Performance Improvement of LCL-Filter-Based Grid-Connected Inverters Using PQR Power Transformation

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Abstract—The demand for three-phase pulsewidth modulation (PWM) inverters in applications such as power control or grid connecting has been on the increase in recent years. Such inverters are connected to the grid via an L filter or an LCL filter to reduce the harmonics caused by the switching. An LCL filter can reduce the harmonics induced by low switching frequency and generates a satisfactory level of grid-side current using a relatively low inductance, as compared to an L filter. The additional poles introduced by the LC part induce resonance in the system, leading to stability problems; this paper presents a compensation method using power theory to improve these issues, so that the performance of the designed LCL filter system can be improved. The effectiveness of the proposed algorithm is verified by simulations and experiments.

Index Terms—Harmonics, LCL filter, power theory, resonance, three-phase pulsewidth modulation (PWM) inverter.

I. INTRODUCTION

RECENTLY, the development of renewable energy technologies has been accelerating, making the simultaneous development of power conversion devices for applications, such as wind and solar power systems extremely important; the development of these technologies are actively underway. The harmonics caused by the switching of the power conversion devices are the main factor-causing problems to sensitive equipment or the connected loads, especially for applications above several kilowatts, where the price of filters and total harmonics distortion (THD) is also an important consideration in the systems design phase [1]. The inductance of the input or output circuits of the power conversion devices have conventionally been used to reduce these harmonics. However, as the capacity of the systems have been increasing, high values of inductances are needed, so that realizing practical filters has been becoming even more difficult due to the price rises and the poor dynamic responses.

These problems caused by realizing practical L filters in large-scale facilities can be solved by using LCL filters [2]–[6]. This is expected because an additional LC part can reduce the harmonics effectively in several hundreds of kilovoltampere. Moreover, an LCL filter realization is easy and effective, with little increase in overall system cost and without having to introduce additional sensors [7]. However, unless all of the filter’s parameters are properly selected, it is not possible to achieve effective reduction of the harmonics, and the additional resonance poles caused by the second LC part can further raise the stability problems. There are two solutions to this situation, namely, 1) introduce passive damping by adding a resistor connected to the parallel capacitor and 2) introduce active damping where no additional resistor is needed. Passive damping is simply a way to guarantee the stability of the system, but there is additional loss caused by the added resistance. To avoid such losses, papers relating to active damping algorithms that are aimed at resolving the stability problems without additional resistors have been announced. Lisserre and Blasko have proposed an active damping system using a lead–lag compensator [8], [9], Lisserre has proposed another active damping method using a band-stop-filter [10], and Dahono have proposed an active damping system using a virtual resistor [11]. But these algorithms require additional voltage sensor, exact tuning of gains, or filter parameters.

This paper proposes the compensation method using power theory, which has implementational advantages because it is simple and realizable without the need for an additional sensor and exact tuning of gains or filter parameters. In this paper, the design of a suitable LCL filter to reduce the aforementioned stability problems is derived. First, the LCL filter design and details of the stability problems of resonance are described, and then the new compensation method, to address the problems using power theory, are presented. Fig. 1 shows the overall control structure and the power conversion part of a wind turbine system for applying the new proposed algorithm for resonance compensation. The power generated by the synchronous generator is connected to the grid through the rectifier, inverter, and an LCL filter. The effectiveness of the proposed algorithm is verified by simulations and experiments.

II. LCL FILTER

The LCL filter comprises two inductors and a capacitor connected in parallel (per phase), as shown in Fig. 1. According to
The designed LCL filter can be expressed as a single-phase equivalent circuit, as shown in Fig. 2, and the transfer function is presented in (1), where $L$ is the converter-side inductor, $L_g$ is the sum of grid-side and transformer inductance, $C_f$ is parallel capacitor of LCL filter, and $R_d$ is resistor for passive damping.

$$G(s) = \frac{i(s)}{v(s)} = \frac{1}{Ls} \frac{(s^2 + R_d C_f z_{LC}^2 s + z_{LC}^2)}{(s^2 + \omega_{res}^2 s + \omega_{res}^2)}$$

The second denominator and numerator are related to the additional LC part of (1). If the damping resistor for the resonance compensation is not connected, as in (1), it can be then represented as follows:

$$G(s) = \frac{i(s)}{v(s)} = \frac{1}{Ls} \frac{(s^2 + z_{LC}^2)}{(s^2 + \omega_{res}^2)}$$

III. RESONANCE COMPENSATION USING POWER THEORY

The pole and zero introduced by the additional LC part causes resonance in the system, since the roots are on the imaginary axis [see (2)] and this can result in a stability problem. If damping resistors are connected, the pole and zero moves into the left-half plane (LHP), so that the stability would be guaranteed [see (1)]. However, this leads to losses caused by the additional inserted resistor. To cope with these problems, a new on-line nonlinear active damping compensation method, using PQR transformation, is proposed. The proposed scheme is shown in Fig. 3 and consists of subsystems to perform the PQR transformation, high-pass filter, and a reference-current-control circuit.

