

# Overview of Multi-Functional Converter Systems

Hideo Nakai, Kazunari Moriya, Hiroki Ohtani, Hiroo Fuma, Yukio Inaguma

## 多機能インバータシステム

中井英雄, 守屋一成, 大谷裕樹, 夫馬弘雄, 稲熊幸雄

### Abstract

There is no doubt that hybrid electric vehicles and fuel cell hybrid electric vehicles contribute greatly to preserving the environment. Both of these types of vehicles use multiple electrical power sources and the power flows between these sources are generally controlled using DC/DC converters. Therefore the DC/DC converter is an extremely important component of both an HEV and FCHV. This paper provides an overview of the Multi-Functional Converter System (MFCS) studies conducted by our laboratory. An MFCS consists of motors, inverters and additional wiring but no DC/DC converters. The MFCS can control the power flow between several AC or DC electrical power sources while, at the same

time, controlling the motor torque. There are basically two types of MFCSs, the main difference being in the location of the electrical power sources in the circuits. One group has an electrical power source between the neutral point of the motor and the DC bus line of the inverter. The second group has one electrical power source between the two neutral points of the motors. This paper describes the basic circuit concepts and introduces their characteristic equations, the controller design concepts, and the differences between the circuits of the two groups. Also described are several experiments that prove the validity of the proposed method.

#### Keywords

Motor, Inverter, DC/DC converter, Neutral point, Zero-phase current, Control

### 要 旨

ハイブリッド電気自動車(HEV)や燃料電池車(FC-HV)は、環境に優しい車として注目を集めている。DC/DCコンバータは複数電源を繋ぐために、これらの自動車においては重要な部品の一つである。本研究では、従来のモータインバータシステムにおいて、回路構成を修正することにより、今までほとんど利用されなかった零相電流を利用できるようにし、モータインバータシステムにDC/DCコンバータ機能を持たせた「多機能インバータ」を開発した。この多機能インバータは、結線方法により、2つのグループに分けられる。

一つ目は、モータ中性点とインバータDCラインの間に電源を置くタイプであり、もう一つは、2つのスター結線を用意し、2つのモータ中性点間に電源を置くタイプである。本論文では、これら2グループの多機能インバータについて、基本的な回路構成、電圧方程式、制御方法と幾つかの派生回路を示している。また、実験結果を示すことにより、多機能インバータが、モータインバータシステムが本来もつ「モータトルクの制御」と、DC/DCコンバータがもつ「複数電源間でのエネルギーの制御」とを両立できることを確認した。

#### キーワード

モータ, インバータ, DC/DCコンバータ, 中性点, 零相電流, 制御

## 1. Introduction

There is no doubt that hybrid electric vehicles (HEV) can contribute greatly to preserving the environment. A problem with these vehicles, however, is that the volume of the HEV powertrain is greater than that of a conventional internal combustion engine (ICE) vehicle powertrain. An HEV<sup>1)</sup> also features electrical drive equipment, which consists of a battery, a traction motor with an inverter and a controller, as well as an ICE. In the power electronics field, it is well known that the volume of a motor can be reduced if the DC voltage on the inverter DC bus line can be increased. Therefore, provided there is a condenser to supply a DC voltage to the inverter, the use of a DC/DC converter between the battery and condenser offers the possibility of reducing the volume.<sup>2)</sup>

Several methods<sup>3-10)</sup> of connecting the different electrical power sources without a DC/DC converter have been investigated over the last 15 years. Since the 1990s, we have been conducting similar studies aimed specifically at HEV applications.<sup>11-14)</sup> The basic approaches that we have taken in our studies are as follows:

(1) Changing the wiring connections in the motor and inverter system to enable the use of zero-phase current.

(2) Using the zero-phase current, which is the unused third degree-of-freedom of a conventional motor and inverter system, to realize the full potential of a DC/DC converter in a motor and inverter system.

We call the system that is based on the above concepts a multi-functional converter system (MFCS). In the laboratory, we have repeatedly succeeded in realizing this concept. It is not possible to explain each and every one of those studies in this paper. Therefore, this paper concentrates on overviewing our MFCS results.

## 2. Multi-function converter system concept

An MFCS can be classified into one of two types according to the location of the electrical power source. One, called the one neutral-point type, has an electrical power source between the neutral-point of the motor and the DC bus line of the inverter. The second, called the two neutral-points type, has an electrical power source between the two neutral-points of the motors.

