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Sensorless Active Damping Method for an LCL Filter in Grid-Connected Parallel Inverters for Battery Energy Storage Systems

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Abstract – A sensorless active damping scheme for LCL filters in grid-connected parallel inverters for battery energy storage systems is proposed. This damping method is superior to the conventional notch filter and virtual damping methods with respect to robustness against the variation of the resonance of the filter and unnecessary additional current sensors. The theoretical analysis of the proposed damping method is explained in detail, along with the characteristic comparison to the conventional active damping methods. The performance verification of the proposed sensorless active damping method shows that its performance is comparable to that of the conventional virtual damping method, even without additional current sensors. Finally, simulation and experimental results are provided to examine the overall characteristics of the proposed method.

Keywords: Active damping, Grid-connected inverter, LCL-filter, Parallel-connected inverter, Energy storage system

1. Introduction

As power consumption increases, it places a great burden on a power plant, requiring expansion of the power plant. However, this expansion is difficult because of the enormous cost and location problems. A battery energy storage system (BESS) is used to solve this problem. A BESS is composed of a battery, grid-connected inverter, and low-pass filter between the inverter and the grid. The required capacity of the BESS varies based on scale and purpose; the parallel structure of grid-connected inverters shown in Fig. 1 is widely considered a good solution because of its expandability and the convenience of repair. A grid-connected inverter, one of the core units of a BESS, causes higher harmonics by pulse width modulation (PWM) switching; Therefore, LCL filters are usually adopted to mitigate the inverter switching ripples. However, if the inverters are not properly controlled, the inherent resonances of the filters can cause serious power quality and stability problems. To solve this problem, both passive damping and active damping methods have been implemented [1-6].

In the passive damping method, a physical resistance is inserted into the LCL filter to reduce the resonance phenomenon. The drawback is that efficiency is reduced because of an increase in circuit loss; however, resonance suppression performance is excellent. In general, a resistor is added in series or parallel to the filter capacitor, or a resistor is added in parallel to the converter-side inductor or the grid-side inductor. Passive damping has a significant influence not only on the resonance suppression effect and system efficiency, but also on harmonic reduction performance according to the damping circuit configuration. The frequency component where resonance occurs without the performance degradation of the LCL filter is ideal. However, actual passive damping methods affect the harmonic suppression performance of the original LCL filter because it affects in all frequency domains [2, 7-9].

Unlike passive damping, active damping can suppress the resonances without additional losses for the filter; therefore, it is increasingly applied to improve system performance. Active damping is classified into two methods: multi loop active damping and filter-based active damping. Filter-based active damping is implemented by an additional filter on the control loop, and an additional sensor is unnecessary. In particular, a notch filter is widely

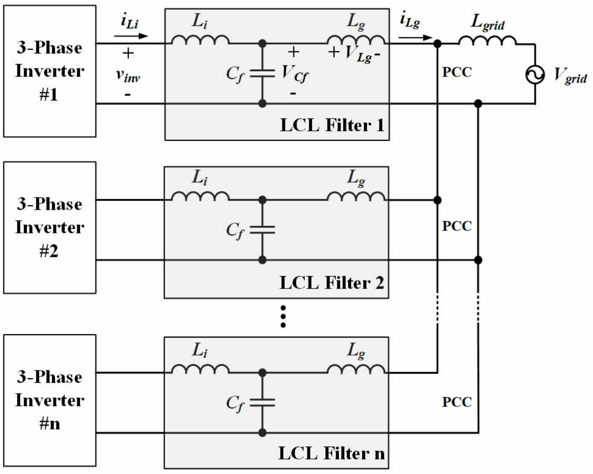

Fig. 1. Configuration of parallel connected inverters with LCL-filters

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adopted for its simplicity and damping quality. In multi loop active damping, the virtual resistor method is widely adopted. The virtual resistor method can reduce the effect of resonance through the feedback loop which includes voltage or current sensing of the filter capacitor branch [10-12].

