Direct active damping control for grid-connected AC/DC converter with LCL filter using augmented look-up table

Chuanjin Zhang\textsuperscript{1} | Yutan Li\textsuperscript{1} | Chenxi Jia\textsuperscript{1} | Hong Fu\textsuperscript{1} | Xiao Zhang\textsuperscript{2} | Hui Zhang\textsuperscript{2}

\textsuperscript{1} School of Intelligent Manufacturing, Jiangsu Vocational Institute of Architectural Technology, Xuzhou, China
\textsuperscript{2} School of Electrical and Power Engineering, China University of Mining and Technology, Xuzhou, China

Abstract
This paper presents a novel approach to adapt the conventional direct power control (DPC) methods that are applied to ac/dc converters with an inductive capacitive inductive (LCL) filter. These new solutions improved the conventional DPC with an active damping algorithm via multi-variable constraint adjustment, which is based on an augmented look-up table and multi-variable comparators. The novel look-up table proposed for the active damping algorithm of the LCL filter allows an optimal voltage vector assignment to be chosen using differences in converter-side current and capacitor voltage. This method is also compared with the DPC method with active damping via the addition of a virtual damping resistor and a harmonic rejection loop. The steady-state (total harmonic distortion of the grid current) and dynamic performances (response time on step changes of the set current), as well as the immunity under distorted grid voltage conditions of the proposed system, are verified through simulation results and experimental measurements.

1 | INTRODUCTION

Three-phase ac/dc voltage converters, due to their bidirectional energy flow, are employed in many grid-connected applications, such as active front-end systems, static synchronous compensators (STATCOM), uninterruptible power systems, and renewable energy sources distributed generating systems (e.g. photovoltaic, wind power etc.) [1–4].

Numerous control algorithms were extensively studied to ensure high-quality current output and obtain proper power flow in an ac/dc converter system. Almost all of the strategies can be divided into two categories based on whether or not the control system contains pulse-width modulation (PWM)/space vector modulation (SVM) modulators: linear control and non-linear control. The linear methods (e.g. voltage-oriented control using proportional–integral regulators [5,6], direct power control (DPC) with SVM [7,8], stationary frame with resonant integrator [9] etc.) are characterised by high-accuracy steady states and constant frequency switching, which facilitates the design of filters connected to the grid. One disadvantage of these control schemes is that the performance depends on the tuning of the current regulator parameters and the coordinate transformation accuracy. The other non-linear control strategies, providing direct control for the current or power of the ac/dc converters without a current regulator and a PWM modulator, mainly include hysteresis current control [10], fuzzy logic control [11], sliding-mode control [12], direct power control with a look-up table (DPC-LUT) [13, 14], model-predictive control (MPC) [15,16] etc. They allow for the best control quality to be achieved in both steady and transient states. The main disadvantage of the non-linear method is the introduced variable switching frequency, which makes ac harmonic filter design challenging, as it must eliminate broadband harmonics.

For an ac/dc converter, a harmonic filter is also essential for the grid connection to attenuate the current harmonics and meet the grid code requirement. When compared with the \textit{L} filter, the inductive capacitive inductive (LCL) filter has less volume, better filtering performance, lower cost, and less inertia [17]. However, the LCL filter can cause strong resonance and requires additional effort for system control. To overcome the inherent resonance of LCL filters, active damping (AD) via a control algorithm is preferred over passive...
The proposed control strategy could possess comparative benefit of the proposed control strategy are summarised as follows.

1. The converter-side current and filter capacitor voltage can be constrained and controlled at the same time by the new look-up table of the proposed control strategy.

2. With the help of the new look-up table, the proposed control strategy achieves AD control while realizing current tracking control.

3. The proposed control strategy could possess comparative dynamic response speed to conventional DPC.

4. Under the premise of obtaining the same quality of the grid-side current, the proposed control method can use an LCL filter with smaller parameters.

The remainder of this paper is organised as follows. In Section II, a mathematical model of the grid-connected ac–dc converter with an LCL filter is described. In Section III, the design and illustration of the DPC-rAD and DPC-dAD control strategies taking into account the existence of the resonance LCL filter are given. Then, Section IV presents the results of the experimental investigations into both steady and transient states as well as under the grid voltage disturbances. Finally, Section V summarises the main conclusions.

2 | MATHEMATICAL MODEL OF GRID-CONNECTED CONVERTER WITH LCL FILTER

Figure 1 shows a three-phase ac–dc converter connected to the grid via a passive LCL filter, as well as the equivalent circuit for the converter with an LCL filter.

