Letters

A Unified Variable Active Impedance Module With Minimum Power Processing

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***Abstract*—This letter proposes a unified concept of the active impedance module and its control method with minimum power processing. The impedance value and type of the proposed active impedance module can be adjusted by configuring the control functions. This enables it to operate as a variable capacitor or inductor, supporting both positive and negative capacitance or inductance. The proposed solution addresses the limitations of existing methods in balancing achievable impedance, power processing, and control requirements. The concept, circuit structure, control method, and impedance characteristics are discussed. A self-contained two-terminal prototype without external electrical signals is developed and tested under different application scenarios and conditions. Experimental results verify the feasibility and effectiveness of its functionality.**

***Index Terms*—Active circuits, capacitors, impedance control, inductors.**

I. Introduction

In power electronic systems, active impedance circuits serve as a solution to emulate the impedance characteristics of passive components. Based on power electronics and control algorithms, they can actively regulate terminal voltage and current to achieve the desired impedance characteristics. Compared to traditional fixed passive capacitors and inductors, active impedance circuits offer a more compact design, lower cost, and the ability to adjust impedance values or characteristics as needed [1], [2]. According to the implementation, there are four types of existing active impedance technologies: Type I [3], [4], [5], Type II [2], Type III [6], and Type IV [7], [8], [9].

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In Type I, active impedance circuits are implemented by utilizing a differentiator or integrator. For example, adjustable active capacitors [3], [4] and inductors [5] are realized by differentiating and integrating the terminal voltage as the current reference, respectively. However, an integrator may introduce DC offset, while a differentiator could cause noise-related issues [2]. Furthermore, active impedance circuits in Type I are limited to implementing a single type of impedance, restricting their applicability to various applications.

In Type II, a power impedance emulation method is introduced to generate the control reference directly by scaling the capacitor current or the inductor voltage [2]. This method can achieve a variable capacitor or inductor. In Type III, a topology and its control method that can emulate both capacitive and inductive characteristics are presented [6]. These methods in Types II and III provide new perspectives on the unified implementation of different impedances. However, in Type II, capacitor current and inductor voltage, directly related to the change rate of capacitor voltage and inductor current, are more sensitive than the latter and thus require higher bandwidth and more precise sensors for signal acquisition. The approach in Type III, due to its topology and control, can only achieve a maximum capacitance and minimum inductance equal to the reference passive capacitor and inductor, respectively.

In the abovementioned methods, active circuits in the active impedance are required to carry the full DC voltage and current and process the full power of the entire active impedance system, leading to high cost, power loss, and large size [10]. In Type IV, a two-terminal active capacitor [7] and a two-terminal active inductor [8], along with their control methods, are proposed, where the active circuits only need to process a part of the power. However, these methods can only achieve fixed capacitance and inductance, respectively, and cannot flexibly change the impedance value and type. In [9], a variable capacitance control method for the two-terminal active capacitor is proposed to achieve variable and robust capacitance control. However, the method is limited to capacitance control and cannot achieve inductance control. For this, an active impedance module is proposed in [11] for implementing variable positive capacitance and inductance. However, due to control limitations, it cannot achieve a unified implementation of both positive and negative capacitance and inductance. Table I compares the performance of existing methods and the proposed solution.

TABLE I
PERFORMANCE COMPARISON OF EXISTING AND PROPOSED SOLUTIONS

	Achievable impedance	Processing power of active circuit	Control demands
Type I [3], [4], [5]	Single-type impedance	Full power	Control distortion needs to be resolved
Type II [2]	Variable impedance ✓	Full power	High-precision sampling required
Type III [6]	Variable impedance, limited achievable range	Full power	No special requirements ✓
Type IV [7], [8], [9]	Single-type impedance	Partial power ✓	No special requirements ✓
The proposed solution	Variable impedance ✓	Partial power ✓	No special requirements ✓

In this letter, a unified active impedance module with variable impedance is proposed. This study addresses the three limitations of the existing methods in Table I that cannot be concurrently considered and has the following contributions: 1) Compared with Type I-III, the active circuit only needs to process a portion of the total power handled by the entire system; 2) Compared with Type IV, the proposed active impedance module can flexibly adjust impedance values and types (including positive/negative capacitive and positive/negative inductive). Furthermore, a prototype of the proposed module has been developed, which only needs to detect the internal feedback signals, and thus can be applied as a self-contained module.

