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# Flying-capacitor Linear Amplifier with N-channel MOSFETs for Radiation Noise Reduction of Wireless Power Transfer System

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**ABSTRACT**: This paper proposed a flying-capacitor linear amplifier (FCLA) for wireless power transfer (WPT) systems. The proposed FCLA consists of only n-channel MOSFETs and an unfolder in the output stage. The FCLA with the unfolder output a sinusoidal voltage and current. Due to the sinusoidal output, the radiation noise harmonics from transmission coils reduces. First, the proposed FCLA configuration and control method is explained. Then, the operation of the proposed FCLA connected to the WPT system is demonstrated by simulation. In addition, harmonic components of current on a primary coil are analyzed. As a result, it is confirmed that the third-order harmonic component is reduced by 49.1 dB in comparison with a conventional two-level inverter. Finally, it is confirmed that the flying capacitor voltage is automatically balanced by a prototype with two-series MOSFETs in the upper arm. Furthermore, the third-order harmonic output voltage is reduced by 19.8 dB compared to the square wave.

**KEYWORDS**: wireless power transfer, radiation noise, flying-capacitor linear amplifier, linear amplifier, flying-capacitor

## 1. INTRODUCTION

In recent years, a wireless power transfer (WPT) system for electric vehicles (EVs) is actively studied(1-3). Especially, an ultra-fast charging of the WPT system is required to charge an onboard large-capacity battery in a short time. However, high-power WPT emits large radiation noise. The radiation noise may cause malfunctions of other electronic equipment or interferes with wireless communication. The WPT system must comply with the regulation established by CISPR. In particular, the regulation of radiation noise harmonic for the high-power WPT systems will be tightened by approximately 30dB. Thus, a reduction method of radiation noise in both low-order and high-order harmonics is required.

Most of the WPT systems previously reported have an inverter, which outputs a square wave voltage(4). The harmonic component of the square wave voltage causes the harmonic current on the transmission coil. The harmonics components of the current on the coil are the critical reason for the harmonic components of the leakage magnetic flux. For this reason, satisfying the regulation is difficult in the high-power WPT system.

Besides, a flying-capacitor linear amplifier (FCLA) has been proposed for suppressing high-frequency leakage current from a switching power converter and removing LC filter(5-7), as substitutes for AC-DC or DC-AC converters. The FCLA efficiently outputs a continuous voltage by operating one of the MOSFETs in a saturation region. However, the conventional FCLA needs not only n-channel MOSFETs (n-MOSFETs) but also p-channel MOSFETs (p-MOSFETs), which have inferior characteristics. The p-MOSFETs in FCLA cause a decrease in efficiency and distortion of the output waveform.

This paper proposed the FCLA with only n-MOSFETs for the WPT system in order to reduce the harmonics of the radiation noise. The current on the transmission coils has no harmonics components in the proposed topology. Thus, the radiation noise harmonics from the coils will be reduced.

In the rest of the paper, first, the configuration of the proposed system is explained. Then, the operation and the self-balancing capability of the flying capacitor (FC) voltage are explained. Finally, the operation of the proposed FCLA and the FC voltage balancing are confirmed by simulation and experimental. The new contribution of this paper is that FCLA with only n-MOSFETs is proposed and the FC voltage balancing is confirmed by experiments.

## 2. FCLA WITH AN UNFOLDER FOR WPT

### 2.1. Conventional FCLA

Figure 1 shows the operating region of a MOSFET. The operating region of the MOSFET is divided into three regions, a linear region, a saturation region, and a cutoff region, depending on the gate-source voltage and drain-source voltage. Traditional switching converters use only linear and cutoff regions. Hence, the switching circuits output a discontinuous voltage that causes electromagnetic interference.

One of the techniques to reduce the harmonics components, linear amplifiers with MOSFETs operated in the saturation region are used. However, the efficiency of the linear amplifiers is theoretically low because a conduction loss of the MOSFET is large due to the operation in a saturation region. In order to overcome the above problem, an FCLA has been proposed[5-7]. The FCLA outputs a sinusoidal voltage by operating one of the MOSFETs connected in series in a saturation region. The efficiency of the FCLA is high because the drain-source voltage of the MOSFET in the saturation region is low[5]. The FCLA operates as a power amplifier that outputs a voltage equal to the input voltage to the gate of each MOSFET by the source follower function of MOSFET. A common reference signal is input to the gate of all of the MOSFETs. Due to a common gate input, the operation region of each MOSFET is uniquely determined to be any linear, saturation, or cutoff region by the output voltage and current. One of the n-MOSFETs is in the saturation region when the FCLA output the positive current. On the other hand, the p-MOSFET is in the saturation region when the FCLA output the negative current.

