Letters

A Two-Terminal Active Capacitor

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***Abstract*—This letter proposes a concept of two-terminal active capacitor implemented by power semiconductor switches and passive elements. The active capacitor has the same level of convenience as a passive one with two power terminals only. It is application independent and can be specified by rated voltage, ripple current, equivalent series resistance, and operational frequency range. The concept, control method, self-power scheme, and impedance characteristics of the active capacitor are presented. A case study of the proposed active capacitor for a capacitive dc-link application is discussed. The results reveal a significantly lower overall energy storage of passive elements and a reduced cost to fulfill a specific reliability target, compared to a passive capacitor solution. Proof-of-concept experimental results are given to verify the functionality of the proposed capacitor.**

***Index Terms*—Active circuits, capacitors, power converter, reliability.**

I. Introduction

SINCE its invention in the 1800s, capacitors have become a key type of components used in electronic circuits and apparatus. The basic structure of a capacitor is with two plates made of conducting materials and an insulation layer of dielectric materials. Electrolytic capacitors, film capacitors, and ceramic capacitors are widely used in power electronic applications. In general, they contribute to a considerable scale of system-level size, cost, and failure, and suffer from one or more issues on energy density, cost, and reliability [1]. This letter proposes a concept of a two-terminal active capacitor implemented by both passive elements and active semiconductor switches. By leveraging the semiconductor switches, the performance of the active capacitor is no longer limited by the property of dielectric materials used in passive capacitors, allowing the possibility to overcome of the above-mentioned issues. The proposed two-terminal active capacitor has the following features: first, it has two terminals only without any additional connection based on the proposed control method and the applied self-power circuit, making it possible to be packaged as a conventional capacitor from the end-users perspective. Second, it has impedance characteristics equivalent to a bulky capacitor or as a variable capacitor within a certain range of frequency depending on the control and switching frequency of its active switches for applications of interest.

In principle, there are various choices of the passive elements and active circuit architectures for the proposed capacitor. In the last two decades, extensive efforts have been made to active capacitive dc links composing of passive elements with a reduced energy storage, and an auxiliary circuit, which provide an inspiration for the presented study. A cost benchmarking of different active capacitive dc-link solutions for a specific single-phase inverter application is presented in [1]. The capacitors, inductors, and semiconductor switches used in the inverter are sized to fulfill same requirements in lifetime and output current total harmonic distortions. The results reveal that a few types of active dc links can achieve lower inverter design cost compared to a passive dc link in the scenario of a relatively high reliability requirement, which is relevant to many industry applications. Especially, solutions having a series-connected auxiliary circuit [2]–[4] are the most cost-effective ones. The methods presented in [3] and [4] enable lowest design cost since the auxiliary circuit processes the ripple voltage of the capacitor connected in series to it, and the ripple current of the dc link only. However, none of the active capacitive dc links can be used as a plug-and-play active capacitor, since they have more terminals than a conventional capacitor, e.g., connections to an external power source for gate drivers and controller, and/or external feedback signals from the main circuits.

This letter presents one of the implementation methods for the proposed active capacitor by adopting the circuit topology studied in [3] and [4] since its potential cost effectiveness in high-reliability applications. A control strategy that does not require any external feedback signal is proposed and a self-power scheme [5] for gate drivers and the controller is applied to achieve the two-terminal active capacitor. The structure of this letter is as follows: Section II presents the concept of the two-terminal active capacitor, and its control and self-power schemes; Section III demonstrates the application of the two-terminal active capacitor for the capacitive dc link of a 500 W single-phase rectifier, followed by the conclusions.

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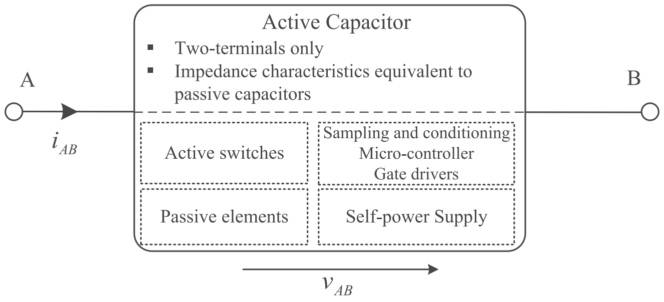


Fig. 1. Concept of a plug-and-play two-terminal active capacitor.

