

A Modulation Strategy for Generating Sinusoidal Output Voltage Under Arbitrary Power Factor Conditions in Flying-Capacitor Linear Amplifiers

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Abstract—This paper introduces a novel modulation strategy for a flying-capacitor linear amplifier (FCLA) that reduces conduction losses and supports operation at an arbitrary power factor. A WPT system using an FCLA that delivers sinusoidal voltage as a power supply has been proposed to minimize radiation noise. However, the existing modulation does not address operation under low power factor conditions resulting from misalignment and load variations. This paper presents a new modulation strategy that enables full-range power-factor operation by complementarily controlling the MOSFETs on the upper and lower arms, allowing regenerative operation. A 15-series FCLA prototype demonstrates that the proposed method maintains a sinusoidal output even with inductive and capacitive loads. Moreover, it improves efficiency by 2.4 points compared to traditional modulation at unity power factor, reaching 96.2% efficiency, thereby showing the effectiveness of the proposed strategy.

Keywords—*electromagnetic interference (EMI), flying capacitor multi-level converter, linear amplifier, wireless power transfer*

I. INTRODUCTION

Power converters widely used in industrial applications achieve high-efficiency power conversion through the switching operation of power semiconductor devices. In recent years, the emergence of wide-bandgap (WBG) semiconductor devices such as silicon carbide (SiC) and gallium nitride (GaN) has enabled further increases in switching speed and high-frequency operation, thereby accelerating the miniaturization and performance enhancement of power converters. However, the high-speed switching results in a high dv/dt or $didt$ rectangular waveform of the output voltage. Consequently, the output contains numerous harmonic components in addition to the fundamental frequency. These switching operations lead to electromagnetic interference (EMI) issues [1].

This issue becomes especially important in wireless power transfer (WPT) systems. Typically, the power supply of a WPT system uses an H-bridge inverter that produces a square-wave output voltage [2]–[4]. The resulting current has a high harmonic content, flowing through the transmission coils and causing leakage magnetic fields. These fields contain harmonic components that are subsequently emitted into the surrounding environment [3], [4]. These leakage magnetic fields can interfere with nearby electronic devices and pose significant challenges to comply with electromagnetic compatibility (EMC) standards established by organizations such as the International Special Committee on Radio

Interference (CISPR) [5]. To mitigate these leakage magnetic fields, several methods using LC filters or additional cancellation coils have been proposed [4], [6], [7]. However, since the fundamental frequency responsible for power transfer is close to lower-order harmonics such as the 3rd and 5th components, it is difficult to suppress these harmonics without affecting the fundamental component.

As a fundamental solution to the aforementioned issues, a flying-capacitor linear amplifier (FCLA), which operates based on the linear operation of a power semiconductor device, has been proposed [8]. The FCLA employs MOSFETs not only as switching devices but also as active devices operating in the linear region, similar to a class-B amplifier, to generate a continuous and smooth output voltage [9]. The FCLA generates a pure sinusoidal voltage free of harmonic distortion. As a result, harmonic components are removed from the primary coil voltage, and current harmonics are greatly diminished. However, previous studies have not considered operation under low power factor conditions caused by coil misalignment or load variations, which pose challenges for practical implementation.

In this paper, a new modulation method is proposed that enables the FCLA to output sinusoidal voltages independent of power-factor conditions, while simultaneously reducing the conduction losses of the MOSFETs in the amplifier. The effectiveness of the proposed modulation technique is confirmed through experimental evaluation under different load power factor conditions. Additionally, the reduction in conduction loss is shown through an FCLA prototype.

II. FLYING-CAPACITOR LINEAR AMPLIFIER

A. Circuit Configuration

Fig. 1 illustrates the circuit configuration of the proposed flying-capacitor linear amplifier (FCLA). The FCLA consists of $2n$ n-MOSFETs, $n-1$ flying capacitors, and a polarity-switching H-bridge. The H-bridge reverses the polarity of the continuous full-wave-rectified voltage generated by the linear operation of the preceding $2n$ MOSFETs, thereby producing a sinusoidal output voltage. As a result, the FCLA generates a voltage free from harmonic components and effectively suppresses electromagnetic interference (EMI).

