Development of Transformerless Multi-Level Medium Voltage Inverters

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Abstract

Reflecting on Climate Change, environmental impact-reducing technologies, such as energy conservation and reduction of CO_2, are getting worldwide attention. As such, the demands for compact and high-efficiency medium-voltage inverters have increased in the field of power and industrial systems. In particular, there is growing interest in "transformerless" multi-level inverters because they do not require any multi-phase winding transformers on the input source side. Thus far, we invented a unique circuit system suitable for adaptation to medium voltages and succeeded in the development of a transformerless a 4kV prototype whereby verifying its effectiveness. Still more, we recently developed a new circuit system to realize higher voltages and higher performance.

1 Preface

Reflecting on Climate Change, environmental impact-reducing technologies, such as energy conservation and reduction of CO_2, are getting worldwide attention. In the field of manufacturing and industrial activities, motor power accounts for about 70% of the total energy consumption and they tend to have a higher voltage to realize higher efficiencies. Motor operation at a constant speed has conventionally been popular with fans, pumps, and blowers used to control ventilation and water supplies. Currently, however, the application of inverters has become commonplace due to its energy saving getting high attention.

The demand for medium-voltage inverters that can drive medium-voltage motors has increased. Required performance characteristics of medium-voltage inverters are as follows:

(1) High efficiency
(2) Compact and light weight design

In order to meet the above requirements, we proposed a new circuit system in 2012 and have been studying the possibility of commercialization by making several prototypes(1)(2) since. Our new approach makes it possible to eliminate multi-phase winding transformers that are generally used in medium-voltage converters. We continue to make efforts to decrease the number of capacitors and reduce the total capacitance in order to meet market requirements. This paper introduces the operational principles of the converter and the features of the transformerless multi-level medium-voltage inverter developed our expertise.

2 Operational Principle

2.1 Circuit Configuration

We propose a new circuit system of the flying capacitor type for converters. The flying capacitor system is a method where potential switching is performed for the flying capacitor to generate multi-level voltage outputs. Fig. 1 shows the circuit configuration of our proposal. This circuit is composed of two blocks, a phase module for a 3-phase input and a 3-phase output, and a DC module. The circuit comes in a Back To Back (BTB) configuration where the input and output circuits are connected through the DC module. The 3-phase input circuit functions as a rectifier and the 3-phase output circuit functions as an inverter. The DC module contains two basic cells directly connected and these basic cells are composed of the DC link capacitors, flying capacitors, and four Insulated Gate Bipolar Transistors (IGBTs). The phase module is composed of ten IGBTs and four diodes. Since the same capacitors are used in common for the rectifier and inverter, the number of capacitors can be decreased and the overall capacitance can be reduced. In this circuit, the active power to be supplied from the power source to the rectifier can be fed directly to the load through the inverter. At that time, since incoming current into the capacitor is made low, it can also reduce capacitance and volume of the capacitors.

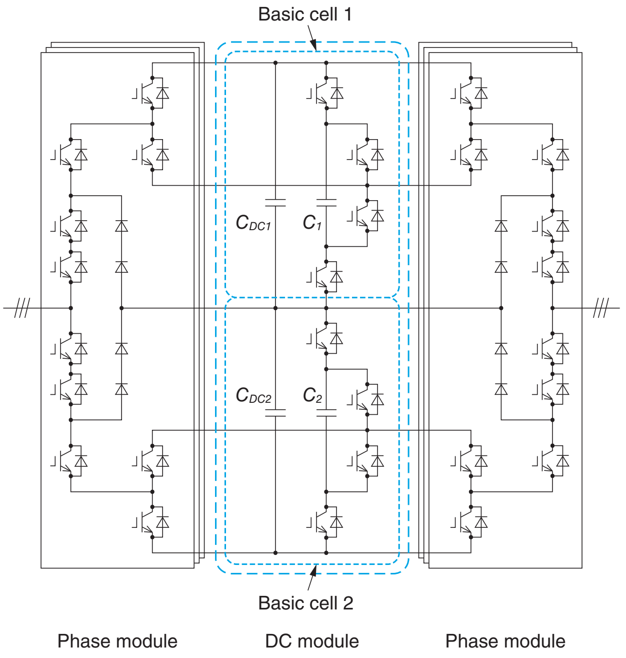


Fig. 1 **Circuit Configuration of our Proposal**

The BTB configuration is shown. It combines the phase modules and the DC module.