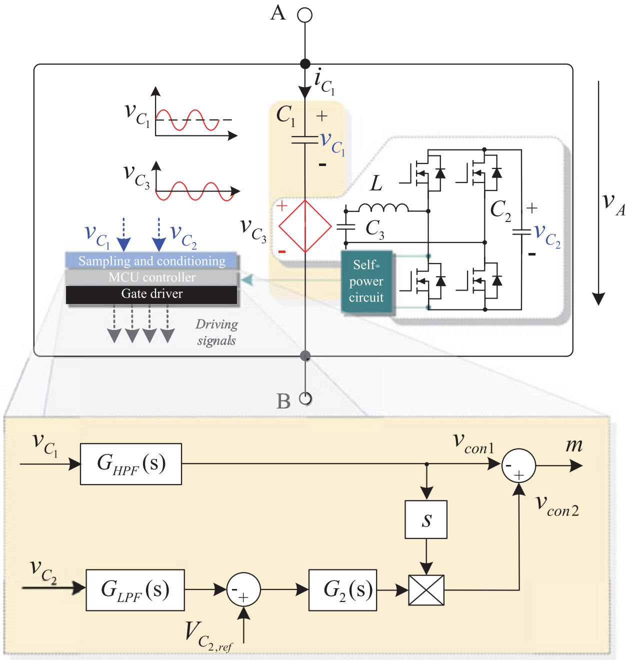


Fig. 2. Implementation of the proposed two-terminal active capacitor with a voltage control strategy.

II. Concept and an Implementation of the Two-Terminal Active Capacitor

A. Concept of the Two-Terminal Active Capacitor

The concept of the two-terminal active capacitor is shown in Fig. 1. v_{AB} and i_{AB} are the voltage and ripple current of the active capacitor, respectively. It consists of active switches, passive elements, a sampling and conditioning circuit, and self-powered controller and gate drivers. There are two power terminals A and B only, making it as convenient as a conventional passive capacitor from application point of view.

B. Control Strategy

Fig. 2 shows an implementation of the proposed active capacitor. The circuit topology has been studied in [3] and [4], consisting of a capacitor C_1 connected in series with a low-voltage full-bridge converter circuit. The full-bridge circuit processes the ripple voltage and ripple current of C_1 only, implying a low VA rating. A voltage control strategy is proposed based on internal voltage signals v_{C_1} and v_{C_2} only, as shown in Fig. 2. Compared to the current control method discussed in [4], the proposed control strategy does not require any current information from external circuits. Therefore, it enables fully independent operation of the active capacitor without any feedback signals from external circuits. The control objective is to shape the impedance seen from AB terminals to be that of an equivalent passive capacitor of interest. A typical way is shown in Fig. 2 to control the voltage v_{C_3} to be out of phase with the ripple components in v_{C_1} and same amplitude, so as to achieve as large equivalent capacitance as possible. The modulation signal contains two parts: v_{con1} is the extracted ripple component of v_{C_1} used to modulate the converter to generate the desired v_{C_3}; and v_{con2} is used to stabilize v_{C_2}. Moreover, the phase of v_{con2} and i_{C_1} is synchronized (i.e., a 90° phase shift with v_{con1}), in order to absorb active power from external circuits through terminals A and B to compensate the power loss of the converter circuit.

Based on small-signal modeling, the closed-loop impedance of the active capacitor is obtained as follows:

$$Z_{\mathrm{ACap}}(s) = \frac{v_{\mathrm{C}_3}(s) + v_{\mathrm{c1}}(s)}{i_{\mathrm{C}_1}(s)} = \frac{MC_1V_{\mathrm{C}_2}G_2(s)G_{\mathrm{LPF}}(s)}{C_2V_{\mathrm{tric}}C_1s} + \frac{M^2C_1V_{\mathrm{tric}} - \alpha C_2V_{\mathrm{C}_2}G_{\mathrm{HPF}}(s) + C_2V_{\mathrm{tric}}}{C_2V_{\mathrm{tric}}C_1s} \tag{1}$$

where $G_{\mathrm{HPF}}(s)$ is the transfer function of the high pass filter (HPF) used to obtain the ripple voltage of v_{C_1}. $G_{\mathrm{LPF}}(s)$ is the transfer function of the low pass filter (LPF) used to obtain the dc component of v_{C_2}. $G_2(s)$ is the transfer function of the PI controller for power loss compensation and $V_{\mathrm{C}_2,\mathrm{ref}}$ is the voltage reference of v_{C_2}. α is the scaling factor of v_{C_2}. M is the modulation index and V_{tric} is the amplitude of the PWM triangular signal.