B. Proposed Modulation Method

Fig. 2 shows the proposed modulation technique for the flying-capacitor linear amplifier (FCLA) with two MOSFET stages ($n = 2$). As seen in Fig. 2 (a), the operating states of the MOSFETs in the upper arm are based on a carrier phase-shift

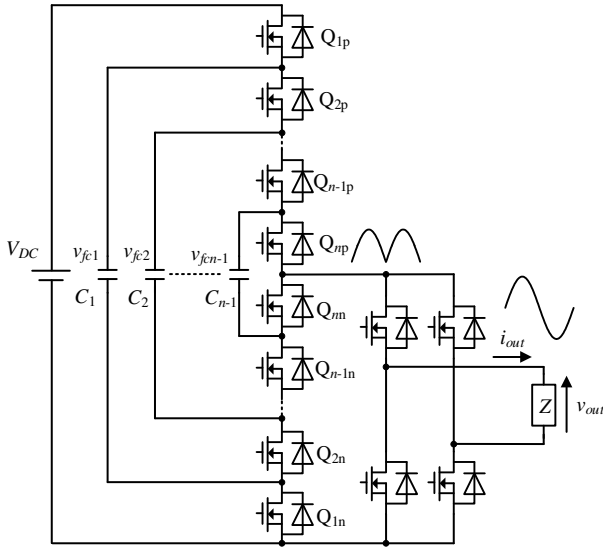


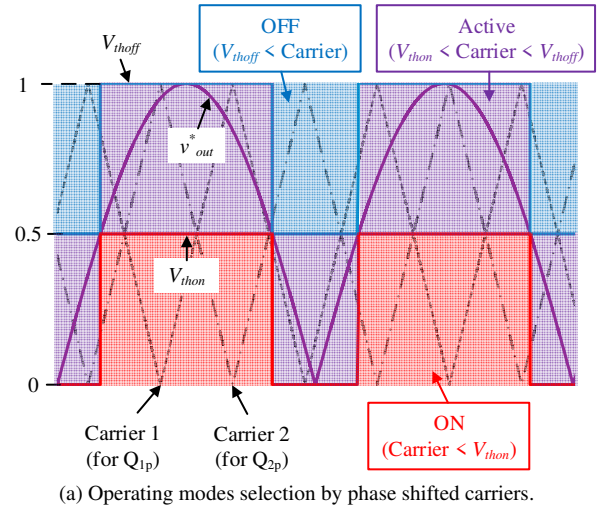
Fig. 1. A n-series flying-capacitor linear amplifier (FCLA).

modulation scheme. This method produces a continuous full-wave rectified voltage. The operating mode of each MOSFET is selected by comparing two threshold voltages (V_{thon} and V_{thoff}) synchronized with the voltage command v^*_{out} , against the corresponding phase-shifted carrier waveforms. As illustrated in Fig. 2 (a), the ON-threshold voltage V_{thon} varies in increments of $1/n$ according to the voltage command v^*_{out} . Meanwhile, the OFF-threshold voltage V_{thoff} is set to a value $1/n$ higher than V_{thon} . When the carrier voltage is below V_{thon} , the MOSFET turns ON. When it exceeds V_{thoff} , the MOSFET turns OFF. For conditions that do not meet either threshold, the MOSFET operates in the linear region. By determining the operating state in this way, the number of MOSFETs in the ON or OFF state is dynamically adjusted, allowing for smooth waveform synthesis and controlled voltage transitions.

Fig. 2 (b) shows the selection method of the operating states for the lower-arm MOSFETs. Similar to conventional multilevel flying-capacitor converters, the operating states of the lower-arm MOSFETs are selected to be complementary to those of the corresponding upper-arm MOSFETs [10]. However, when the MOSFETs operate in the linear region, both devices in a complementary pair are driven simultaneously. In this state, the drain-source (D-S) voltage command for the lower-arm MOSFETs is set as the inverse of that for the upper-arm devices. This modulation approach effectively prevents simultaneous conduction of switching devices and thus avoids short circuits or undesired parallel connections between the DC supply and the flying capacitors. Furthermore, the proposed method enables the generation of sinusoidal output voltage under both power running and regenerative operating conditions.

