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# Pure Sinusoidal Output Current-Source Inverter Using Inductor Modules

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***Abstract*-A novel topology of a current-source inverter (CSI) is proposed in the paper, which can deliver a pure sinusoidal current waveform without sacrificing its efficiency and its equipment size. The proposed circuit has a hybrid structure, and combines a switching-operation based multilevel CSI and a linear current amplifier with a low-amplitude current output. The former multilevel CSI employs multiple inductor modules to generate a staircase multilevel current waveform, while the latter linear amplifier generates a compensating current to reform the staircase multilevel waveform to the pure sinusoidal waveform. Because the most part of the output current is created by the switching-operation based multilevel CSI, the system efficiency hardly deteriorates. In addition, the system does not require large LC filters because it directly delivers the pure sinusoidal current to the load. In the paper, current drooping phenomenon of the inductor modules due to their power losses is discussed, and the countermeasure is proposed.**

## INTRODUCTION

In general, power converters are operated on the basis of switching action to maximize the conversion efficiency, but LC filters are indispensable to reduce the harmonics caused by the switching action. On the other hand, linear amplifiers such as a class-A or a class-AB can generate a pure sinusoidal waveform sacrificing the conversion efficiency. The ultimate goal for the power converters is to generate the pure sinusoidal waveform with low total harmonic distortion (THD) without using large LC filters or sacrificing the efficiency. One of the approaches to achieve this goal is use of high-frequency pulse width modulation (PWM) techniques. The approach, however, has a fatal drawback to increase the switching losses as the frequency increases although the higher switching frequency significantly contributes reduction of the LC filter size. Therefore, it is definitely necessary to develop the power converter that can solve the above problems at the same time. Another approach is improvement of the THD by employing multilevel techniques such as a neutral-point clamped (NPC) topology, a flying capacitor topology, and so forth [1]. The multilevel techniques are very effective to reduce the harmonics and EMC noise, but have an inherent drawback of the complicated circuitry and control algorithm, and the conduction loss of the main switching devices [2].

This paper proposes a new approach as a solution to the above problems, i.e., a hybrid power converter that combines a switching operation based power converter and a low-amplitude linear amplifier. There have been several proposals of the hybrid inverter topologies made by the authors so far [3]. Figs. 1 and 2 show the examples of the hybrid inverter feeding the pure sinusoidal current to the load, i.e., a DC current source type and a fish-bone structure type, respectively [4] [5]. However, these circuits demand more DC current sources, more inductors, and more isolated gate drive circuits for the main switching devices as the number of output levels is increased.

A new topology of the hybrid current source inverter (CSI) is discussed in the paper, which is based on a simple H-bridge configuration featuring inductor modules [6] [7]. Feasibility of the new topology is confirmed through the comparison of circuit configurations and operation principles.

## CIRCUIT CONFIGURATION AND OPERATION PRINCIPLE

### *A. Inductor Module Based CSI with Pure Sinusoidal Output*

Fig. 3 shows the proposed inductor module based hybrid CSI. The circuit is composed of a main multilevel inverter and a low-amplitude variable linear current source. The former is a combination of an H-bridge CSI and a set of an inductor module. The inductor module is a component block made of two transistors, two diodes, and an inductor as

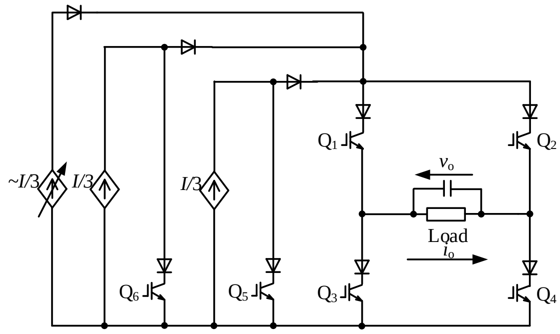

Fig. 1. Hybrid CSI with DC current source modules.

