INSTANTANEOUS ACTIVE AND REACTIVE POWER CONTROL IN OFF-GRID SMART HOUSE

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ABSTRACT
Reduction of carbon dioxide emissions is a big challenge for the entire world. Therefore, a residential photovoltaic (PV) system has recently begun to spread and the increasing penetration rate of the renewable energy is expected. However, output power from PV depends on isolation condition and entails uncertainty. So if many PV systems are integrated into the electrical power system, voltage and frequency fluctuation in the power system will occur. Therefore, reduction of PV generation or isolation from the power system is required to the demand side. In this study, the completely off-grid smart house which is not connected with the power system is proposed. In the house, off-grid PV system, storage battery, electrical vehicle (EV), and Home Energy Management System (HEMS) are introduced.

INTRODUCTION
The carbon dioxide reduction is a big challenge for the entire world. Accordingly, the energy efficiency of household is recognized major problem. As a method to this problem, Home Energy Management System (HEMS) is presented in (Yoshikawa and Awai, 2011; Niyato et al., 2011; Han and Lim, 2010; Son et al., 2010; Jin and Kunz, 2011). HEMS automatically perform energy saving without manual action. In off-grid smart house, the power from PV system and the changes of consumption causes steep fluctuation of the power supply voltage. This fluctuation have adverse effect to the home electric appliances. In previous studies, related to inverter control, the inverter is operated with feedback control based on the root mean square or average value of voltage in (Jung et al., 2007; Hu et al., 2011; Tirumala et al., 2002). These control methods cat not suppress steep voltage fluctuation. For solving this problem, this research study applies the inverter control method based on single phase dq transformation system (Yamauchi et al., 2012; Miyagi et al., 2014). In order to put the off-grid smart house into practice, a consideration of the state of charge (SOC) for a fixed battery is needed. In this study, the HEMS adjusts the energy consumption of electric appliances considering the battery remaining capacity to avoid the shortage of energy. Furthermore, efficient operation of PV is performed by Maximum Power Point Tracking (MPPT) (Esram and Chapman, 2007). The effectiveness of this study is verified by MATLAB/SimPowerSystems.

SYSTEM MODEL
The smart house model is shown in Figure 1. In this model, HEMS is able to control electric appliances. The communication between HEMS and appliances is performed by wireless communication techniques. The fixed battery with a capacity of 2 kWh and an inverter with a rated output of 3kW has been introduced. Simulation circuit is illustrated in Figure 2. The DC-DC buck-boost converter which is connected to PV panels executes the MPPT control of PV. To keep a voltage in the DC-Link, the DC-DC boost converter is connected to the DC-Link. Moreover, a fixed battery is also connected to the DC-Link. In this way, the power losses can be decreased, because the power inverter for a battery is not required. There is another advantage that it will maintain the level of output power from PV.

PV System
The model of the PV array is simulated by basic equation and current source (Itako and Mori, 2005). Table 1 shows the parameters of PV. The Single-Ended Primary Inductance Converter (SEPIC) is used as a DC-DC converter for PV (Duran et al., 2011). Figure 3 illustrates SEPIC. SEPIC has both advantages protection for the occurrence of a short-circuit and same polarity of input and output voltages.

Fixed Battery System
A fixed battery is connected to DC-DC boost converter, which is shown in Figure 4. The DC-DC converter boosts the output voltage of a battery from 200V to 350V. The Droop control method is applied for the purpose of maintaining the voltage in the DC-Link. The current command value for the DC-DC converter is determined by the PI control using SOC for a fixed battery. The battery control system is shown in Figure 5. The allowable voltage range in the DC-Link is ±20V ($V_{DC}=330\sim370V$).

INVERTER CONTROL METHOD
In this section, the inverter control method based on instantaneous active and reactive power is explained.
the Phase-locked loop circuit that can estimate phase in a high accuracy is required. This research uses the ALOF-PLL circuit to estimate the phase (Han et al., 2009).