C. Operating Modes

Fig. 3 shows all the operating modes of the 2-series FCLA when the conventional modulation method is applied. During power running operation, the FCLA has multiple distinct operating modes that generate the same output voltage. Moreover, an active-state MOSFET on the upper arm enables FCLA to generate a continuous output voltage. However, when the lower-arm MOSFETs are conducting, the conventional modulation method keeps all lower-arm MOSFETs off, causing the body diodes to conduct and resulting in losses due to the forward voltage. On the other hand, when the output voltage and current have opposite



(a) Operating modes selection by phase shifted carriers.

	1	2	3
Q_{kp}	ON 	OFF 	Active
Q_{kn}	OFF 	ON 	Active

(b) Complementary switch operations.

Fig. 2. A proposed modulation strategy for a 2-series FCLA.

polarities, the input current of the full bridge flows toward the power supply side. In this interval, all lower-arm MOSFETs are off. Thus, regardless of the operating state of the upper-arm MOSFET, only a current path returning to the DC power supply exists. As a result, the output voltage is clamped to the DC supply voltage, causing distortion in the output voltage waveform.

Fig. 4 shows all the operating modes of the 2-series FCLA when the proposed modulation method is applied. The FCLA has multiple distinct operating modes that generate the same output voltage. Depending on each operating mode, the current paths within the FCLA vary, and consequently, the charging and discharging states of the flying capacitors also change. Thus, by appropriately transitioning between these operating modes, the voltage balance of the flying capacitors is maintained. In this study, the voltage balancing of the flying capacitors is achieved by determining the operating modes of the MOSFETs based on the phase-shifted carrier signals shown in Fig. 2.

Under the proposed modulation scheme, each complementary pair of MOSFETs transitions between operating modes while maintaining a complementary relationship. Both power running and regenerative operations are achieved within the same output voltage range and mode transitions, and no operating state involves conduction through the body diodes of the MOSFETs. Consequently, the proposed FCLA modulation method is expected to effectively reduce conduction losses. During the input current of the full bridge flows toward the power supply side, when the output voltage is below V_{DC}/n , there exists no operating mode that allows energy recovery to either the DC source or the flying

