Power Smoothing Control Methods Using Moving Average and FIR Filters in Distributed Generation Systems

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Photovoltaic (PV) generation has attracted much attention as a new electric-power generation system. However, the output power of PV generation systems experiences significant fluctuations, which negatively affect the electric-power reliability of the grid. It is therefore necessary to smoothen it using power-smoothing control methods. This paper evaluates different power-smoothing control methods using a moving average filter and finite impulse response filters for distributed generation systems with energy storage devices. We analyze the gain and phase characteristics of these filters, and we perform computer simulations to evaluate the effectiveness of the smoothed electric power generated by PV generation systems.

Key Words
Photovoltaic generation, Moving average, Finite impulse response filter

1. Introduction

Recently, global warming and the depletion of natural resources have become serious issues. Photovoltaic (PV) generation systems have attracted much attention as environmentally-friendly renewable energy sources. However, the output power of PV generation systems shows a great deal of fluctuation due to the variation in the solar radiation intensity. Therefore, power fluctuations in the load-frequency control (LFC) range (1/1200 - 1/120 Hz) may negatively affect the grid.

Distributed generation systems with electric double-layer capacity (EDLC) systems have been proposed to compensate for the power fluctuations in PV generation systems. EDLC systems have the advantages of high energy density, long life-time, and fast response, which make them useful as energy storage devices. However, these systems have a low withstand voltage and are expensive. It is therefore necessary to apply more effective power-smoothing control methods to reduce the EDLC capacity and suppress fluctuations in the LFC range. In previous studies, the moving average (MA) filter, which is a conventional method, was compared to other filters when applying the power-smoothing control method. The characteristic of the MA filter is determined uniformly because it has only one design parameter. Therefore, to obtain more desirable filter characteristics, it is necessary to have a more flexible filter design.

In this paper, we propose the use of a finite-impulse response (FIR) filter as a filter that can be designed flexibly. The FIR filter is an extension of the MA filter, and can be designed to have desirable filter characteristics because it has a few parameters. However, the FIR filter has not been compared with the MA filter as a power-smoothing control method. This paper evaluates the smoothing effect and the EDLC capacity by simulating the performance of

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distributed generation systems with an EDLC system using both the MA filter and the FIR filter.

2. Distributed generation system

Fig. 1 shows the components of distributed generation systems with an EDLC system. This distributed generation system consists of a PV system, an EDLC system, and a power conditioning system (PCS). The PV system is composed of solar panels and a DC/DC converter. The EDLC system is composed of an EDLC and a DC/DC converter. The PV system and the EDLC system are connected in parallel at the DC link. The EDLC system compensates for power fluctuations in the PV system by charging and discharging energy.

The power relationship at the DC link is given by

\( P_{\text{PVsys}} = P_{\text{ECsys}} \) (1)

where \( P_{\text{PVsys}} \) is the PV output power, \( P_{\text{ECsys}} \) is the power to the EDLC system, and \( P_{\text{DC}} \) is the power on the DC side of the PCS. The power command value, \( P_{\text{PC_DC}} \), is calculated in the next section using the power-smoothing control methods. The EDLC charges when \( P_{\text{PVsys}} \) is larger than \( P_{\text{ECsys}} \). In contrast, the EDLC discharges when \( P_{\text{PVsys}} \) is smaller than \( P_{\text{ECsys}} \). The smoothed power is supplied to the domestic power load through the PCS, and the surplus power flows back to the grid.

3. Power-Smoothing Control

3.1 Moving average filter

The power command value of the PCS obtained using the MA filter is given as

\[ P_{\text{PC_DC_MA}} (t) = \frac{1}{N} \sum_{i=0}^{N-1} P_{\text{PVsys}} (t-iT_s) \] (2)

where \( t \) is the time, \( T_s \) is the sampling period, \( T_{\text{MA}} \) is the MA filter period and \( N \) is the number of data samples (\( N = T_{\text{MA}}/T_s \)). The MA filter is a low-pass filter.