**The Single Phase dq Transformation System**

The root mean square value (RMS) $V_{RMS}$ is calculated from AC voltage $v = \sqrt{2}V \sin(\omega t)$ as follows:

$$V_{RMS} = \sqrt{\frac{1}{T} \int_0^T v^2 dt}$$

$$= \sqrt{\frac{1}{T} \int_0^T (\sqrt{2}V \sin \omega t)^2 dt}$$

(1)

If this equation is used to estimate the phase of the voltage, the command signal is delayed. The delay has the risk of an accident with appliances. The control method using the single-phase dq transformation, estimates an instantaneous voltage value. Figure 6 illustrates Single-phase dq transformation system. Input voltage $V$ is converted into digital signals $v$ and $v'$. Where, the digital signal $v'$ is delayed $\delta t$ from $v$ in the phase by a delay block. Figure 7 shows the digital signals $v$ and $v'$. The $\Delta v$ that is difference between $v$ and $v'$ can be calculated as follows:

$$\Delta v = v - v' = \sqrt{2}V \sin \omega t - \sqrt{2}V \sin(\omega t - \delta \theta)$$

$$= \sqrt{2}V \sin \omega t - \sqrt{2}V \sin \omega t \cos \delta \theta$$

$$+ \sqrt{2}V \cos \omega t \sin \delta \theta$$

(2)

where, $V \sin \omega t$ and $V \sin \omega t \cos \delta \theta$ are eliminated in the analogue/digital conversion processing. Then, only $\sqrt{2}V \cos \omega t \sin \delta \theta$ keep remains. Moreover, $\Delta v$ is obtained as shown in Figure 8. The $\beta$ axis component $v_\beta$ can be obtained by holding the $\Delta v$ for 10 $\mu$s and multiplying by $K = 1/\sin(\delta \theta)$ as shown in

**Table 1 PV panel constants**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV short-circuit current[A]</td>
<td>18.3</td>
</tr>
<tr>
<td>PV open circuit voltage[V]</td>
<td>230.0</td>
</tr>
<tr>
<td>Diode saturation current[A]</td>
<td>$1.94 \times 10^{-16}$</td>
</tr>
<tr>
<td>PV Short-circuit current at standard temperature[A]</td>
<td>18.3</td>
</tr>
<tr>
<td>Diode saturation current at standard temperature[A]</td>
<td>$1.94 \times 10^{-16}$</td>
</tr>
<tr>
<td>Standard cell temperature[K]</td>
<td>298</td>
</tr>
<tr>
<td>Amount of solar radiation[kW/m²]</td>
<td>1</td>
</tr>
<tr>
<td>Area of a solar panel [m²]</td>
<td>1.47</td>
</tr>
<tr>
<td>Number of solar panels</td>
<td>14</td>
</tr>
<tr>
<td>The total area of solar panels [m²]</td>
<td>20.58</td>
</tr>
<tr>
<td>Energy gap[V]</td>
<td>$1.767 \times 10^{-19}$</td>
</tr>
<tr>
<td>Elementary charge[C]</td>
<td>$1.6 \times 10^{-19}$</td>
</tr>
<tr>
<td>Boltzmann’s constant</td>
<td>$1.38 \times 10^{-23}$</td>
</tr>
<tr>
<td>Constant independent of temperature</td>
<td>2.0 $\times 10^{-2}$</td>
</tr>
<tr>
<td>Junction constant</td>
<td>1.95</td>
</tr>
<tr>
<td>Constant determined by the material</td>
<td>2.8</td>
</tr>
</tbody>
</table>
From ALOF-PLL:

\[ V_{m} = V_{i} / 2 \]

**Figure 6** Single-phase \(dq\) transformation system

**Figure 7** \(v\) and \(v'\)

**Figure 8** Differential value, \(\Delta v\)

**Figure 9** Beta axis component, \(v_{\beta}\)

**Figure 10** Input voltage, \(v\)

**Figure 11** Magnitude of input voltage, \(V_{m}\) and \(V_{RMS}\)

**Figure 12** Active and reactive power detection circuit

**Active and Reactive Power Detection**

Figure 12 shows the active and reactive powers detection circuit. This circuit calculate active and reactive powers \(P, Q\) using the single-phase \(dq\) transformation system, and phase difference, \(\theta\), between \(V_{r}\) and \(I_{inv}\) as follows:

\[
P_{inv} = V_{m}I_{m} \cos \theta \tag{5}
\]

\[
Q_{inv} = V_{m}I_{m} \sin \theta \tag{6}
\]