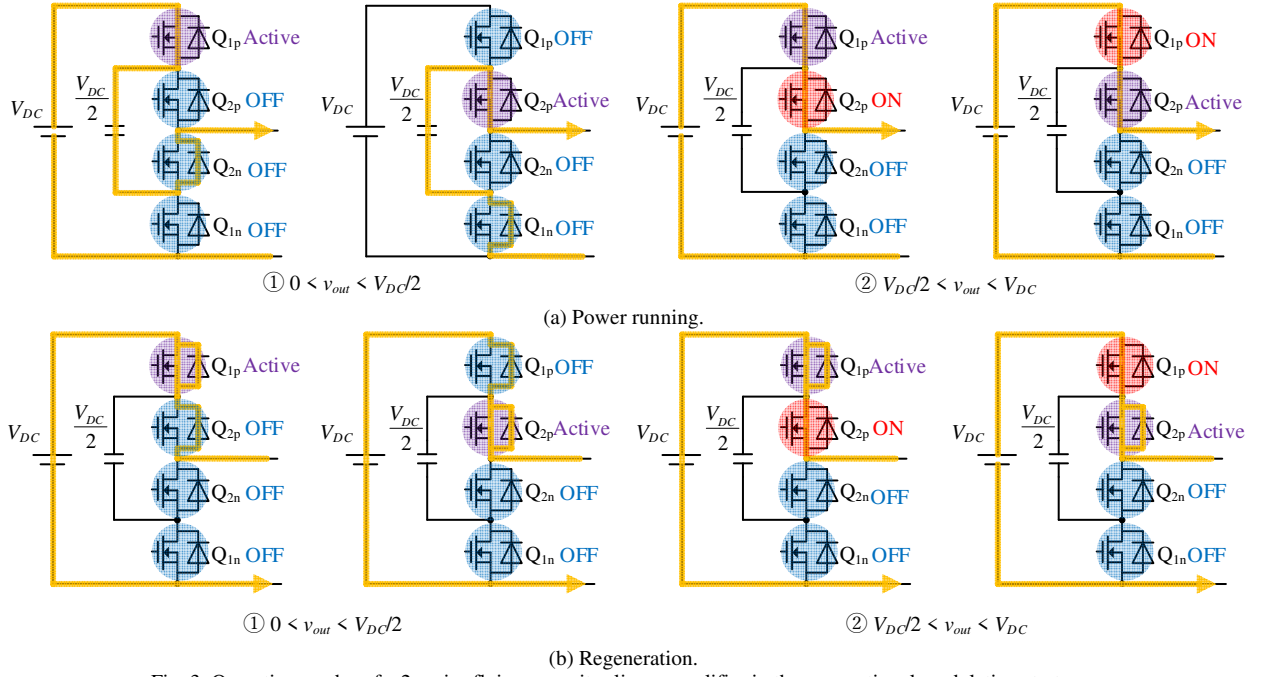


Fig. 3. Operating modes of a 2-series flying-capacitor linear amplifier in the conventional modulation strategy.

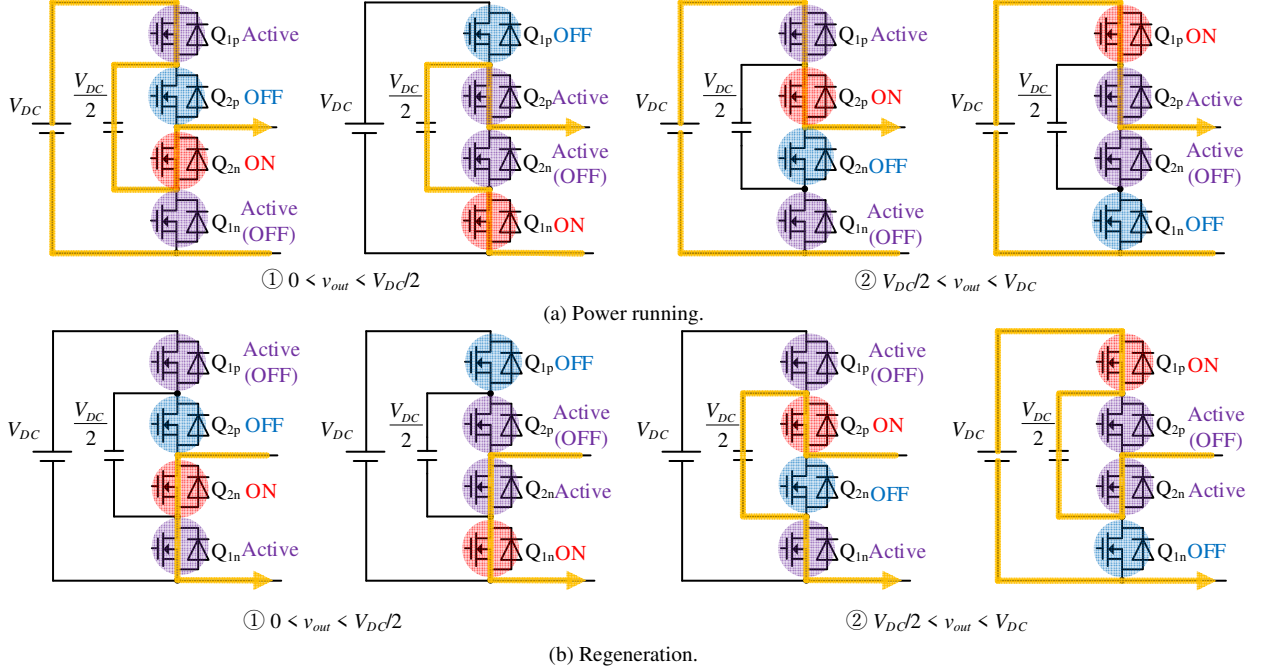


Fig. 4. Operating modes of a 2-series flying-capacitor linear amplifier in the proposed modulation strategy.

capacitors. In this condition, the power is dissipated within the MOSFETs operating in the on or active state. As a result, the efficiency becomes lower than that in the power running operation. However, as the number of FCLA stages n increases, the duration of the period in which the output voltage remains below V_{DC}/n is reduced. Hence, the overall efficiency under low-power-factor conditions can be improved by increasing the number of FCLA stages.

