# 2-Phase Series Capacitor Synchronous Rectifier in Active Clamp Forward Converter 

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#### Abstract

A 2-phase series capacitor synchronous rectifier (SC-SR) in active clamp forward (ACF) converters is proposed to solve the inductor cooling problems caused by the recent trend of increasing the output current. The proposed 2-phase SC-SR can achieve the interleaved operation by adding only one flying capacitor to the $\mathbf{2}$-parallel conventional SRs without increasing the number of the primary circuit elements and transformer. Furthermore, the proposed 2-phase SC-SR can achieve the automatic inductor current balancing, which helps distribute the heat evenly in the two inductors. In the measurement at 140 V -to- 5 V conversion, the peak efficiency of the ACF converters with the proposed 2 -phase SC-SR and conventional SR was $90.3 \%$ and $85.9 \%$ at 28 Aout, respectively, resulting in the improvement in efficiency by $4.4 \%$. In addition, the interleaved operation of the proposed 2phase SC-SR reduced the output current ripple from 10.8 A to 6.4 A compared to the conventional SR at 40 Aout. The current imbalance between the two output inductors of the proposed 2phase SC-SR was less than $\mathbf{1 0 \%}$ under heavy load even without any control or compensation, demonstrating the practicability of the proposed 2-phase SC-SR in ACF converters.


Keywords- Active clamp forward converter, Synchronous rectifier, Series capacitor converter, current sharing.

## I. Introduction

Active clamp forward (ACF) converters [1-2] are suitable for a high step-down conversion in applications such as EV/HEV, servers, and data centers [3-5]. The trend of increasing the output current in recent years, however, causes problems due to the increased heat generation in the output inductor of the ACF converter with the conventional synchronous rectifier (SR), which is shown in Fig. 1. To suppress the heat generated in the inductor, it is conceivable to connect the converters in parallel and perform the interleaved operation [6-8]. Alternatively, to reduce the increase in the number of elements including transformers, paralleling only the secondary circuit is also possible, but this way cannot achieve interleaving because the transformer is shared and the secondary circuit operation depends on the secondary current of the transformer. In addition, paralleling two inductors without interleaving increases the output current and voltage ripple due to the reduced equivalent inductance. In order to prevent this, it is necessary to increase the inductor size.

To solve these problems, this paper proposes a 2-phase series capacitor synchronous rectifier (SC-SR), which can be regarded as applying a circuit topology of non-isolated 2phase series capacitor (SC) buck converters with two output inductors [9-13] to the synchronous rectifier in isolated DCDC converters. Similar to the non-isolated SC buck converter, the proposed SC-SR can achieve the interleaved operation and current balancing of the two output inductors in the isolated DC-DC converter, distributing the heat evenly to the two inductors. In this paper, the operating principle of the proposed 2-phase SC-SR in an ACF converter is presented and the practical feasibility of the proposed 2-phase SC-SR is demonstrated by experiments.


Fig. 1. Active clamp forward converter with conventional synchronous rectifier.


Fig. 2. Active clamp forward converter with proposed 2-phase series capacitor synchronous rectifier (SC-SR).

## II. Proposed 2-Phase Series Capacitor Synchronous Rectifier (SC-SR)

## A. Circuit operation

Fig. 2 shows the ACF converter with the proposed 2-phase SC-SR, which consists of 4 switches, 2 inductors, and 1 flying capacitor. The phase A consists of $Q_{\mathrm{Sla}}$ and $Q_{\mathrm{S} 2 \mathrm{a}}$, where $Q_{\mathrm{Sla}}$ is operated synchronously with $Q_{\mathrm{P} 1}$, and $Q_{\mathrm{S} 2 \mathrm{a}}$ is alternately turned on and off with $Q_{\text {sla }}$ in continuous current mode. The phase B is composed of $Q_{\mathrm{s} 1 \mathrm{~b}}$ and $Q_{\mathrm{s} 2 \mathrm{~b}}$, where $Q_{\mathrm{s} \text { ıb }}$ is operated with $180^{\circ}$ phase difference from $Q_{\text {sla }}$ for interleaving and $Q_{S 2 b}$ are also alternately turned on and off $Q_{\mathrm{Slb}}$ in continuous current mode. The duty cycles $D_{\mathrm{a}}$ and $D_{\mathrm{b}}$ are defined as the on-time ratios of $Q_{\mathrm{Sla}}$ and $Q_{\mathrm{Sl}}$ in each phase and this paper assumes that $D_{\mathrm{a}}$ and $D_{\mathrm{b}}$ do not exceed $50 \%$.