### 2.2. Configuration of the proposed FCLA

Figure 2 shows the configuration of the FCLA with an unfolder for WPT. The proposed FCLA consists of only n-MOSFETs. The proposed FCLA with unfolder is connected to the WPT system, which is operated in a unity power factor due to the resonance characteristic of the WPT system. Thus, the FCLA output only a positive current by using the unfolder. For this reason, it is possible to replace the p-MOSFETs with diodes.

In addition, gate drive circuits are connected between the gate and source of each MOSFET, which independently controls the operation region of MOSFET, such as saturation region, linear region, and cutoff region. Note that the FCLA has various patterns that output the same voltage. The flying capacitor (FC) voltages are balanced using the degree of freedom of the patterns.

### 2.2. FC voltages balancing using phase-shifted carriers

When a common reference signal inputs to the gates, the FC voltages do not balance. In order to balance the FC voltages, the operating region of each MOSFET must be individually controlled. For this purpose, an isolated gate drive unit (GDUs) is needed. The independent GDUs connected to each MOSFET change the current path on the FCLA for balancing the FC voltages. The capable voltage range for the FC balance control is determined by the number of n-MOSFETs in the cutoff region. When $k$ MOSFETs are in the cutoff region in $n$-series FCLA with $n$ MOSFETs are connected in series, the controllable voltage range is expressed as

$$\frac{n-k-1}{n}V_{DC} < v_{out} \leq \frac{n-k}{n}V_{DC} \quad \cdots\cdots (1),$$

where $k$ is the number of MOSFETs operating in cutoff region. The output voltage is controlled by the active operation of one of the MOSFETs, which is not in the cutoff region. Furthermore, it is possible to control the charge and discharge of FC by selecting the MOSFETs to be in the cutoff region according to the output voltage.

However, it is complicated to select the region of each MOSFET to keep the FC voltages balance because the degree of freedom of the current path of FCLA is enormous. In the proposed system, the region of each MOSFET is selected by the phase-shifted carrier-based PWM, which is used in the conventional flying capacitor converter.

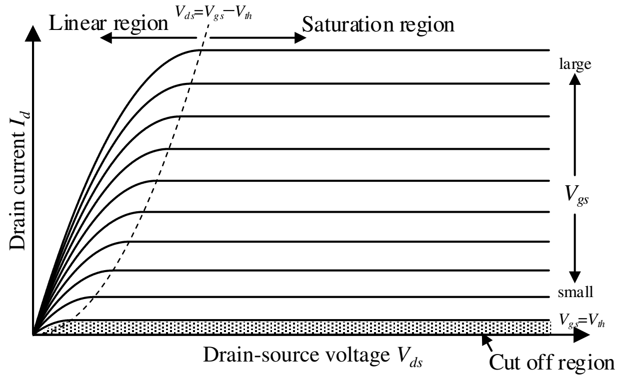



Fig. 1. Operating region of n-MOSFETs

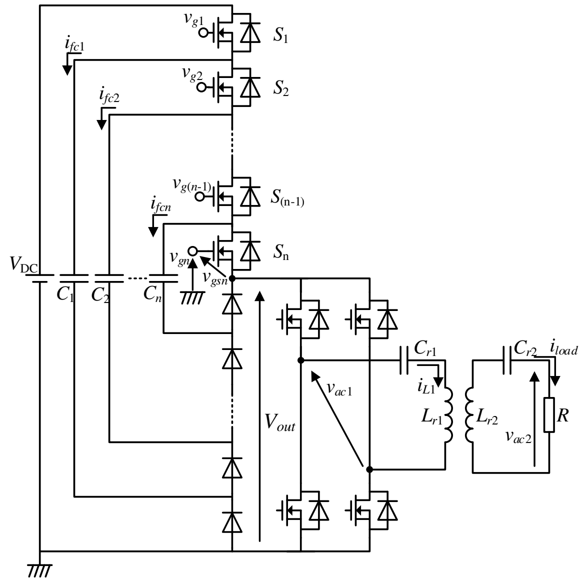



Fig. 2. FCLA with the unfolder for WPT.

