

A Novel Multiple DC-Inputs Direct Electric-Power Converter

Kantaro Yoshimoto, Kengo Maikawa and Shou Satou

Nissan Motor Co., Ltd.

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ABSTRACT

A new multiple dc-inputs direct electric-power converter (D-EPC) has been developed. It is placed between multiple dc power sources and an ac motor, eliminating the need for a dc/dc converter generally used in conventional converter/inverter systems. The D-PEC can improve the efficiency of the motor drive system with a more compact size. Its power distribution control is carried out by allotting voltage ratios to each of two different dc power sources on a time average basis. A new pulse-width-modulation (PWM) generation technique to drive switching devices in the D-EPC has also been developed. Tests have verified that the three-phase ac motor can be operated by controlling the power distribution between the two power sources.

1. INTRODUCTION

A fuel-cell vehicle (FCV) is built around a motor drive circuit with two different dc power sources: a fuel-cell stack and a secondary battery. In a configuration shown in Fig.1 (a), a bi-directional dc/dc converter is placed between the battery and the fuel-cell stack. The converter combines electric power from two separate sources having different voltages, and also controls battery charging currents from the stack or the power produced by regenerative braking. In another example shown in Fig.1 (b), the converter is placed between the fuel-cell stack and the battery. In both cases, power conversion losses may occur in the switching devices, reactor and/or other circuit components in the converter and inverter. Usually installing the dc/dc converter on a vehicle is troublesome owing to the large dimension and weight of the reactor.

Methods for controlling electric power of dual sources to the motor without using a dc/dc converter have been studied in previous works⁽³⁾⁽⁴⁾. These involve an open-end winding motor, and two inverters as shown in Fig.2. However, the open-end windings requires a six-wire cable for a three-phase motor, which inevitably causes an excessive on-state loss in the second inverter when the system is supplied by a single power source.

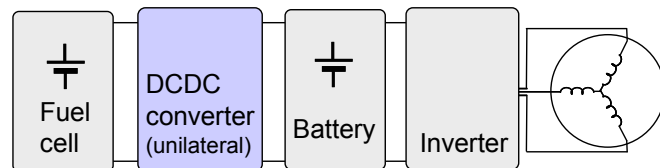
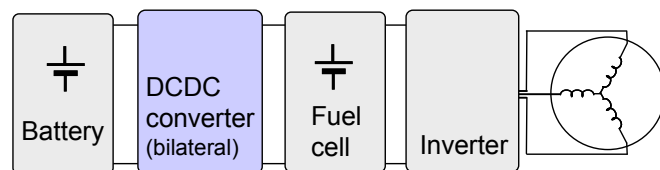


Fig. 1. Typical power conversion system configurations in FCVs.

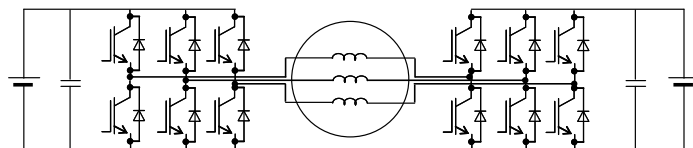


Fig. 2. An open-end winding topology.

In ac/ac power conversion applications, it is well known to use the matrix converter topology. The matrix converter can improve power conversion efficiency through direct power conversion while achieving reduction in size by eliminating a dc/dc converter.

On the basis of this direct conversion principle, a new multiple dc-inputs direct electric-power converter (D-EPC) has been developed. The D-EPC is a semiconductor switching circuit that can add multiple dc input voltages. The circuit topology is similar to the matrix converter except for replacing an ac input with multiple dc inputs. During every pulse-width-modulation (PWM) cycle, the D-EPC alternately activates one of the multiple inverter circuits, which are connected to one of the power sources. It can achieve the most efficient power distribution by controlling the duty ratios of the power sources. The D-EPC doesn't require any changes in motor wirings as shown in references (3) and (4). When the system is driven by a single power source, the D-EPC can operate in a similar manner to ordinary inverters by activating one inverter and disabling the others.

This paper describes the power distribution control method for the D-EPC circuit, the modulation factor calculation to achieve the most efficient power distribution and the PWM pulse generation technique, as well as the test results obtained by using prototype circuits.