2.2 5-Level Output Approach

When the DC link capacitors C_{DC1} and C_{DC2} are controlled at a voltage of 2E and the flying capacitors C_1 and C_2 are at a voltage of E, five potentials (2E, E, 0, −E, and −2E) can be generated. Subsequently, these five levels of potentials are outputted by selecting adequate switching pattern of phase modules. **Fig. 2** shows an example of phase module switching patterns. Circles in the figure indicate the IGBTs that are currently turned on. The phase modules have five switching patterns from which five kinds of potential outputs can be generated. Regarding the modulation system, a carrier comparison type of Pulse Width Modulation (PWM) is adopted and based on the result of modulation, a suitable switched pattern is selected.

Capacitors C_{DC1} and C_{DC2} can make voltages constant by controlling the active power in the same manner as for conventional power converters.

2.3 Voltage Control for Flying Capacitors

Two kinds of switching patterns are used to control voltage of capacitors C_1 and C_2. **Fig. 3** shows the charge-discharge mode of the flying capacitor. When a current flow is carried in the direction of the arrow along the dotted line, C_1 is charged by selecting Mode1. It is discharged when Mode2 is selected. By selecting a desired current path for C_1 in such a manner, voltage control becomes possible. Similarly, C_2 is also used for

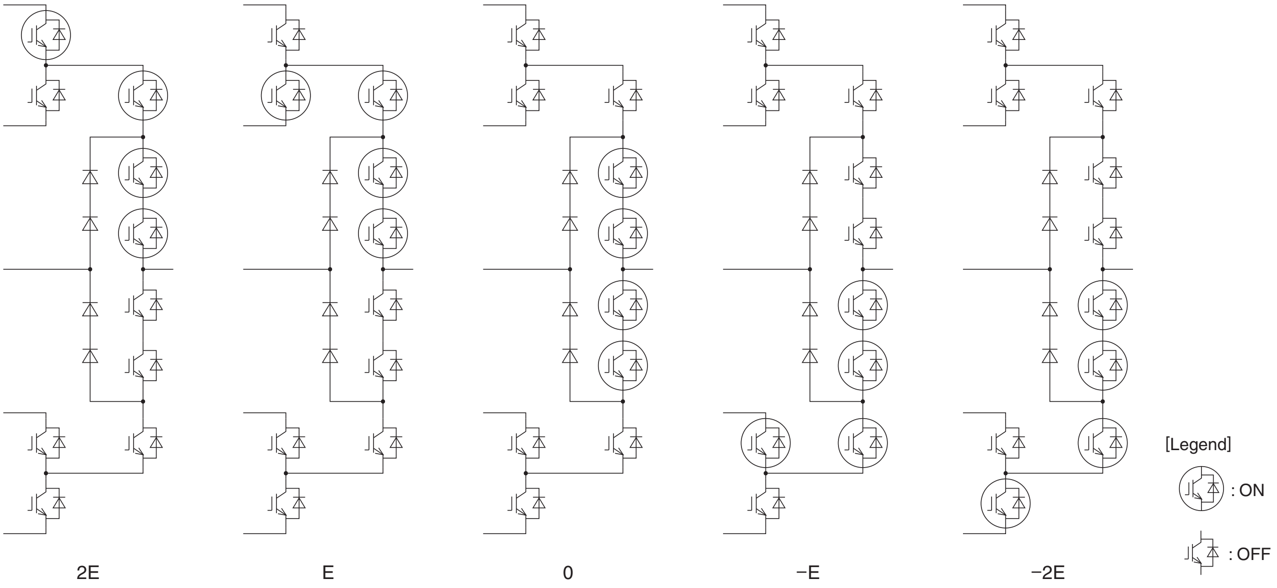
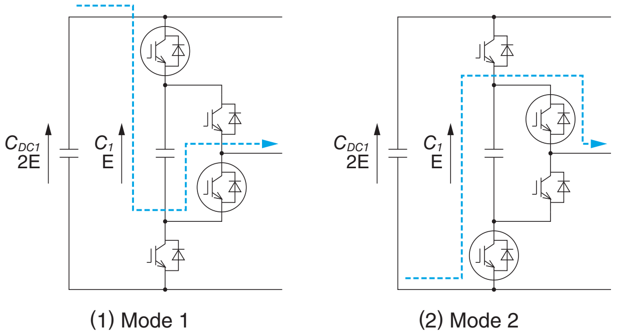