### 2.1 MFCS using one neutral-point

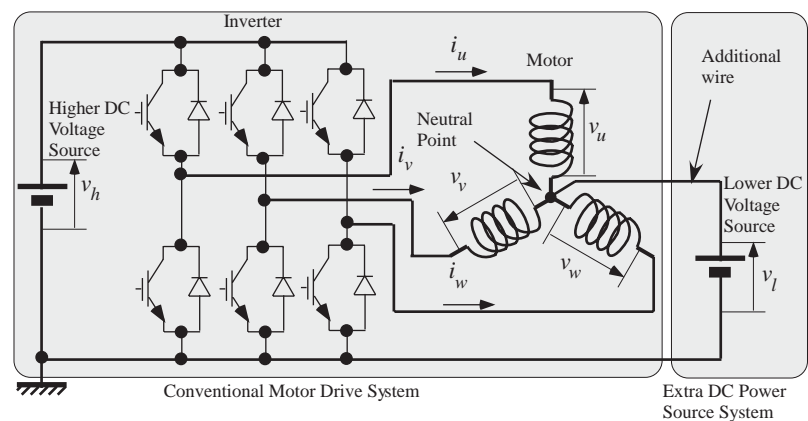
#### 2.1.1 Basic circuit

The typical, simple MFSC circuit shown in **Fig. 1** consists of a conventional motor drive system and an extra DC power source system. The drive system has an inverter, a motor and a higher DC voltage source (HDCVS) that supplies a DC voltage to the inverter bus line. The extra system has a lower DC voltage source (LDCVS) and an additional wire that connects the neutral-point of the three-phase motor to the inverter DC negative bus line. In this section, we explain the equations with a non salient-pole type motor, a battery for the HDCVS and the LDCVS. The equations can easily be extended to cover the salient-pole type, a condenser for the HDCVS, and a battery for the LDCVS.

#### 2.1.2 Characteristic equation

This section explains the voltage equation for the MFCS.

The relationships between the phase voltages in a three-phase motor are described by Eq. (1). The phase voltages given by Eq. (2) take the electric potential of the neutral-point into consideration.



**Fig. 1** Example of the one neutral-points type MFSC circuit and power sources.

$$\left\{ M_a \begin{pmatrix} 1 & -1/2 & -1/2 \\ -1/2 & 1 & -1/2 \\ -1/2 & -1/2 & 1 \end{pmatrix} + l_a \mathbf{I}_3 \right\} \frac{d}{dt} \begin{pmatrix} i_u \\ i_v \\ i_w \end{pmatrix} =$$

$$\begin{pmatrix} v_u \\ v_v \\ v_w \end{pmatrix} - R \begin{pmatrix} i_u \\ i_v \\ i_w \end{pmatrix} + \Phi \begin{pmatrix} \sin(\theta) \\ \sin(\theta - 2\pi/3) \\ \sin(\theta + 2\pi/3) \end{pmatrix} \dots (1)$$

$$\begin{pmatrix} v_u \\ v_v \\ v_w \end{pmatrix} = \begin{pmatrix} k_u v_h - v_l \\ k_u v_h - v_l \\ k_w v_h - v_l \end{pmatrix} \dots (2)$$

Where  $\theta$ ,  $M_a$ ,  $l_a$ ,  $R$ ,  $\Phi$ ,  $\mathbf{I}_n$  are the electric rotor angle, the main flux element of the self-inductance, the leakage flux element of the self-inductance, the resistance of the coil, the amplitude of the magnetic flux, and an identity matrix with n-dimensions, respectively. Also,  $i_u$ ,  $i_v$ ,  $i_w$ ,  $v_u$ ,  $v_v$ ,  $v_w$ ,  $v_h$ ,  $v_l$ ,  $q$  are defined in Fig. 1. The switching conditions of the inverter legs are indicated by  $k_u$ ,  $k_v$ , and  $k_w$ . If the upper switch of the inverter leg turns on, then  $k_x = 1$  ( $x = u, v, w$ ). If the lower switch of the inverter leg turns on, then  $k_x = 0$  ( $x = u, v, w$ ).

