A Basic Study of a Coordinated Control Method for Heat Pump Water Heaters and Electric Vehicle Battery Chargers in Residence with PV Systems

Yuji Hanai†, Kazuaki Yoshimura*, Junya Matsuki* and Yasuhiro Hayashi**

Abstract - In recent years, Photovoltaic generation (PV) has gained a lot of attention due to its potential for contributing to part of the solution to global warming. In addition, the introduction of PV increased rapidly in many houses. If PV is introduced on a large scale, this may cause the allowable voltage produced by each customer to increase thereby deviate the allowable voltage. The installation of a storage battery can decrease the PV’s output and control power surges. However, there are serious problems in respect to the installation cost and storage space of batteries. Therefore in this research, the authors propose and verify a new coordinated control method of heat-pump water heaters and electric vehicle battery chargers in a residence with a PV system. The proposed method compensates for the voltage rises and drops deviating from the allowable range by coordinated control of heat-pump water heaters and electric vehicle battery chargers. In order to verify the proposed method, an experimental simulation using an analog type distribution system simulator is carried out.

Keywords: Coordinated control, PV system, Heat-pump water heater, Electric vehicle, Distribution system, Voltage control

1. Introduction

Photovoltaic generation (PV) has become more popular as part of the solution to global warming, the depletion of fossil fuels, and to energy conservation. Recently, the PV has become more widespread in households due to the improvement in the cost and by the introduction of incentive system from the Japanese government. In addition, a surplus power buyback program by electric power companies [1]-[3]. However, power generation from houses flowing backward may disrupt the line voltage. If PV is introduced on a large scale, this may cause the allowable voltage produced by each customer to increase thereby deviating the allowable voltage. Currently to avoid this problem, the power generation output of each PV is controlled by using a power conditioner system (PCS). However, there are problems that can cause a decrease in the system efficiency [4]. When the PVs generated too much power, this can cause the power to go outside of the allowable range. The installation of a storage battery can decrease the PV output and control power surges [5]. However, there are serious problems in respect to the installation cost and space of batteries.

To solve these problems, we focus on coordinating the control of the extra power generated from PV by using a hot water storage type heat pump water heater (HP-WH) and an electric vehicle battery charger (EV-BC) [6]. The voltage problem can be solved by flexibly operating the HP-WH and the EV-BC during daytime use during periods of PV output control. Consequently, the overload of power can be cancelled and stress on transformers and other equipment will be lessened. Therefore, by operating the customer loads in a coordinately, we consider both customer side and distribution network side and enjoy the benefit from both.

This research proposes a coordinated control method for HP-WHs and EV-BCs in residence with PV systems aiming at avoiding PV output control and keeping distribution system voltage. In addition, Active Network distribution System With Energy Resources (ANSWER) constructed in university is used for validity verification of proposed method.
2. Coordinated Control Method of the HP-WH and the EV-BC

2.1 Operation of Customer’s Devices and Their Impact

Customer’s devices such as HP-WHs and EV-BCs operate at midnight when the electric power rate is less expensive. However, these customer’s devices rating capacity are relatively-large. Consequently, it is possible that too much voltage can be a problem and overload the transformers when all of those devices operate at the same time. Additionally, the voltage will rise due to the PV output. PCS can possibly decrease the PV output to avoid the problem in the rise of voltage. At the same time, the coordinated operation of multi-customer’s HP-WHs and EV-BCs that are not limited to midnight operation will not only avoid PV output suppression but also help to resolve the distribution system voltage problem, the transformer overload operation problem and improve the utilization factor by local load leveling. Fig. 1 shows the operation of customer’s devices.

2.2 Coordinated Control Method of the HP-WH and the EV-BC

This research has aimed at maximization of the PV output and keeping voltage of customer and distribution system by coordinated control of the HP-WH and the EV-BC. And customer’s houses have already introduced HP-WHs, EV-BCs and PVs.

Fig. 2 shows the control blocks of the EV-BC, HP-WH and PV, respectively.