Focusing on the circuit operation in a steady state, the main circuit states and ideal waveforms of the proposed 2-phase SC-SR are shown in Figs. 3 and 4. During state 1, $Q_{\text {sla }}$ in the phase A is turned on synchronously with $Q_{\mathrm{P} 1}$, where the series capacitor $C_{\mathrm{t}}$ is connected in series with $L_{\mathrm{a}}$ and the transformer supplies the current $I_{\mathrm{La}}$, which charges $C_{\mathrm{t}}$. Also, $Q_{\mathrm{S} 2 \mathrm{~b}}$ is on in the phase B, so $I_{\mathrm{Lb}}$ freewheels through $Q_{\mathrm{S} 2 \mathrm{~b}}$. During state 2, $Q_{\text {Sla }}$ is turned off synchronously with $Q_{\mathrm{P} 1}$ and the transformer stops supplying the current, so the current path of $I_{\mathrm{La}}$ changes from $Q_{\text {sla }}$ to $Q_{\mathrm{s} 2 \mathrm{a}}$. Since $I_{\mathrm{Lb}}$ continues to freewheel through $Q_{\mathrm{s} 2 \mathrm{~b}}, C_{\mathrm{t}}$ is neither charged nor discharged, keeping the voltage $V_{\mathrm{Ct}}$ constant. During state $3, Q_{\mathrm{S} 1 \mathrm{~b}}$ turns on instead of $Q_{\mathrm{S} 2 \mathrm{~b}}$ in the phase B , where $C_{\mathrm{t}}$ is connected in series with $L_{\mathrm{b}}$ and supplies the current $I_{\mathrm{Lb}}$, which discharges $C_{\mathrm{t}}$. Also, $Q_{\mathrm{S} 2 \mathrm{a}}$ is on in the phase A and $I_{\mathrm{La}}$ continues to flow through $Q_{\text {S2a }}$. Finally,


Fig. 3. Main circuit states in the proposed 2-phase SC-SR.
during state $4, Q_{\mathrm{S} 2 \mathrm{~b}}$ turns on instead of $Q_{\mathrm{Slb}}$, so $I_{\mathrm{La}}$ and $I_{\mathrm{Lb}}$ freewheel through $Q_{\mathrm{S} 2 \mathrm{a}}$ and $Q_{\mathrm{s} 2 \mathrm{~b}}$ as in state 2 .

## B. Voltage conversion ratio

Based on the voltage-second balance in $L_{\mathrm{a}}$ and $L_{\mathrm{b}}$, the output voltage $V_{\mathrm{O}}$ of the ACF converter with the proposed 2phase SC-SR is given as follows:

$$
\begin{align*}
0 & =\left\langle V_{\mathrm{La}}\right\rangle \\
& =\left(\frac{n_{\mathrm{S}}}{n_{\mathrm{P}}} V_{\mathrm{IN}}-V_{\mathrm{Ct}}-V_{\mathrm{O}}\right) D_{a} T_{\mathrm{S}}+\left(0-V_{\mathrm{O}}\right)\left(1-D_{a}\right) T_{\mathrm{S}} \\
& \Leftrightarrow \quad V_{\mathrm{O}}=\left(\frac{n_{\mathrm{S}}}{n_{\mathrm{P}}} V_{\mathrm{IN}}-V_{\mathrm{Ct}}\right) D_{a}  \tag{1}\\
0 & =\left\langle V_{\mathrm{Lb}}\right\rangle \\
& =\left(V_{\mathrm{Ct}}-V_{\mathrm{O}}\right) D_{b} T_{\mathrm{S}}+\left(0-V_{\mathrm{O}}\right)\left(1-D_{b}\right) T_{\mathrm{S}} \\
& \Leftrightarrow \quad V_{\mathrm{O}}=V_{\mathrm{Ct}} D_{b} \tag{2}
\end{align*}
$$

where $V_{\mathrm{IN}},\left\langle V_{\mathrm{La}}\right\rangle,\left\langle V_{\mathrm{Lb}}\right\rangle, n_{\mathrm{P}}, n_{\mathrm{S}}$, and $T_{\mathrm{S}}$ are the input voltage, the average induced voltage of $L_{\mathrm{a}}$, the average induced voltage of $L_{\mathrm{b}}$, the number of transformer primary winding turns, the number of transformer secondary winding turns, and the switching period, respectively.