Using the transformation matrix, the  $i_u$ ,  $i_v$ , and  $i_w$  currents can be transformed into the direct and quadrature axes (dq-axes) currents  $i_d$ ,  $i_q$ , and zero-phase current  $i_0$ . In the same way, switching conditions  $k_u$ ,  $k_v$ , and  $k_w$  can be transformed into switching conditions  $k_d$ ,  $k_q$ , and  $k_0$ . The voltage equation for the dq-axes is described by Eq. (3).

The voltage equation for the zero-phase current and condenser voltage is described by Eq. (4). The inductance  $L_a = \frac{3}{2} M_a + l_a$ , and the angular velocity  $\omega = \theta/t$ .

$$\begin{pmatrix} L_a & 0 \\ 0 & L_a \end{pmatrix} \frac{d}{dt} \begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{pmatrix} k_d \\ k_q \end{pmatrix} v_h$$

$$-\begin{pmatrix} R & -\omega L_a \\ \omega L_a & R \end{pmatrix} \begin{pmatrix} i_d \\ i_q \end{pmatrix} - \begin{pmatrix} 0 \\ \omega \Phi \end{pmatrix} \dots (3)$$

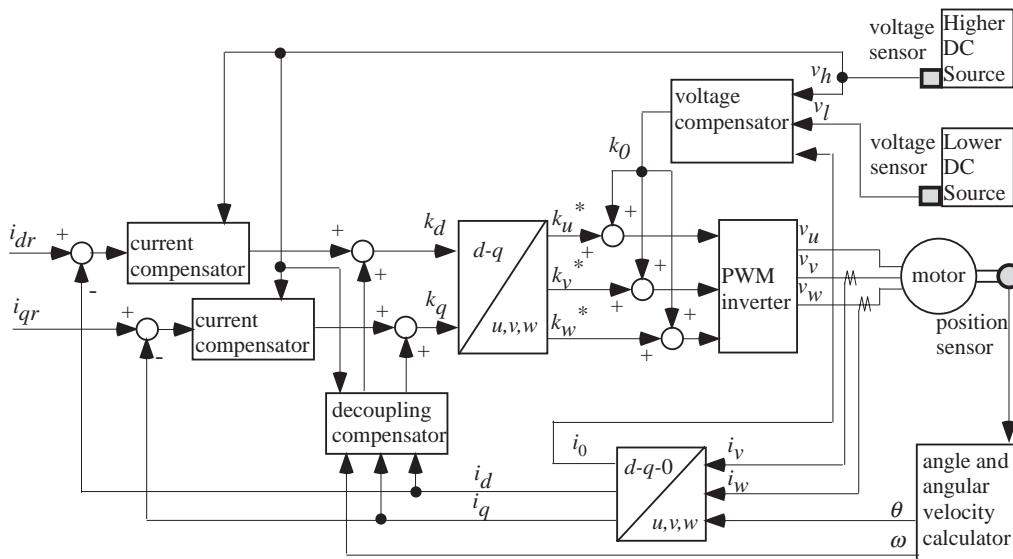
$$\frac{d}{dt} i_0 = -(R/l_a) i_0 - (\sqrt{3}/l_a) v_l + (1/l_a) k_0 v_h \dots (4)$$

### 2.1.3 Controller design

The faculty of the motor depends on Eq. (3), while the faculty of the DC/DC converter depends on Eq. (4). This proves that it is possible to control the motor torque and each of the power flows between the HDCVS and the LDCVS.

An example control diagram is shown in **Fig. 2**. In this figure,  $i_{dr}$  and  $i_{qr}$  represent the reference currents for the dq-axes. The voltage compensator determines only the control input  $k_0$  using the measured signals,  $v_l$ ,  $v_h$  and  $i_0$ . The current and the decoupling compensators determine only the control inputs  $k_d$  and  $k_q$  using the measured signals,  $i_d$  and  $i_q$ . The control signal for the PWM inverter is made by adding  $k_0$  to  $k_d$  and  $k_q$  ( $k_u^*$ ,  $k_v^*$ ,  $k_w^*$ ).