Fig. 2 **Example of a Phase Module Switching Patterns**

Each phase module can generate five types of potential outputs.



(1) Mode 1

(2) Mode 2

Fig. 3 **Charge-Discharge Mode of the Flying Capacitor**

Charge-discharge control of a flying capacitor is performed by mode changeover in the basic cell.

voltage control by selecting two kinds of switching patterns.

When the phase voltage command value is defined by (1) and the phase current detection value is defined by (2), the rate of using C_1 in regard to the voltage command value of (1) is given by (3). Since the current carried in the basic cell is identical with the phase current flowing during the period of (3), the amount of this current is given by (4) that is a product of (2) and (3).

$$v^*_u = m \sin \theta_u \cdots\cdots (1)$$

$$i_u = \sqrt{2}\, I_u \sin (\theta_u - \phi) \cdots\cdots (2)$$

$$D_{u1} = \begin{cases} +1 - v^*_u & (+0.5 < v^*_u \leqq +1.0) \\ v^*_u & (0.0 < v^*_u \leqq +0.5) \\ 0 & (v^*_u \leqq 0.0) \end{cases} \cdots\cdots (3)$$

$$\hat{i}_{cell1} = i_u \times D_{u1} \cdots\cdots (4)$$

In the expressions above, Value m denotes the modulation index of the phase voltage, Value I_u denotes the rms value of the phase current, Value θ_u denotes a phase of the voltage command value, and Value ϕ denotes a phase difference between voltage and current.

Fig. 4 shows outline diagram of basic cell current estimation method. In **Fig. 1**, six phase modules are connected through the DC modules. As such, all currents are carried in the basic cells. In this case, the estimated current value flowing through the basic cells is given by (5) below.

$$\hat{i}_{cell1\_btb} = i_u \times D_{u1} + i_v \times D_{v1} + i_w \times D_{w1} + i_r \times D_{r1} + i_s \times D_{s1} + i_t \times D_{t1} \cdots\cdots (5)$$

Since the current value flowing in the basic cells can be estimated based on the detected values of voltage command value of the phase module and phase current value, current control is possible without installing additional current sensors.

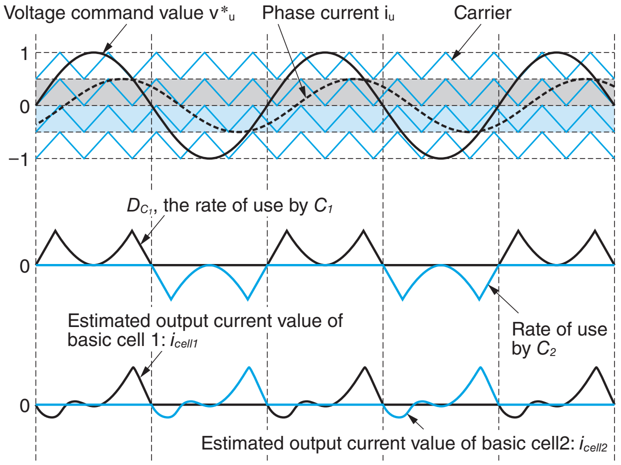


Fig. 4 **Outline Diagram of Basic Cell Current Estimation Method**

According to the phase voltage command value and the phase current detection value, the currents of the basic cells are estimated.