II. CONCEPT OF THE ACTIVE IMPEDANCE MODULE

A. Circuit Configuration

The proposed active impedance module consists of an H-bridge circuit in series with a switchable passive impedance unit Z as shown in Fig. 1(a). The active impedance module can operate in two impedance modes, capacitive impedance mode, and inductive impedance mode, by controlling the power relay S.

When S is switched to point p, capacitor C_1 is connected to the circuit, and the active impedance module operates in the capacitive impedance mode. In this mode, C_1 is used to extract the AC voltage information applied to the active impedance module, which is then used to generate the voltage control reference. Based on this voltage reference, the adjustment of the impedance can be achieved by controlling the terminal voltage v_{ab} of the active impedance module. When S is switched to point q, inductor L_{s} is connected to the circuit, and the active impedance module operates in the inductive impedance mode. In this mode, L_{s} functions to filter out high-frequency harmonics, while the AC current information used to generate the current control reference, and is provided by inductor L_1. By controlling the terminal current i_{ab} of the active module, the impedance adjustment can be achieved. The diode D and resistor R form a freewheeling circuit to ensure the continuity of the inductor current when S is switched from point q to point p.

B. Control Strategy

To achieve both capacitive and inductive impedance, this letter proposes a unified active impedance control method. As shown

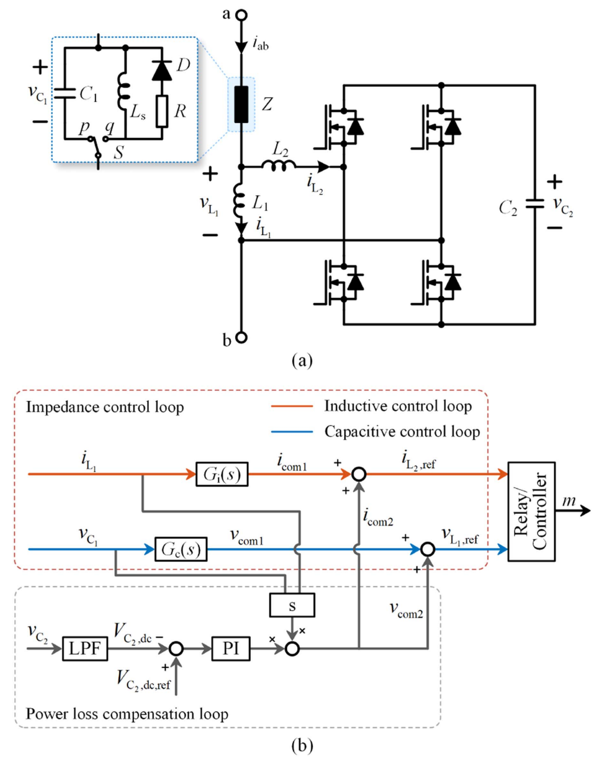

Fig. 1. System diagram of the active impedance module. (a) Circuit diagram of the active impedance module. (b) Impedance control for the active impedance module.

in Fig. 1(b), the proposed unified impedance control method includes two different impedance control loops corresponding to capacitive and inductive impedance modes.

For the capacitive impedance mode, S is switched to point p and the active impedance module implements a voltage-controlled circuit. The voltage reference $v_{\mathrm{L_1,ref}}(s)$ of the H-bridge circuit is obtained as follows:

$$v_{\mathrm{L_1,ref}}(s) = G_{\mathrm{c}}(s) \cdot v_{\mathrm{C_1}}(s) \tag{1}$$

where $v_{\mathrm{C_1}}(s)$ is the voltage of the capacitor C_1, and $G_{\mathrm{c}}(s)$ is the control function for the capacitive control loop.