III. THEORETICAL EFFICIENCY

In this section, the input power P_{in} , output power P_{out} , and theoretical efficiency η of the FCLA, including the polarity-switching H-bridge, are derived under the following conditions. The derivation is carried out based on the assumptions (a)–(d) listed below.

- (a) Only unity-power-factor operation is considered.
- (b) Voltage of flying capacitor C_k is maintained $(n-k)V_{DC}/n$.
- (c) Each series-connected MOSFET on the upper arm operates as an active state in the order Q_{np} to Q_{1p} .
- (d) The power loss of the gate driver and flying capacitor is not considered.

The output voltage v_{out} , current i_{out} , and power P_{out} of the n -series FCLA are

$$v_{out} = V_{DC} \sin \theta, \quad (1)$$

$$i_{out} = I_{max} \sin \theta, \quad (2)$$

$$P_{out} = \frac{V_{DC} I_{max}}{2}. \quad (3)$$

One of the MOSFETs in an FCLA (Q_{kp}) operates as active state, and its drain-source voltage $v_{kp,act}$, and drain current i_{kp} change continuously. The power loss of Q_{kp} in the active state is calculated as

$$P_{active,k} = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} v_{kp,act} i_{kp} d\theta = \frac{2}{\pi} \int_{\theta_k}^{\theta_{k-1}} \left(\frac{n-k+1}{n} V_{DC} - v_{out} \right) i_{out} d\theta$$

$$= \frac{2V_{DC} I_{max}}{\pi} \left\{ \frac{n-k+1}{n} (\cos \theta_k - \cos \theta_{k-1}) + \frac{\theta_k - \theta_{k-1}}{2} + \frac{\sin 2\theta_{k-1} - \sin 2\theta_k}{4} \right\}, \quad (4)$$

where $\theta_k = \sin^{-1}\{(n-k)/n\}$. Also, the power loss of Q_{kp} on the upper arm in the on state is calculated as

$$P_{upper,k} = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} v_{kp,upper} i_{kp} d\theta = \frac{2}{\pi} \int_{\theta_{k-1}}^{\frac{\pi}{2}} R_{on} i_{out}^2 d\theta$$

$$= \frac{R_{on} I_{max}^2}{\pi} \left(\frac{\pi}{2} - \theta_{k-1} + \frac{\sin 2\theta_{k-1}}{2} \right), \quad (5)$$

where $v_{kp,upper}$ is a voltage drop of on-state MOSFETs, and R_{on} is the on-state resistance of MOSFETs. The conduction loss of a MOSFET on the lower arm (Q_{kn}) is calculated as

$$P_{lower,k} = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} v_{kn,lower} i_{kn} d\theta = \begin{cases} \frac{2}{\pi} \int_0^{\theta_k} V_F i_{out} d\theta \\ \frac{2}{\pi} \int_0^{\theta_k} R_{on} i_{out}^2 d\theta \end{cases}$$

$$= \begin{cases} \frac{2V_F I_{max}}{\pi} (1 - \cos \theta_k) \\ \frac{R_{on} I_{max}^2}{\pi} \left(\theta_k - \frac{\sin 2\theta_k}{2} \right) \end{cases}, \quad (6)$$

where i_{kn} is the drain current of Q_{kn} and V_F is the forward voltage of the body diode of each series-connected MOSFET. In the conventional modulation method, the lower MOSFET remains off, causing the body diode to conduct and resulting in losses due to the forward voltage V_F . Thus, the losses of the lower-arm MOSFET are calculated using an expression based on V_F . In contrast, the proposed modulation method turns the lower MOSFET on when it conducts, thereby suppressing these losses. In this case, the losses are calculated using an expression based on the on-resistance R_{on} .