The transfer function of the MA filter in the \( z \) domain is shown in the following equation.

\[ H_{\text{MA}} (z) = \frac{P_{\text{PC_DC_MA}} (z)}{P_{\text{PVsys}} (z)} = \frac{1}{N} \frac{1-z^{-N}}{1-z^{-1}} \] (3)

Therefore, the gain and phase characteristics of the MA filter are defined by Eqs. (4) and (5), respectively.

\[ |H_{\text{MA}} (f)| = \frac{T_s}{T_{\text{MA}}} \frac{\sin N \pi f T_s}{\sin N \pi f T_{\text{MA}}} \] (4)

\[ \theta (f) = \tan^{-1} \frac{\text{Im}[H_{\text{MA}} (f)]}{\text{Re}[H_{\text{MA}} (f)]} \] (5)

where \( \text{Re}[H_{\text{MA}} (e^{j \omega})] \) and \( \text{Im}[H_{\text{MA}} (e^{j \omega})] \) are shown as following.

\[ \text{Re}[H_{\text{MA}} (f)] = \sin 2\pi f T_s \sin 2\pi f T_{\text{MA}} (1 - \cos 2\pi f T_s) \] (6)

\[ \text{Im}[H_{\text{MA}} (f)] = \sin 2\pi f T_s (1 - \cos 2\pi f T_{\text{MA}}) (1 - \cos 2\pi f T_s) \] (7)

The purpose of this study is to suppress the power fluctuations at frequencies that are higher than the LFC range. The components in the pass band should not be suppressed to reduce the EDLC capacity. Therefore, the parameter of the MA filter, \( T_{\text{MA}} \), is determined so that the gain in the LFC range becomes less than -10 dB in order to suppress the power fluctuation. To prevent fluctuations in the pass band, it is desirable that the gain becomes -10 dB at 1/1200 Hz. \( T_{\text{MA}} \) is determined as 886 s by performing the calculation: \( 20\log_{10}[H_{\text{MA}} (f)] = -10 \) dB, where \( f = 1/1200 \) Hz and \( T_s = 2 \) s.

3.2 Finite impulse response filter

For the low-pass filter, we designed an FIR filter using the window function. The power command value of the PCS obtained using the FIR filter is given as

\[ P_{\text{PC_DC_FIR}} (t) = \sum_{i=0}^{N-1} h_i P_{\text{PVsys}} (t-iT_s) \] (8)

where \( h_i \) \( (i = 0, \ldots, N-1) \) are filter coefficients that determine the filter characteristic. \( h_i \) is calculated by the inverse Fourier transform of \( H_i \) as an ideal filter, and is given by

\[ H_i (e^{j \omega}) = \begin{cases} 1 & (0 \leq \omega \leq \omega_c) \\ 0 & (\omega_c < \omega < \omega) \end{cases} \] (9)

where \( \omega_c \) is the cutoff angular frequency. The impulse
The response of $H(e^{j\omega})$ is calculated as

$$h_i = \int_{-\infty}^{\infty} e^{j\omega \omega} = 2 \frac{f_c}{f_s} \sin \frac{2\pi f_c}{f_s}$$  \hspace{1cm} (10)$$

where $f_c$ is the cutoff frequency and $f_s$ is the sampling frequency. The impulse response shown in Eq. (10) is infinite. Because $h_i$ must be a finite dimension, $h_{di}$ is multiplied by a window function and is shifted so that it begins with 0. The Kaiser window shown in Eq. (11) is applied to the window function because of its high flexibility.\(^{10}\)

$$w_i = \frac{I_0(\alpha \sqrt{\frac{1 - \frac{2i}{N-1}}{\frac{N-1}{2} - i \leq \frac{N-1}{2}}})}{I_0(\alpha)}$$

\hspace{1cm} \begin{cases} 
\frac{N-1}{2} \leq i \leq \frac{N-1}{2} \\
2 < i \leq \frac{N-1}{2}, \frac{N-1}{2} < i
\end{cases}$$  \hspace{1cm} (11)

where $I_0(\alpha)$ is the zero-order modified Bessel function and $\alpha$ is the parameter that determines the window function characteristic. Fig. 2 shows the characteristic of the Kaiser window as $\alpha$ varies. The side-lobe height of the Kaiser window is controlled by changing $\alpha$.