When the AC voltage $v_{\mathrm{L_1}}(s)$ perfectly follows its reference $v_{\mathrm{L_1,ref}}(s)$, there is

$$v_{\mathrm{L_1}}(s) = v_{\mathrm{L_1,ref}}(s) = G_{\mathrm{c}}(s) \cdot v_{\mathrm{C_1}}(s). \tag{2}$$

The impedance model of the active impedance module with capacitive control can be derived as

$$Z_{\mathrm{ab,c}}(s) = \frac{v_{\mathrm{C_1}}(s) + v_{\mathrm{L_1}}(s)}{i_{\mathrm{ab}}(s)} = \frac{v_{\mathrm{C_1}}(s) + G_{\mathrm{c}}(s) \cdot v_{\mathrm{C_1}}(s)}{i_{\mathrm{ab}}(s)} = \frac{1}{\frac{1}{1+G_{\mathrm{c}}(s)} C_1 s} = \frac{1}{C_{\mathrm{eq}} s} \tag{3}$$

where $i_{\mathrm{ab}}(s)$ is the terminal current flowing through the active impedance module. According to (3), the active impedance module can be implemented as an equivalent capacitor C_{eq} with a capacitance value of $\frac{1}{1+G_{\mathrm{c}}(s)} C_1$.

TABLE II
IMPEDANCE OUTPUT OF THE ACTIVE IMPEDANCE MODULE BASED ON DIFFERENT CONTROL FUNCTIONS

Control Function*		Impedance Output DC	Impedance Output AC
$G_c(s)$	$K_c > -1$	$1/\left(\frac{C_1}{1+G_{HPF}(s)K_c}s\right)$	$1/\left(\frac{C_1}{1+K_c}s\right)$
	$K_c < -1$	$-1/\left(\frac{C_1}{G_{HPF}(s)\lvert K_c\rvert-1}s\right)$	$-1/\left(\frac{C_1}{\lvert K_c\rvert-1}s\right)$
$G_i(s)$	$K_i > -1$	$\left(L_s+\frac{1}{1+G_{HPF}(s)K_i}L_1\right)s$	$\left(L_s+\frac{1}{1+K_i}L_1\right)s$
	$K_i < -1$	$\left(L_s-\frac{1}{G_{HPF}(s)\lvert K_i\rvert-1}L_1\right)s$	$\left(L_s-\frac{1}{\lvert K_i\rvert-1}L_1\right)s$

* When $K_c > -1/\ K_c < -1$, the active impedance module implements a positive/ negative capacitor, and when $K_i > -1/\ K_i < -1$, it implements a positive/ negative inductor.

Similarly, for the inductive impedance mode, S is switched to point q and the active impedance module implements a current-controlled circuit. When the controller reaches steady state, the inductor current $i_{L_2}(s)$ tracks its reference $i_{L_2,ref}(s)$, there is

$$i_{L_2}(s) = i_{L_2,ref}(s) = G_i(s) \cdot i_{L_1}(s) \tag{4}$$

where $i_{L_1}(s)$ is the current of inductor L_1 and $G_i(s)$ is the control function for the inductive control loop. The impedance model of the active impedance module with inductive control can be expressed as

$$\begin{aligned} Z_{ab,i}(s) &= L_s s + \frac{v_{L_1}(s)}{i_{L_1}(s) + i_{L_2}(s)} \\ &= L_s s + \frac{v_{L_1}(s)}{i_{L_1}(s) + G_i(s) \cdot i_{L_1}(s)} \\ &= \left(L_s + \frac{1}{1+G_i(s)}L_1\right)s = L_{eq}s. \end{aligned} \tag{5}$$

It can be seen that the active impedance module based on inductive control can be implemented as an equivalent inductor L_{eq} with variable inductance value of $L_s + \frac{1}{1+G_i(s)}L_1$.