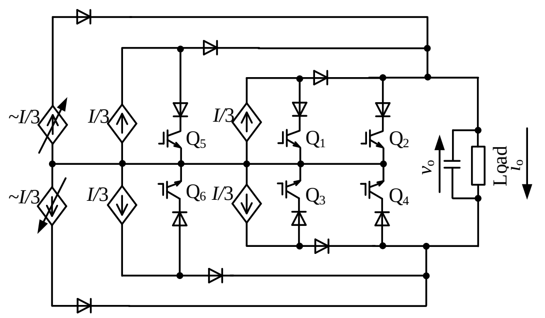

Fig. 2 Hybrid CSI with fish-bone structure.



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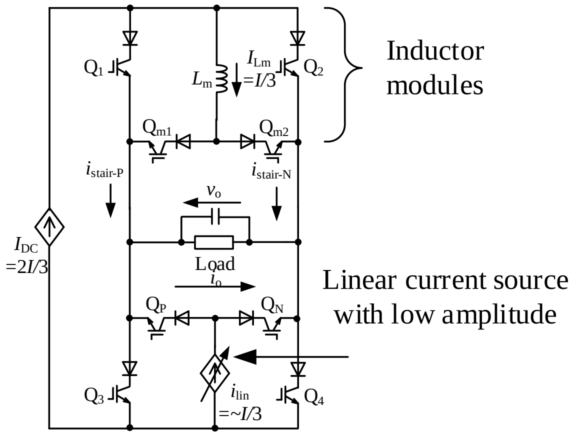


Fig. 3. Proposed hybrid CSI with inductor module.

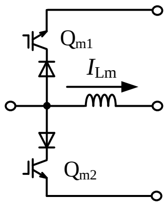
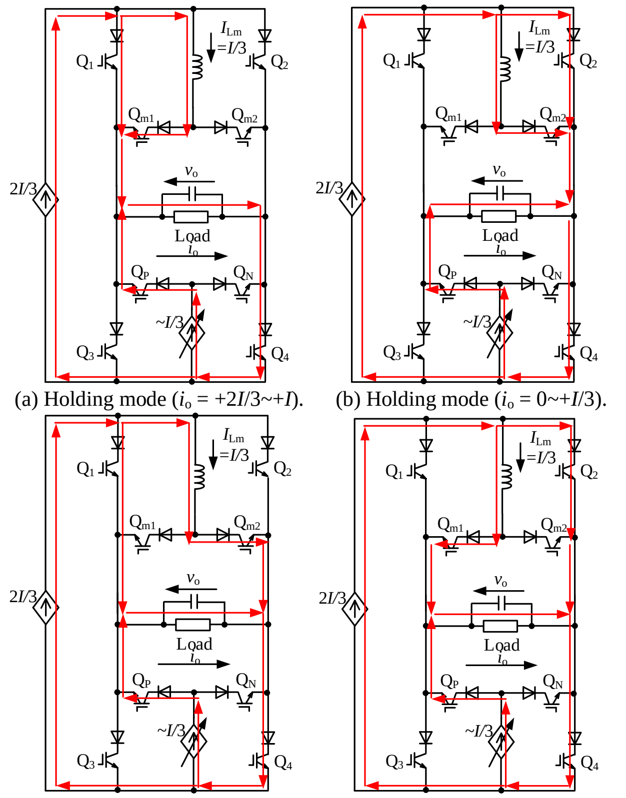


Fig. 4 Inductor module.

TABLE I Switching States of 5-Level Inductor Module Based Hybrid CSI.

| $Q_1$ | $Q_2$ | $Q_3$ | $Q_4$ | $Q_{m1}$ | $Q_{m2}$ | $Q_P$ | $Q_N$ | $i_o$ | Mode |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | $+2I/3\sim+I$ | H |
| 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | $+I/2\sim+2I/3$ | C |
| 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | $+I/2\sim+2I/3$ | D |
| 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | H |
| 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | H |
| 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | $-I/2\sim-2I/3$ | C |
| 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | $-I/2\sim-2I/3$ | D |
| 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | $-2I/3\sim-I$ | H |