An EV-BC charging control sets each control voltage for voltage rise (\(V_{EV,MAX}\)) and voltage drop (\(V_{EV,MIN}\)) (Fig. 2 (a)), and compensates for the amount of deviation from each
control voltage with the PI controller. The amount of compensation to each voltage deviation and charging schedule of EV-BC is decided beforehand (charging power $P_{EV}$). It is given as a charging output instruction value $P_{EV}^*$. The charging output is controlled by keeping the voltage drop within a range of 80-100% of rating capacity. An 80-100% rating capacity is not hurt the convenience of the EV. The charging output is controlled by the voltage rise within the range of 0-100% of rating capacity. Additionally, if EV-BC’s capacity is maximum, charging output $P_{EV}^*$ drops to zero and stops charging the EV-BC.

A HP-WH hot-water supply control is same as the EV-BC control (Fig. 2(b)). The HP-WH hot-water supply control sets each control voltages of voltage rise ($V_{HP\ MAX}$) and voltage drop ($V_{HP\ MIN}$). The amount of compensation in voltage deviation to the operation schedule of the HP-WH decided beforehand (consumption power $P_{HP}$). This is given the hot-water supply output instruction value $P_{HP}^*$. The hot-water supply output controls for the voltage drop within the range of 80-100% of rating capacity. An 80-100% rating capacity is not hurt the convenience and efficiency of HP-WH [7]. The hot-water supply output is controlled for the voltage rise within the range of 0-100% of rating capacity. Additionally, the amount of the tank capacity of the HP-WH is calculated by the integral value of amount of hot-water supply by hot-water supply output $P_{HP}^*$ ($P_{HP}^* \times$ heat quality conversion factor $K$). If the HP-WH’s tank capacity is maximum, hot-water supply output $P_{HP}^*$ drops to zero and stops hot-water supplying the HP-WH.

A PV output control sets only the control voltages of the voltage rise ($V_{PV\ MAX}$) (Fig. 2(c)) and compensates for the amount of deviating from each control voltage with the PI controller. The amount of compensation to voltage deviation is subtracted from the generated power of the PV. It’s given as the PV output instruction value $P_{PV}^*$. PV generated power output controls the voltage rise within the range of 0-100% of the rating capacity and the voltage rise is reduced.

However, the control of the EV’s charging is only possible when connected to the system. Therefore application potency of the EV is lower than the HP-WH. Consequently, it is preferable to give priority to the EV’s charging. Therefore, setting different control voltages for each controllable load (EV-BC, HP-WH and PV) as shown in Fig. 3 is determined. When voltage rise problems occur, the voltage rise is reduced by charging EVs first. On the other hand, when voltage drop problems occur, the voltage drop is reduced by hot-water supplying by HP-WHS first. Thus, PV output is maximized by giving priority to the EV charging. The operation schedule of EV-BCs and HP-WHS are decided beforehand in order to operate around midnight when electric power rate is cheaper in this research.

3. Demonstration Experiment

In order to check the validity of the proposed method, an analog-type distribution system simulator (ANSWER: Active Network distribution System With Energy Resources) was used to verify the experiment’s results. Furthermore, the scheduled value of the HP-WHs and the EV-BCs were compared to the experiment and evaluated. In this manner, the proposed method was validated.
3.1 Simulation model

Fig. 4 shows a distribution model. It is built on the ANSWER and experimental simulations that were carried out. Experimental systems used in this research are built using LRT equipment, distribution line equipments (four), inverter equipments (four) and load equipments (twelve). In addition, a lower feeder in Fig. 4 assumes the role of absorbing the reverse power flow from the PVs. The experimental time is shortened to 3600 seconds which is one twenty fourth of the day in which the HP-WHs and the EV-BCs and the PV and load operation. The inverter power conditioning simulates the Electrical loads, the HP-WHs, the EV-BCs and the PVs output. Fig. 5 shows the profile of the Electrical load and the PV output. Additionally, Fig. 6 shows the operation schedule of the HP-WH and the EV-BC. Table 1 shows setting values of each of the HP-WH and the EV-BC. In order to simplify the experiment, the sending voltage, the line impedance, the load impedance and the inverter output instruction value are balanced in three-phase.