A. PQR Transformation

The phase voltage in Cartesian $a$-$b$-$c$ coordinates can be transformed to stationary $0$-$\alpha$-$\beta$ coordinates, as shown [16]

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & 1 & 1 \\ \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}.$$  (3)

If the three-phase voltages are balanced, the voltage in $0$-$\alpha$-$\beta$ coordinates can be expressed only with $v_a$ and $v_b$ that is sinusoidal and orthogonal. The voltage vector in $0$-$\alpha$-$\beta$ coordinates

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**Fig. 1.** Proposed LCL filter system for wind turbine applications.

**Fig. 2.** Equivalent single-phase LCL filter.

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can be transformed in $p$–$q$–$r$ coordinates as

$$
\begin{bmatrix}
v_p \\
v_q \\
v_r 
\end{bmatrix} = \frac{1}{v_{0,\alpha,\beta}} \begin{bmatrix}
v_0 & v_{\alpha} & v_{\beta} \\
v_{0,\alpha,\beta} & v_{\alpha,\beta} & v_{\alpha,\beta} \\
v_{0,\alpha,\beta} & v_{\alpha,\beta} & v_{\alpha,\beta}
\end{bmatrix} \begin{bmatrix}
v_0 \\
v_{\alpha} \\
v_{\beta} 
\end{bmatrix} = \begin{bmatrix}
v_{0,\alpha} \\
v_{0,\beta} \\
v_{0,\beta}
\end{bmatrix}
$$

(4)

where $v_{\alpha,\beta} = \sqrt{v_\alpha^2 + v_\beta^2}$ and $v_{0,\alpha,\beta} = \sqrt{v_0^2 + v_{0,\alpha}^2 + v_{0,\beta}^2}$.

As shown in Fig. 4, the voltage vector exits on the $p$-axis.

Also, the output currents in $abc$-coordinates can be transformed in $p$–$q$–$r$ coordinates as

$$
\begin{bmatrix}
i_o \\
i_d \\
i_q 
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
\sqrt{2}/2 & 1/2 & 1/2 \\
1/2 & -\sqrt{2}/2 & -\sqrt{2}/2 \\
-\sqrt{3}/2 & 0 & 0
\end{bmatrix} \begin{bmatrix}
i_a \\
i_b \\
i_c 
\end{bmatrix}
$$

and

$$
\begin{bmatrix}
i_p \\
i_q \\
i_r
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
1/3 & 0 & -1/3 \\
0 & -v_{0}\alpha\beta & 0 \\
v_{0}\beta & 0 & -v_{0}\beta
\end{bmatrix} \begin{bmatrix}
v_0 \\
v_{\alpha} \\
v_{\beta}
\end{bmatrix} = \begin{bmatrix}
i_o \\
i_d \\
i_q
\end{bmatrix}
$$

(5)

The instantaneous real and imaginary powers can be expressed as

$$
\begin{bmatrix}
p \\
q_d \\
q_r
\end{bmatrix} = \begin{bmatrix}
v_o i_p + v_{\alpha} i_q - v_{\beta} i_r \\
-v_{\alpha} i_p - v_{\beta} i_r \\
v_{0,\alpha} i_a + v_{0,\beta} i_b - v_{0,\beta} i_c
\end{bmatrix}.
$$

(6)

The three instantaneous powers are linearly independent of each other, and hence, the three current components can be controlled independently by compensating the three instantaneous powers, respectively [12]–[14].

B. Resonance Compensation Using PQR Transformation

The output current $i_{\text{inv, abc}}$ from the inverter on the resonance caused by the LCL filter is expressed by each of the three frequency components as

$$
i_{\text{inv, abc}} = i(\omega_{\text{fund}}) + i(\omega_{\text{sw}}) + i(\omega_{\text{res}}).
$$

(7)

We now apply power theory methods to compensate for the ac components of the input current to reduce the harmonic components caused by the resonance.