The gain and phase characteristics of the FIR filter are expressed in the following equations.

$$|H_{\text{FIR}}(f)| = \sqrt{\left( \sum_{i=0}^{N-1} h_i \cos (2 \pi f T_s) \right)^2 + \left( \sum_{i=0}^{N-1} h_i \sin (2 \pi f T_s) \right)^2}$$

\hspace{1cm} (12)

$$\theta(f) = \tan^{-1} \left( \frac{-\sum_{i=0}^{N-1} h_i \sin (2 \pi f T_s)}{\sum_{i=0}^{N-1} h_i \cos (2 \pi f T_s)} \right)$$  \hspace{1cm} (13)

The FIR filter characteristics vary with the design parameters of $f_c$, $N$, and $\alpha$. Figs. 3, 4, and 5 show the gain and phase characteristics of the FIR filter as the design parameters vary. When the gain decreases in the pass band, the FIR filter characteristics are undesirable because the EDLC capacity increases. Moreover, the phase delay causes an increase in the EDLC capacity. Therefore, FIR filters are not designed to lower the gain in the pass band, but to minimize the phase delay under the same condition.

**Fig. 2** Kaiser window obtained by changing $\alpha$

**Fig. 3** Frequency characteristics of FIR filter obtained by changing $f_c$ when $N = 1001$ and $\alpha = 4.0$

**Fig. 4** Frequency characteristics of FIR filter obtained by changing $N$ when $f_c = 5.0 \times 10^{-4}$ Hz and $\alpha = 4.0$
In this paper, we designed three types of FIR filter, FIR1, FIR2, and FIR3. The parameters for each design are as follows:

**FIR1:**
- \( N_1 = 343 \)
- \( f_{C1} = 4.3 \times 10^{-4} \text{ Hz} \)
- \( \alpha_1 = 0.1 \)

**FIR2:**
- \( N_2 = 443 \)
- \( f_{C2} = 5.2 \times 10^{-4} \text{ Hz} \)
- \( \alpha_2 = 0.2 \)

**FIR3:**
- \( N_3 = 543 \)
- \( f_{C3} = 6.3 \times 10^{-4} \text{ Hz} \)
- \( \alpha_3 = 1.02 \)

We set \( N_2 = 443 \) to ensure that it is equal to the number of data samples of the MA filter, \( N_{MA} \). For comparison, \( N_1 \) and \( N_3 \) were set as 343 and 543, which are \( N_{MA} \pm 100 \). \( f_{C1} \), \( f_{C2} \), \( f_{C3} \), \( \alpha_1 \), \( \alpha_2 \), and \( \alpha_3 \) were set such that these gains do not decrease in the pass band, and that the gains become -10 dB at 1/1200 Hz.

Fig. 6 shows the frequency characteristics of the MA filter and three types of FIR filters. Fig. 6(a) shows that the gain characteristics of all three types of FIR filter are lower than that of the MA filter. The gains of FIR1 and FIR2 in the pass band are lower than those of the MA filter and FIR3. On the other hand, Fig. 6(b) shows that the phase delay of FIR1 is the smallest in the frequency band up to 1/1200 Hz.

4. System Evaluation

We used the rate of reduction of the power fluctuation \( \varepsilon_\delta \) [%] to evaluate the smoothing of the power fluctuation, and it is expressed as

\[
\varepsilon_\delta = \frac{P_{\text{conv_max}} - P_{\text{pro_max}}}{P_{\text{conv_max}}} \times 100
\]

where \( P_{\text{conv_max}} \) and \( P_{\text{pro_max}} \) are the maximum amplitude of the power fluctuation in the conventional and proposed systems, respectively.