The power loss compensation loop in the controller is used to regulate the capacitor voltage v_{C_2} to compensate for the power loss in the system. Notably, the control only requires the signals from the active module, implying that it can be implemented as a self-contained module.

C. Control Function

The control functions $G_c(s)$ and $G_i(s)$ are used to implement changes to the impedance type and value of the active impedance module according to (3) and (5). For AC applications, it has $G_c(s) = K_c$ and $G_i(s) = K_i$, while for DC applications, it has $G_c(s) = G_{HPF}(s)\ K_c$ and $G_i(s) = G_{HPF}(s)\ K_i$. K_c and K_i are constants, and $G_{HPF}(s)$ is the high-pass filter used to obtain the AC component of $v_{C_1}(s)$ and $i_{L_1}(s)$. Table II lists the impedance of the proposed active impedance module for different control functions, and the impedance transition is shown in Fig. 2.

Fig. 3 shows the impedance characteristics of the active impedance module with different control functions configured according to Table II. The parameters used for the curves in Fig. 3 are listed in Table III and will be discussed in Section III.

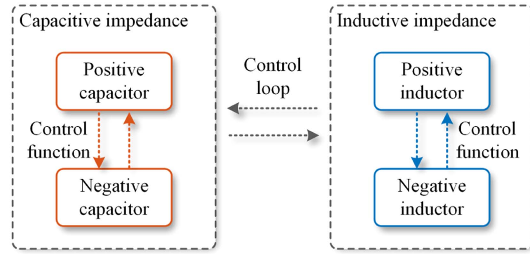

Fig. 2. Impedance transition diagram for the unified active impedance module.

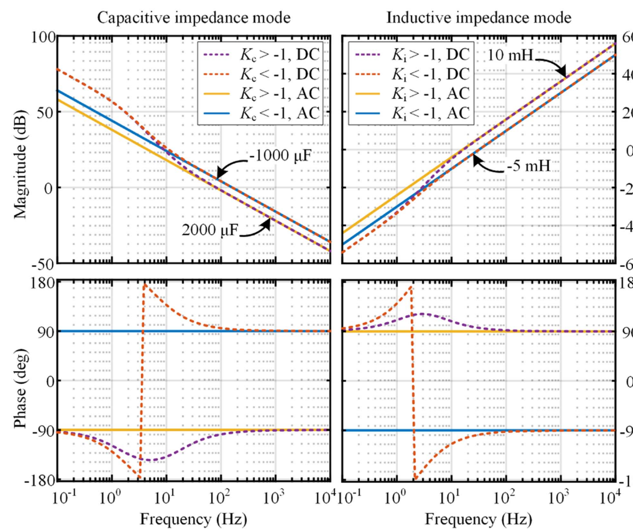

Fig. 3. Impedance characteristics of the active impedance module with control functions configured according to Table II for the two impedance modes.

TABLE III
SPECIFICATION OF THE CIRCUIT IMPLEMENTING THE ACTIVE IMPEDANCE MODULE

Parameter	Value	Parameter	Value
Load resistor R_1	5 Ω	Load resistor R_2	800 Ω
DC capacitor C_1	200 μF	DC capacitor C_2	2000 μF
DC inductor L_1	3000 μH	AC inductor L_2	22 μH
AC inductor L_s	104 μH	Switching frequency f_{sw}	50 kHz

With $K_c > -1$ and $K_c < -1$, the active impedance module emulates a 2000-μF positive capacitor and a -1000-μF negative capacitor, respectively, and with $K_i > -1$ and $K_i < -1$, the active impedance module emulates a 10-mH positive inductor and a -5-mH negative inductor, respectively. In DC applications, the impedance characteristics at low frequencies exhibit some shift due to the high-pass filter. Thus, with the proposed control method, the active impedance module can unify capacitive and inductive impedance outputs.