From (4) to (6), the efficiency of the n -series FCLA is

$$\eta = \frac{P_{out}}{P_{out} + \sum_{k=1}^n (P_{active,k} + P_{upper,k}) + \sum_{k=1}^{n-1} P_{lower,k}}. \quad (7)$$

TABLE I. EXPERIMENTAL CONDITIONS

Parameter	Symbol	Value
DC voltage	V_{DC} [V]	100
Output frequency	f [kHz]	85
Capacitance of flying-capacitors	- [μ F]	11
The number of series MOSFETs	n	15

TABLE II. ELECTRICAL CHARACTERISTICS OF MOSFETs

Parameter	IAUCN04S6N017T (Series MOSFETs)	SCT3030AR (H-bridge)
Drain-source breakdown voltage	40 V	650 V
On-state resistance	1.8 m Ω	28 m Ω
Diode forward voltage	0.73 V	3.2 V

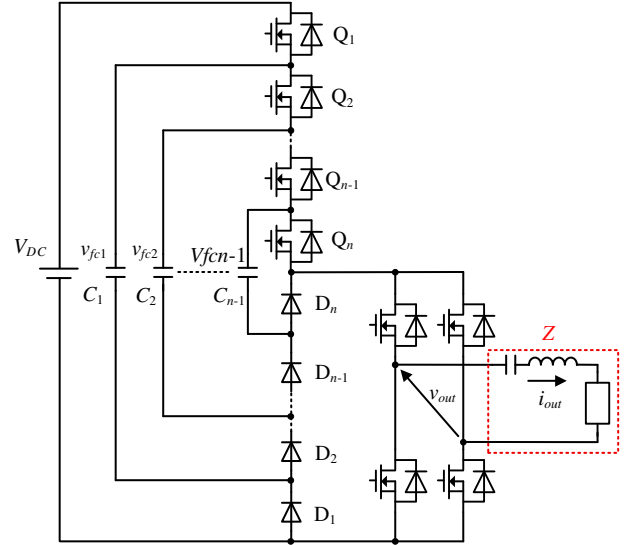


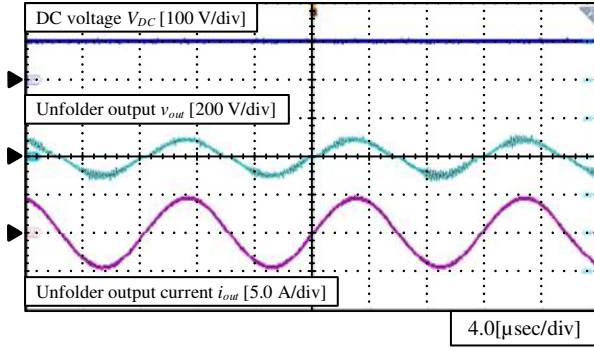
Fig. 5. Circuit configuration for validating the proposed modulation method of the FCLA.

IV. EXPERIMENTAL VALIDATION

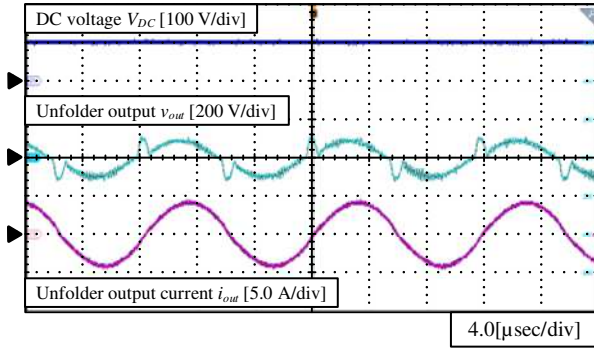
The proposed modulation method is validated with a 15-series ($n = 15$) FCLA prototype. Two cases are compared. One is the conventional method in which all lower-arm MOSFETs remain off during operation, and the other is the proposed modulation method. The experimental conditions and device parameters are summarized in Tables I and II, respectively. Fig. 5 shows the circuit configuration for validation of the proposed modulation method. To emulate the operation of the FCLA applied to a series-series (SS) compensated WPT system, an RLC resonant load was connected to the FCLA, and experiments were conducted. In this setup, the power factor was varied by adjusting the inductance and capacitance values of the inductor and capacitor.