shown in Fig. 4. The main inverter having the H-bridge CSI and one inductor module can generate a 5-level current waveform to the load, and its switching states are indicated in TABLE I. The "Mode" in the table means the operation statuses of the inductor module, where "H," "C," and "D" correspond to a holding mode, a charging mode, and a discharging mode, respectively. Since the main inverter generate the 5-level staircase current waveform, 5 kinds of output current levels are delivered to the load, i.e., $i_o$ = $+I$, $+I/2$, 0, $-I/2$, and $-I$. It should be noted that there is redundancy in the switching states. By taking advantage of the redundant switching states, the 5-level currents can be generated with keeping the inductor module current constant by alternating the charging and discharging modes of the inductor. On the other hand, the variable linear amplifier outputs a low-amplitude linear current waveform to compensate for the difference between the staircase multilevel current waveform fed by the main inverter and the sinusoidal output current command. This strategy can efficiently reduce the power loss of the linear amplifier because of the low-amplitude output, compared with the class-A linear amplifier generating a full peak-to-peak sinusoidal waveform. In addition to the advantage described



(a) Holding mode ($i_o$ = $+2I/3\sim+I$). (b) Holding mode ($i_o$ = $0\sim+I/3$).
(c) Charging mode ($i_o$ = $+I/2$). (d) Discharging mode ($i_o$ = $+I/2$).
Fig. 5. Operation modes of inductor module based hybrid CSI.

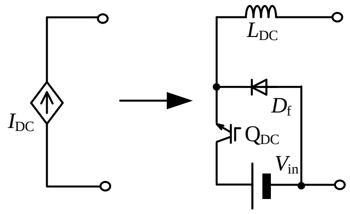


Fig. 6 Chopper based DC current source.

above, the filter capacitor across the load can also significantly be reduced owing to the sinusoidal current waveform output that has been synthesized by superimposing the low-amplitude linear waveform onto the staircase multilevel waveform.

Fig. 5 shows operation modes of the proposed hybrid CSI. The inductor current is kept constant in the current holding mode (a) because of a short circuit across the inductor, and the maximum level of $i_o$ = $+2I/3\sim+I$ is given to the load, where the main inverter generates $i_{stair-P}$ = $+2I/3$ and the variable linear current source outputs $i_{lin}$ = $0\sim+I/3$. In the similar way, the current holding mode (b) makes a short circuit across the inductor to keep the inductor current constant. However, only the variable current source supplies the current to the load, resulting in the minimum level output of $i_o$ = $0\sim+I/3$. In the charging mode (c), the inductor current slightly increases because the inductor is connected in parallel with the load, which makes the energy transfer from the DC current source to the inductor possible. The output current of the main inverter is $i_{stair-P}$ = $+I/3$, and the variable linear current source outputs $i_{lin}$ = $0\sim+I/3$, resulting in the

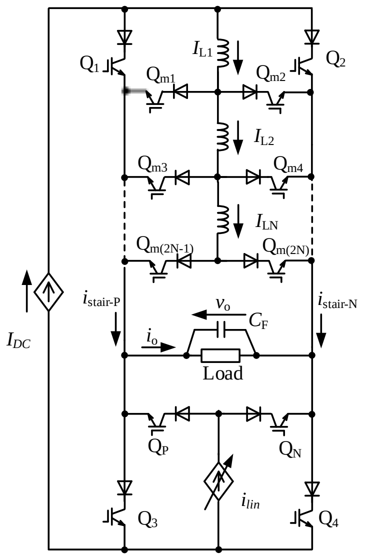



Fig. 7. Generalized multilevel inductor module based hybrid CSI.

intermediate output level of $i_o = +I/3$~$+2I/3$. The DC current source is shorted and the inductor releases its energy in the discharging mode (d); thus, the same intermediate output level of $i_o = +I/3$~$+2I/3$ is fed to the load with decreasing the inductor current slightly. The main inverter, i.e., the inductor module based CSI, alternates the charging mode (c) and the discharging mode (d) among the four modes to output the intermediate current level corresponding to the half of the DC current source. This alternating operation of the inductor module makes it possible to keep the inductor current constant at $I/3$, which is efficient utilization of the switching state redundancy.