In addition, by substituting the control functions $G_c(s)$ and $G_i(s)$ into (2) and (4), respectively, the active H-bridge circuit processes only part of the AC voltage and current. Especially, in DC applications, the DC voltage is clamped by capacitor C_1, and DC current is shunted by inductor L_1, significantly reducing the electrical stress and processing power of the active circuit.

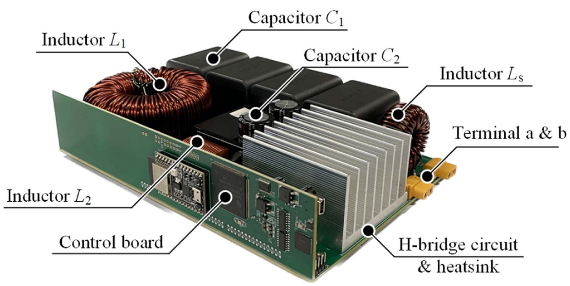

Fig. 4. Hardware prototype of the active impedance module.

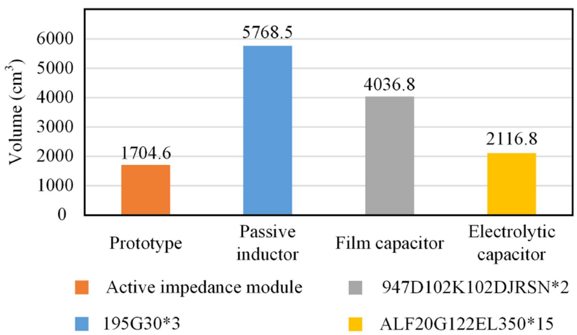

Fig. 5. Volume comparison between the active impedance module and passive inductors (195G30), film capacitors (947D102K102DJRSN), and electrolytic capacitors (ALF20G122EL350).

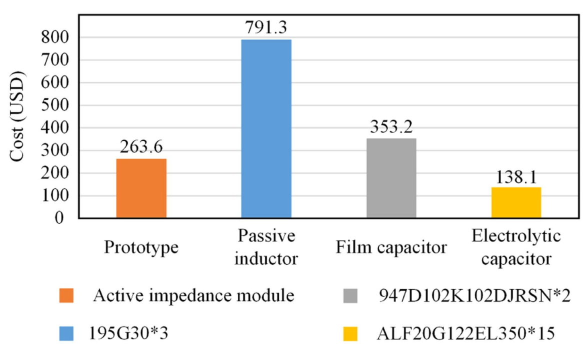

Fig. 6. Cost comparison between the active impedance module and passive inductors (195G30), film capacitors (947D102K102DJRSN), and electrolytic capacitors (ALF20G122EL350). Price data are sourced from Digikey [14].

III. Implementation of the Active Impedance Module

A. Hardware Realization

The hardware prototype of the designed active impedance module is shown in Fig. 4. The prototype is designed based on a volume-optimized design procedure, which is built upon multiple models [1], [12], [13], with the design objective of achieving a capacitance of 2000 μF and an inductance of 15 mH. Its circuit parameters and specifications are listed in Table III, where R_1 and R_2 are the loads in the experimental circuit shown in Fig. 8.

To evaluate the performance of the designed active impedance module, it is compared with passive inductors and capacitors. These passive components have the same electrical specifications and impedance values as the active impedance module.

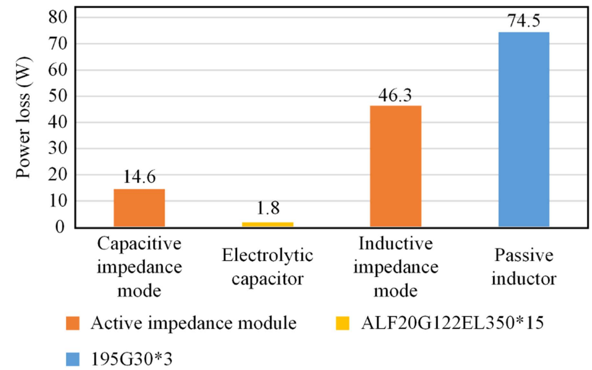

Fig. 7. Power loss comparison between the active impedance module, passive inductors (195G30), and electrolytic capacitors (ALF20G122EL350).