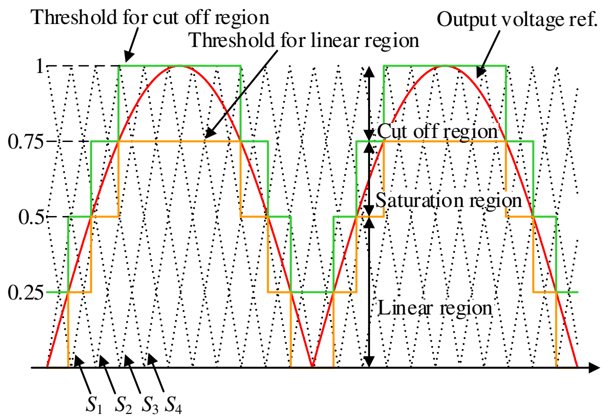



Fig. 3. Region selection based on phase-shifted PWM.

Figure 3 shows the selection method of the MOSFET's region of a 4-series FCLA using carrier comparison with the phase-shifted asynchronous carrier. The region of each MOSFET is selected from linear, cutoff, or saturation region. In this method, the region is selected by comparing two thresholds with the carrier. One is the threshold value for selecting the cutoff region, which changes stepwise according to the output voltage. When the carrier is larger than the threshold for the cutoff region, the MOSFET is in the cutoff region. The other is the threshold for selecting the linear region, which is $1/n$ smaller than the threshold for selecting the cutoff region. When the carrier is less than the threshold for the linear region, the MOSFET is in the linear region. Moreover, one MOSFET, which does not in the linear region nor cutoff region, is in the saturation region. The carrier frequency must be asynchronous with the output frequency in order to select a region that balances the FC voltage. In FCLA, the carrier frequency is set to a value close to the output frequency to avoid redundant changes. When the carrier frequency is close to the output frequency, the FC voltages balance do not keep because the summation of the product of current and conduction time of each FC is not zero. When the carrier frequency is out of synchronization with the output frequency, the MOSFET region changes every cycle. As a result, the FC voltage balances in a longer period than the output period because the FC charge/discharge current path also changes every cycle.

### 2.3. The output voltage control

Figure 4 shows a block diagram of the FCLA voltage control. The FCLA operates as a current amplifier with unity voltage gain with respect to the gate-to-ground voltage $v_{gn}$ by the function of the source follower of the MOSFET. Hence, the independent GDUs must output a gate-source voltage $v_{gsn}$ , whose gate-ground voltages $v_{gn}$ are equal to the output voltage $V_{out}$. The gate-source voltages $v_{gsn}$ are controlled by the feedback of the output voltage $V_{out}$ and adding the offset $V_{on}$, $V_{off}$ according to the selection of the region of each MOSFET. Furthermore, the feedback control suppresses disturbances caused by nonlinearity of MOSFET and a region transition.

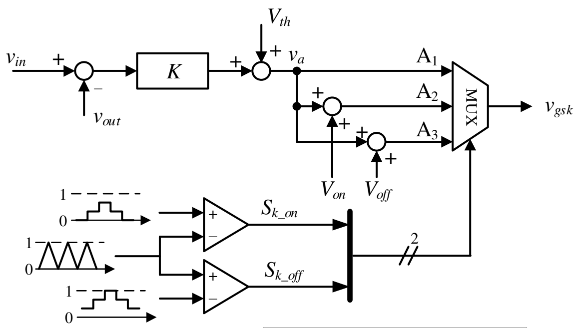
The output voltage of the FCLA is expressed as

$$V_{out} = \frac{V_{DC}}{n}\sum_{k=1}^{n} S_k + \sum_{k=1}^{n-1} \Delta V_{fck}\left(S_{k+1} - S_k\right) \cdots\cdots\cdots\cdots\cdots\cdots (2),$$

where $S_k$ is the state of the $k$-th MOSFET, and represents the cutoff region as "0", the linear region as "1", and the saturation region as $0 < S_k < 1$. The second term in (2) shows the effect of FC voltage error on the output voltage range. From (2), when the FC voltage is unbalanced, the output voltage changes. Due to this, the output voltage does not follow the command voltage in the pattern selected by comparing with the carriers.