### *B. DC Current Source*

A CSI needs a DC current source, where a large reactor is often employed in series with a DC voltage source to configure the DC current source. However, this scheme makes the power converter large and heavy, so another scheme has been taken in the proposed circuit as shown in Fig. 6. The DC current source is composed of a current regulated buck chopper with high-frequency switching devices to reduce the smoothing inductor value. The current control is achieved by a current feedback loop using a PI regulator and a triangular wave based modulator.

### *C. Generalized Configuration of Proposed Hybrid CSI*

Fig. 7 shows a generalized configuration of the proposed hybrid CSI, which employs multiple inductor modules to generate a staircase multilevel current waveform and to reduce the amplitude of the variable linear current. Assuming that the number of the inductor modules is $N$ and that the number of the output current levels is $M$, the following equation is derived from the configuration of the CSI:

$$M = 2N + 3. \tag{1}$$

Let the $k$th inductor module current $I_{L(k)}$, the current can be expressed by the following recursive relationship:

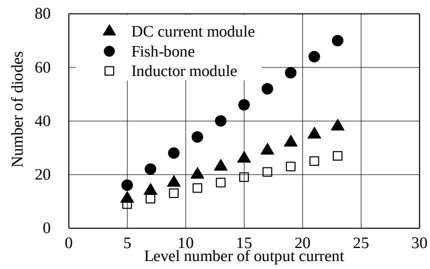
$$I_{L(k+1)} = I_{L(k)} - \frac{I}{N+2}\text{, and} \tag{2}$$

TABLE II COMPARISON OF COMPONENT COUNTS.

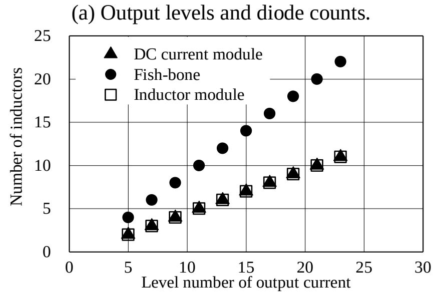
| Circuit components | DC-source module | Fishbone | Proposed inductor module |
|---|---|---|---|
| Transistor | 8 | 10 | 9 |
| Diode | 11 | 16 | 9 |
| Inductor | 2 | 4 | 2 |
| Gate drive power supply | 5 | 5 | 4 |
| Liner current source | 1 | 2 | 1 |

TABLE III COMPARISON OF COMPONENT COUNTS.

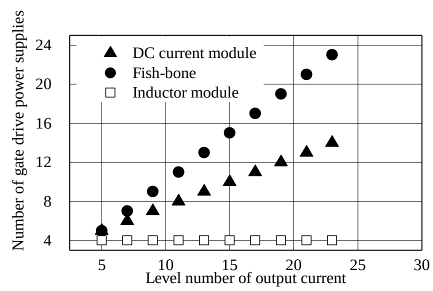
| Circuit components | DC-source module | Fishbone | Proposed inductor module |
|---|---|---|---|
| Transistor | $M + 3$ | $2M$ | $M + 4$ |
| Diode | $(3M + 7)/2$ | $3M + 1$ | $M + 4$ |
| Inductor | $(M - 1)/2$ | $M - 1$ | $(M - 1)/2$ |
| Gate drive power supply | $(M + 5)/2$ | $M$ | 4 |
| Liner current source | 1 | 2 | 1 |




(a) Output levels and diode counts.




(b) Output levels and inductor counts.




(c) Output levels and gate drive power supply counts.