To analyze the inverter switch condition in the steady state, we assume that  $k_x$  ( $x = u, v, w$ ) is a continuous variable. Given this assumption,  $k_u$  is



**Fig. 2** The controller diagram of the one neutral-point type MFCS.

shown using  $k_d$ ,  $k_q$ , and  $k_0$  in **Fig. 3**. Figure 3 indicates that the mean value of  $k_u$  controls the DC voltage, while the alternative element controls the motor torque. Here, we consider the higher and lower DC voltages in Fig. 3. Given the definition of  $k_u$ , it is clear that  $v_h$  corresponds to 1 on the vertical axis. Also,  $v_l$  is equal to the value of B, because the voltage at the neutral-point is  $v_l$ . Given that the voltage of the neutral-point is  $v_l$  and that of the inverter DC bus line is  $v_h$ , it becomes clear that  $v_h = 2v_l$  is a good condition for driving the motor.

## 2.2 MFCS using two neutral-points

### 2.2.1 Basic circuit

An MFSC circuit with two neutral-points is shown in **Fig. 4**. A system using this MFSC circuit consists of two conventional motor drive systems and an extra DC power source. The drive system has two three-phase inverters, two three-phase motors, and an HDCVS that supplies a DC voltage to the inverter bus line. The extra system consists of an LDCVS and an additional wire that connects the neutral-point of one three-phase motor to that of the other motor.

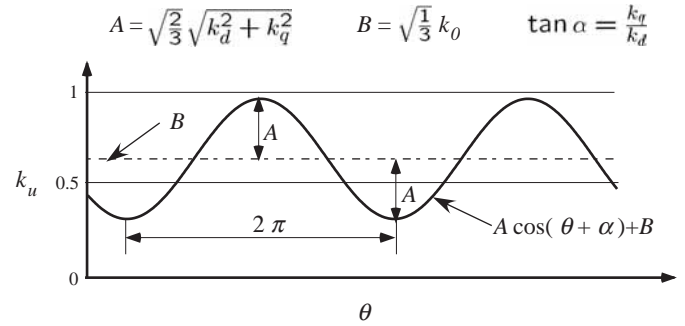
### 2.2.2 Characteristic equation

The method of introducing the equations has already described for the one neutral-point type and is very similar in this case. Therefore, only the results are described here. The voltage equation for the dq-axes currents of the two motors are described by Eq. (5). The voltage equation for the zero-phase current and condenser voltage is described by Eq. (6). The dq-axes inductance, the leakage inductance, the resistance, and the angular velocity for the two motors are  $L_{dx}$ ,  $L_{qx}$ ,  $l_{ax}$ ,  $R_x$ , and  $\omega_x$  ( $x = 1, 2$ ), respectively.

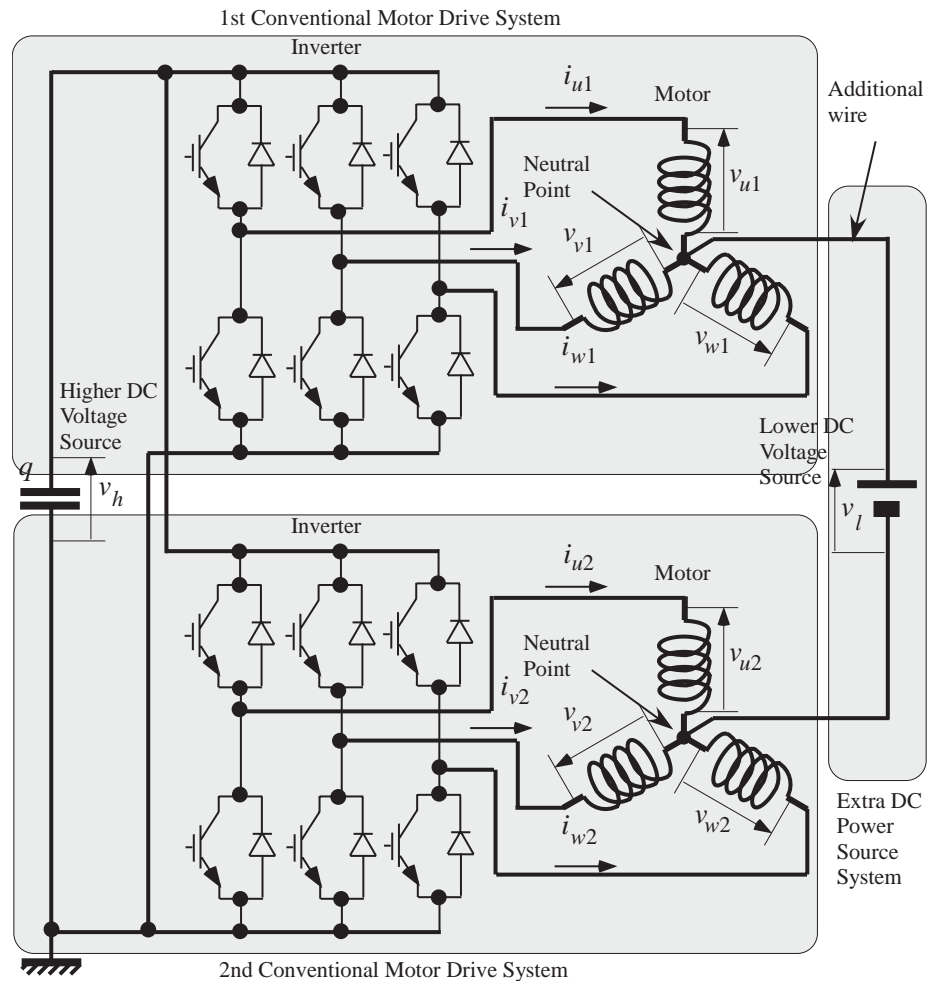
$$\begin{pmatrix} L_{dx} & 0 \\ 0 & L_{qx} \end{pmatrix} \frac{d}{dt} \begin{pmatrix} i_{dx} \\ i_{qx} \end{pmatrix} = \begin{pmatrix} k_{dx} \\ k_{qx} \end{pmatrix} \frac{q}{C}$$