A. Operating Waveforms

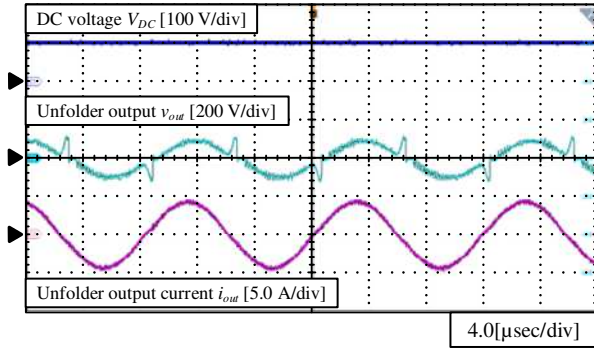
Fig. 6 shows operating waveforms of the 15-series FCLA with a conventional modulation method under some power factor conditions. Under the unity power factor operating condition, the conventional modulation method successfully generates a sinusoidal output voltage. However, when the power factor deviates from unity, the output voltage is clamped to the DC supply voltage during the input current of the full bridge flows toward the power supply side. This occurs because all lower-arm MOSFETs are turned off in the



(a) Load power factor: 1.0.
(Load impedance Z : 20.4 Ω)

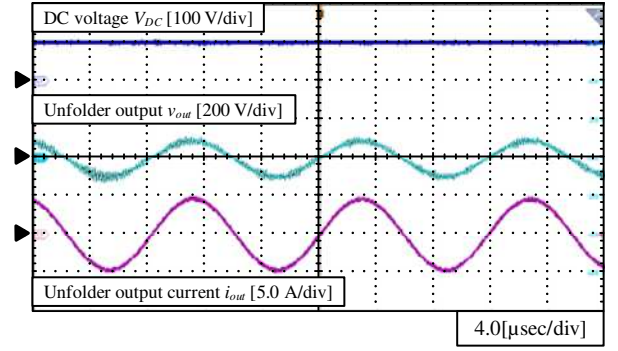


(b) Load power factor: 0.90 (Inductive).
(Load impedance Z : 22.8 Ω)

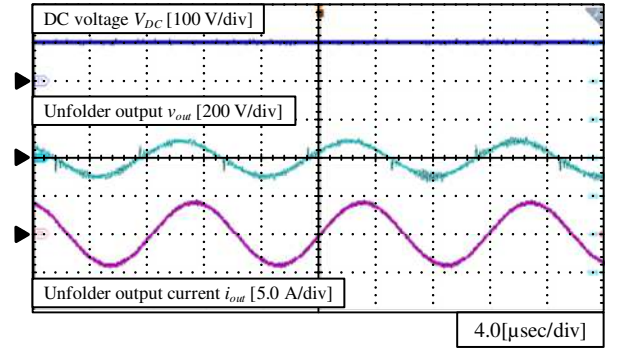


(c) Load power factor: 0.90 (Capacitive).
(Load impedance Z : 22.8 Ω)

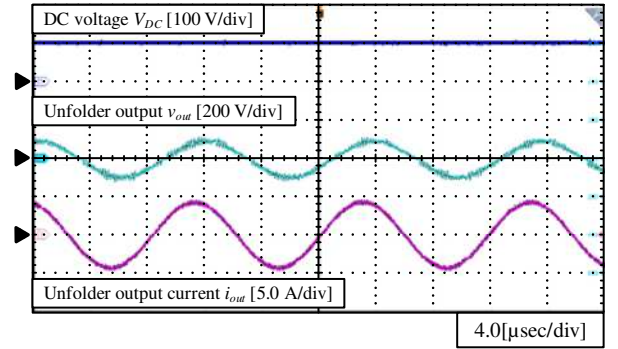
Fig. 6. Waveforms of the 15-series flying capacitor linear amplifier in the conventional modulation method.