Fig. 8. Comparison of component counts.

$$I_{L(1)} = \frac{N}{N+2} I\ . \tag{3}$$

TABLE II and TABLE II indicate the component counts of the conventional circuits and the proposed circuit. It can be found in the tables that the proposed circuit requires the fewest components to generate the $M$-level current waveform. In addition, because the amplitude of the variable linear current can be reduced as the number of the current levels of the main inverter increases, higher conversion efficiency is

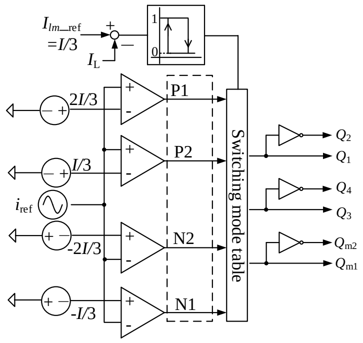


Fig. 9. Control block diagram of 5-level main CSI.

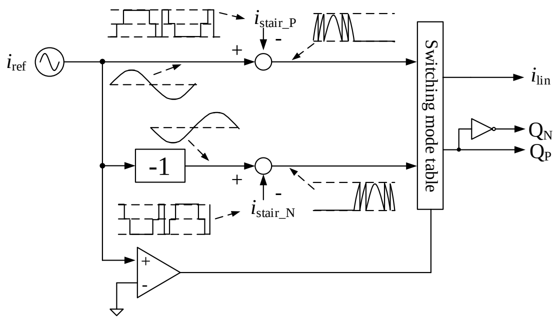


Fig. 10. Control block diagram of variable current source.

expected. One of the remarkable features of the proposed circuit is constant counts of the gate drive circuit power supplies regardless of the increase of the number of the output current levels; hence, the proposed circuit has an advantage when more current levels are demanded. Some relationships between the number of the output current levels and the component counts are shown in Figs. 8 (a)-(c). The component counts increase with the output current levels, but the proposed circuit has a gradual increase tendency of the component counts, compared with the other circuits.

## VERIFICATION OF OPERATION BY SIMULATIONS

### *A. Simulation Results of 5-Level Hybrid CSI*

Fig. 9 shows a control block diagram of the main 5-level CSI. The switching signals are created by comparing a sinusoidal current command $i_{ref}$ with four different DC threshold references. The current of the inductor module is detected with a current sensor, and is controlled by a relay regulator with a hysteresis band. The control error between the inductor current command $I_{Lm\_ref}$ and the feedback current $I_{Lm}$ is quantized by the relay regulator. Either a charging mode or a discharging mode is selected, according to the quantized signal “1” or “0,” respectively. The main inverter can provide the load with $i_{stair\text{-}P} = +I/3$ by keeping the inductor current around its command with the charging and the discharging modes. Fig. 10 shows a control block diagram of the variable linear current source. It delivers the linear current waveform corresponding to the difference between the sinusoidal current command $i_{ref}$ and the staircase multilevel current waveform $i_{stair\text{-}P}$ and $i_{stair\text{-}N}$ generated by the 5-level CSI. Either a switch $Q_P$ or $Q_N$ is turned on in a positive or a negative half cycle of the output current.

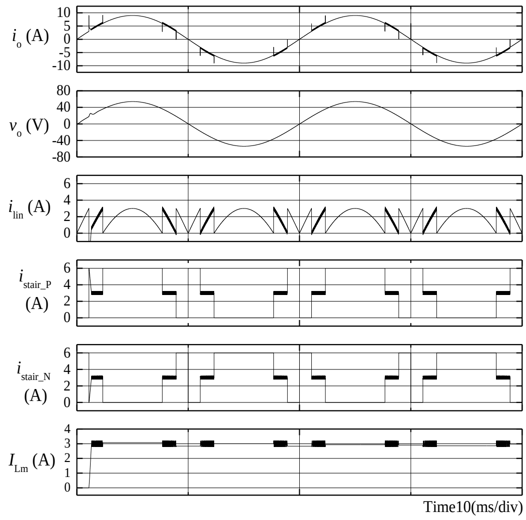


Fig. 11. Simulation waveforms of proposed 5-level hybrid CSI.

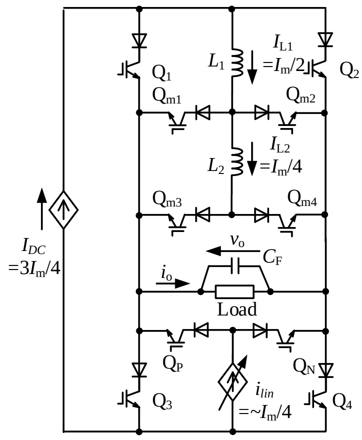


Fig. 12. Inductor module based 7-level hybrid CSI.