Table 1. Setting value of HP water heater and EV battery charger

<table>
<thead>
<tr>
<th>HP water heater</th>
<th>Heat-pump rated output</th>
<th>1.0 [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tank capacity</td>
<td>13500 [kcal]</td>
</tr>
<tr>
<td></td>
<td>COP</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Controllable output range</td>
<td>0% - 100%</td>
</tr>
<tr>
<td></td>
<td>Upper threshold voltage: $V_{HP \text{ MAX}}$</td>
<td>1.045 [pu]</td>
</tr>
<tr>
<td></td>
<td>Lower threshold voltage: $V_{HP \text{ MIN}}$</td>
<td>0.955 [pu]</td>
</tr>
<tr>
<td>EV battery charger</td>
<td>EV charger rated output</td>
<td>1.5 [kW]</td>
</tr>
<tr>
<td></td>
<td>EV battery charger capacity</td>
<td>16 [kWh]</td>
</tr>
<tr>
<td></td>
<td>Initial amount of charging capacity</td>
<td>8 [kWh]</td>
</tr>
<tr>
<td></td>
<td>Controllable output range</td>
<td>0% - 100%</td>
</tr>
<tr>
<td></td>
<td>Upper threshold voltage: $V_{EV \text{ MAX}}$</td>
<td>1.040 [pu]</td>
</tr>
<tr>
<td></td>
<td>Lower threshold voltage: $V_{EV \text{ MIN}}$</td>
<td>0.950 [pu]</td>
</tr>
</tbody>
</table>

The following is an explanation of each model.

(1) Electrical load: an electrical load is a general customer’s load profile. Fig. 5 shows the electrical load of experimental value. This electrical load consists of the customer’s loads other than the HP-WH and the EV-BC.

(2) PV: The PV system rating output is 3.0 kW; it’s generally installed in the residence. The generated output of the PV in the experimental was from a sunny day. Fig. 5 shows the PV generated output of the experimental value. In addition, when the voltage rise problem occurs, the working PCS’s output control function and controlled generated power and control start voltage of the upper voltage deviation is setting 1.050 pu.

(3) HP-WH: The HP-WH’s rating output is 4.0 kW; it’s also generally installed in the residence. The HP-WH’s performance is defined as the COP (Coefficient Of Performance). The COP depends on the tap water’s temperature and the HP-WH’s hot-water supply temperature. If the tap water temperature is higher and hot-water supply temperature is lower the COP rises. The HP-WH’s consumption power is obtained by dividing the rated power with the COP. The middle season was assumed in this research. The COP was given a 4.0 (constant) for simplicity in this research. The HP-WH’s hot-water supply heat quality of one hour is 860 kcal (= 1.0 kWh × 860 kcal/kWh). Furthermore, the hot-water supply temperature was 60 degrees C, the tap water temperature was 15 degrees C, the tank capacity was 300 litters and the heat quality conversion of tank was 13,500 kcal (= 60 deg C – 15 deg C) × 300 l). The HP-WH’s operation schedule was three hours at the electric power discount rate time (2:00 - 5:00); the average thermal demand of the customer during the middle season is assumed. The control start voltage of the upper voltage deviation is set at 0.945 pu and the lower voltage deviation is set at 0.955 pu. The control delay of the HP-WH and the efficiency of the thermal storage of tank are not considered for the simplification of this research.

(4) EV-BC: The EV-BC rating output is 16kWh. The charging current of the rating operation is 15 A (constant current load). The consumption power is 1.5 kW because it is assumed that the charge is 100 V. The EV-BC’s operation schedule was five hours of electric power at the discount rate time (1:00 - 6:00). The same conditions apply to the HP-WH. Moreover the EV daytime driving is considered. The initial charge capacity of the EV-BC is assumed to be 50% of the rating capacity. The EV is charged to about 96 %. The control start voltage of the upper voltage deviation is set at 1.040 pu and the lower voltage deviation is set at 0.950 pu. The control delay of the EV-BC and the efficiency charge are not considered for the simplification in this research.