Table 1 **Switching Pattern for a DC Module**

The charge-discharge mode is determined based on a combination of switching pattern and the current polarity of the basic cell.

v_{C_1}, v_{C_2}	i_{cell1}, i_{cell2}	Mode
<E	<0	Mode 2 (C_1 and C_2 charged)
<E	>0	Mode 1 (C_1 and C_2 charged)
>E	<0	Mode 1 (C_1 and C_2 discharged)
>E	>0	Mode 2 (C_1 and C_2 discharged)

Table 1 shows the switching pattern for a DC module. To control the flying capacitor voltages of v_{C_1} and v_{C_2} to Value E, such voltage control is carried out by selecting a suitable switching pattern of the DC module. If Mode2 is selected while the current polarity is positive or Mode1 is selected while this current polarity is negative, the flying capacity is discharged. On the contrary, if Mode1 is selected while the current polarity is positive or Mode2 is selected while this current polarity is negative, the flying capacitor is charged. In this way, the flying capacitor voltage can be controlled to a required voltage value by making charge-discharge switchover according to the current polarity and flying capacitor voltage defined by (5).

2.4 Downscaled Model Configuration

In order to confirm performance of the proposed circuit, we produced a downscaled model for evaluation. **Fig. 5** shows circuit configuration of the downscaled model. **Table 2** shows specifications of

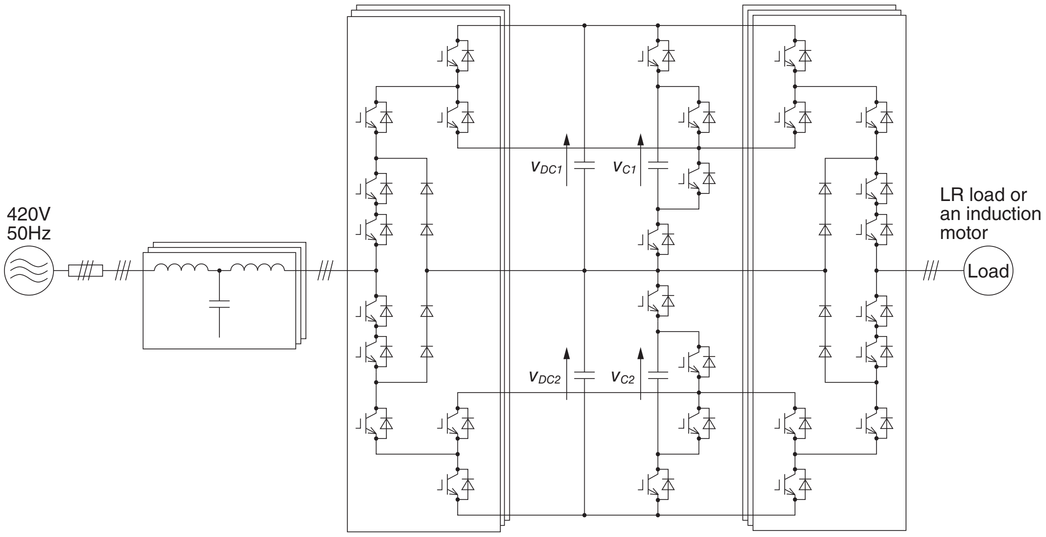


Fig. 5 Circuit Configuration of Downscaled Model

Testing was carried out by adding an input filter and a load to the proposed circuit configuration.

Table 2 Specifications of the Downscaled Model

Main circuit specifications of the produced downscaled model are shown.

Item	Specifications
System voltage	420V
Rated power	8kVA
System voltage frequency	50Hz
Carrier frequency	1kHz
Rated output of induction motor	5.5kW
No. of poles of induction motor	4pole
Rated frequency of induction motor	50Hz

the downscaled model. The input side is connected with an AC power supply of 420V and 50Hz through an input filter for the purpose of harmonics removal. The output side was connected with an induction motor or a load which was configured by resistor and inductor (LR load). In this circuit configuration, Voltages v_{DC1} and v_{DC2} were set up at 360V while v_{C_1} and v_{C_2} were at 180V, respectively. In this state, DC voltage control and input power factor control were carried out on the input side and frequency control was conducted on the output side. With the use of the produced downscaled model, the following two tests were carried out.