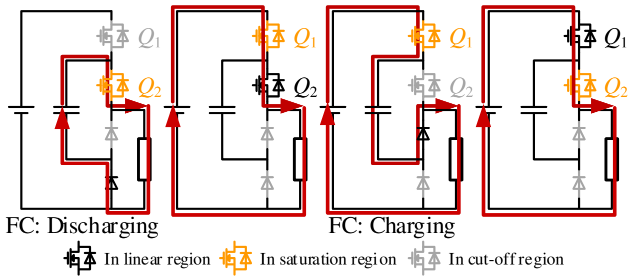
Figure 5 shows the current path in a two-series FCLA. The FCLA has several patterns of the operation region that output the same voltage range. However, the current paths are different among the pattern which output the same voltage range. In other words, the charge or discharge of FCs is controllable by variation of the patterns.

Figure 6 shows the output voltage ranges for each pattern of the two-series FCLA. Fig. 6(a) shows the range when the FC voltage is balanced, and Fig. 6(b) and (c) show the range when the FC voltage is unbalanced. The controllable range of the FC voltage varies with the FC voltage error. However, the operating range is selected based on the assumption of balance. Thus, the FCLA with unbalancing FC does not output the voltage following the command value. When the output voltage command is in the unable voltage range



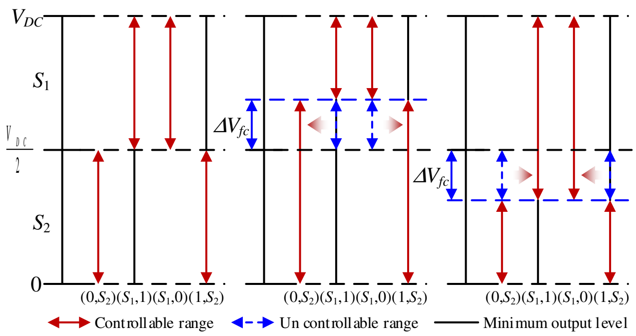

| MUX | | |
|---|---|---|
| $S_{k\_on}$ | $S_{k\_off}$ | $v_{gsk}$ |
| 1 | 1 | $A_1$ |
| 1 | 0 | $A_2$ |
| 0 | 1 | $A_3$ |

Fig.4. Voltage control diagram.




(a) $Q_1$: Cutoff $Q_2$: Saturation (b) $Q_1$: Saturation $Q_2$: Linear (c) $Q_1$: Saturation $Q_2$: Cutoff (d) $Q_1$: Linear $Q_2$: Saturation

Fig.5. Current path of 2-series FCLA.




(a) FC voltage balance (b) FC voltage excess (c) FC voltage shortage

Fig. 6. Controllable range of output voltage of 2-series FCLA.

Table 1. Simulation conditions

| Parameters | Symbol | Value |
|---|---|---|
| Primary voltage | $V_{DC1}$ | 283 V |
| Secondary voltage | $v_{out}$ | 200 V |
| Output power | $P$ | 1 kW |
| Transmission freawuency | $f$ | 85 kHz |
| Coupling Coefficient | $k$ | 0.3 |
| Primary inductance | $L_1$ | 250 μH |
| Secondary inductance | $L_2$ | 250 μH |
| Primary capacitance | $C_{r1}$ | 14.0 nF |
| Secondary capacitance | $C_{r2}$ | 14.0 nF |
| Number of series | $n$ | 16 |
| Flying capacitance | $C_k$ | 1 μF |
| MOSFETs in FCLA | TK5R1E06PL (Toshiba) | |
| MOSFETs in unfolder | SCT3017AL(Rohm) | |

shown in blue arrows in Fig. 6, the voltage controller transitions the operating region of the MOSFET to follow the command value. A pattern with an unable range is a pattern that has a current path increasing the error of the FC voltage. The voltage controller transitions this pattern to the pattern that does not increase or decrease the voltage error. This capability automatically keeps balancing the FC voltage.