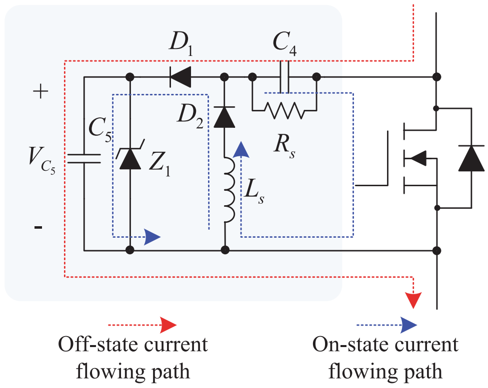


Fig. 3. Self-power circuit to supply gate drivers and controller.

C. Self-Power Supply

A self-power unit is used to obtain the power for the gate drivers and the controller of the active circuit directly from the drain-source terminals of a MOSFET. Fig. 3 shows the self-power circuit that has been reported for the application of a high-voltage power module [5]. During the startup of external circuits, the voltage across the active capacitor two terminals v_{AB} is gradually established. At the beginning, all of the MOSFETs

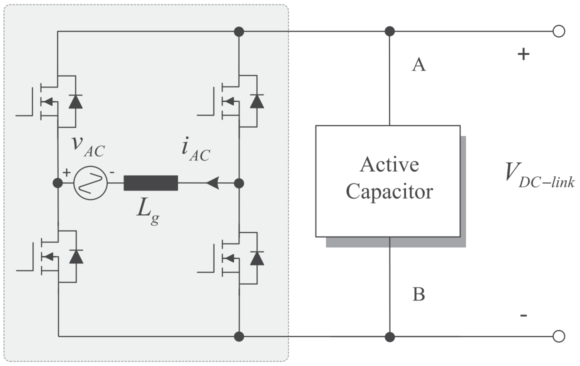


Fig. 4. Circuit topology of the single-phase rectifier with an active capacitor.

in the active capacitor are in OFF state. C_2 is charged from 0 through the body diodes of the MOSFETs. The stored energy in C_2 charges C_5 through the resistor R_s until 15 V clamped by the zener diode. The voltage V_{C_5} is the power supply for the gate drivers and controller of the active capacitor. When the MOSFET turns ON, the voltage of C_4 is applied across the inductor L_s. The current of the inductor increases. The energy stored in C_4 is then transferred to the inductor. After the inductor current reaches its peak value, it starts to decrease and charges the capacitor C_5. Therefore, v_{C_5} is maintained at a steady value (i.e., 15 V) during both ON state and OFF state of the MOSFETs. C_5 provides a continuous power source for the gate drivers and the controller.

III. APPLCATION OF THE ACTIVE CAPACITOR IN A CAPACITIVE DC-LINK

The proposed two-terminal active capacitor serves as a plug-and-play solution in part of the applications where passive capacitors are used. It aims to overcome one or more aspects of challenges in cost reduction, energy-density enhancement, and reliability improvement. As one of the important applications, this section presents a case study of the proposed active capacitor for the capacitive dc-link of a 500 W single-phase rectifier, as shown in Fig. 4. The rectifier is equipped with a start up resistor and a controllable switch to bypass the resistor when the startup process is over. Table I lists the specifications of the system and the key component parameters. In the presented 500-W prototype, the power loss of active capacitor is 7.5 W, while the efficiency is 98.5%.

