Design of a Power Flow Control Method for Hybrid Active Front-End Converters

Tzung-Lin Lee  Zong-Jie Chen  Shang-Hung Hu
Department of Electrical Engineering
National Sun Yat-sen University 70, Lienhai Rd., Kaohsiung 80424, TAIWAN
Email: tllee@mail.ee.nsysu.edu.tw

Abstract—Active front-end converters with bidirectional power flow capability have been extensively used for utility applications of power electronics. Large passive filters are normally required at the grid side of the converter to mitigate switching EMI noise. This may become a critical issue, in terms of installation space and potential resonance of the passive filter. This paper proposes a hybrid active front-end converter and its power flow control method. The hybrid converter is composed of a capacitor and a voltage source converter in series connection. Bidirectional real power of the converter can be controlled by the output voltage vector perpendicular to the grid voltage, and reactive power delivery of the converter for grid voltage regulation can be determined by the output voltage vector parallel to the grid voltage. Due to series connection capacitor, the converter can be operated between a low-voltage dc side and high-voltage grid side without any low-frequency transformer, which is the significant advantage of the proposed method. A harmonic resistance is also emulated in the proposed method to assure stable operation of the converter for unintentional voltage spike coming from the power system. Operation principles are explained in detail, and computer simulations and experimental results are provided to validate the effectiveness of the proposed approach.

KEYWORDS
Hybrid active front-end converter, power flow control

I. INTRODUCTION

Active front-end converters have been extensively used in various power conversion applications requiring bidirectional power flow capability, such as adjustable speed drives, uninterruptible power supply systems, inverter based distributed generators, and active power filters [1], [2]. Passive power filters, such as LC or LCL filters, are usually deployed between the converter and the grid to mitigate switching EMI noise produced by the converter [3], [4]. However, the required passive filters is a critical issue in terms of installation space and weight, and potential harmonic resonance between the passive filters and the grid may cause instability of the converter.

Various active damping approaches have been proposed to suppress the harmonic resonances of passive filters, but power rating of the converter may be limited due to high switching frequency [5], [6], [3]. Multilevel inverters with reduced switching voltage would provide acceptable EMI noise at the cost of high component count and complex control [7], [8]. A shunt hybrid circuit has been proposed in active filtering applications of medium-voltage range, where a series capacitor replaces the bulky low-frequency transformer to reduce kVA rating of the active filter and the resulting switching ripples [9], [10]. Authors have presented simulation results of transformerless interface converters applied in distributed generation systems with unity power factor operation [11].

This paper proposes a power flow control method for a hybrid active front-end converter. The proposed converter is composed of a capacitor and a voltage source converter in series connection. Bidirectional real power of the converter can be controlled by the output voltage vector perpendicular to the grid voltage, and reactive power delivery of the converter for grid voltage regulation can be determined by the output voltage vector parallel to the grid voltage. Since the series capacitor sustains a part of the fundamental voltage, the converter can be operated with a reduced dc voltage compared with the conventional grid-connected inverter. This algorithm allows the fundamental power control between the low-voltage dc side and the high-voltage grid side without any low-frequency transformer, which is a significant advantage in terms of both installation space and switching EMI noise of the converter. The proposed interface converter also emulates harmonic resistance to reduce transient voltage of the converter resulting from the capacitive switching of the power system.

II. OPERATION PRINCIPLES

A simplified one-line diagram of the proposed hybrid active front-end converter (HAFEC) is shown in Fig. 1. The proposed HAFEC is composed of a capacitor $C$ and a voltage source converter in series connection to the grid $U$. The operation of the proposed HAFEC includes both real power control ($S$ is at A) and reactive power control ($S$ is at B) modes. The reference voltage generator determines the voltage command $E_{abc}^*$ according to the operational mode. The voltage controller then produces the current command $i_{abc}^*$ of the converter. Subsequently, the current controller generates the output voltage command $v_{abc}^*$ for the PWM of the converter. Operational principles are detailed as follows.

A. Operation modes

In the real power control mode, the angle command $\theta_A^*$ is set as $-90^\circ$ for maximum real power conversion and the voltage command $E_{A}^*$ is determined by using a PI controller to regulate the real power output according to the real power command $P^*$. The real power is calculated by using the instantaneous power theory [12]. If the HAFEC is operated...
in the reactive power control mode, the angle command $\theta_B^*$ should be set as $0^\circ$ for maximum reactive power delivery. The voltage command $E_B^*$ is based on the required reactive power for restoring the grid voltage to the nominal value, which can be implemented by a synchronous reference frame (SRF) PI controller [13].