Since $V_{\mathrm{Ct}}$ and $V_{\mathrm{O}}$ are derived according to (1) and (2), the voltage conversion ratio $M$ of the ACF converter with the proposed 2-phase SC-SR is obtained as follows:

$$
\begin{align*}
& V_{\mathrm{Ct}}=\frac{n_{\mathrm{S}}}{n_{\mathrm{p}}} \frac{D_{\mathrm{a}}}{D_{\mathrm{a}}+D_{\mathrm{b}}} V_{\mathrm{IN}}  \tag{3}\\
& V_{\mathrm{O}}=\frac{n_{\mathrm{s}}}{n_{\mathrm{p}}} \frac{D_{\mathrm{a}} D_{\mathrm{b}}}{D_{\mathrm{a}}+D_{\mathrm{b}}} V_{\mathrm{IN}} \tag{4}
\end{align*}
$$



Fig. 4. Idealized waveforms of the proposed 2-phase SC-SR.


Fig. 5. Voltage conversion ratio $M$ vs. duty cycle $D\left(=D_{\mathrm{a}}=D_{\mathrm{b}}\right)$.

$$
\begin{equation*}
M=\frac{V_{\mathrm{O}}}{V_{\mathrm{IN}}}=\frac{n_{\mathrm{S}}}{n_{\mathrm{p}}} \frac{D_{\mathrm{a}} D_{\mathrm{b}}}{D_{\mathrm{a}}+D_{\mathrm{b}}} . \tag{5}
\end{equation*}
$$

Fig. 5 shows $M$ as functions of $D$ in the ACF converter with the proposed 2-phase SC-SR and conventional SR, where $D=D_{\mathrm{a}}=D_{\mathrm{b}}$ is assumed for simplicity. The proposed 2-phase SC-SR achieve half the step-down ratio with the same $n_{\mathrm{P}}, n_{\mathrm{S}}$, and $D$ as the conventional SR. In other words, the proposed 2-

TABLE I. COMPARISON OF NUMBER OF COMPONENTS AND FEATURES IN CIRCUIT CONFIGURATIONS.

|  | Switch number | Transformer number | Inductor number | Flying capacitor number | Inductor current | Current balancing | Interleaving |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ACF converter with SR (Fig. 1) | $\begin{aligned} & \text { Pri.: } 2 \\ & \text { Sec.: } 2 \end{aligned}$ | 1 | 1 | - | $I_{\text {O }}$ | - | - |
| 2-parallel ACF converters with SR (Fig. 6) | $\begin{aligned} & \hline \text { Pri.: } 4 \\ & \text { Sec.: } 4 \\ & \hline \end{aligned}$ | 2 | 2 | - | $I_{\mathrm{O}} / 2$ (If ideal) | $\begin{gathered} \text { Yes } \\ \text { (Control required) } \end{gathered}$ | Yes |
| ACF converter with 2-parallel SRs (Fig. 7) | $\begin{aligned} & \hline \text { Pri.: } 2 \\ & \text { Sec.: } 4 \\ & \hline \end{aligned}$ | 1 | 2 | - | $I_{\mathrm{O}} / 2$ (If ideal) | No | No |
| ACF converter with proposed 2-phase SC-SR (Fig. 2) | $\begin{aligned} & \text { Pri.: } 2 \\ & \text { Sec.: } 4 \end{aligned}$ | 1 | 2 | 1 | $I_{\mathrm{O}} / 2$ | Yes <br> (Automatic) | Yes |

phase SC-SR can reduce the number of transformer primary winding turns to half that of the conventional SR in order to achieve the same step-down ratio, contributing to a reduction in the copper loss due to the transformer primary windings.