The equivalent circuit shows that the converter-side induc-
tor \( L_1 \) handled the high-frequency voltage of the inverter output \( u_{\text{out}} = u_{\text{dc}} - u_{\text{in}} \). The capacitor sunk the majority of the high-frequency ripple current of \( i_1 \) and left only the line frequency component in the grid current. The grid-side induc-
tor \( L_2 \) attenuated the grid-side current to meet the grid code. The relationships described by the equivalent circuit were usually transformed into the \( dq \) rotating reference frame oriented by the grid phase as follows [15]:

\[
\begin{align*}
\dot{e}_{dq} &= L_2 \frac{d^2 e_{dq}}{dt^2} + i_{2dq} R_2 + u_{cdq} + j \omega L_2 i_{2dq} \\
i_{2dq} &= C \frac{d u_{cdq}}{dt} + i_{1dq} + j \omega C u_{cdq} \\
u_{cdq} &= L_A \frac{d i_{1dq}}{dt} + i_{1dq} R_1 + j \omega L_A i_{1dq} + u_{dq},
\end{align*}
\]

(1)
Due to the subjoin of the capacitance branch, the control system was changed from first-order to third-order. The transfer function of the converter with an LCL filter is presented as

\[ \frac{i_2(s)}{u_{\text{con}}(s)} = \frac{1}{L_2C_1s^3 + (L_2 + L_4)s} \]  

where \( u_{\text{con}} \) represents the output phase voltage of the converter. Equation (2) shows that the grid current suffers from a resonance problem; therefore, the LCL filter may have caused the steady-state and transient distortion of the output current due to resonances. Also, the filter capacitor would bring more reactive power consumption. If the resistances \( R_1 \) and \( R_2 \) that represent the inductor power losses were ignored, then the phase relationships of the current and voltage vectors would appear, as presented in Figure 2.

Figure 2 shows that additional reactive power consumed by the capacitor further increased the phase difference between the converter output voltage and the grid voltage. If the capacitor reactive power influence was ignored, then it would shift the power factor at the grid.

3 | CONTROL METHODS AND CONTROLLER DESIGN

The main task of the LCL filter used in the ac-dc converter was to get a higher attenuation of high-frequency harmonic voltage and improve the grid-side current quality. However, the presence of the resonance peak of the LCL filter means that directly applying the DPC-LUT method designed for ac-dc converters with the \( L \) filter to the converter with an LCL filter would increase the grid current total harmonic distortion (THDi) values [2]. Therefore, damping control methods must be added based on the original DPC-LUT to suppress current resonance.

3.1 | DPC-rAD method

The DPC method utilised the converter-side current \( i_1 \) as the direct feedback signal to control the active and reactive power, thereby making the system respond faster. Therefore, the converter as well as the converter-side inductor could be considered a controlled current source, as shown in Figure 3.

In the passive damping method, a suitable passive resistor paralleled with the capacitor [see Figure 3(a)] could effectively dampen the resonant peak, but better damping effectiveness usually results in higher power losses. The parallel resistance was equivalent to providing a resonant current leak path; therefore, the passive damping resistor could be replaced by a controlled current source [see Figure 3(b)]. The controlled current was proportional to the resonance component of the capacitor voltage as \( i_d = k_d \cdot \tilde{u}_c \), and the transfer function of the circuit shown in Figure 3(b) was found as

\[ \frac{i_2(s)}{i_1(s)} = \frac{\frac{1}{L_2C}}{s^2 + \frac{k_d}{C} + \frac{1}{L_2C}}. \]  

The parameters \( \tilde{u}_{C,d} \) existing in the damping power expression were the capacitor voltage resonance components, which were extracted through a notch filter at the resonant frequency. The same suppression effect of the resonance peak as of the parallel resistor could be obtained by setting a reasonable damping factor \( k_d \). Then, the active and reactive power damping components, presented in the following equation, should be subtracted from the fundamental active and reactive power references

\[
\begin{align*}
p_d &= \frac{3}{2} \tilde{u}_{C,d} \cdot k_d \cdot \tilde{u}_{C,d} \\
g_d &= -\frac{3}{2} \tilde{u}_{C,d} \cdot k_d \cdot \tilde{u}_{C,d}.
\end{align*}
\]