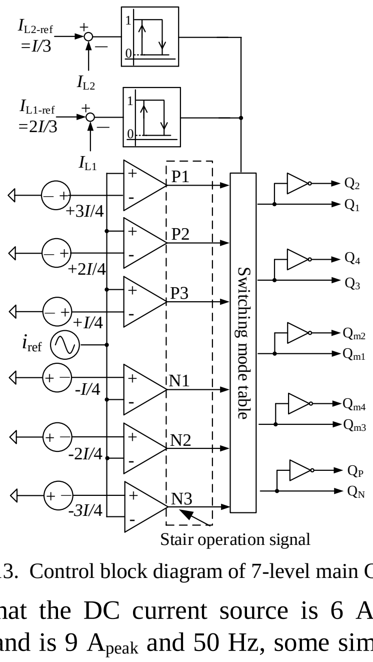


Fig. 13. Control block diagram of 7-level main CSI.

Assuming that the DC current source is 6 A, the output current command is 9 $A_{peak}$ and 50 Hz, some simulation tests have been conducted using a power electronics simulator PSIM. The inductor current is controlled to follow its

TABLE IV. SWITCHING STATES OF 7-LEVEL INDUCTOR MODULE BASED HYBRID CSI.

| $Q_1$ | $Q_2$ | $Q_3$ | $Q_4$ | $Q_{m1}$ | $Q_{m2}$ | $Q_{m3}$ | $Q_{m4}$ | $i_o$ | $L_1$ | $L_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | $+3I/4\sim +I$ | H | H |
| 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | $+I/2\sim +3I/4$ | D | H |
| 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | $+I/2\sim +3I/4$ | C | D |
| 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | $+I/2\sim +3I/4$ | H | C |
| 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | $+I/4\sim +I/2$ | H | D |
| 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | $+I/4\sim +I/2$ | D | C |
| 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | $+I/4\sim +I/2$ | C | H |
| 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | $0\sim +I/4$ | H | H |
| 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | $0\sim -I/4$ | H | H |
| 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | $-I/4\sim -2I/4$ | C | H |
| 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | $-I/4\sim -I/2$ | D | C |
| 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | $-I/4\sim -I/2$ | H | D |
| 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | $-I/2\sim -3I/4$ | H | C |
| 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | $-I/2\sim -3I/4$ | C | D |
| 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | $-I/2\sim -3I/4$ | D | H |
| 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | $-3I/4\sim -I$ | H | H |

command $I_{Lm\_ref}$ = 3 A within the hysteresis band of 0.4 A. The load consists of a 6-Ω resistor and a 0.6-mH inductor with a parallel filter capacitor of 20 $\mu$F. The variable linear current source is regarded to be ideal, and superimposes the linear current waveform to compensate for the staircase 5-level current waveform generated by the main inverter. Fig. 11 shows the operation waveforms obtained by the simulation. As seen in the figure, the output current $i_o$ to the load is a sinusoidal wave with low distortion, which is created by superimposition of the variable linear current $i_{lin}$ onto the staircase currents $i_{stair\text{-}P}$ and $i_{stair\text{-}N}$ generated by the 5-level CSI. The inductor module current $I_{Lm}$ is kept at 3 A by alternating the charging mode and the discharging mode.

The proposed circuit can improve the total conversion efficiency as the number of the output current level is increased because the amplitude of the variable linear current is decreased to the contrary.