TABLE I
SPECIFICATION OF THE SINGLE-PHASE SYSTEM WITH ACTIVE CAPACITOR

Parameters	Description	Value
P	Power rating	500 W
v_{AC}	Grid voltage (RMS)	110 V
f_{a}	Fundamental frequency	60 Hz
$V_{\mathrm{dc-link}}$	DC-link voltage	200 V
L_{g}	Inductance of grid side inductor	0.75 mH
α_{v}	DC-link voltage ripple ratio	5%
f_{sw}	Switching frequency	20 kHz
$V_{\mathrm{C}_2,\mathrm{ref}}$	Reference of v_{C_2}	60 V
C_1	Capacitance of C_1	50 μF/250 V/86.3 cm^3 KEMET C4ATDBW*2
C_2	Capacitance of C_2	470 μF/100 V/9 cm^3 CHEMI-CON EKZN101E
C_3	Capacitance of C_3	3 μF/63 V/0.6 cm^3 EPCOS B32522Q
L	Inductance of L	100 μH/3 A/34.3 cm^3 Coilcraft AGP4233
C_4	Capacitance of C_4	68 nF/63 V/0.1 cm^3 EPCOS B32529C
C_5	Capacitance of C_5	56 μF/25 V/0.1 cm^3 CDE HZA566M025
L_{s}	Inductance of L_{s}	5 uH/0.2 A/0.1 cm^3 Coilcraft XAL6060
R_{s}	Resistance of R_{s}	10 kΩ

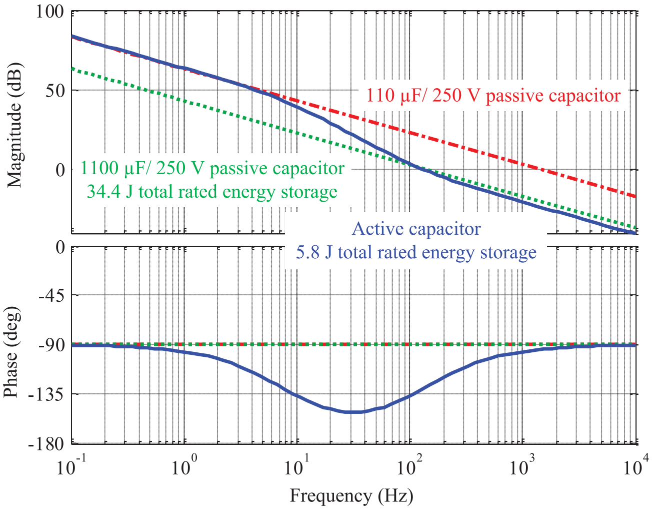
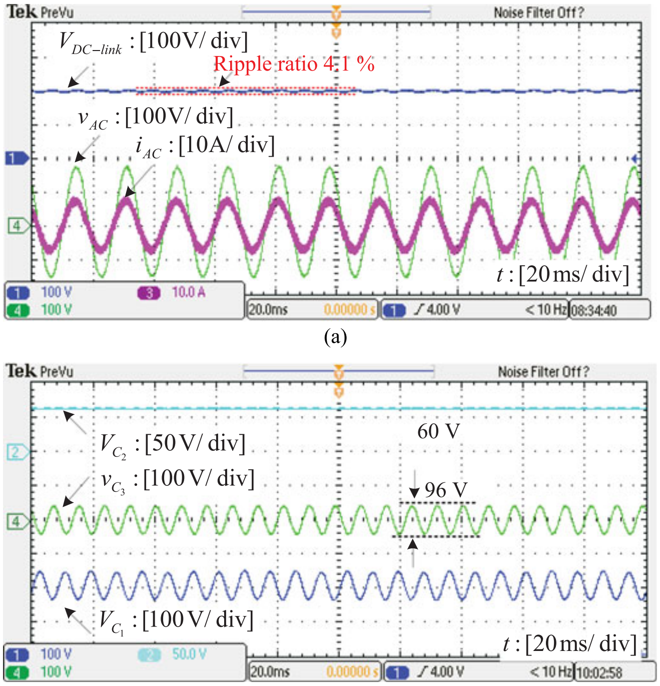


Fig. 5. Bode diagram of the impedance of the active capacitor in the dc-link application.

In this case study, an active capacitor with 5.8 J rated energy storage in its passive elements is used. The impedance of the active capacitor is shown in Fig. 5. In the low frequency range (i.e., below 10 Hz), the impedance characteristics of the active capacitor is equivalent to a 110 μF capacitor, as shown in Fig. 5, which is determined by the value of C_1. For a frequency at 120 Hz or above, the impedance of the active capacitor is equivalent or lower than a passive capacitor with 34.4 J rated energy storage. It implies that the active capacitor can achieve the same or even better harmonic filtering with 16.9% energy storage compared to a passive capacitor. Fig. 6 shows the experimental waveforms of the rectifier and the key components inside the active capacitor. The voltage ripple of the dc link is 4.1%, which fulfills the design specification. The average voltage of C_2 is controlled at 60 V. It can be noted that the ripple voltage of C_1 is approximately out of phase with v_{C_3}. The slight phase shift is due to the mechanism to absorb active power to compensate the power loss of the active capacitor. Fig. 7 shows the comparative results of the rectifier with a passive capacitor with 34.4 J rated energy storage, revealing a negligible difference in system-level performance in terms of the dc-link voltage ripple and input current waveform.