However, using this method to suppress resonance would increase the low-order harmonics in the capacitor current, and selecting a smaller damping factor could help reduce these low-order harmonics. To ensure a high level of damping, an active harmonic rejection controller (5) was introduced in conjunction with the AD approach. The rejection harmonics reference
The capacitor between $L_2$ and $L_1$ greatly increased the attenuation capability of the high frequency harmonic, but it consumed more reactive power at the line frequency. Therefore, reactive power compensation for the capacitor must be implemented in the converter control system. The entire DPC with the AD scheme via modified reference power (including three parts: 1) AD components, 2) low-order harmonic rejection, and 3) reactive power compensation) was better explained through the block diagram in Figure 4. These three-part control signals have to be added to the fundamental references ($p_{\text{ref}}$ and $q_{\text{ref}}$).

Figure 5 shows the simulation results of the DPC-rAD, and the simulation parameters are given in Table 1. The THDi value of the phase current was 4.52%. The AD algorithm has a significantly limited value of the resonance harmonics of the LCL filter in the grid current.

### 3.2 DPC-dAD method

In the grid-oriented $dq$ synchronous rotating coordinate system, the active power could be represented by the current vector $i_{2d}$ and the reactive power by $i_{2q}$. Moreover, the state of the grid-side current $i_{2dq}$ was usually achieved by adjusting the converter-side current $i_{1dq}$ [18]. However, when the converter-side current

\[
p_{\text{ref}} = \frac{k_p}{1 + \frac{s}{s_T}} \left( p_{\text{ref}} - \frac{1}{1 + \frac{s}{s_T}} p_{\text{ref}} \right)
\]  

\[i_{\text{ref}} = i_{\text{ref}} \left( 1 + \frac{k_i}{s \cdot T_i} \right) \cdot \left( i_{\text{ref}} - \frac{1}{s \cdot T_i} i_{\text{ref}} \right).
\]

Figure 4  Block diagram of the DPC-rAD control system for grid-connected converters with LCL filters

**TABLE 1** System parameters of three-phase converter with LCL filter

| System parameter               | Note | Value |
|--------------------------------|------|-------|
| Phase voltage peak value       | $e$  | 310 V |
| Grid voltage frequency         | $f_E$| 50 Hz |
| DC-bus voltage                 | $U_{dc}$| 680 V |
| Converter-side inductance      | $L_1$| 3.1 mH|
| Converter-side residual resistance | $R_1$| 0.05 $\Omega$ |
| Grid-side inductance           | $L_2$| 1.6 mH |
| Grid-side residual resistance  | $R_2$| 0.02 $\Omega$ |
| Filter capacitor               | $C$  | 20 $\mu$F |
| Sampling frequency             | $f_s$| 20 kHz|

**FIGURE 5** Simulation results of the grid phase current $i_{1a}$ (100 A/div) and voltage $e_a$ (100 V/div) for the DPC-rAD method
$i_{1dq}$ was taken as the only controlled object, harmonic components related to the $\omega_{res}$ would appear in the grid-side current $i_2$. Figure 6 shows the simulation results of DPC-LUT for $L$ filter applied to the LCL filter without any changes, using the simulation parameters in Table 1.

Figure 6 shows that the oscillation trend of the grid-side current was consistent with the capacitor voltage oscillation. The capacitor voltage spectrum shows that the significant harmonic frequencies were also concentrated around the frequencies [see Figure 6(c)]. While broadband harmonic distributions exist, the harmonic of $i_1$ did not increase significantly at the resonance point [see Figure 6(d)]. This means that the spectrum of voltage $u_{L1a}$ generated by $i_1$ should not contain the harmonic component at the resonance frequency accessory [see Figure 6(f)]. Therefore, the harmonic component in the capacitor voltage must be caused by the harmonic frequency harmonic component [see Figure 6(e)] in the converter output voltage.

Therefore, if the corresponding control of the capacitor voltage could be performed while tracking the converter-side current, then the resonance components in the grid-side current could be effectively suppressed. Considering the capacitor voltage remained unchanged during a sampling period, the third equation of (1) could be transformed into

$$I_{1dq}^* = I_{1dq} \left(1 - \frac{T_s}{L_1} R_1\right) + \frac{T_s}{L_1} (U_{adj} - U_{dq}).$$

From (6), the converter output voltage $u_{adj}$ together with the capacitor voltage $u_{adj}^*$ determined the converter-side current in $i_{1dq}$, and the type space vector selection rules for the converter-side current controlling are shown in Figure 7.

