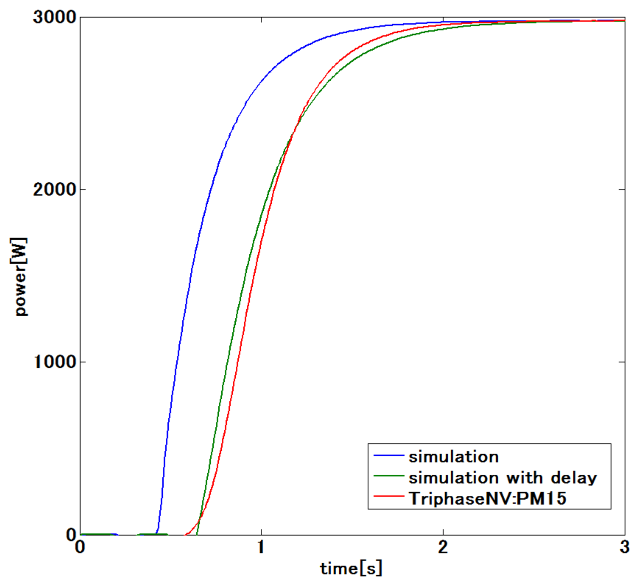


Figure.8 Result of step response test

Power output of the PV is based on the actual measurements on cloudy day as shown in Fig. 9. HIL test was performed for 10 minutes from 13:00 to 13:10.

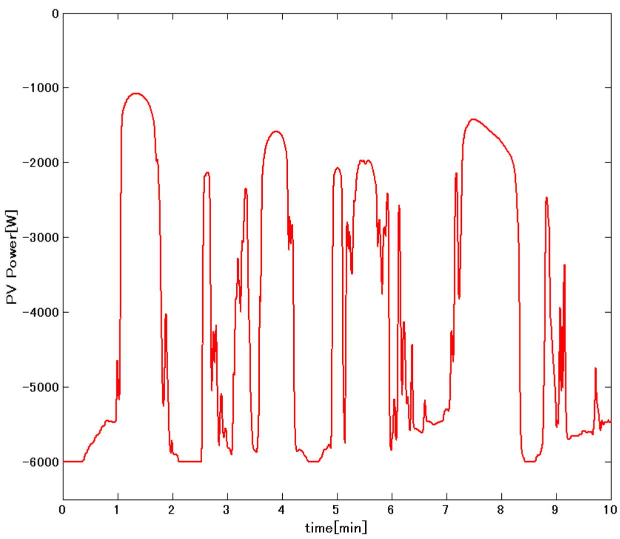
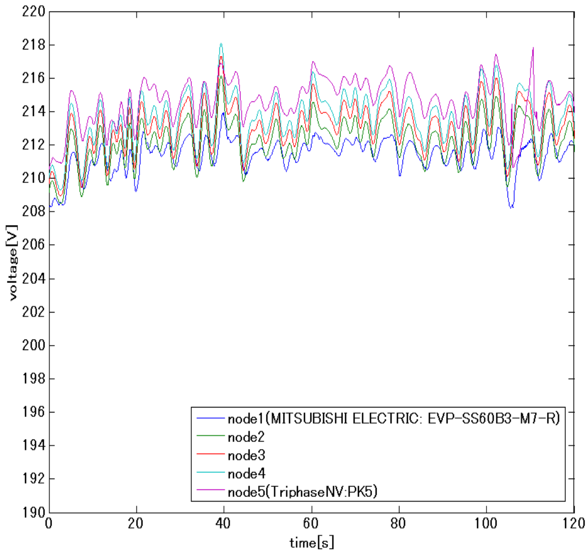


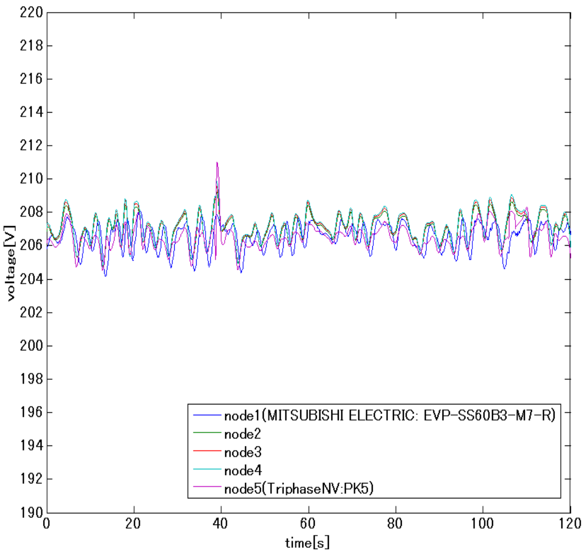
Figure.9 Power output of photovoltaic generation

B. Result of Voltage

Experimental results of voltage are shown in Fig. 10. Voltage fluctuation is obviously suppressed by the proposed control. Compared with simulated results in Fig. 11, similar control performance is obtained in the HIL case despite of small vibration. From Table 2, voltage is violated from target value without control. However, both HIL and simulation cases can stabilize the violation within the target. Those results are showing that there is no interference in the smart inverters even if two actual inverters are interconnected to the HIL.