## C. Inductor current sharing

In terms of cooling the inductors, it is important to properly share the output current between the two inductors. This paper presents that the proposed 2-phase SC-SR can achieve the automatic inductor current balancing without the need for control under ideal conditions.

Since the output current $I_{\mathrm{O}}$ of the ACF converter with the proposed 2-phase SC-SR is supplied through $L_{\mathrm{a}}$ and $L_{\mathrm{b}}$, the following equation is given.

$$
\begin{equation*}
I_{\mathrm{O}}=I_{\mathrm{L}}=I_{\mathrm{La}}+I_{\mathrm{Lb}} \tag{6}
\end{equation*}
$$

Considering the charge balance at $C_{\mathrm{t}}$ in a steady state, the amount of charge flowing into $C_{\mathrm{t}}$ in state 1 and the amount of charge flowing out from $C_{\mathrm{t}}$ in state 3 are the same, so the following equation is obtained.

$$
\begin{align*}
& \left\langle Q_{\mathrm{Ct}}\right\rangle=I_{\mathrm{La}} D_{\mathrm{a}} T_{\mathrm{S}}-I_{\mathrm{Lb}} D_{\mathrm{b}} T_{\mathrm{S}}=0 \\
& \Leftrightarrow I_{\mathrm{La}} D_{\mathrm{a}}=I_{\mathrm{Lb}} D_{\mathrm{b}}  \tag{7}\\
& \frac{I_{\mathrm{La}}}{I_{\mathrm{Lb}}}=\frac{D_{\mathrm{b}}}{D_{\mathrm{a}}} \tag{8}
\end{align*}
$$

As a result, the ratio of $I_{\mathrm{La}}$ and $I_{\mathrm{Lb}}$ is determined only by the ratio of $D_{\mathrm{a}}$ and $D_{\mathrm{b}}$ without depending on the circuit parameters. Therefore, the inductor current balance can be achieved automatically by satisfying the condition of $D_{\mathrm{a}}=D_{\mathrm{b}}$, where $I_{\mathrm{La}}$ and $I_{\mathrm{Lb}}$ share half of $I_{\mathrm{O}}$ as follows:

$$
\begin{equation*}
I_{\mathrm{La}}=I_{\mathrm{Lb}}=\frac{I_{\mathrm{O}}}{2} \tag{9}
\end{equation*}
$$

In practice, there are the dead-time periods in addition to the main circuit states shown in Figs. 3 and 4, so some compensation may be required to achieve the perfect current balance. However, if the current imbalance in the proposed 2phase SC-SR is practically permissible, there is a sufficient possibility of practical use.

TABLE I summarizes the discussions and shows the comparison of the circuit configurations. Although the 2parallel ACF converters with the conventional SR shown in Fig. 6 require many circuit elements, the interleave operation is applicable. However, due to parameter variations, the


Fig. 6. 2-parallel active clamp forward converters with conventional synchronous rectifier.


Fig. 7. Active clamp forward converter with 2-parallel conventional synchronous rectifiers.
current control is necessary to achieve the inductor current balance. The ACF converter with the 2-parallel conventional SRs shown in Fig. 7 can reduce the number of circuit elements, but it cannot achieve the interleaved operation and current balancing because the inductor current distribution depends on the circuit parameters. The ACF converter with the proposed 2-phase SC-SR can achieve the interleaved operation and current balancing by adding only one flying capacitor to the 2-parallel conventional SRs.

## III. EXPERIMENTAL VERIFICATION

## A. Experomental setup and conditions

To demonstrate the feasibility of the proposed 2-phase SCSR , experiments were conducted with the ACF converter prototype shown in Fig. 8. The primary circuit and transformer


Fig. 8. Experimental prototype for active clamp forward converter with the proposed 2-phase SC-SR.
was taken from the DC-DC converter for Toyota Yaris HV, and the proposed 2-phase SC-SR, which is the secondary side rectifier circuit, was fabricated using the $61.0 \mathrm{~mm} \times 58.4 \mathrm{~mm}$ 2-layer PCB with replaceable inductors, which was used in two pairs each of 2 turns and 8 turns. The pair of 2 -turn inductors was used for the efficiency and waveform measurements to clearly observe the change in the output current ripple and its effect due to the interleaved operation of the proposed 2-phase SC-SR. On the other hand, the pair of 8turn inductors was used for the current balance measurement to verify the operation of the proposed 2-phase SC-SR in continuous current mode.