For parallel-connected inverters, the variation of the frequency response and resonant frequency can cause much more deterioration of power quality and stability problems according to parameters such as the variation of the inductance or resonant frequency. Therefore, notch filter active damping is not suitable for parallel-connected inverters, because it requires accurate resonant frequency. Further, in the virtual resistor method, although it is robust for inaccuracy of the resonant frequency, additional sensors are necessary and the number of sensors increases in proportion to the number of inverters, resulting in increased system manufacturing cost [13, 14].

Therefore, we propose a virtual resistor method without additional sensors, called the sensorless active damping method. In this damping method, the filter capacitor current is calculated by the synthesis of the grid voltage and grid inductor current instead of the direct use of the sensing value in the conventional damping method. The theoretical analysis of the proposed damping method is explained in detail, along with the characteristic comparison to the conventional active damping methods. Through the performance verification of the proposed sensorless active damping method, it is noted that the performance is comparable to the conventional virtual damping method, even without additional current sensors. Finally, informative simulation and experimental results are provided to examine the overall characteristics of the proposed method.

2. Modeling of Parallel Connected Inverters

Fig. 2 shows the circuit diagram of a single inverter. The inverter is connected to the grid through the LCL filter. An ideal utility grid voltage does not have high-order harmonic components. Therefore, it can be treated as a short circuit in the high-frequency band. It can be presented through the Thevenin equivalent model and Fig. 3 shows the Thevenin equivalent model of a single grid-connected inverter with an LCL filter. The Thevenin voltage and impedance are as follows:

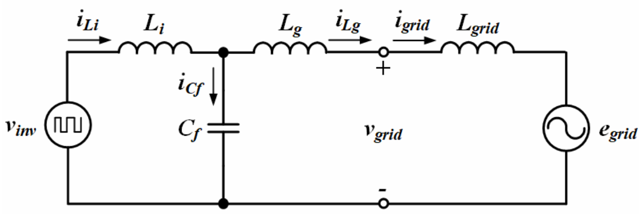

Fig. 2. Circuit diagram of a single grid-connected inverter

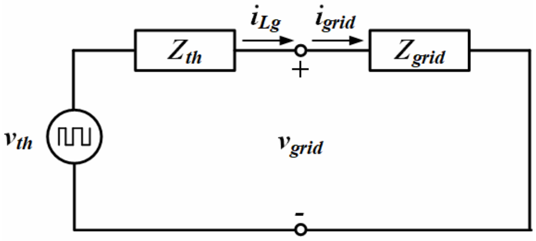

Fig. 3. Thevenin equivalent model of a single grid-connected inverter

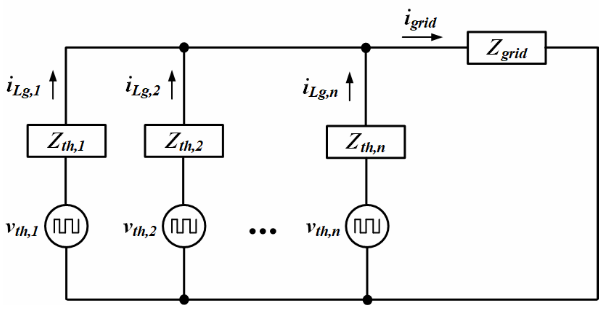

Fig. 4. Thevenin equivalent model of parallel-connected inverters with LCL-filters

$$v_{th}(s)=\frac{v_{inv}(s)}{s^2L_iC_f+1} \tag{1}$$

$$Z_{th}(s)=\frac{s^3L_iL_gC+s\left(L_i+L_g\right)}{s^2L_iC_f+1} \tag{2}$$

$$Z_{grid}(s)=sL_{grid} \tag{3}$$

Fig. 4 shows the grid-connected inverter connected in parallel. Assuming each inverter is configured with the same hardware and software, the grid-side inductor currents of all inverters are the same. Therefore, the grid-side inductor current (i_{Lg}) is expressed as Eq. (4).