2. OPERATION OF D-EPC

Figure 3 shows a D-EPC circuit diagram. Each positive terminal of the two DC power sources (a) and (b) is connected to a corresponding positive rail of twin inverter circuits having lower arms in common. This configuration forms a core of the D-EPC. Each of the three common lower arms between three-phase ac outputs and the common bus consists of a unilateral switching device shunted by a freewheeling diode as in conventional inverters. On the other hand, each of six upper arms between the positive terminals and the ac outputs is built with a bilateral switch to prevent any short circuit from occurring between two positive terminals when one of the upper arms switches turns on. The bi-directional switch consists of two unilateral switching devices having a mutually opposite conduction direction in parallel with each other. The switching device must have reverse blocking capability because there is a case when a large reverse voltage is applied across the device depending on the voltage condition of the dc power sources. Reverse-blocking capability can be realized by connecting a diode in series with an insulated gate bipolar transistor (IGBT). Reverse blocking IGBTs have been developed for matrix

converter applications, and they could be employed in the D-EPC.

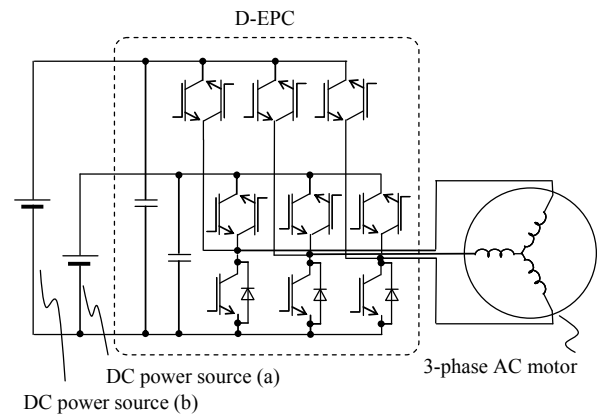


Fig. 3. Circuit diagram of D-EPC.

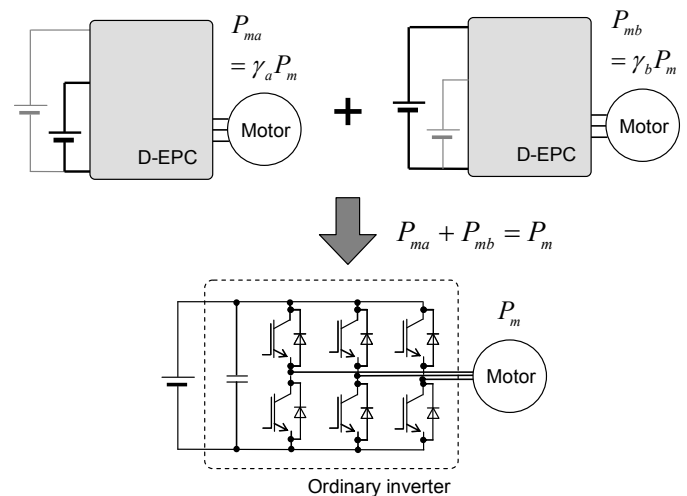


Fig. 4. Principle of power distribution.

3. POWER DISTRIBUTION CONTROL

3-1. POWER DISTRIBUTION CONTROL BY VOLTAGE ALLOTMENT

The total output power P_m is the sum of power P_{ma} and P_{mb} from the two power sources (a) and (b), respectively, and is given by Eq. (1).

$$P_m = P_{ma} + P_{mb} \dots \dots \dots (1)$$

Because power P_m is the product of the output voltage V_m and the motor current I_m , and the current I_m is automatically determined if the torque demand and other operating conditions are specified, the power distribution control should be done by allotting output voltages V_{ma}

and V_{mb} of the power sources (a) and (b) according as Eq. (2).

$$V_m I_m = V_{ma} I_m + V_{mb} I_m \dots\dots\dots(2)$$

Calculation of the power distribution for the U-phase is shown in Eq. (3). Power distribution ratios turns out to be identical to the output voltage allotment ratios of γ_a and γ_b of each power source.

$$\begin{aligned} v_u i_u &= v_{ua} i_u + v_{ub} i_u \\ &= \gamma_a v_u i_u + \gamma_b v_u i_u \dots\dots\dots(3) \end{aligned}$$

$$\begin{aligned} v_{ua} &= \gamma_a v_u \\ v_{ub} &= \gamma_b v_u \dots\dots\dots(4) \\ \gamma_a + \gamma_b &= 1 \end{aligned}$$

If the output voltages are allotted in such a manner that the sum of the two ratios is always kept to unity as in Eq. (4), it is possible to keep the supply voltage v_u constant despite a change in power distribution ratios as shown in Fig.4. The phase voltage waveforms after power distribution are shown in Fig.5. The D-EPC is also capable of charging one of the dual power sources by reversing the polarity of the other source voltage.