Since the capacitor voltage of the LCL filter was not as stable as the grid voltage, the capacitor voltage may be affected at each time that the space vector changing. By discretising (1), the
difference in the capacitor voltage in one sampling period could be obtained as follows:

$$\Delta u_{cd}(k+1) = \frac{i_{2dq}(k) - j\omega C u_{cd}(k) - i_{1dq}(k) - 0.5\Delta i_{1dq}(k+1)}{C} T_c$$  (7)

where $\Delta i_{1dq}(k+1)$ was the difference of the converter-side current when the voltage vector state was switching.

Because of the working mechanism of the DPC method and the characteristics of the LCL filter, the response of the grid-side current to the space vector relatively lagged behind the converter side. Therefore, ignoring the changes in the grid-side current in a very short time, the capacitor voltage difference (7) could be further modified as follows:

$$\Delta u_{cd}(k+1) \approx \frac{-i_{1dq}(k) - 0.5\Delta i_{1dq}(k+1)}{C} T_c.$$  (8)

The change in converter-side current translated into a change in the capacitor current at the moment of the voltage vector switching. Therefore, the capacitor voltage could be controlled indirectly by dominating the converter current trend. Taking the situation of $u_{cd} - n_{cd} > H_{adq}$, $n_{iq} - n_{iq}^* > H_{aq}$ as an example, due to $\Delta u_{cd}(k+1) < 0$, the control strategy should choose one voltage vector that can force $\Delta i_{1dq}(k+1) > 0$ as the output voltage vector of the converter at the following moment. If the current status of the converter-side current was $i_{1q} > H_{aq}$, then the vector selecting was just the opposite according to the current tracking control law and the capacitor voltage harmonic suppression law, as shown in Figure 8(a).

Figure 8(b) and (d) shows the voltage vector selection with different error states of capacitor voltages when $i_{1q} > H_{aq}$.

When the deviations of the capacitor voltage $\delta u_{cd}$ were within the tolerance range $\pm H_{adq}$, the new DPC-dAD control only aimed at tracking the command current. Its corresponding control laws are shown in Figure 7 (colouring part in Table 2). Once $\delta u_{cd}$ exceeded the allowable range, the newly introduced control law was enabled. Meanwhile, the vector selection rule for

$$S_{adq} = \begin{cases} +1, & \delta_{adq} > H_{adq} \\ 0, & H_{adq} \geq \delta_{adq} \geq -H_{adq} \\ -1, & -H_{adq} \geq \delta_{adq} \end{cases}$$  (9)

$$S_{cdq} = \begin{cases} 1, & \delta_{cdq} > H_{cdq} \\ 0, & -H_{cdq} \geq \delta_{cdq} \geq -H_{cdq} \end{cases}$$  (10)
current tracking would be temporarily disabled. The hysteresis loop width of the current and the voltage comparator have effects on the operating state of the system, such as switching frequency, current ripple, damping effect etc. When the voltage loop width is set to be large, the damping control effect is not obvious, but the voltage loop width setting cannot be too small; otherwise, it will easily cause the system to oscillate and unstable. The setting of current loop width also has contradictory problems, smaller loop width will increase switching frequency and loss, but larger loop width will increase current ripple.

From (6) and (8), it seems that the robustness of the whole system is affected by varying parameters $L$ and $C$. Next, the robustness will be analysed in depth. When $L$ changes within $\pm 50\%$, it still satisfied $T_1^c R_1/L_1 \ll 1$. Therefore, the change of $L$ does not have enough influence on the state of the converter-side current vector ($i_{dcq}$). No matter the changes of $L$, the sign of the coefficient $(T_1/L_1)$ will never change. Then, the effect of the converter voltage vector on the direction of the current vector change obtained by (6) will not change, but only the magnitude of the current change in one switching period will be changed. The switching frequency of the proposed DPC-dAD strategy is not fixed. When the width of the comparator has been set, if the variable parameters affect the voltage vector on the current vector change in the unit switching period, the system will automatically change the switching frequency to adjust the effect. Similarly, when $C$ in (8) changes, the switching frequency will also be automatically adjusted to meet the control requirements.

Take the first sector as an example to specifically explain the selection of the voltage vector for capacitor voltage control, as shown in Figure 9.