2.4.1 4-Quadrant Operation Test with an Induction Motor

For this testing, an inverter load was connected to an induction motor. An output frequency command was given to start acceleration from 0Hz up to forward rotation at 50Hz. This rotation was changed into a reverse rotation from forward 50Hz to 0Hz and further to reverse 50Hz. After that, the rotation was stopped. **Fig. 6** shows the result of the induction motor test. Even in the case of a 4-quadrant operation, fluctuation was low in DC and flying capacitor voltages, and we confirmed that this would offer stable operation.

2.4.2 Sudden Load Change Test with a LR Load

This testing was carried out by changing the inverter load into the LR load. **Fig. 7** shows the result of a sudden load change test with an LR load. The shown waveforms were observed when the load resistance was changed while operation was maintained at an output voltage frequency of 50Hz. A sudden load change was purposely caused in the area surrounded by the dotted lines in the figure. In a moment when a sudden load change was caused, variations can be seen in DC and flying capacitor voltages. After the lapse of a certain period, however, voltage fluctuations seemed to settle down. We confirmed that the input current followed up the output load.

3 Application to Transformerless Multi-Level Medium Voltage Inverters

We are working on product commercialization of transformerless multi-level medium voltage inverters for 6.6kV motor drive, where the above power conversion circuit is employed. **Table 3** shows specifications of the product and its features are itemized below.

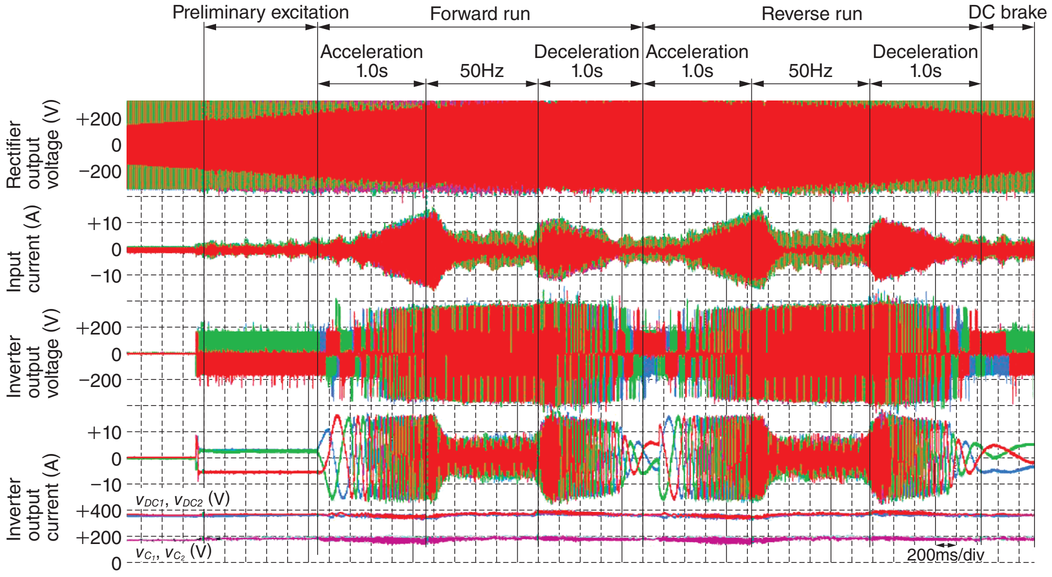


Fig. 6 **Result of Induction Motor Test**

As a result of making acceleration and deceleration from the output frequency, four-quadrant operation was attained.