*B. Simulation Results of 7-Level Hybrid CSI*

The 7-level hybrid CSI is depicted in Fig. 12. Two sets of the inductor modules are used in the H-bridge CSI to generate the 7-level current waveform. The switching states are shown in TABLE IV. It is required to control independently both the inductor currents at constant values at the same time. When the main inverter outputs $i_{stair} = \pm I/2, \pm I/4$, the two inductors can be operated in the charging mode, the holding mode, and the discharging mode; hence, both the inductor currents can be kept at constant values by changing the modes appropriately among the three. Fig. 13 shows a control block diagram of the 7-level hybrid CSI. Each switching signal is created by comparing the sinusoidal current command with one of the six different DC threshold references. In the case of the 7-level inverter, if one inductor is controlled to charge or to discharge, the other inductor continues the charging or the discharging mode. Therefore, one of the inductors is controlled with a priority, and the control is switched to the other inductor at the moment of polarity change of the other inductor current. The inductor currents are controlled to be

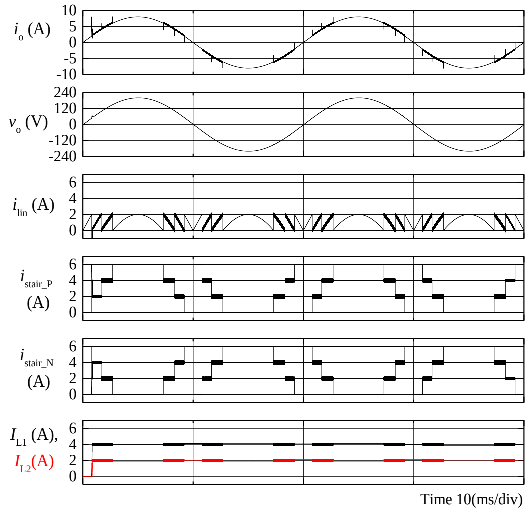



Fig. 14. Simulation waveforms of proposed 7-level hybrid CSI.

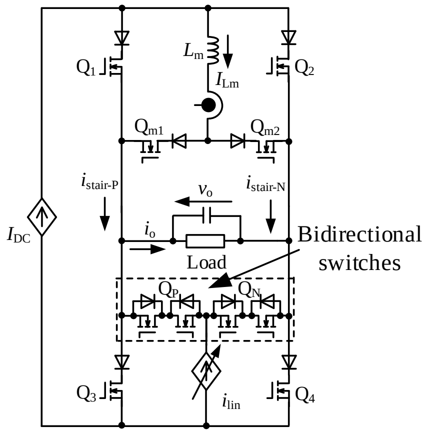



Fig. 15. Inductor module based hybrid CSI with bidirectional switches

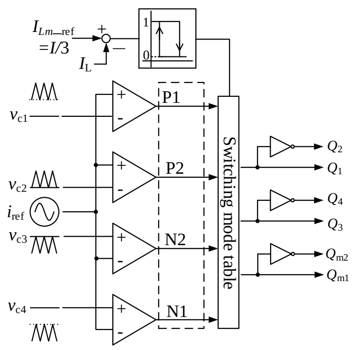



Fig. 16. Proposed control method.

constants of $I_{L1} = I/2$ and $I_{L2} = I/4$, according to the recursive relationship (2) and (3) described previously.

The simulation has been conducted under the condition of the inductors $L_1 = L_2 = 0.7$ mH, and the hysteresis bands for the $I_{L1}$ control and the $I_{L2}$ control are set at 0.2 A. The load is composed of a resistance of 25 Ω and a 1.5-$\mu$F filter capacitor. Fig. 14 shows the simulation result, where the pure sinusoidal output current waveform can be confirmed. In addition, the staircase 7-level current waveforms $i_{stair\text{-}P}$ and $i_{stair\text{-}N}$ are properly generated, and the variable linear current compensates for the staircase 7-level current to synthesize the pure sinusoidal current waveform. The inductor module currents are also controlled to follow their commands, and they are kept at constants of 4 A and 2 A, respectively.