Figs. 5 and 6 show the comparison results in terms of volume and cost, respectively.

The results indicate that, compared to passive inductors, film capacitors, and electrolytic capacitors with the same electrical specifications, the designed active impedance module achieves a volume reduction of 70.4%, 57.8%, and 19.47%, respectively, demonstrating significant volume efficiency. In terms of cost, it is 66.7% and 25.4% lower than passive inductors and film capacitors, respectively, but higher than electrolytic capacitors. This is because the primary focus of the active impedance module design in this study is volume optimization, while cost was not the main consideration.

Fig. 7 shows the power loss comparison between the active impedance module operating in two impedance modes and passive components, including capacitors and inductors, under experimental conditions. It can be observed that, due to material properties, the passive capacitor solution achieves low power loss. The active impedance module incurs higher losses because of the presence of power switching devices and inductors. Nevertheless, compared to the passive inductor solution, the active impedance module exhibits lower losses.

Notably, the active impedance module can function as both a variable capacitor and a variable inductor, offering greater flexibility. Therefore, to ensure a fair comparison, its volume and cost should be compared with the combined total of passive inductors and capacitors (whether film or electrolytic). In this regard, the active impedance module demonstrates a significant advantage in both volume and cost compared to the combination of traditional passive components.

B. Experimental Verification

In this part, the variable impedance performance and applicability of the proposed active impedance module are experimentally verified. The experiments include the tests of the active impedance module in capacitive and inductive impedance modes for both AC and DC applications.

Fig. 8 illustrates the experimental circuit for implementing the active impedance module. When the active impedance module is in series with load R_1, S switches to the point q, and it operates in inductive impedance mode. When it is in parallel with load R_2, S switches to the point p, and it operates in capacitive impedance

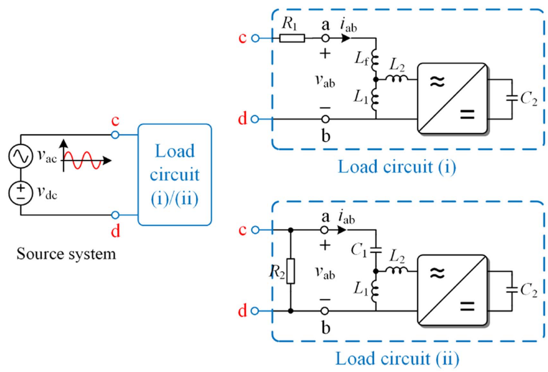

Fig. 8. Experimental circuit for the implementation of the active impedance module. Load circuits (i) and (ii) are test circuits for the active impedance module operating in series and parallel with the load, respectively.

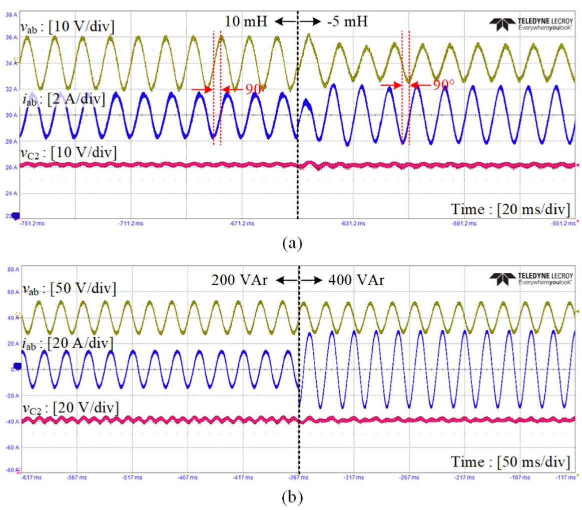

Fig. 9. Experimental waveforms of the active impedance module based on inductive impedance mode. (a) DC application, the impedance changes from a positive inductance of 10 mH to a negative inductance of -5 mH. (b) AC application, the active impedance module generates inductive reactive power changed from 200 to 400 VAr.