The voltage values used in the algorithm are estimated from the duty ratios of the inverter and dc-link voltages, which avoids the need for an additional voltage sensor as [15]

$$
v_{\alpha} = \sqrt{2/3} V_{\text{dc-link}} \left\{ D_a - \frac{1}{2} (D_b + D_c) \right\}
$$

$$
v_{\beta} = \frac{1}{\sqrt{2}} V_{\text{dc-link}} (D_b - D_c).
$$

(8)
Equation (6) implies that instantaneous real and imaginary powers are calculated through the estimated voltages and measured currents. The reference current control can control the system currents to achieve and maintain three-phase sinusoidal balanced conditions in any circuit situation.

The output phase currents $i_{a}, i_{b},$ and $i_{c}$ are transformed to their $p$–$q$–$r$ coordinates via the $PQR$ transformation, as shown in (5), resulting in $i_{p}, i_{q},$ and $i_{r}.$

The $i_{p}$ and $i_{q}$ currents consist of ac components ($i_{pac}$ and $i_{qac},$ respectively) and dc components ($i_{pd}$ and $i_{qdc},$ respectively). Fig. 5(a) shows the $p$-axis current on $p$–$q$–$r$ coordinates transformation of measured current. The $P$ and $Q$ can be controlled independently.

Table I presents the rated conditions of the simulation studies, and Table II shows the $LCL$ filter parameters.

Fig. 5 shows (a) passive damping. (b) Undamped.

The $i_{r}$ current is mainly related with neutral-line current between grid and system (neutral point of $LCL$ filter). However, if the zero-sequence voltage exists in the system, not only the compensation of the $i_{r},$ but also an additional compensation of $i_{r}^{'},$ are needed to eliminate the neutral-line current from the system. Then, if $i_{r}^{'}$ is controlled to $i_{r}^{'} = -i_{p} \tan \theta_{2} \tan \theta_{2} = V_{0} / V_{\alpha \beta},$ the current vector locates on the $\alpha$–$\beta$ plane [17].

The compensation currents can be represented as

$$
\begin{align*}
\begin{bmatrix} i_{P}^{\text{comp}} \\ i_{Q}^{\text{comp}} \\ i_{R}^{\text{comp}} \end{bmatrix} &= \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{\alpha} \\ v_{\beta} \\ v_{0} \end{bmatrix} \\
&= \begin{bmatrix} -v_{\alpha}v_{\beta} \\ v_{\alpha} \end{bmatrix} - \begin{bmatrix} v_{\alpha}v_{\beta} \\ v_{\alpha} \end{bmatrix} \begin{bmatrix} i_{P}^{\text{comp}} \\ i_{Q}^{\text{comp}} \\ i_{R}^{\text{comp}} \end{bmatrix},
\end{align*}
$$

(10)

The proposed compensation scheme is simple, clear, and calculating the compensation currents: $i_{d}^{\text{comp}}$ and $i_{q}^{\text{comp}}$ can be performed instantaneously in the synchronous $d$ and $q$ frames with each control variable being able to be controlled independently.

In (9), by selecting the instantaneous imaginary power and the ac component of the instantaneous real power, the compensation current is determined to compensate the harmonics caused by the switching and resonance effects. The compensation current $i_{d}^{\text{comp}}$ and $i_{q}^{\text{comp}}$ are designed to control the inputs, so that the overall current harmonics are reduced.

IV. SIMULATION

To confirm the validity of the proposed algorithm, simulation has been performed using PSIM. The simulation studies are...
Fig. 6. Simulated waveforms of (top) line-to-line voltage, (middle) inverter-side current, and (bottom) grid-side current. (a) Connected damping resistor (5Ω). (b) Undamped (no resistor).

Fig. 7. Simulated waveforms of control input current and proposed compensation current. [(Top) $q$-axis and (bottom) $d$-axis.]
Fig. 8. Simulated waveform of proposed algorithm applying at 0.2 s. [(Top) line-to-line voltage, (middle) inverter-side current, and (bottom) grid-side current.]

Fig. 9. Simulated waveform of (top) line-to-line voltage and (bottom) inverter-grid-side current. (a) With 3 mH of Grid inductance. (b) With 3 uH of Grid inductance.
Fig. 10. Frequency analysis of $d$- and $q$-axes currents in the synchronous reference frame. (a) Undamped. (b) Proposed active damping.

Fig. 11. Structure of the experiment setup (10 kW).
operated under the conditions given in Table I, and the LCL filter, which has parameters, as presented in Table II, has been designed (see, [2] for further details).

Fig. 6 shows the simulated waveforms for the series-connected damping resistor to the capacitor as well as when no damping resistor is used.

If the damping resistor, with a similar impedance level to the filter capacitor at the resonance frequency, is connected, then the resonance poles caused by the LCL filter move toward the stable region, so that the stability should be guaranteed [2]. However, when the system is undamped, the switching cause considerable unwanted resonance, as shown in Fig. 6(b).