The experimental results of the self-power supply are shown in Fig. 8. The voltage of C_5 is 15 V during the operation, providing a stable source to power the gate drivers and the controller.



(a)

(b)

Fig. 6. Experimental results of the 500 W single-phase rectifier with an active capacitor having 5.8 J rated energy storage in its internal passive elements. (a) Waveforms of the dc-link voltage, and rectifier input voltage and input current. (b) Voltage waveforms of the key internal components of the active capacitor.

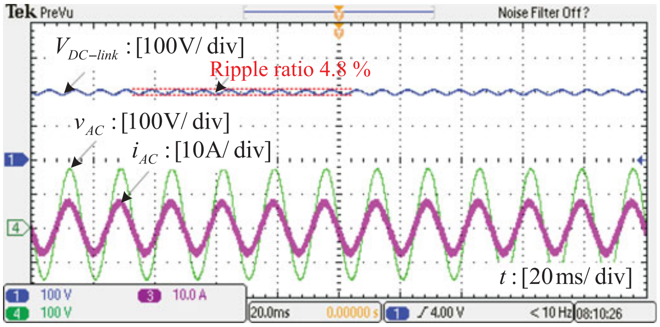


Fig. 7. Experimental results of the 500 W single-phase rectifier with a passive capacitor with 34.4 J rated energy storage.

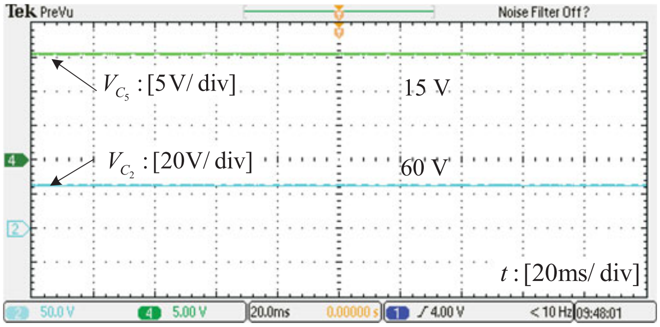


Fig. 8. Experimental results of the self-power supply in the active capacitor.

By following the same reliability-oriented component sizing procedure and cost modeling approach discussed in [1], the costs of the 500-W rectifier with the proposed active capacitor and a passive dc link are estimated. The component cost information is from Digi-Key [6] with an order quantity of 1000 units. The total component cost of the rectifier with the active capacitor is 102% of that with the passive dc link when the designed reliability is 0.9 at 15 years (i.e., B10 lifetime 15 years). With a more stringent reliability requirement by 30 years of B10 lifetime, the proposed two-terminal active capacitor enables a 36% cost reduction compared to the passive capacitor solution. It expects that there is room for further cost reduction and energy density improvement through the design and control optimization of the active capacitor [7].

IV. CONCLUSION

A concept of two-terminal active capacitor is proposed to overcome the challenges in cost, energy density, and reliability of conventional passive capacitors. One of the cost-effective implementations of the active capacitor is presented based on a voltage control strategy without any external feedback signal and a self-power method for internal gate drivers and controller. The proposed active capacitor has the same level of convenience as passive capacitors from application point of view, while it has the potential to a significant reduction in overall energy storage of passive elements and a reduced design cost or size.

In the dc-link application of a single-phase 500-W rectifier, the active capacitor uses 16.9% energy storage of a passive capacitor to fulfill the same design specifications. The total component cost of the rectifier is estimated to be 102% and 64% of a passive capacitor solution for a designed B10 lifetime (i.e., reliability is equal to 0.9) of 15 and 30 years, respectively. Future research and development of the active capacitor on design optimization, scalability study, and accelerated lifetime testing expect to further improve the overall performance, making it more competitive in practical applications.

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