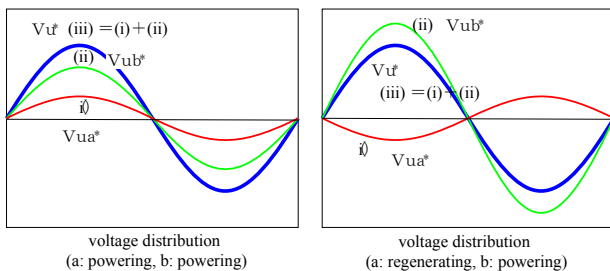


Fig. 5. Output voltage allotment.

3-2. PULSE VOLTAGES IN PWM CYCLE

On the above basis of the output voltage allotment rule, the circuit alternately activates either one of the dual inverter circuits, i.e., power source (a) or (b), in PWM cycles as shown in Fig. 6. The resulting output voltage waveforms are shown in Fig. 7. A series of voltage allotment substantially acts as modulating the voltage pulse width like in the conventional PWM technology. The voltage pulses in each activation interval are time-averaged to provide output voltages V_{ma} and V_{mb} , respectively and then the sum of V_{ma} and V_{mb} yields v_u in the U-phase line.

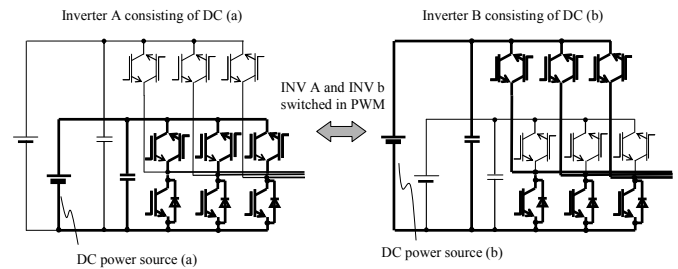


Fig. 6. Voltage allotment in PWM cycle.

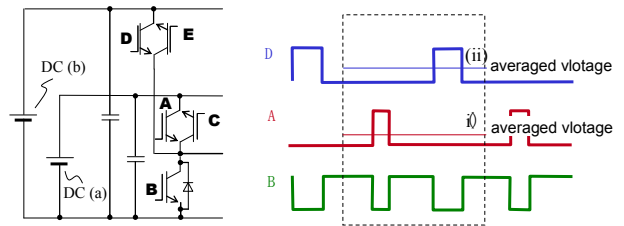


Fig. 7. PWM voltage pulse.

4. PWM PULSE GENERATION METHOD

The D-EPC is used with five switches per phase and a unique PWM pulse generation technique in order to achieve the above time-division modulation of voltage pulses. Because the D-EPC has two positive terminals, it is necessary to prevent short-circuits not only between the positive and negative terminals, but also between two positive terminals. When Switch A in Fig. 7 is turned on, Switch C is usually turned on to generate a freewheeling path. If Switch E turns on at this moment, and if the voltage of power source (a) is higher than that of power source (b), a short circuit will occur between the positive terminals, which causes PWM pulses to be generated so as to turn off Switch E while Switch A is turned on source (a) is higher than that of power source (b).

Thus, PWM pulses are generated according to the following rules.

1. To avoid a short circuit between the positive terminals A and E as well as D and C, PWM pulses are generated as $S_A = S_E$ and $S_D = S_C$, where S_N denotes switch N and binary numbers 1 and 0 represent drive signals given to switches.

2. The drive signal of switch B is generated as

$$S_B = S_C \bullet S_E$$

The PWM pulse generation rules and pulse patterns in Fig.7 lead to a PWM generation technique using a triangular wave comparison as shown in Fig. 8. The