Fig. 7 compares the simulated waveform of the control input currents transformed into the synchronous d-q coordinates with the compensation currents determined in the proposed algorithm.

In Fig. 7, the dc component of the current tracks the reference value, but the ac component oscillates because of the resonance. The proposed compensation current using power theory has an almost similar frequency and magnitude to the ac component of the control input.

The waveform of the line-to-line voltage and phase current applied to the proposed compensation method is shown in Fig. 8, where the oscillation caused by the resonance is seen to decrease because of the compensation actions and only the fundamental sine wave is supplied to the control input.

The LCL filter resonance strongly depends on the grid impedance. Due to the change of grid impedance, the resonant frequency and magnitude are varied with the changes of filter parameters. But the proposed algorithm selectively compensates the harmonics caused by switching and resonant frequency. Therefore, as shown in Fig. 9, there are no problems with the resonant frequencies.

The unbalanced grid voltage in the grid-connected inverter is needed to be discussed. The frequency analysis of grid currents at the unbalanced grid voltage is shown in Fig. 10.

In Fig. 10(a), the frequency component of the oscillation that was caused by the unbalanced grid voltages is much lower than the resonance frequency of the LCL filter. Since the proposed compensation method was designed to eliminate the high-frequency component that was caused by the resonance of LCL filter, there is no problem in removing those harmonics. However, it is not easy to remove the relative low-frequency oscillations by the unbalanced voltage at the same time. The oscillations caused by the resonance is seen to decrease after the compensation acts at 0.15 s; however, the low-frequency oscillations still exist. Fig. 10(b) is the frequency analysis of the d- and q-axes currents after the compensation. The unbalance voltage can affect the control system. However, it does not affect the performance of the proposed algorithm and the LCL filters because the frequency component of the oscillation that was caused by the unbalanced grid voltages is much lower than the resonance frequency of the LCL filter.

V. EXPERIMENTS

Fig. 11 shows the configuration of the equipment used in the experiments that have been performed on a 10-kW experimental device operating at the same rated conditions of the simulation studies. The motor–generator (MG) set was used as a model of the wind power generator, which formed the basis of the experimental studies, to control the speed and torque of the 4.4 kW, eight-pole synchronous machine with a 5.5 kW, 380 V, 1740 r/sec four-pole induction machine. The part of power conversion has 3.5-kHz switching frequency and consists of two insulated-gate bipolar transistor (IGBT) converters having a dc-link capacitor between two IGBT converters. The converter of the MG-set side connects with the stator of the generator and the converter of the grid-side connects with the grid through the LCL filter.
Fig. 14. Frequency spectra (the grid and converter currents) at each harmonics order with undamped.

Fig. 15. Their spectra (the grid current and the converter one) at each harmonics order with proposed algorithm.

Fig. 16. Experimental result of current for transient condition [(top) inverter-side current and (bottom) grid-side current].
If the LCL filter is applied to the system without damping, resonance occurs, and Fig. 12 shows the improvement of this stability problem when the proposed compensation current using power theory is used to compensate via the control input.

In Fig. 13, the inverter- and grid-side currents of the system using the LCL filter without additional losses are compared by applying the proposed algorithm. The oscillation component caused by resonance is compensated by the proposed algorithm, and the harmonics caused by the switching are reduced by the LCL filter. Fig. 14 shows the harmonics analysis before and after the compensation due to the proposed algorithm.

The current ripple caused by resonance is compensated by the proposed algorithm and is reduced by approximately 90% at the resonance frequency. Consequently, in Fig. 14, the inverter- and grid-side currents applying the proposed algorithm are reduced by approximately 90% without additional losses.

The current ripple caused by the resonance is compensated by the proposed algorithm, and the harmonics caused by switching are reduced by the filter. The analysis of the LCL filter performance is shown in Fig. 15. The inverter-side current, affected by only the L, and the grid-side current affected by the LCL filter have almost similar properties at low frequencies, but 95% of the harmonics of the switching frequency (3.5 kHz) are reduced.

To verify the transient condition stability of the proposed algorithm, when the motor speed modeled on the blade of the wind turbine is decreased from 1200 to 900 r/sec, the output current of the generator decreased from 6 to 2 A-Peak, as shown in Fig. 16.

VI. CONCLUSION

This paper has proposed an algorithm to improve the system performance by alleviating the problem of resonance caused by the use of LCL filters in high switching systems. The resonance and switching harmonics are reduced by using a compensator, based on power theory. The paper has presented results from simulations and experiments that have been performed with a 10-kW experimental setup. Future research include applying the proposed algorithm to a several megawatt wind power system.

REFERENCES

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