$$i_{Lg}(s)=\frac{V_{th}(s)}{Z_{th}(s)+nZ_{grid}(s)} \tag{4}$$

Therefore, the admittance to the grid-side inductor current is calculated using Eqs. (1) - (4) as follows:

$$i_{Lg}(s)=v_{inv}(s)\cdot Y_{LCL}(s) \tag{5}$$

$$\begin{aligned}Y_{LCL}(s)&=\frac{i_{Lg}(s)}{v_{inv}(s)}\\&=\frac{1}{s^3L_iC_f\left(L_g+nL_{grid}\right)+s\left(L_i+L_g+nL_{grid}\right)}\end{aligned} \tag{6}$$

As can be seen in Eq. (6), the resonance frequency (ω_r) of the plant Y_{LCL} depends on the number of inverters n. The expression is as follows:

$$\omega_r(n) = \sqrt{\frac{L_i + L_g + nL_{grid}}{L_i C_f \left(L_g + nL_{grid}\right)}} \tag{7}$$

Fig. 5 shows the variation of admittance according to the number of parallel-connected inverters. As shown in Fig. 5, the resonant frequency decreases as the number of parallel connected inverters n increases.

3. Proposed Active Damping Method Without Additional Sensor

3.1 Conventional active damping methods

The block diagram of the notch filter active damping method is shown in Fig. 6. The output of the current controller contains the resonance components, and it is simply damped by adding a notch filter, which is the band-reject filter. Therefore, accurate calculation of resonant frequency is essential, and inaccuracy of the resonant frequency causes the serious problem for the system stability. This problem can be solved by wide band frequency design. However, it could cause the phase delay to be large below the resonant frequency and the filtering performance is deteriorated.

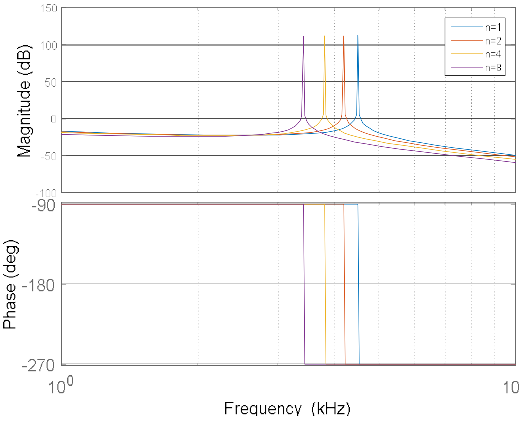

Fig. 5. Variation of admittance of conventional parallel connected inverters

In contrast, the virtual resistor active damping method, which is shown in Fig. 7, is robust against parameter variation. Resonant peak attenuation is carried out by sensing the filter capacitor current (i_{cf}) through the current sensors, multiplying H_v, and adding the result of the current controller. This process is identical to generating the voltage reference in the case of the passive damping method using a real resistor that connected in parallel with the filter capacitor.

3.2 Proposed active damping method

As explained above, although the conventional virtual resistor method is superior to the notch filter with respect to the robustness of the variation of the resonance frequency, it should use additional sensors. To overcome this problem, a sensorless active damping scheme is proposed as follows.