## 3. SIMULATION OF PROPOSED SYSTEM

### 3.1. Operation waveform

Figure 7 shows the simulation waveform of the proposed FCLA with the unfolder connecting to the WPT system, and Table 1 shows the simulation conditions. The simulation is demonstrated with SPICE simulator using the MOSFET models, which are provided by the MOSFET manufacturer. Fig. 7 (a) shows the FCLA output voltage command, output voltage, and the voltage and current waveforms on the primary and secondary sides of the transmission coil. Figure. 7 (b) shows the FC voltages waveform. From Fig. 7 (a), it is confirmed that the output voltage of FCLA follows the command. In addition, it is confirmed that the proposed FCLA inputs a sinusoidal voltage to the transmission coil and operates the WPT in resonant conditions. From Fig. 7 (b), it is confirmed that the FC voltages are balanced by selecting the operation region of the MOSFETs using the phase-shifted carriers.

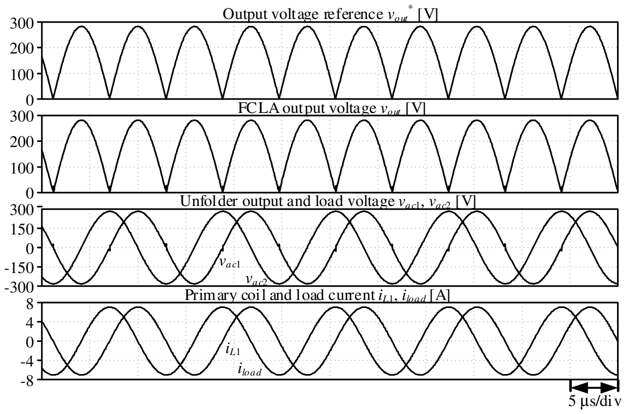
Figure 8 shows the operating waveform when the voltage of Cfc15 is 20% of the balanced condition. From Fig. 6, FCLA with the unfolder output a sine wave when the FC voltages are unbalanced. After the 100 ms from the start of the simulation, the FC voltages are balanced by the FC voltages self-balancing capability.

### 3.2. Analysis of current harmonics

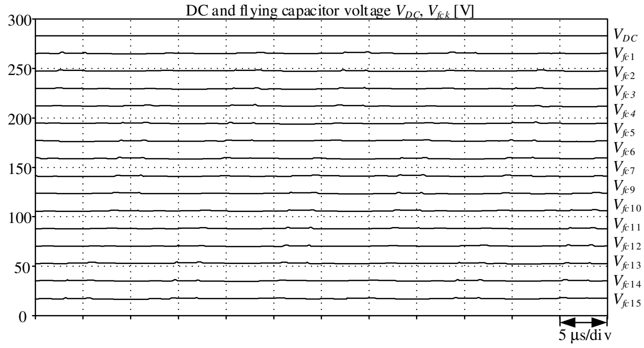
Figure 9 shows the harmonics analysis results of the current on the primary coil when 16-series FCLA with the unfolder and 17-level FCC are used as the power supply of the WPT systems, respectively. In addition, the analysis results when an inverter that outputs a square wave voltage, which is typically used in a conventional WPT system, is compared. From Fig. 9, the current harmonics are reduced by using the FCLA, in which the MOSFET operates in the saturated region. Focusing on the third harmonic component, the harmonic of current using FCLA is reduced by 13.2dB in comparison with using the FCC, and 49.1dB in comparison with using the inverter. Moreover, the current harmonics are reduced by 10 dB or more for the odd-numbered components over the 5th.