(a) Without Control



(b) With Control

Figure.10 Experimental results of Voltage at Each Node

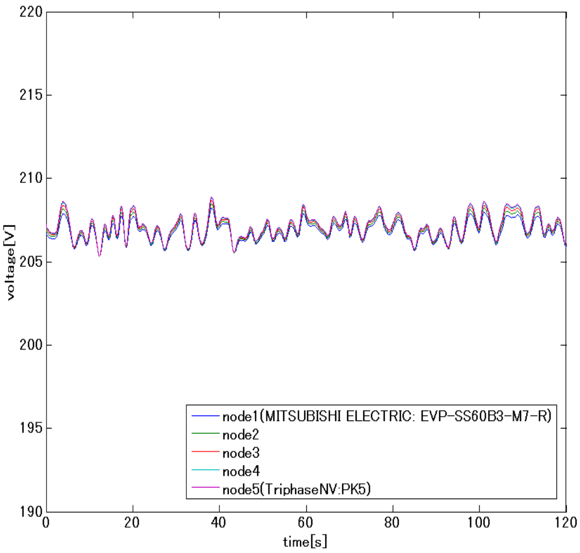


Figure.11 Simulation results of voltage at each node

Table.2 Maximum voltage deviation at each node

	Without control(HIL) [V]	with control (HIL)[V]	with control (simulation) [V]
node1	213.95	211.44	211.17
node2	216.15	211.9	211.73
node3	217.31	212.28	212.15
node4	218.09	212.51	212.43
node5	218.23	211.91	212.57

C. Result of Frequency

Experimental results of frequency are shown in Fig. 12, and RMS values of frequency deviation are summarized in Table 3. Freq/Watt and Freq-Volt/Watt control have significant performance on frequency stabilization. Freq-Volt/Watt control, which is additional control for EV charging and discharging, is suitable for suppressing both voltage and frequency deviations.

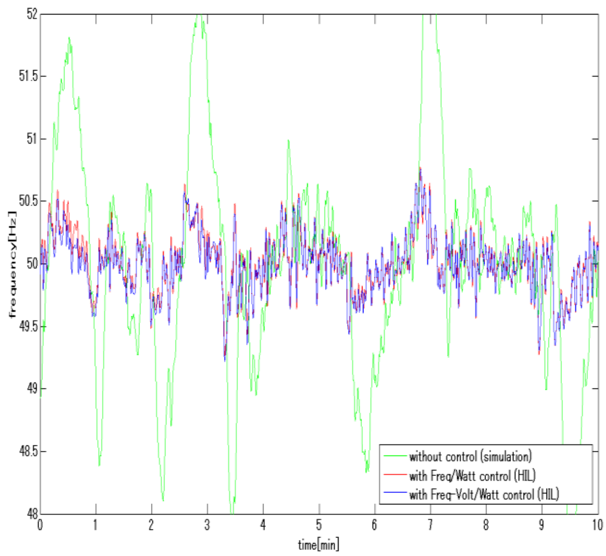


Figure.12 Experimental and simulation results of frequency

Table.3 RMS and maximum deviation of frequency

	rms[Hz]	dF max[Hz]
with Freq-Volt/Watt control (HIL)	0.2389	0.7782
with Freq/Watt control (HIL)	0.2421	0.7727
without control (simulation)	0.9492	3.018

V. CONCLUSION

In this paper, autonomous smart inverter control combined reactive power control using PV and EV to suppress voltage fluctuation and EV active power control considering frequency fluctuation and voltage fluctuation was proposed. It is confirmed that the proposed smart inverter control can perform stable control even when the frequency and voltage fluctuate by verifying and evaluating using HIL with two actual smart inverters under the condition that a large amount of EV and PV were introduced to a distribution feeder It is confirmed that autonomous control combined with control of active power and reactive power using EV can suppress frequency fluctuation without voltage fluctuation.

In case of control active and reactive power at the same time, it is concerned about interference and transient instable phenomena in the inverter control loop and between the inverters. The HIL test in this paper clearly shows that there are no interferences in the control loops and the inverters even when two actual inverters are interconnected to the distribution feeder.

ACKNOWLEDGMENT

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