$$i_{Cf} = C_f \frac{d}{dt}\left(V_g + L_g \frac{di_{Lg}}{dt}\right) \tag{8}$$

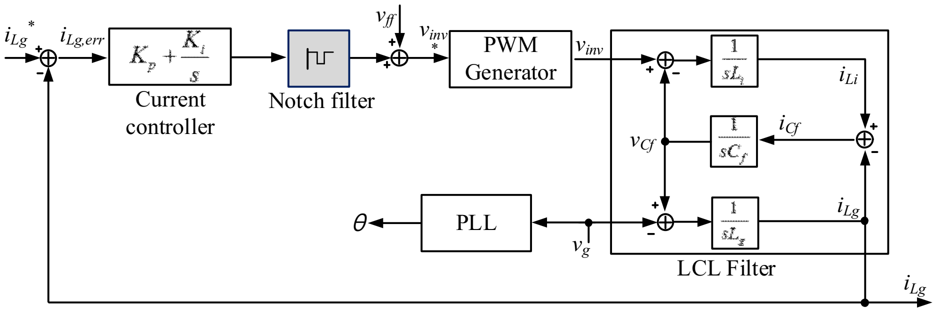

Fig. 6. Block diagram of the conventional notch filter active damping method

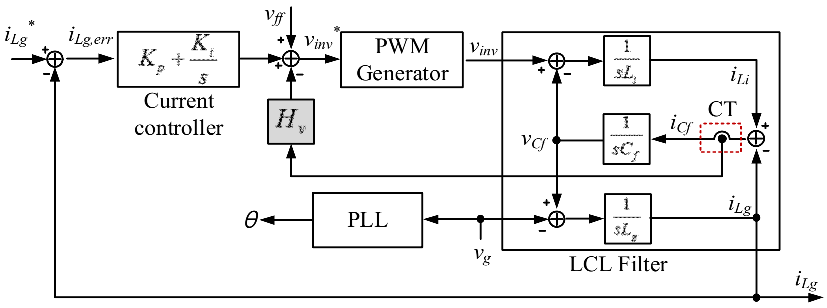

Fig. 7. Block diagram of conventional virtual resistor active damping

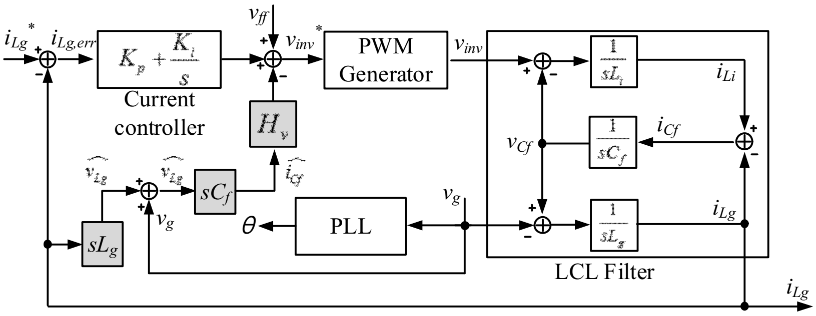

Fig. 8. Block diagram of proposed sensorless damping method

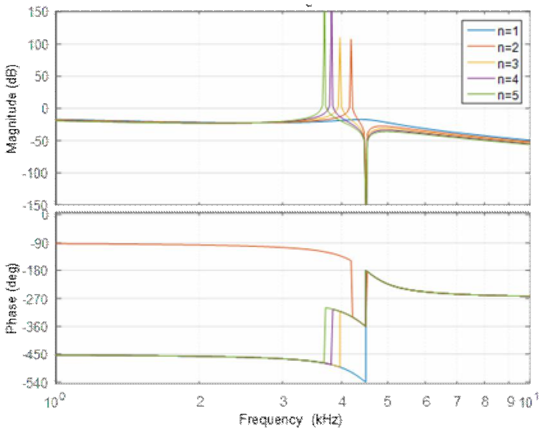

Fig. 9. Admittance of parallel connected inverters with notch filter method

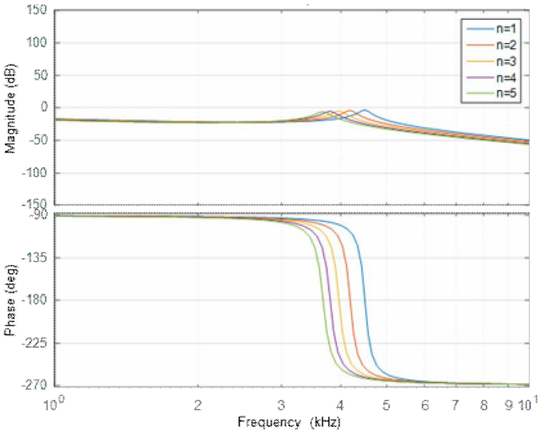

Fig. 10. Admittance of parallel connected inverters with proposed sensorless active damping method

The instantaneous value of the filter capacitor current is required to apply the virtual resistor method. Therefore, the filter capacitor current should be synthesized by using V_{grid} and I_{Lg}. This process can be expressed by Eq. (8).