3.2 Experimental Results

Fig. 7 shows the experimental results of the scheduled operation of the HP-WH and the EV-BC in Fig. 6, and Fig. 8 shows the experimental results of the coordinated control of the HP-WHs and the EV-BCs based on the proposed method, respectively.

The system voltage deviation and the PV output control occur during the schedule operation of the HP-WHs and EV-BCs as seen in Fig. 7. During the early-morning hours (2:00 - 5:00), the voltage of the CUST3 deviates to a lower
voltage because of the overload operation of HP-WHs and EV-BCs operate in same time. During the midday hours (10:30 - 14:00), the system voltage rises due to increase of the PV output. The PV output of the CUST3 is controlled to compensate for the voltage rise. The amount of the PV output is controlled to 0.627 kWh (in this case the 6.6 kV system conversion value is about 548 kWh). On the other hand, when the HP-WHs and EV-BCs are coordinated controlled based on proposed method, the lower voltage deviation and the PV output control are avoided as seen in Fig. 8. During the early-morning hours (2:00 - 5:00), the output of the HP-WHs and the EV-BCs of the CUST3 is decreased as a result the voltage drop is eased, and all the voltages keep within the allowable voltage. In addition, the operation of the hot-water supply of the HP-WH is given priority to the voltage drop because the control start voltage of the HP-WH is higher than the control start voltage of the EV-BC. During the midday hours (10:30 - 14:00), the EV-BCs of the CUST1 to 3 and the HP-WHs of the CUST 2 and 3 compensate for the voltage rise by increasing the PV output and keeping all the voltages in the allowable range. In addition, the operation of the charging output of the EV-BC is also given priority to the voltage rise because the control start voltage of the HP-WH is lower than the control start voltage of the EV-BC. A lot of customers (the HP-WHs, the EV-BCs, the PVs) distributed in distributed line are simulated by three inverters in this research. A momentary voltage fluctuation occurs due to the limitation of tank capacity of HP-WHs and the limitation of the charge capacity of the EV-BCs thereby causing a shutdown. However, in reality this is not a problem because the line impedance and the operation condition of each controllable load are various and the amount of control and the control time are distributed.

Therefore, the proposed method is confirmed as a viable way to keep the allowable voltage and maximize the PV output by coordinated control of the HP-WHs and the EV-BCs. In addition, the PV output of 0.627 kWh (the 6.6 kV system conversion value is about 548 kWh) can be use by not controlling the PV output with load control in this experiment. If the CO₂ conversion factor is 0.555 kg/kWh, the CO₂ can reduce by about 304 kg the 6.6kV system conversion value [8].
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Therefore, the proposed method is able to keep the allowable voltage and maximize the PV output by coordinated control within a range of possible power conditioning (80% - 100%) of the HP-WHs and the EV-BCs.

4. Conclusion

In this research, a way of maximizing the PV output and keeping the system voltage is proposed by using a coordinated control method of HP-WHs and EV-BCs in residence with PV systems. In order to determine the validity of proposed method, experimental verifications using an analog-type distribution system simulator (ANSWER) are carried out. The proposed method for setting the control start voltages when voltage problems occur is based on an operation schedule of the HP-WHs and the EV-BCs that operate during the discount rate time and coordinated control within the range of a possible power conditioning (80% - 100%) of the HP-WHs and the EV-BCs.

In the experimental results, it was confirmed to be able to keep the allowable voltage and maximize the PV output by the coordinated control of the HP-WHs and the EV-BCs based on the proposed method. Setting each voltage and centralizing the control are future tasks and are scheduled to be initiated in the future. Additionally, considering the unbalanced three-phase condition of the PVs and the loads, the heat demand of different season is scheduled.

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References

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