We evaluate the effect of reducing the capacity of the EDLC \( E_{EC} \) [kWh] using the maximum energy stored in the EDLC. This maximum energy is expressed by

\[
E_{EC} = \frac{1}{2} C_{\text{EDLC}} (v_{EC_{\text{max}}}^2 - v_{EC_{\text{min}}}^2)/3600
\]

where \( C_{\text{EDLC}} \) is the capacitance of EDLC, \( v_{EC_{\text{max}}} \) is the maximum voltage and \( v_{EC_{\text{min}}} \) is the minimum voltage of EDLC.

The smoothing control is evaluated by the effective value of the power on the AC side of the DC/AC converter in the LFC range. \( P_{\text{PC_AC,LFC}} \) [W] is expressed by

\[
P_{\text{PC_AC,LFC}} = \sqrt{\frac{1}{n} \sum_{f_1}^{f_2} P_{\text{PC,AC}}(f)}
\]

where \( f_1 \) and \( f_2 \) are the frequencies at both ends of the LFC range.

5. Power-Smoothing Control Results

For the simulation, we used the solar radiation intensity and temperature data obtained on a sunny day at Okayama city on May 1, 2013. We used the power
electronics circuit simulation software PSIM for the simulation.

Fig. 7 shows the domestic load power, $P_L$, which was used for the simulation, and Fig. 8 shows the grid power, $P_S$, in a conventional distribution generation system. When the grid power is a negative value, it means that the surplus power is fed back to the grid. The conventional distribution generation system consists of a PV system and a PCS, i.e., it is the distribution generation system shown in Fig. 1 without the EDLC system.

Figs. 9 and 10 show the power-smoothing control results obtained using the MA filter and FIR3. These results indicate that $P_{PV_{sys}}$ is smoothed by the power-smoothing control methods. Moreover, Figs. 9(b) and 10(b) show the power flows back to the grid, and they are observed to be smoothed compared with Fig. 8.

Table 1 shows the system evaluation results for the MA filter, FIR1, FIR2, and FIR3. It can be seen that the three types of FIR filters are superior to the MA filter from the perspective of the rate of reduction of the power fluctuation and the power in the LFC range. This is because the gain of the FIR filter is lower than that of the MA filter in the frequency band up to $1/1200$ Hz, as shown in Fig. 6(a). However, suppressing the components in the pass band causes an increase in the EDLC capacity, and thus the EDLC capacity increases. Therefore, the capacity of the EDLC system obtained using FIR1 and FIR2 are very large. Therefore, FIR1 and FIR2 are not suitable for power-smoothing control. FIR3 is superior to the MA filter because the $P_{PC\_AC\_LFC}$ of FIR3 is reduced by $5\%$ (25 W) compared to that of the MA filter, although the EDLC capacity of the MA filter decreased by $8.6\%$ ($3.72 \times 10^{-2}$ kWh) compared to that of FIR3.

6. Conclusion

This paper evaluates the MA filter and three types of FIR filters from the viewpoint of a power-smoothing control method for distributed generation systems using a PV system and an ELDC system. These filters are designed so that the gain becomes lower than -10 dB in the LFC range. The simulation results indicate that the MA filter...
and FIR3 are suitable for power-smoothing control. FIR3 is superior to the MA filter from the perspective of the rate of reduction of the power fluctuation and the power in the LFC range, although the EDLC capacity results in a slight increase. Consequently, FIR3 is most effective for power-smoothing control using the four smoothing control methods.

(i) The MA filter and FIR filters are designed to realize power-smoothing control so that these gains do not decrease in the pass band and that the gains become -10 dB at 1/1200 Hz.

(ii) We compared the characteristics of the MA filter with those of FIR filters. There is a trade-off to be made between the gain and the phase characteristics in the FIR filter design.

(iii) The simulation results show that the EDLC capacity for the MA filter is reduced by $3.72 \times 10^{-2}$ kWh compared with that of FIR3. However, the rate of reduction of the power fluctuation using FIR3 is 6% higher than that using the MA filter. The power in the LFC range obtained using FIR3 is reduced by 25 W compared with that using the MA filter. This study concluded that FIR3 is the most effective power-smoothing control method based on the above two viewpoints.

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