The experimental conditions and selected components are listed in TABLE II. In order to compare the operating waveforms and efficiency of the conventional SR and proposed 2-phase SC-SR, the conventional $S R$ was implemented using $Q_{\mathrm{Sla}}, Q_{\mathrm{S} 2 \mathrm{~b}}$, and $L_{\mathrm{b}}$ in Fig. 8 (b), where $Q_{\mathrm{Slb}}$ was bypassed using a shunt resistor and $L_{\mathrm{a}}$ was removed. Then, $Q_{\mathrm{Sla}}$ was operated synchronously with $Q_{\mathrm{P} 1}$, and $Q_{\mathrm{S} 2 \mathrm{~b}}$ was alternately turned on and off with $Q_{\text {sla }}$.

The proposed 2-phase SC-SR was operated as shown in Fig 4. Then, according to (6) and (8), the distribution of $I_{\mathrm{La}}$ and $I_{\mathrm{Lb}}$ can be actively changed using $D_{\mathrm{a}}$ and $D_{\mathrm{b}}$ as follows:

$$
\begin{equation*}
I_{\mathrm{La}}=\frac{D_{b}}{D_{a}+D_{b}} I_{\mathrm{O}} \tag{10}
\end{equation*}
$$

TABLE II. EXPERIMENTAL CONDITIONS AND SELECTED COMPONENTS.

| Parameters | Value and Design Selection |
| :--- | :--- |
| Input voltage $V_{\mathrm{IN}}$ | 140 V |
| Output voltage $V_{\mathrm{OUT}}$ | 5 V |
| Switching frequency | 200 kHz |
| Transformer turns ratio $n_{\mathrm{P}}: n_{\mathrm{S}}$ | $4: 1$ |
| Power MOSFETs $Q_{\mathrm{P} 1-2}$ | $600 \mathrm{~V}, 29 \mathrm{~A}, R_{\mathrm{DS}(\text { on }) \text { max }}: 99 \mathrm{~m} \Omega$, <br> FMC 60 N 099 S 2 A, Fuji Electric |
| Power MOSFETs | $100 \mathrm{~V}, 180 \mathrm{~A}, R_{\mathrm{DS}(\mathrm{on}), \text { max }}: 2.3 \mathrm{~m} \Omega$, |
| $Q_{\mathrm{Sla}}, Q_{\mathrm{S} 2 \mathrm{a}}, Q_{\mathrm{SIb}}, Q_{\mathrm{S} 2 \mathrm{~b}}$ | $\mathrm{STH} 315 \mathrm{~N} 10 \mathrm{~F} 7-6$, STMicroelectronics |,


(a) $V_{\mathrm{DS}, \mathrm{Sla}}, V_{\mathrm{DS}, \mathrm{S} 2 \mathrm{a}}, V_{\mathrm{DS}, \mathrm{Slb}}$, and $V_{\mathrm{DS}, S 2 \mathrm{~b}}$.

(b) $V_{\mathrm{O}}, V_{\mathrm{Ct}}, I_{\mathrm{L}}, I_{\mathrm{La}}$, and $I_{\mathrm{Lb}}$.

Fig. 9. Measured waveforms of the proposed 2-phase SC-SR at $I_{\mathrm{O}}=40 \mathrm{~A}$.


Fig. 10. Measured waveforms of the conventional SR at $I_{\mathrm{O}}=40 \mathrm{~A}$.

$$
\begin{equation*}
I_{\mathrm{Lb}}=\frac{D_{\mathrm{a}}}{D_{\mathrm{a}}+D_{\mathrm{b}}} I_{\mathrm{O}} \tag{11}
\end{equation*}
$$

Therefore, the waveforms and efficiency of the proposed 2-phase SC-SR were measured with the perfect current balance achieved. Since the step-down ratio $M$ also varies depending on $D_{\mathrm{a}}$ and $D_{\mathrm{b}}$ in this experiment, $D_{\mathrm{a}}$ and $D_{\mathrm{b}}$ were manually adjusted so that the output voltage $V_{\mathrm{O}}$ matched the target value, which was set to 5 V .