(a) Load power factor: 1.0.
(Load impedance Z : 20.4 Ω)



(b) Load power factor: 0.90 (Inductive).
(Load impedance Z : 22.8 Ω)



(c) Load power factor: 0.90 (Capacitive).
(Load impedance Z : 22.8 Ω)

Fig. 7. Waveforms of the 15-series flying capacitor linear amplifier in the proposed modulation method.

conventional modulation method, leaving only a current path to the DC power supply.

Fig. 7 shows operating waveforms of the 15-series FCLA with the proposed modulation method under some power factor conditions. Under the unity power factor operating condition, the proposed modulation method successfully generates a sinusoidal output voltage. Furthermore, unlike the conventional modulation method, the proposed method generates a sinusoidal output voltage even when driving a load with a low power factor.

B. Efficiency and Loss Analysis

Table III shows the measured power conversion efficiency of the FCLA at an unity power factor, obtained using a power analyzer (PW6001, HIOKI) and the theoretical efficiency by (7). Although the voltage and current are sinusoidal, the accuracy of the active power calculated from power analyzer

measurements significantly degrades at high-frequency AC operation, such as 85 kHz, compared with low-frequency conditions. Therefore, the efficiency values listed in Table III should be regarded as reference values.

Compared with the conventional operation in which the lower-arm MOSFETs are all turned off, the proposed modulation method demonstrates an efficiency improvement of approximately 2.4 percentage points and achieves 96.2% efficiency. This improvement is attributed to the proper turn-on of the lower-arm MOSFETs, which suppresses the conduction loss caused by the forward voltage V_F of the body diodes.

Fig. 8 shows the loss breakdown of the 15-series FCLA for the conventional and proposed modulation methods calculated from the theoretical loss expressions in (4)–(6). The category “Other loss” represents the difference between the measured losses and the theoretical losses. The loss

breakdown of the FCLA with the conventional modulation method indicates that the losses caused by active-state MOSFETs and the conduction loss of the body diodes are dominant. In the proposed modulation method, the conduction of the body diodes is prevented by properly turning on the lower-arm MOSFETs. As a result, the associated losses are reduced, and the efficiency is improved.

V. CONCLUSION

This paper proposed a modulation approach that enables the flying-capacitor linear amplifier to produce a sinusoidal voltage regardless of the power factor and to minimize conduction losses. The proposed modulation technique allows open-loop operation of the FCLA across all power factors because the operating modes of each series MOSFET remain unchanged, whether in power-running or regeneration operations. Additionally, since the MOSFETs are switched on without conducting through their body diodes, this method is expected to significantly reduce conduction losses. Experimental results verify that this modulation scheme allows the FCLA to generate a sinusoidal output voltage even at low power factors. Moreover, this method improved efficiency by 2.4 percentage points compared to conventional operation with body-diode conduction, achieving 96.2% at a unity power factor.

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TABLE III. EFFICIENCY OF THE 15-SERIES FCLA IN LOAD POWER FACTOR: 1.0

	Input power	Output power	Efficiency	Theoretical efficiency
Conventional modulation	238 W	223 W	93.8%	93.9%
Proposed modulation	242 W	233 W	96.2%	96.2%

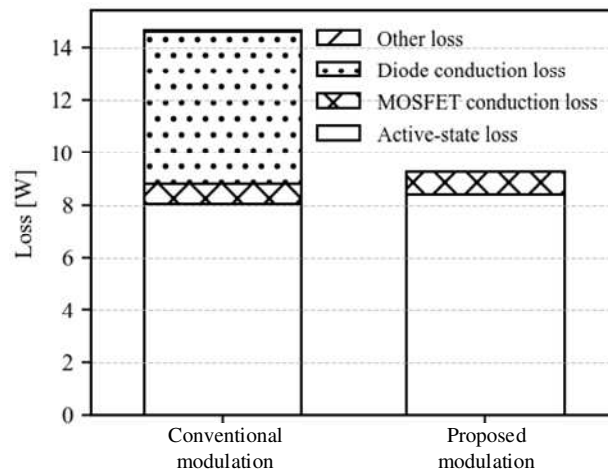


Fig. 8. Loss analysis.

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