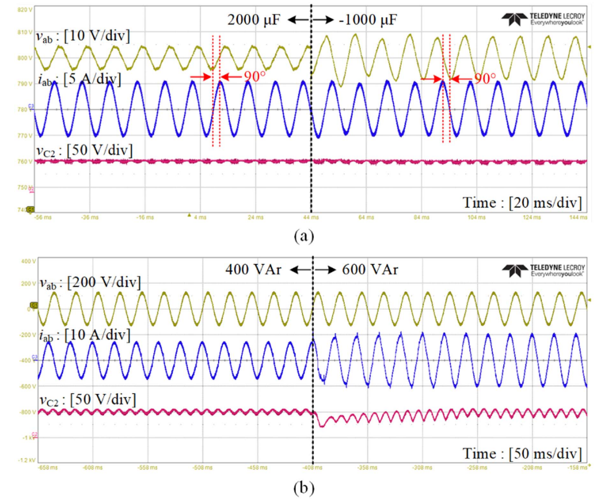

Fig. 10. Experimental waveforms of the active impedance module based on capacitive impedance mode. (a) DC application, the impedance changes from a positive capacitance of 2000 μF to a negative capacitance of -1000 μF. (b) AC application, the active impedance module generates capacitive reactive power changed from 400 to 600 VAr.

mode. The compatibility of series and parallel applications of the active impedance module extends its applicability.

Fig. 9 shows the experimentally measured waveforms of the active impedance module based on the inductive control loop. By designing the control function $G_{\mathrm{i}}(s)$, the active impedance module functions as a variable inductor. In the DC application, as shown in Fig. 9(a), the active impedance module processes an average DC current of 30 A with a ripple of 100 Hz. The active impedance module achieves impedance switching from a positive inductance of 10 mH to a negative inductance of -5 mH. When the active impedance module operates as a positive or negative inductor, its terminal voltage v_{ab} leads or lags the terminal current i_{ab} by nearly 90°, respectively. In the AC application, the active impedance module acts as a static VAr compensator (SVC). In Fig. 9(b), the active impedance module generates inductive reactive power changed from 200 to 400 VAr in a 50-Hz AC system.

Fig. 10 shows the experimental waveforms of the active impedance module operating in capacitive impedance mode. By designing the control function $G_{\mathrm{v}}(s)$, the active impedance module is implemented as a variable capacitor. As shown in Fig. 10(a), in an 800-V DC application with a 100-Hz ripple, the active impedance module achieves an impedance switch from a positive capacitance of 2000 μF to a negative capacitance of -1000 μF. In Fig. 10(b), the active impedance module generates capacitive reactive power changed from 400 to 600 VAr under a 50-Hz AC application.

Overall, the experimental results show that, by configuring $G_{\mathrm{i}}(s)$ and $G_{\mathrm{v}}(s)$ based on Table II, the impedance of the active impedance module can be adjusted flexibly. In DC applications, the active impedance module functions as a variable inductor or capacitor, while in AC applications, it serves as an SVC to provide variable inductive and capacitive reactive power.

IV. Conclusion

This letter proposes the concept of a unified active impedance module with minimum power processing. With the proposed topology and control strategy, it can function as a variable positive or negative capacitor or inductor. Compared to existing active impedance methods, the active impedance module achieves variable impedance with only partial power processing. A prototype of the active impedance module is developed and tested. It offers a self-contained solution without the need for external electrical information. Case studies verify that the designed active impedance module can switch between different impedance values and types. AC and DC tests in both series and parallel scenarios demonstrate that it meets the functional requirements of various applications.

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