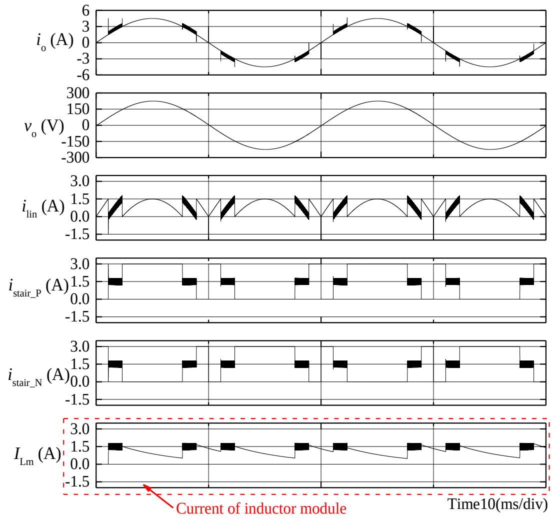
### *C. Compensation Technique for Drooping Current of Inductor Module*

It is important to reduce the power loss in the inductor module in the proposed multilevel CSI because the inductor has to keep its current at a constant value at any time. However, the power loss of the inductor such as a copper loss and an iron loss causes the current drooping, especially in the holding mode. Therefore, a low-frequency PWM technique is introduced into the system to compensate for the drooping current of the inductor module, which may sacrifice the conversion efficiency due to the switching losses but the switching frequency can be limited to several kHz at most owing to the long time constant of the drooping phenomenon. Figs. 15 and 16 show the main circuit configuration and the control block diagram. In order to achieve the low-frequency PWM, the constant threshold level signals are replaced with multilevel triangular waveforms, and the sinusoidal current command is compared with the triangle waveforms. By using this approach, the charging mode often interrupts the holding mode even in the zero-current level output and the maximum-current level output situations, resulting in the almost constant inductor current.

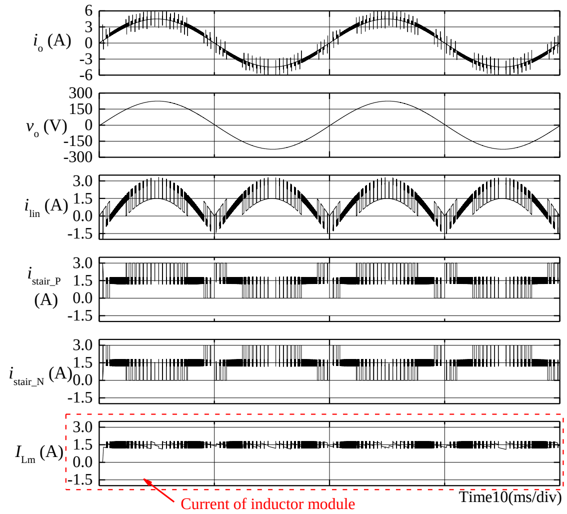
The proposed compensation technique for the drooping current has been evaluated by the simulation. The frequencies of the output current command and the PWM carrier are 50 Hz and 3 kHz, respectively. The inductance and the winding resistance of the inductor in the inductor module are 1 mH and 0.2 Ω, respectively, and the hysteresis band of the inductor current control is set at 0.5 A. The load is composed of a 50-Ω resistor and 1.5-$\mu$F capacitor. Figs. 17 (a) and (b) show the operation waveforms of the proposed methods without and with the PWM. As can be seen in the inductor module currents of the waveforms, the current droops during the holding mode of the inductor module when the PWM is not applied, but even a low-frequency PWM is significantly effective to keep the inductor current at constant value around 1.5 A within the hysteresis band.

## CONCLUSION

In the paper, a novel topology of a hybrid CSI has been proposed, which combines a switching operation and a linear operation. The main inverter generates a staircase multilevel current waveform, and the linear amplifier compensates for the staircase multilevel waveform to the sinusoidal one. It has been demonstrated that the pure sinusoidal current waveform can be fed to the load without a large LC filter, high-frequency PWM, nor a full range linear amplification like a class-A amplifier. In addition, a compensation technique has been proposed to avoid drooping effect of the inductor module current caused by the power loss of the inductor, which makes it possible to keep the inductor current constant.




(a) Waveforms without inductor current drooping compensation.




(b) Waveforms with inductor current drooping compensation.

Fig. 17. Simulation results of inductor current drooping compensation.

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