The voltage vector selection in other sectors is similar to the first sector, so they will not be listed one by one. Accounting for the reactive power consumed that was caused by the filter capacitor when the reference grid-side current in the $dq$ coordinate system ($i_{2dq}$) was known, the reference values of the capacitor voltage and converter-side current ignoring the high-frequency components could be calculated as follows:

$$
\begin{align*}
\bar{u}_{c_{dcq}} &= \bar{c}_{dq} - R_2 i_{2_{dcq}}^* - j \omega L_2 i_{2_{dcq}}^* \\
\bar{u}_{1_{dcq}} &= \bar{i}_{1_{dcq}} - j \omega C i_{c_{dcq}}
\end{align*}
$$

Finally, the proposed control scheme is shown in Figure 10. As two of the three states (capacitor voltage and converter-side current) of the LCL filter were controlled, the resonant energy oscillation between the inductances and the capacitance was effectively avoided.

To verify the feasibility of the proposed DPC-dAD algorithm and explain the working mechanism of AD, a set of dynamic simulations of the proposed DPC-dAD were implemented in MATLAB/Simulink. Figure 11 shows the waveforms of the simulations results. The simulation results include all four possible situations. The three pictures included in each working condition are displayed in sequence from top to bottom: a) difference between the actual value and the reference value of the converter-side current in the synchronous ($dq$) coordinate system; b) the difference of the filter-capacitor voltage in the $dq$-coordinate system; and c) switching signals of phases $a$, $b$, and $c$.

Taking Figure 11(a) as an example for analysis, the proposed AD method was introduced into the control system at $T_1$. Before $T_1$, the control system directly utilised the traditional DPC strategy for the grid-connected converter with only an $L$ filter. While the converter-side current changed according
FIGURE 10  Block diagram of the proposed DPC-dAD control system for grid-connected converters with LCL filter

FIGURE 11  Simulation results with the proposed AD method implemented at different states under the conditions of active powers being 50 kW (generating) and the reactive powers being 0 Var. (a) The situation of \( \Delta u_{qc} > 0, \Delta u_{cd} < 0 \). (b) Situation of \( \Delta u_{qc} > 0, \Delta u_{cd} > 0 \). (c) Situation of \( \Delta u_{qc} < 0, \Delta u_{cd} < 0 \). (d) Situation of \( \Delta u_{qc} < 0, \Delta u_{cd} > 0 \).
to the reference value [see (a) in Figure 11 (a)], a large deviation existed between the feedback capacitor voltage and the reference value [see (b) Figure 11 (a)]. The state of the converter system at $T_1$ can be expressed by the capacitor voltage deviation and the converter-side current deviation as follows: $\Delta u_{cd} > 0$, $\Delta u_{cq} < 0$, $\Delta i_{1d} > 0$, and $\Delta i_{1q} < 0$.

According to the traditional DPC control law (colouring part in Table 2), $V_3$ (001) should be selected. However, the voltage vector generated by the active AD strategy was $V_3$ (010) in the same situation. Moreover, $V_3$ made the forward deviation of the $d$-axis current $i_{1d}$ increase sharply. This analysis indicated that the changing current of the converter was opposite to the capacitor current in a short time. The $d$-axis component of the capacitor current suddenly became a large negative value at $T_1$, then the $d$-axis component of the capacitor voltage decreased in the following period. On the other hand, due to the sharp increase of $i_{1d}$, the output vector of the converter continuously switched between $V_5$ and $V_6$ in the next period (blue shaded area), which made $i_{2d}$ continuously drop.

The time to $T_2$ and the polarity of $i_{2d}$ changed, and $u_{cd}$ appeared at the inflection point simultaneously. After an adjustment round, the capacitor voltage deviation and current deviation were well suppressed from $T_1$. However, (a) in Figure 11(a) shows that, although the oscillation of the capacitor voltage deviation was effectively controlled, the average value of the current deviation was increased when compared with the previous value. Therefore, an important aspect of the proposed damping strategy was that a compromise exists between the AD control level and the current tracking control effect. The analysis of other states was the same and will not be repeated here.

4 | EXPERIMENTAL IMPLEMENTATIONS AND RESULTS

Experimental studies were conducted on a two-level voltage source converter with an LCL filter, as shown in Figure 12. The parameters used in the testing are shown in Table 1 (identical to those used in the simulation). The dead time in the practical implementation was $t_d = 3\mu s$. The hysteresis loop width of the current comparator was $H_{ddq} = 5A$, and width of the voltage comparator was $H_{uv} = 12V$. The control algorithms were implemented in a fully digital system using Texas Instruments DSP TMS320F28335 and Xilinx FPGA XC6SLX9. The DSP was used as the main controller responsible for DPC-AD control, and FPGA was used for gate driver signal generation with dead time. The current and voltage signals of the main circuit were directly measured by the current clamp and voltage differential probe of the Tektronix Oscilloscope, and the actual current spectrum was measured by the Fluke-435.