Note that, if a dc capacitor is used in the dc side of the converter, the dc voltage can be controlled by drawing reactive current from the grid [2]. Therefore, the voltage command $E_{abc}$ can be obtained for different operating modes.

B. Voltage and current controls

A PI-based voltage controller in the SRF is implemented to generate the current command $i_{qd}^*$ of the converter according to the measured voltage $E_{abc}$. Based on the current command $i_{abc}$, the measured current $i_{abc}$, and the measured voltage $E_{abc}$, the current regulator in the stationary frame calculates the voltage command $v_{abc,f}$ of the fundamental frequency as follows [1],

$$v_{abc,f} = E_{abc} - \frac{L_i}{\Delta T}(i_{abc}^* - i_{abc}).$$

(1)

$L_i$ is the output inductor of the inverter, and $\Delta T$ is the sampling period. Harmonic damping for suppressing the transient voltage coming from the upstream of the power system is also emulated, whose operation is defined as follows,

$$v_{abc,h}^* = R \cdot i_{abc,h}.$$  

(2)

$R$ represents harmonic resistance, $i_{abc,h}$ is harmonic current component, and $v_{abc,h}^*$ is harmonic voltage command of the HAFEC, respectively. Harmonic current component $i_{abc,h}$ can be extracted by a high pass filter (HPF) in the SRF. Finally, the space vector PWM is employed to synthesize the gating signals of the inverter. Based on this algorithm, the HAFEC current can be controlled with the desired power flow requirement.

$$U = |U| \angle 0^\circ$$

$$E = |E| \angle \theta$$

(3)

C. Power flow analysis

Fig. 2 shows the single-phase equivalent circuit of the proposed HAFEC at the fundamental frequency. The inverter and its output inductor are considered as an ideal voltage source $E$, due to the proposed voltage control. $U$ is the grid voltage, $\theta$ is the angle of $E$ leading $U$, and $X_c$ is the reactance of series capacitor, respectively. Inverter output real power $P$, inverter output reactive power $Q$, the reactive power injected into the grid $Q_r$ can be expressed as follows,

$$P = -3X_c(|E||U|\sin\theta)$$

$$Q = 3X_c(|E|^2 - |E||U|\cos\theta)$$

$$Q_r = 3X_c(|U|^2 - |E||U|\cos\theta)$$

(3)
Obviously, maximum real power transfer is at $\theta = \angle \pm 90^\circ$ and maximum reactive power delivery is at $\theta = \angle 0^\circ$ or $\angle 180^\circ$, respectively. Therefore, the real power or the reactive power can be separately and adequately controlled by regulating voltage command $E_A*$ or $E_B*$ with the corresponding angle condition. In this paper, $\theta_A = -90^\circ$ and $\theta_B = 0^\circ$ are used for power controlling.

The converter is at the discharging mode $P > 0$ in Fig. 4(a) and at the charging mode $P < 0$ in Fig. 4(b), respectively. In addition, the converter is operated as an inductor $Q > 0$ in Fig. 4(c) or a capacitor $Q < 0$ in Fig. 4(d), respectively.

III. SIMULATION RESULTS

Fig. 5 shows the simulation circuit and circuit parameters are given as follows:
- Power system: 220 V(line-to-line), 20 kVA, 60 Hz.
- $C = 200 \mu$F, $L_s = 1.0 \text{ mH}$, $L_i = 1.0 \text{ mH}$, $L_l = 30 \text{ mH}$.
- $V_{dc} = 100 \text{ V}$, $U_{rms} = 127 \text{ V}$.
- The converter is a conventional three-phase voltage source inverter. The PWM frequency and the sampling frequency are 10 kHz and 20 kHz, respectively.

Fig. 6 shows 1 kW power conversion for both discharging and charging modes. At $t = 2s$, the HAFEC starts in operation with $P^* = 1 \text{ kW}$. The converter voltage $E$ is increased and maintained $90^\circ$ lagging the grid voltage $U$ for supplying real power to the grid as shown in Fig. 6(a). At the steady
state, $E_{rms}=35\,\text{V}$, $I_{rms}=10\,\text{A}$, $P=1\,\text{kW}$, and $Q=-280\,\text{var}$. Subsequently, $P^*$ is changed to $-1\,\text{kW}$ at $t=3\,\text{s}$. Fig. 6(b) shows the HAFEC enters the charging mode and draws 1 kW from the grid when reaching the steady state. At this time, $E$ is kept 90° leading the grid voltage $U$.