Using Eq. (8), the proposed sensorless active damping method can be implemented as show in Fig. 8. The hat operator represents the synthesized values. In Fig. 8, it is noted that the filter capacitor current can be successfully obtained without sensing the actual current by current sensor.

As shown in Eq. (8), the synthesis is composed to the differential form. In particular, the sampling frequency should be over four times the switching frequency, as per the Nyquist sampling theory for accurate synthesis of the capacitor current because the process includes the bidifferential. Further, the sampling frequency is very low compared with the fundamental frequency of the grid; therefore, the phase delay between the real capacitor current value and synthesized value of the resonant frequency can be neglected.

$$Z_v = \frac{L_i}{C_f H_v} \tag{9}$$

$$Y_{LCL,damped} = \frac{1}{s^3 L_g L_i C_f + s^2 L_i L_g / Z_v + s\left(L_i + L_g\right)} \tag{10}$$

The admittance of the LCL filter on the proposed damping method is expressed by Eqs. (9) and (10). When H_v is constant, Z_v can be equivalent to the resistor which is a frequency-invariant passive component. This means that H_v determines the amplitude of the virtual damping resistor. Figs. 9 and 10 show the performance examination of the proposed sensorless active damping method, compared to the conventional notch filter damping method in parallel connected inverters. As shown in Fig. 9, in the case of the notch filter, as the number of parallel connected inverters is increased, the resonant peak is not attenuated and becomes higher. On comparing Fig. 9 with the proposed sensorless active damping method shown in Fig. 10, it can be noted that the resonant peak is successfully attenuated with multiple parallel inverters.

4. Verification of the Proposed Active Damping Method

4.1 Simulation results

To verify the validity of the proposed method, simulation was carried out. The simulation parameters are summarized in Table 1. The estimated capacitor current and actual capacitor current are shown in Fig. 11. Even

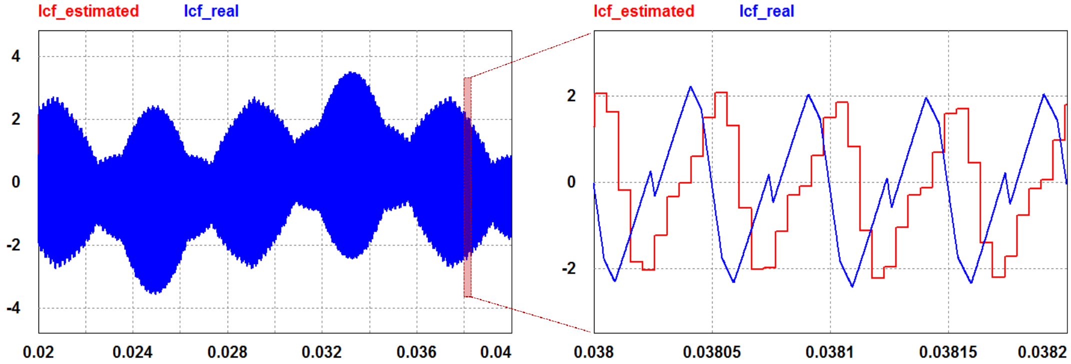

Fig. 11. Estimated capacitor current and actual capacitor current

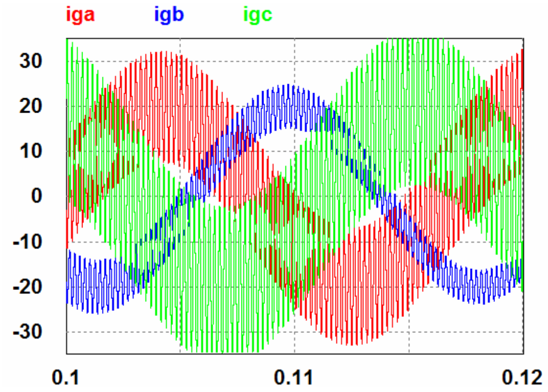

Fig. 12. Simulation waveforms of 8-parallel-connected inverter with conventional notch filter method