## 4. EVALUATION OF FC VOLTAGE BALANCE

Figure 10 shows the circuit configuration of a prototype to verify the balancing flying capacitor voltages in FCLA. The prototype has two-series connected MOSFETs. As the power supply for the WPT system, the FCLA should have more than 16-series connected MOSFETs considering the efficiency and the breakdown voltage of MOSFET. However, the purpose of the prototype is to verify the FC voltage balance. Thus, the prototype has only two-series connected MOSFETs. In addition, the DC voltage of the




(a) FCLA output voltage reference, output voltage, primary and secondary transmission coils voltage and current




(b) Flying capacitor voltages
Fig. 7. Simulation waveform

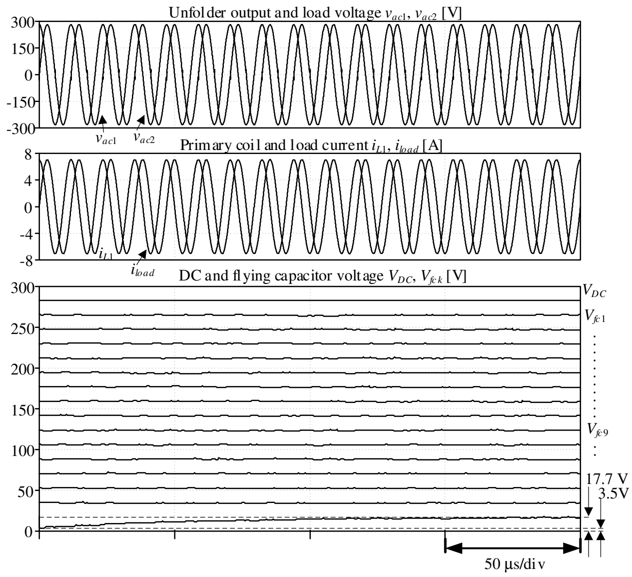



Fig. 8. Simulation waveform when the FC voltage unbalanced

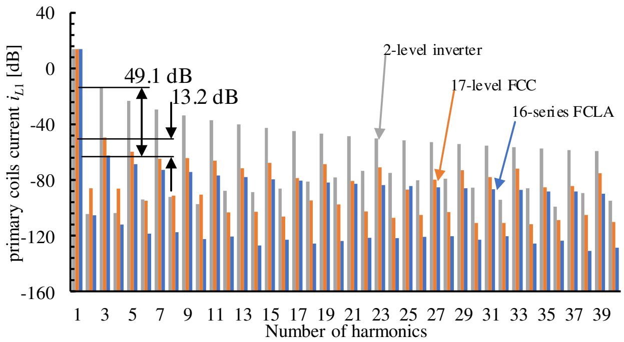



Fig. 9. Harmonic analysis for primary coil current

prototype is 80 V to make the voltage applied to each MOSFET equal to the high-power WPT system with 16-series FCLA. The command value of the output voltage is a full-wave rectified voltage waveform with an amplitude of 80 V and a frequency of 50 Hz. In addition, a 100 Ω resistor is connected to the unfolder as a load.

Figure 11 shows the output voltage command value, FCLA output voltage, FC voltage, and unfolded output voltage of the prototype. From Fig. 11 (a), it is confirmed that the FC voltage is balanced at 40V, which is half of the DC voltage, due to the operation region selection by the carrier comparison and the output voltage controller. From Fig. 11 (b), it is seen that the FCLA outputs a full-wave rectified voltage following the output voltage command. In addition, the unfolder outputs a continuous sinusoidal voltage to the load. The distortion of the FCLA output voltage is caused by the voltage controller losing control of the MOSFET due to its nonlinearity and the time delay of the isolation amplifiers used in the GDUs.

Figure 12 shows the results of harmonic analysis of the unfolder output voltage. It also shows the theoretical value of the harmonic components of the square wave, which is output by inverter used in conventional WPT system as the primary power supply. From Fig. 12, it is seen that the FCLA reduces odd-order harmonic components by more than 15 dB compared to the square wave. In particular, the third-order harmonic component of the output voltage is reduced by 19.8 dB. However, even-order components can also be observed in the prototype. This is due to the distortion of the FCLA output voltage and the phase difference between the output voltage and unfolded switching.