Fig. 7 shows the reactive power control for grid voltage regulation. The reference grid voltage is set as 182 V(peak). Before the HAFEC is started, the grid voltage is 185 V(peak) due to no loading. After the HAFEC is engaged, the grid voltage is restored to its reference value, 182 V(peak), with $Q=822\,\text{var}$ and $I=8.1\,\text{A}$ as illustrated in Fig. 9(b). In contrast, the converter output current $I$ lags the grid voltage $U$ and the converter output voltage by 90° simultaneously as shown in Fig. 9(a). TABLE II gives $Q$ and $I$ when $E_B^*=25\,\text{V}$, 30 V, 35 V, 40 V, respectively. More reactive power delivery to the grid with increasing $E_B^*$ is verified.

**TABLE I**

<table>
<thead>
<tr>
<th>$E_A^*$</th>
<th>25V</th>
<th>30V</th>
<th>35V</th>
<th>40V</th>
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</thead>
<tbody>
<tr>
<td>$I$</td>
<td>11.7A</td>
<td>12A</td>
<td>12.4A</td>
<td>12.8A</td>
</tr>
<tr>
<td>$P$</td>
<td>620W</td>
<td>775W</td>
<td>934W</td>
<td>1095W</td>
</tr>
<tr>
<td>$Q$</td>
<td>-88var</td>
<td>-121var</td>
<td>-160var</td>
<td>-205var</td>
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A power flow control method for a hybrid active front-end converter is presented in this paper. The maximum real power flow can be converted between the dc side and ac side with bidirectional capability, and the maximum reactive power can be controlled for grid voltage regulation by adequately adjusting the converter voltage vector. Thanks to a series capacitor between the converter and the grid, the converter can be operated with a reduced dc voltage without any low-frequency transformer, compared with the conventional grid-connected inverter. This is a significant advantage, in terms of both installation space and switching EMI noise of the converter. Fig. 10 shows switching ripples between the proposed hybrid active front-end converter and the conventional grid-connected converter, where both converters deliver the same real power (1kW) to the grid. Obviously, the conventional grid-connected converter produces about 5 times current switching ripple compared with the proposed method.

As shown in (3), the power delivery of the proposed HAFEC is dependent on both \( E \) and \( X_c \), where \( E \) is related to the required dc voltage of the converter and \( X_c \) is the reactance of the series capacitor. Fig. 11 shows the relationship of power conversion for \( E \) to \( X_c \). \( E \) is roughly inverse to \( X_c \) for fixed power delivery, and required \( E \) or \( X_c \) is increased with power output. Based on Fig. 11(a) and Fig. 11(b), the maximum dc voltage and the series capacitor can be determined for the required power output.

### TABLE II

<table>
<thead>
<tr>
<th>( E )</th>
<th>25V</th>
<th>30V</th>
<th>35V</th>
<th>40V</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I )</td>
<td>8.8A</td>
<td>8.7A</td>
<td>8.5A</td>
<td>8.3A</td>
</tr>
<tr>
<td>( Q )</td>
<td>471var</td>
<td>559var</td>
<td>637var</td>
<td>718var</td>
</tr>
</tbody>
</table>

### V. Summary

Fig. 8. Voltage, current, real power output and reactive power output when the HAFEC is in real power operation mode. (\( P: 500 \, \text{W/div}, Q: 500 \, \text{var/div}, E, U: 100 \, \text{V/div}, I: 10 \, \text{A/div} \))

(a) Inverter output voltage \( E \), inverter output current \( I \), and grid voltage \( U \) of phase a.

(b) Inverter output real power \( P \) and inverter output reactive power \( Q \).

Fig. 9. Voltage, current and reactive power output when the HAFEC is in reactive power operation mode. (\( P: 500 \, \text{W/div}, Q: 500 \, \text{var/div}, E, U: 100 \, \text{V/div}, I: 10 \, \text{A/div}, U_{peak}: 10 \, \text{V/div} \))

(a) Inverter output voltage \( E \), inverter output current \( I \), and grid voltage \( U \) of phase a.

(b) Inverter output reactive power \( Q \) and grid voltage peak value \( U_{peak} \) (with 180V offset).
Fig. 10. Comparison of switching ripples between the proposed HAFEC and the conventional grid-connected converter when they produce 1kW real power output concurrently.

Fig. 11. The relationship of $E$ to $X_c$ for various power output.

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REFERENCES