In order to show that the proposed control algorithm can effectively control both active power and reactive power, the grid-connected ac/dc converter was used as a PWM rectifier and a STATCOM to perform related verification experiments.

4.1 | Steady-state waveforms

The THDi values and waveforms of the grid phase current $i_{2d}$ and grid voltage $e_g$ in a steady state (working as a PWM rectifier) are shown in Figure 13.

The current comparison of the grid side and the converter side shows that the capacitor in the LCL filter has a strong filtering effect on the high-frequency harmonics contained in the converter-side current. The above two AD strategies in DPC control could effectively suppress the resonance current, and both of the output currents could meet the requirements of the grid for current distortion (<5%). However, the THDi value of the DPC-rAD method was higher and amounted to 4.6%, for increasing the damping factor $k_d$ results in a reduction of harmonic resonance frequencies at the expense of lower harmonics [see (4) and (6)]. A lower-grid current distortion was achieved by using the DPC-dAD control [see Figure 13(b)] with the capacitor voltage comparator and new look-up table (see Table 2). The value of current hysteresis width $H_{ddq}$ affected the quality of grid current $i_1$ and the value of voltage hysteresis width $H_{uv}$ determined the damping level of resonance harmonics.

Further observation of the converter-side currents under two control methods shows that the current distortion of DPC-dAD is more obvious. However, these harmonics are mainly distributed in the high frequency band, and the distortion rate of the grid-side current of DPC-dAD is lower. Therefore, under the premise of obtaining the same quality of the grid-side current, the proposed control method can use an LCL filter with smaller parameters.

4.2 | Transient state waveforms

In transient states, the control system response to the step change of the reference grid current was investigated. Figure 14 shows the waveforms in a transient state during the step changes of reference grid current vector $d$-axis component ($i_{2d}^*$). When the reference increased suddenly, $i_{2d}^*$ changed from 10 to 20 A. On the other hand, $i_{2d}^*$ changed from 20 to 10 A as the reference suddenly decreased. Figure 14 shows that when the reference value was abrupt, grid-side current of the system could quickly...
FIGURE 13  Experimental results of grid phase current $i_a$ and voltage $e_a$ for control strategy. (a) DPC-rAD. (b) DPC-dAD. (c) Spectrum of DPC-rAD. (d) Spectrum of DPC-dAD

FIGURE 14  Experimental results for step changes of $i_a^d$. (a) Changes from 10 to 20 A with DPC-rAD. (b) Changes from 20 to 10 A with DPC-rAD. (c) Changes from 10 to 20 A with DPC-dAD. (d) Changes from 20 to 10 A with DPC-dAD
track the given value under both algorithms, achieving smooth transitions and good dynamic characteristics.

It can be seen from the converter-side current of the system in the transient state that the proposed DPC-dAD strategy responds more drastically to changes in the given value. However, the grid-side current of the DPC-dAD has a shorter transition process than DPC-rAD at a given sudden change situation. It means that the DPC-dAD has a faster response speed, but this weak advantage can be ignored in practical applications.

4.3 Non-ideal grid environment waveforms

Due to the non-linear loads, connecting large loads caused short-circuit faults, grid voltage dips (especially in a single-phase), and distortions to occur often in power systems. Control algorithms should be robust enough to cope with this type of disturbance. Figure 15 shows grid voltage and current waveforms in phase a under the distorted grid voltage, which included third, fifth, seventh, and other harmonics, and the THD is 5.6%.

Under the distorted grid voltage, the THD rate of the grid-side current of both control algorithms was increased. The grid-side current THD of DPC-rAD increased from 4.6% to 15.1%, and the THDi of DPC-dAD increased from 3.5% to 4.2%. The comparison shows that the DPC-dAD algorithm has a better harmonic suppression effect than DPC-rAD when the grid voltage was distorted.