## B. Measured waveforms and efficiency

Figs. 9 and 10 show the measured waveforms of the proposed 2-phase SC-SR and conventional SR, respectively. Although the voltage waveforms of each switch shown in Fig. 9 (a) contain ringing, the steady waveforms are consistent with Fig. 4, demonstrating the validity of the circuit analysis in this study. In addition, the waveform of $V_{\mathrm{Ct}}$ shown in Fig. 9 (b) indicates charging in state 1 and discharging in state 3 , demonstrating the expected circuit operation. Furthermore, the proposed 2-phase SC-SR achieved the interleaved operation, which reduced the current ripple $\Delta I_{\mathrm{L}}$ from 10.8 A to 6.4 A compared to the conventional SR at $I_{\mathrm{O}}=40 \mathrm{~A}$.

Fig. 11 shows the measured efficiency comparison between the ACF converters with the proposed 2-phase SCSR and conventional SR. The peak efficiency of the proposed 2-phase SC-SR and conventional SR is $90.3 \%$ and $85.9 \%$ at $I_{\mathrm{O}}=28 \mathrm{~A}$, respectively, resulting in the improvement in efficiency by $4.4 \%$. In addition, compared with the conventional SR, the proposed 2-phase SC-SR can reduce the efficiency drop under heavy load. These results indicate that the proposed SC-SR can reduce the heat generation in the inductors under heavy load conditions.

## C. Measured inductor current difference

In order to demonstrate the practicality of the proposed 2phase SC-SR, the experiment was conducted to show how much current balance can be achieved without any control or compensation. In this experiment, both $D_{\mathrm{a}}$ and $D_{\mathrm{b}}$ were set constant at $40 \%$ and $V_{\mathrm{O}}$ was not regulated.

Figs. 12 and 13 show the measured inductor DC currents and normalized current difference between the inductors in the proposed 2-phase SC-SR. As the output current increased, the current imbalance decreased and was below $10 \%$ at heavy load. Since the heat generation of the inductors is dominant under heavy load, the experimental results demonstrate the practicality of the proposed 2-phase SC-SR. It is expected that the current imbalance can be further reduced by proposing a compensation operation that considers the dead time, which is one of the important issues in future work.

## IV. Conclusions

A 2-phase series capacitor synchronous rectifier (SC-SR) in active clamp forward (ACF) converters was proposed to solve the output inductor cooling problems caused by the recent trend of increasing the output current. This paper presented that the proposed 2-phase SC-SR achieved the interleaved operation by adding only one flying capacitor to the 2-parallel conventional SRs without increasing the number of the primary circuit elements and transformer. In addition, the inductor current balancing in the proposed 2-phase SC-SR was analytically described based on the ideal circuit operation.

In the measurement at 140 V-to- 5 V conversion, the interleaved operation of the proposed 2-phase SC-SR reduced the output current ripple from 10.8 A to 6.4 A compared to the conventional SR at $40 \mathrm{~A}_{\text {out }}$. The peak efficiency of the


Fig. 11. Measured efficiency comparison between the ACF converters with the proposed 2-phase SC-SR and conventional SR.


Fig. 12. Measured inductor DC currents in the ACF converter with the proposed 2-phase SC-SR.


Fig. 13. Normalized current difference between the inductors in the ACF converter with the proposed 2-phase SC-SR.
proposed 2-phase SC-SR and conventional SR was 90.3 \% and $85.9 \%$ at 28 Aout, resulting in the improvement in efficiency by $4.4 \%$. The current imbalance between the two output inductors of the proposed 2-phase SC-SR was less than $10 \%$ under heavy load even without any control or compensation. These results demonstrated the practicability of the proposed 2-phase SC-SR in ACF converters.

As future work, a parameter optimization including the dead time and the active clamp capacitance of ACF converter will be conducted to improve the converter performance. In addition, a control strategy to achieve the output voltage regulation and the inductor current balancing at the same time will be proposed.

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