## 5.CONCLUSION

In this paper, the FCLA for WPT systems with the unfolder is proposed in order to reduce the harmonics of the radiation noise. The proposed topology needs no p-channel MOSFET. The FCLA with unfolder does not output the harmonics of current to the transmission coils because the FCLA outputs a continuous voltage. Due to the sinusoidal output, the harmonics components of radiation noise will not be emitted from coils. In addition, the FCs charging/discharging are also controlled by the individual GDU connected to each MOSFET. The operation of the proposed FCLA connected to WPT is verified by simulation, and it is confirmed that power transmission is possible. It is also confirmed that the operation when the FC voltage is unbalanced, and the self-balancing capability of the FC voltages. Moreover, the harmonics of the primary coil current are compared when 16-series FCLA or 17-level FCC is used as a power supply for the WPT system. As a result, using the FCLA reduced the 3rd current harmonics by 13.2 dB compared to using the FCC. Finally, it is confirmed by the prototype that the FC voltage is balanced by the selection of the operation region by carrier comparison and the output voltage controller. In addition, the proposed FCLA reduces the odd-order harmonics of the output voltage by more than 15 dB compared to the square wave.

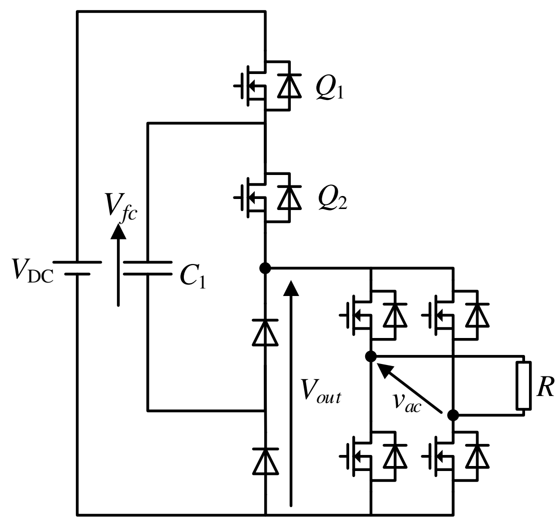
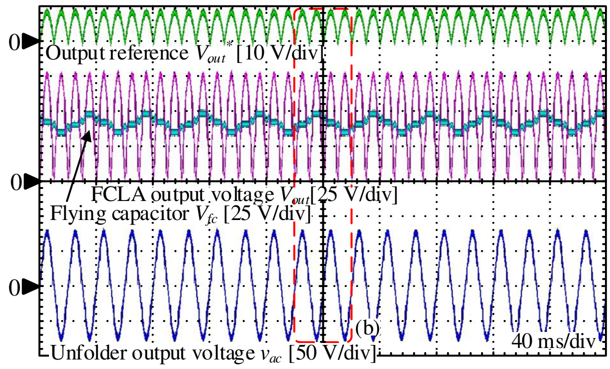
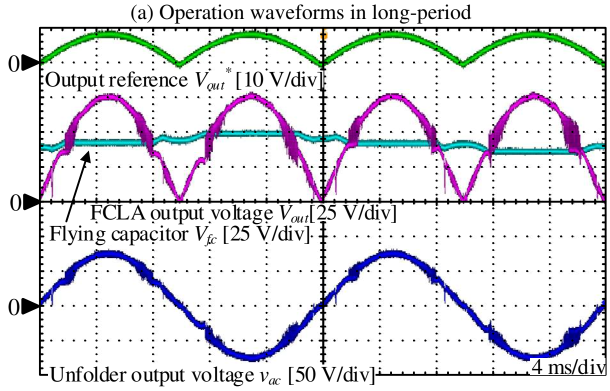



Fig.10. Circuit configuration of prototype.




(a) Operation waveforms in long-period




(b) Enlarged operation waveforms

Fig. 11. Operation waveforms of 2-series FCLA.

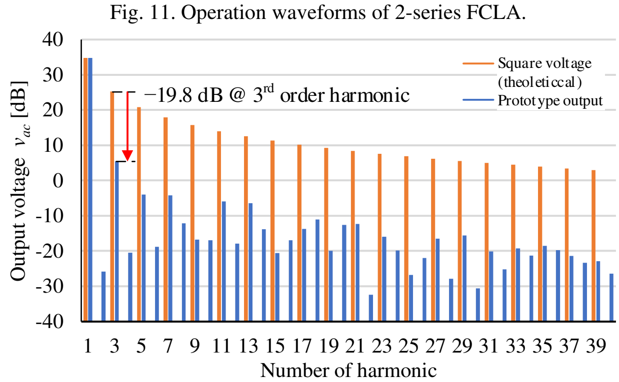



Fig. 12. Harmonic analysis of unfolder output voltage.

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