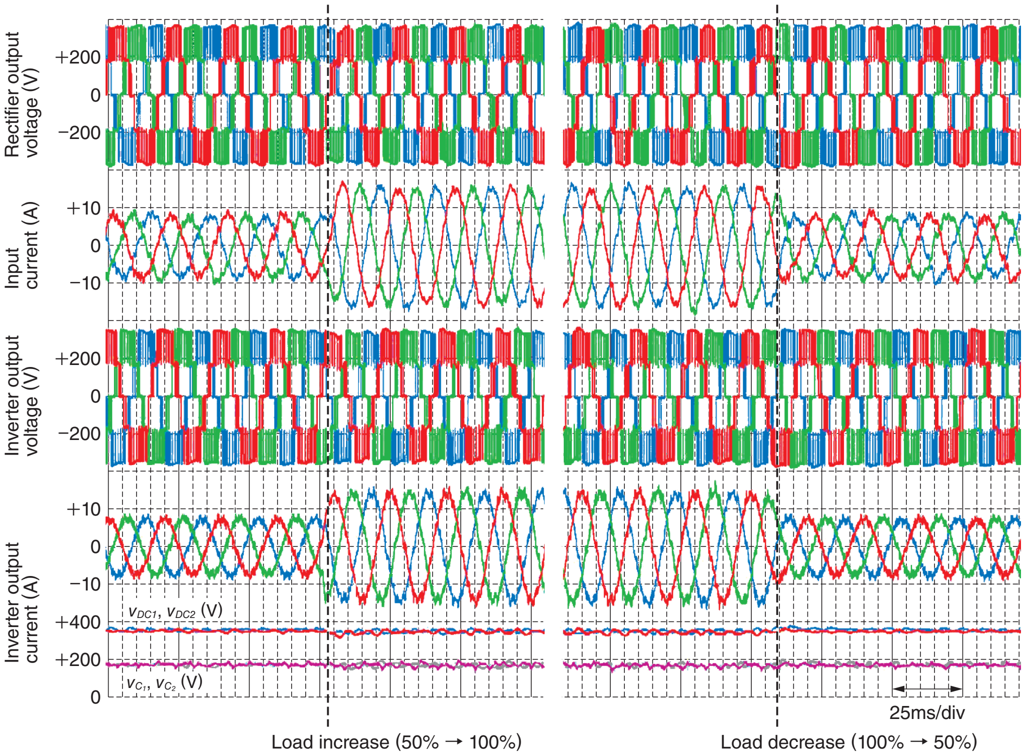


Fig. 7 **Result of Sudden Load Change Test with a LR Load**

Stabilized operation was attained even though a sudden change in load was purposely caused during operation at the rated speed.

(1) 98% efficiency that is the highest in industrial field (97% for our former product)

(2) Smallest size in the industrial world (53% volumetric rate compared with our former product)

(3) Power regeneration function as standard specification

(4) Reduction of input harmonics (IEEE519 compliant)

Compared with conventional systems, since high efficiency is secured, the effect of energy conservation is better than our conventional model when applied to flow rate control for machinery such

Table 3 Specifications of Transformerless Multi-Level Medium-Voltage Inverters

Specifications of transformerless multi-level medium-voltage inverters under development are shown.

Item	Specifications
Rated output	1MW
Input/output voltage	6000/6600V (Output voltage is lower than input voltage.)
Output frequency	0-75Hz
Maximum efficiency	98% or above
Operational domain	Four-quadrant operation
Control mode	V/f control Speed sensorless vector control Vector control with speed sensor
Input power factor	1
Protective construction	IP21
Maintenance	Front maintenance
Cooling configuration	Forced-air-cooled
Approx. dimensions	W2200 × H2100 × D1100mm ※ Not including cooling fan size.

as fans and pumps. This system is also suitable for application to machines that make sudden deceleration or repeat frequent acceleration and deceleration. It is also useful if it requires a smaller footprint for inverter installation.

4 Postscript

In order to realize medium-voltage inverters featuring highly efficient, compact, and light weight design which are high in the market demand, we developed five-level medium-voltage drive in a unique circuit configuration. In this newly proposed system, no multi-phase winding transformer is required and the number of flying capacitors to be used is minimal. It excels in terms of compact and high efficiency design.

Going forward, we will work on increasing applications, by utilizing such features.

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