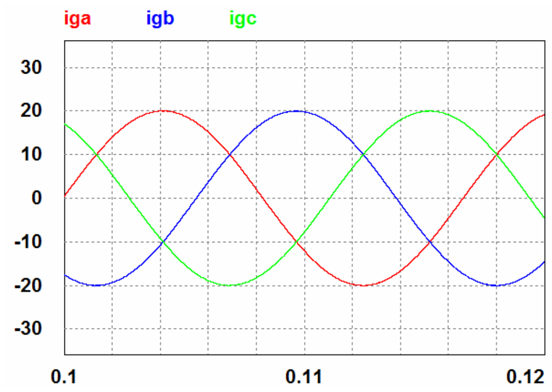

Fig. 14. Simulation waveforms of 8-parallel-connected inverter with proposed active damping method

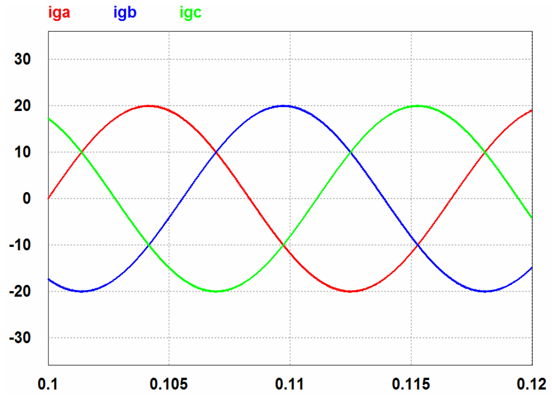

Fig. 13. Simulation waveforms of 8-parallel-connected inverter with conventional virtual resistor method

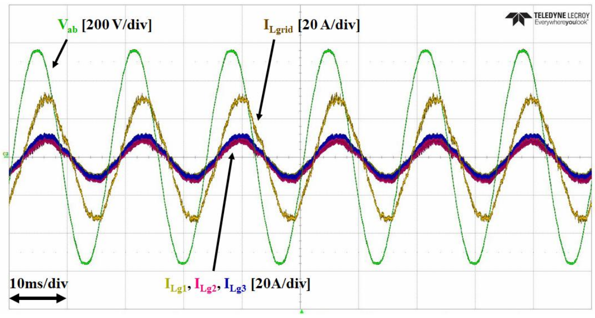

Fig. 15. Experimental results of the 3-parallel connected inverter with proposed active damping method

though there is the delay (13 μs) between the estimation and actual value, it is sufficiently short in comparison with the grid frequency, 60 Hz. Figs. 12, 13, and 14 present the performance comparison of the conventional and the proposed active damping methods. As shown in Fig. 14, the proposed sensorless active damping method is comparable to the conventional virtual damping method, while the notch filter method does not meet the performance requirement in the multi-parallel inverters.

Table 1. System parameters of inverter system

Parameter	Value
DC-Link Voltage (V_{DC})	650 V
Grid Voltage (V_{grid})	380 V_{LL}
Switching Frequency (f_{sw})	20 kHz
Inverter-side Inductor (L_i)	800 uH
Grid-side Inductor (L_g)	300uH
Filter Capacitor (C_f)	4.7 uF
Line Inductance (L_{grid})	100 uH
Sampling Frequency (f_{sample})	100 kHz
Z_v	170.2 Ω
H_v	1

4.2 Experimental results

The specification of the prototype system is the same as the simulation, presented in Table 1. The system is composed of 3-parallel-connected inverters. In the condition of a 6.6-kW load, the experimental waveform is shown in Fig. 15.

The average THD_i of the output currents is 3.66%, as measured by a power analyzer. Therefore, the proposed active damping method is reasonable for the damping of parallel connected inverters for grid-connected inverters.

5. Conclusion

An active damping method without additional sensors was proposed and its validity was verified through simulation and experiments. The performance of the proposed method was comparatively analyzed with two conventional methods. The results indicate that, in the proposed method, the capacitor current is comparably synthesized without an additional sensor, and the damping performance is equal to that of the conventional virtual resistor method. The proposed active damping method can be used for grid-connected inverters with parallel connections for various applications such as the BESS and renewable energy sources.

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