Figure 16 shows the results of laboratory tests for a 25% single-phase voltage dip. Grid currents were both unbalanced during a single-phase voltage dip for two control methods. However, the grid-side current imbalance of DPC-dAD was much smaller than that of DPC-rAD. As a result, the DPC-dAD algorithm was considered to have better imbalance adaptability.
4.4 | Reactive power tracking control waveforms

When the grid connected ac/dc converter operates as a STATCOM, the control system response to the step change of the reference reactive power was directly investigated. Figure 17 shows the waveforms in a transient state during the step changes of current vector $q$-axis component of the reference reactive power ($i_{2q}^*$). When the reference increased suddenly, $i_{2q}^*$ changed from 10 to 20 A and the STATCOM outputs capacitive reactive power. On the other hand, $i_{2q}^*$ changed from -20 to -10 A as the reference suddenly decreased and the STATCOM outputs capacitive reactive power. Figure 17 shows that when the reference value was abrupt, grid-side current and current vector $q$-axis component of the reactive power ($i_{2q}$) could quickly track the given value under both algorithms, achieving smooth transitions and good dynamic characteristics.

It can be seen that the tracking control result of reactive current in the transient process is basically similar to that of active current. When the reference value was abrupt, current of reactive power could quickly track the given value under both algorithms, achieving smooth transitions and good dynamic characteristics. The DPC-dAD has a little faster response speed than DPC-rAD.

5 | CONCLUSION

In this study, a novel DPC-dAD method has been proposed and compared with a direct power control scheme that included an active damping algorithm (DPC-rAD). Filter resonance oscillations were damped using a novel multi-variable control method, which was based on a new look-up table with more comparators (both current and voltage) that facilitated simultaneous control of the converter-side current and capacitor voltage in the current control system. Simulation results confirmed the operating mechanism effectiveness and the high performance of the control algorithms, and experimental investigations proved that the presented control method ensured excellent performance in both steady and transient states. In contrast to the DPC-rAD method, a lower THDi and imbalance value were guaranteed even under grid voltage distortions and unbalanced voltage dips. The new solutions improved the DPC method with an active damping algorithm by eliminating low-order grid current harmonics and decreasing the grid voltage distortion sensitivity.

ACKNOWLEDGEMENTS

This work was supported in part by the Natural Science Foundation of the Jiangsu Higher Education Institutions of China under Grant 18KJB470009, in part by the Construction System Technology Project of Jiangsu Province under Grant 2020ZD33, and in part by the Natural Science Foundation of the Jiangsu Higher Education Institutions of China under Grant 19KJB470018.

ORCID

Chuanjin Zhang https://orcid.org/0000-0002-1958-7994

REFERENCES

1. Sharma, R., et al.: A hidden block in a grid connected active front end system: Modelling, control and stability analysis. IEEE Access 5(5), 11852–11866 (2017)
2. Ziaeeinjad, S., Mehtazi-Sani, A.: Design tradeoffs in selection of the DC-side voltage for a D-STATCOM. IEEE Trans. Power Delivery 33(6), 3230–3232 (2018)

3. Shrinin, D.A., et al.: Uninterruptible power system with parallel operation of AC/DC and DC/DC converters. In: Proc. 16th Int. Young Spec. Micro/Nanotechnol. Electron Devices Conf., pp. 508–513 (2015)

4. Han, Y., et al.: Modeling and stability analysis of LCL-type grid-connected inverters: A comprehensive overview. IEEE Access 7, 114975–115001 (2019)

5. Giglia, G., et al.: Experimental comparison of three-phase distributed generation systems based on VOC and DPC control techniques. In: Proc. IEEE Power Electron. Appl. Conf., pp. 1–12 (2007)

6. Yin, H., Dieckerhoff, S.: Experimental comparison of DPC and VOC control of a three-level NPC grid connected converter. In: Proc. IEEE Power Electron. Distrib. Gen. Syst. Symp., pp. 1–7 (2015)

7. Malinowski, M., Jasinski, M., Kazmierkowski, M.: Simple direct power control of three-phase PWM rectifier using space-vector modulation (DPC-SVM). IEEE Trans. Ind. Electron. 51(2), 447–454 (2014)

8. Zhi, D., Xu, L., Williams, R.W.: Improved direct power control of grid-connected DC/AC converters. IEEE Trans. Power Electron. 24(5), 1280–1292 (2009)

9. Fantino, R.A., Busada, C.A., Solsona, J.A.: Optimum PR control applied to LCL filters with low resonance frequency. IEEE Trans. Power Electron. 33(1), 793–801 (2018)

10. Serpa, L.A., Round, S.D., Kolar, J.W.: A virtual-flux decoupling hysteresis current controller for mains connected inverter systems. IEEE Trans. Power Electron. 22(5), 1766–1777 (2007)