$$-\begin{pmatrix} R_x & -\omega_x L_{qx} \\ \omega_x L_{dx} & R_x \end{pmatrix} \begin{pmatrix} i_{dx} \\ i_{qx} \end{pmatrix} - \begin{pmatrix} 0 \\ \omega_x \Phi_x \end{pmatrix} \dots \dots \dots (5)$$

( $x = 1, 2$ )



**Fig. 3** The representation of the inverter switching variable  $k_u$  using the control inputs ( $k_d$ ,  $k_q$ ,  $k_0$ ).



**Fig. 4** Example of the two neutral-points type MFSC circuit and power sources.

$$\frac{d}{dt} \begin{pmatrix} i_0 \\ q \end{pmatrix} = \begin{pmatrix} -(R_1 + R_2)/(l_{a1} + l_{a2}) (k_{01} - k_{02}) / \{C(l_{a1} + l_{a2})\} & 0 \\ k_{01} - k_{02} & 0 \end{pmatrix} \begin{pmatrix} i_0 \\ q \end{pmatrix} + \begin{pmatrix} -\sqrt{3}v_h / (l_{a1} + l_{a2}) \\ k_{d1}i_{d1} + k_{q1}i_{q1} + k_{d2}i_{d2} + k_{q2}i_{q2} \end{pmatrix} \dots \dots (6)$$

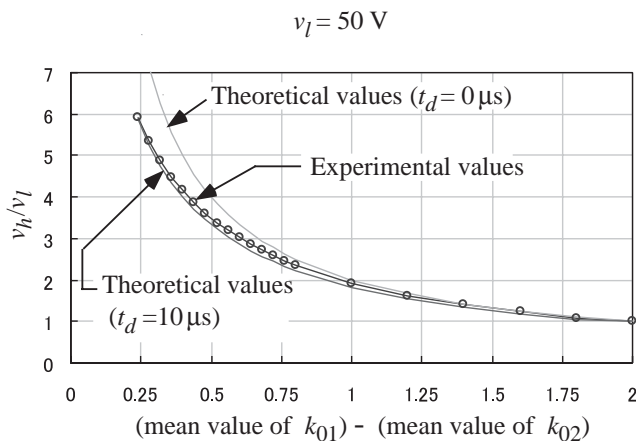
### 2.2.3 Controller design

The motor torque, which is given by Eq. (5), can be controlled independently of  $k_{01}$  and  $k_{02}$ . The DC voltage, whose characteristic equation is given by (6), depends on all the control inputs. Therefore, the controller is designed as described below, based on the fact that the time constant demanded for the motor torque is generally faster than that of the condenser voltage. First, the motor torque controller for which the inputs are  $k_{dx}$ ,  $k_{qx}$  ( $x = 1, 2$ ) is designed. Then, the condenser voltage controller for which the inputs are  $k_{0x}$  ( $x = 1, 2$ ) is designed, assuming the signal ' $k_{d1} i_{d1} + k_{q1} i_{q1} + k_{d2} i_{d2} + k_{q2} i_{q2}$ ' to be a disturbance.