**Command Value Determination for Inverter Control**

A single-phase inverter, controls the magnitude and phase of the output current. In this research, due to using \(PQ\) feedback control, the current command value is determined by the \(PQ\) information that has been detected by the active and reactive powers detection circuit. Then, rearranging Equations (5) and (6), the magnitude of the output current command value \(I_{com}\) and the phase difference \(\theta\) are calculated as follow:

\[
I_{com} = \sqrt{P_{inv}^{2} + Q_{inv}^{2}} \tag{7}
\]

\[
\theta = \arcsin \frac{Q_{inv}}{V_{m}I_{m}} \tag{8}
\]

By substituting the command values \(P_{inv}, Q_{inv}\) for \(P_{inv}, Q_{inv}\) in above equation, the inverter output current command can be determined as follow:

\[
I_{ref} = \sqrt{2}I_{com} \sin(\omega_{H}t^{*} + \theta) \tag{9}
\]

In this study, the inverter uses control method based on the instantaneous active and reactive powers feedback control. The inverter control system is shown in Figure 13. The load voltage \(V_{l}\) and DC-Link voltage \(V_{DC}\) are controlled by the inverter using PWM control.
HEMS

Energy management in the proposed smart house is achieved by the HEMS. The algorithm of energy management is shown in Figure 14. The power consumption of appliances are adjusted considering SOC for the battery. The adjusting of power consumption is performed based on priority level of all appliances.

SIMULATION RESULTS

In the proposed smart house, in order to avoid depletion of the SOC for a storage battery, HEMS adjusts the power consumption based on priority of loads. The priority of critical loads in order of highest to lowest is \( L_1, L_2, L_3, L_4 \). \( L_1 \) is supplied with a stable power during all the time. In order to confirm load control by the HEMS during simulation time that is 4 seconds, the initial value of SOC for the storage battery is set 70.003%. When the SOC for the storage battery is less than 70%, the loads are controlled by the HEMS. The simulation result is illustrated in Figures 15~26. Figure 15 shows the inverter output current \( I_{\text{inv}} \). The inverter output current is decreased by the HEMS due to low SOC for the storage battery. Figure 16 shows receiving voltage \( V_r \), which is 200V. According to Figure 16, regardless of the adjusting of load, the receiving voltage was maintained at a 200V. The inverter output active and reactive powers \( P_{\text{inv}}, Q_{\text{inv}} \) are shown in Figure 17. In Figure 17, it is clear that inverter output active and reactive powers are decreasing during low consumption of load. Figures 18, 19 shows the DC-Link voltage \( V_{\text{DC}} \) and the output current of the storage battery, \( I_b \) respectively. The DC-Link voltage \( V_{\text{DC}} \) is maintained at a 350V by the control of the inverter and the storage battery. Figure 20 shows the SOC \( \xi_b \) for the storage battery. The different SOCs for the storage battery are illustrated due to with or without load control. The frequency of receiving voltage \( f_H \) is shown in Figure 21. According to Figure 21, the frequency of receiving voltage is maintained at 60Hz. Figures 22, 23, 24 show the amount of solar radiation, \( I_N \), the output current of the PV, \( I_P, V_P \), and the output voltage of the PV, \( V_P, V_r \) respectively. The MPPT control is performed by using the hill climbing method in 1.4s cycles. Figure 25 shows the load currents \( I_{L1}, I_{L2}, I_{L3}, I_{L4} \) with load control. In this Figure, it is clear that the load currents \( I_{L2}, I_{L3} \) and \( I_{L4} \) are limited by HEMS when SOC of battery is low. On the other hand, Figure 26 shows the load currents \( I_{L1}, I_{L2}, I_{L3}, I_{L4} \) without load control. In this Figure, the load currents are constant.
CONCLUSION

In this paper, the completely off-grid smart house which is not connected with the power system is proposed. The off-grid PV system, storage battery, EV, and HEMS have been introduced into the smart house. In the off-grid smart house, the bad influence to appliances due to fluctuation of the PV output power is recognized problem. Furthermore, because the house cannot receive the electric power from power grid, the depletion of energy in storage battery should be avoided. By applying the dq transformation system to control the inverter instead of conventional control system, instantaneous inverter control is achieved. This has suppressed the voltages and frequency fluctuation of power supply. Moreover, in order to save the electric energy, the HEMS controlled power consumption of electric appliances considering SOC for the storage battery.
Figure 26 Load currents without control

(a) Load current without control, $I_{L1}$

(b) Load current without control, $I_{L2}$

(c) Load current without control, $I_{L3}$

(d) Load current without control, $I_{L4}$

REFERENCES