11. Bouafia, A., Krim, F., Gaubert, J.P.: Fuzzy-logic-based switching state selection for direct power control of three-phase PWM rectifier. IEEE Trans. Ind. Electron. 56(6), 1984–1992 (2009)

12. Vicera, R.P., et al.: Sliding mode controller in a multiloop framework for a grid-connected VSI with LCL filter. IEEE Trans. Ind. Electron. 65(6), 4714–4723 (2018)

13. Nosuchi, T., et al.: Direct power control of PWM converter without power-source voltage sensors. IEEE Trans. Ind. Appl. 34(3), 473–479 (1998)

14. Kulikowski, K., Sikorski, A.: New DPC look-up table methods for three-level AC/DC converter. IEEE Trans. Ind. Electron. 63(12), 7930–7938 (2016)

15. Falkowski, P., Sikorski, A.: Finite control set model predictive control for grid-connected AC-DC converters with LCL filter. IEEE Trans. Ind. Electron. 65(4), 2844–2852 (2018)

16. Zhang, X., et al.: Direct grid-side current model predictive control for grid-connected inverter with LCL filter. IET Power Electron. 11(15), 2450–2460 (2018)

17. Wang, B., et al.: Linear ADRC direct current control of grid-connected inverter with LCL filter for both active damping and grid voltage induced current distortion suppression. IET Power Electron. 11(11), 1748–1755 (2018)

18. Xin, Z., et al.: Highly accurate derivatives for LCL-Filtered grid converter with capacitor voltage active damping. IEEE Trans. Power Electron. 31(5), 3612–3625 (2016)

19. Wang, X., Blaabjerg, F., Chiang Loh, P.: Grid-current-feedback active damping for LCL resonance in grid-connected voltage-source converters. IEEE Trans. Power Electron. 31(1), 213–223 (2016)

20. Said-Romdhane, M.B., et al.: Robust active damping methods for LCL filter-based grid-connected converters. IEEE Trans. Power Electron. 32(9), 6739–6750 (2017)

21. Yao, W., et al.: Design and analysis of robust active damping for LCL filters using digital notch filters. IEEE Trans. Power Electron. 32(3), 2360–2375 (2017)

22. Giobataru, M., et al.: Adaptive notch filter based active damping for power converters using LCL filters. In: Proc. IEEE 7th Int. Symp. Power Electron. Distrib. Gener. Syst., pp. 1–7 (2016)

23. Pena-Aizola, R., et al.: Systematic design of the lead-lag network method for active damping in LCL-filter based three phase converters. IEEE Trans. Ind. Inf. 10(1), 43–52 (2013)

24. Ricciutto, D., et al.: Robustness analysis of active damping methods for an inverter connected to the grid with an LCL-filter. In: Proc. IEEE Energy Convers. Congr. Exposition, pp. 2028–2035 (2011)

25. Malinowski, M., Bernet, S.: A simple voltage sensorless active damping scheme for three-phase PWM converters with an LCL filter. IEEE Trans. Ind. Electron. 55(4), 1876–1880 (2008)

26. Scoltock, J., Geyer, T., Madawala, U.K.: A model predictive direct current control strategy with predictive references for MV grid-connected converters with LCL filters. IEEE Trans. Power Electron. 30(10), 5926–5937 (2015)

27. Pantei, N., Hoffmann, N., Fuchs, F.W.: Finite control set model predictive current control for grid-connected voltage-source converters with LCL filters: A study based on different state feedbacks. IEEE Trans. Power Electron. 31(7), 5189–5200 (2016)

28. Zhang, X., et al.: Hysteresis model predictive control for high-power grid-connected inverters with output LCL filter. IEEE Trans. Ind. Electron. 63(1), 246–256 (2016)

29. Vazquez, S., et al.: Model predictive control for power converters and drives: Advances and trends. IEEE Trans. Ind. Electron. 64(2), 935–947 (2017)

30. Serpa, L.A., et al.: A modified direct power control strategy allowing the connection of three-phase inverters to the grid through LCL filters. IEEE Trans. Ind. Electron. 43(5), 1388–1400 (2007)

How to cite this article: ZHANG, C., LI, Y., JIA, C., FU, H., ZHANG, X., ZHANG, H. Direct active damping control for grid-connected AC/DC converter with LCL filter using augmented look-up table. IET Power Electron. 14, 1089–1101 (2021). https://doi.org/10.1049/pel2.12090