### 3. Results of experiments

Our apparatus consisted of a synchronous motor, which incorporated two sets of three-phase star-connected coils and two neutral-points, two three-phase inverters, a battery as the LDCVS and a condenser as the HDCVS. This apparatus is a two neutral-points type MFCS.

The effectiveness of the condenser voltage control was examined without the dq-axes currents. Two sets of theoretical results and one set of measured results are given in **Fig. 5**. One set of the theoretical values corresponds to the case in which the inverter



**Fig. 5** The characteristic of DC/DC converter.

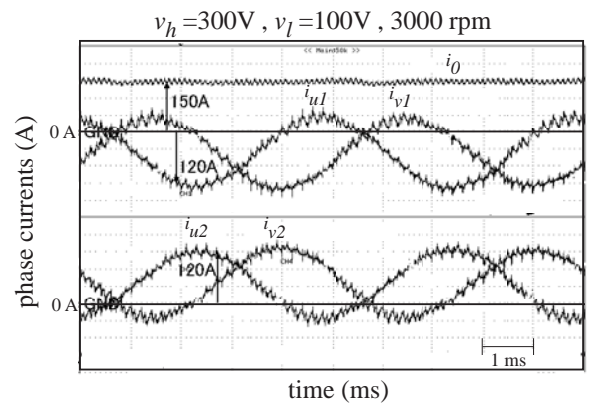
dead time  $t_d$  is  $0 \mu s$ , while the second shows the case where  $t_d = 10 \mu s$ . The circles indicate the values obtained by experiment. The values obtained by experiment agree well with the theoretical results because the  $t_d$  value for this apparatus is about  $10 \mu s$ . This proves that the MFCS can realize the characteristics of a DC/DC converter.

**Figure 6** shows the phase currents and zero-phase current under controlling  $v_h$ . This figure shows that the phase currents flow like the currents of a conventional system and that the zero-phase currents flow at the same time as the alternating current elements. Therefore, these results confirm that the MFCS can achieve the characteristics of a DC/DC converter while simultaneously controlling the motor-inverter system.

### 4. Conclusion

This paper has provided an overview of our MFCS studies. The MFCS consists of motors, inverters and additional wiring but no DC/DC converter. The MFCS can realize the functions of a DC/DC converter while simultaneously controlling the motor. We have described the basic circuit concepts and their characteristic equations and controller design concepts. The validity of the MFCS has been confirmed by experiment.

The advantage of the MFCS is that it can achieve the characteristics of a DC/DC converter and provide motor control without the need for DC/DC converter circuits. To date, however, very few practical examples of the MFCS have appeared. We believe that the MFCS will be widely applied in the future.



**Fig. 6** Phase currents and zero-phase current under controlling the higher DC voltage  $v_h$ .



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#### Hideo Nakai

Year of birth : 1963

Division : HV Electric Drive System Lab.

Research fields : Control, estimation and modeling of electrical power trains, motors, inverters, vehicle suspensions, engine mounts and acoustic noise

Academic degree : Dr. Eng.

Academic society : Jpn. Soc. Mech. Eng.,  
Inst. Electr. Eng. Jpn.,  
Soc. Instrum. Control Eng.



#### Kazunari Moriya

Year of birth : 1969

Division : HV Electric Drive System Lab.

Research fields : Control of electric motors, power electronics topologies

Academic society : Inst. Electr. Eng. Jpn.



#### Hiroki Ohtani

Year of birth : 1971

Division : HV Electric Drive System Lab.

Research fields : Motor drive system



#### Hiroo Fuma

Year of birth : 1956

Division : HV Electric Drive System Lab.

Research fields : SiC Semiconductor, Inverter and converter for motor

Academic society : Inst. Electr. Eng. Jpn.,  
Jpn. Soc. Appl. Phys.



#### Yukio Inaguma

Year of birth : 1946

Division : HV Electric Drive System Lab.

Research fields : Power electronics

Academic society : Soc. Automot. Eng.  
Jpn., Inst. Electr. Eng. Jpn.,  
Soc. Instrum. Control Eng.