Voltage Control of Intermittent Pulse Density Modulation for Two Battery-operated HEECS Choppers and its Application for Range Extension of Electric Vehicles

Ayataro Tamura* Student Member,
Takuro Umihara* Student Member,
Hidemine Obara* Member,

Takayuki Ishibashi* Student Member
Yukinori Tsuruta* Member
Atsuo Kawamura* Fellow

(Manuscript received Nov. 15, 2018, revised March 4, 2019)

This paper proposes voltage control of two battery-operated high-efficiency energy conversion system choppers, which have a very high efficiency of 99.3% and are suitable for power trains of electrical vehicles. However, due to the topology of the choppers, one disadvantage is that the chopper output voltage control has a large transient response, for example, when the duty ratio is changed from zero to a finite value, because of the inherent dead time in the switching phenomena. The minimum pulse width of the gate signal is physically determined by the delay time in the switching phenomena. As a result, there exists a dead time when the duty ratio is changed in this case. Similar phenomena occur when the duty ratio is changed around unity. Consequently, an overcurrent is observed during these types of transient periods and the system shuts down due to overcurrent protection. To solve this problem, intermittent pulse density modulation is proposed such that the output voltage is controlled by the average duty ratio. This makes it possible to output both the very low and the very high average duty ratios with multiple sampling periods. As a result, the transient response was experimentally verified to be improved even though the voltage ripple under this control increased compared with that under simple pulse width modulation (PWM) control.

Keywords: voltage control, electric vehicle, power train, buck chopper, motor test bench, power electronics

1. Introduction

The use of a greater number of electric vehicles (EVs) is said to be one of the solutions to environmental problems such as global warming; however, EVs have the disadvantage of a short driving range for a given battery capacity when compared with internal combustion engine vehicles.

Several approaches for driving range extension have been investigated such as the optimization of motor control⁽¹⁾ or the use of a new power train^{(2)–(7)}. Figure 1 depicts a typical EV power train, which may be called a “non-chopper” type power train. This structure is very simple. Because the inverter input voltage is fixed by the battery voltage, the switching loss is proportional to the input voltage. For inverter loss reduction, a series-chopper-based power train has been proposed^{(4)–(7)}, in which a DC–DC converter is inserted between the battery and inverter, and the inverter input voltage is controlled according to the motor speed. A higher efficiency chopper, called a two-battery High Efficiency Energy Conversion System (HEECS) chopper based on a partial booster circuit, has been proposed⁽⁸⁾. The efficiency of the HEECS is higher than 99.3% over a wide operating range⁽⁸⁾. Driving energy consumption is reduced by the HEECS chopper-based power train compared with typical EV power trains in driving

Fig. 1. Power trains for electric vehicles⁽²⁾

cycle tests⁽⁶⁾.

However, the chopper output-voltage control has a large transient response when the duty ratio is changed from zero to a finite value, and when it is changed from a finite value to zero. This phenomenon is called a limit cycle oscillation. This large transient voltage switching initiates the overcurrent protection and the system shuts down. The same phenomenon occurs when the duty ratio becomes exactly unity.

This study presents a solution to this problem by a proposed intermittent pulse-density control. This paper is organized as follows: section 2 explains the basic operation of the two-battery HEECS chopper. In section 3, the proposed intermittent voltage control method is shown, and its effect is analyzed. In section 4, the simulations of step responses and frequency characteristics are shown and compared with

* Graduate School of Engineering, Yokohama National University 79-5, Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan

 Fig. 2. Power train using two-battery HEECS chopper ⁽⁶⁾

 Fig. 3. Basic operation of two-battery HEECS chopper ⁽⁶⁾

experimental results. In section 5, experiments of range extension of electric vehicles are described. Finally, section 6 summarizes the conclusions.

2. Operation Modes of Two-battery High Efficiency Energy Conversion System Chopper-based Power Train

The two-battery HEECS chopper consists of two voltage sources and one buck chopper as shown in Fig. 2. Figure 3 shows the three typical operation modes of this chopper. In a low-speed range, the HEECS chopper outputs only battery voltage E_1 as shown in Fig. 3(a). In a middle-speed range, the HEECS chopper output voltage is the sum of battery voltage E_1 and the buck chopper output voltage as shown in Fig. 3(b). In a high-speed range, HEECS chopper outputs battery voltage E_1 plus battery voltage E_2 as shown in Fig. 3(c).

The output voltage V_{HEECS} and efficiency η_{HEECS} of the HEECS chopper are expressed as

$$V_{HEECS} = E_1 + dE_2, \dots\dots\dots (1)$$

$$\eta_{HEECS} = \frac{P_1 + \eta_{chop}P_2}{P_1 + P_2}, \dots\dots\dots (2)$$

where E_1 , E_2 , d , P_1 , P_2 , and η_{chop} represent the voltage of E_1 , the voltage of E_2 , the duty ratio, the output power of E_1 , the output power of E_2 and the efficiency of the buck chopper, respectively. In a low-speed range, the duty ratio is set to $d = 0$ and in a high-speed range, the duty ratio is set to $d = 1$. Thus, the overall efficiency of the HEECS is higher than the efficiency of the chopper and the HEECS efficiency is over 99% ⁽⁸⁾⁻⁽¹⁰⁾.

3. Basic Operation of the Chopper-based Power Train and a Problem During the Actual Operation

3.1 Basic Operation of Chopper-based Power Train

The DC link voltage, which has a constant DC voltage in the low speed range, is controlled as shown in Fig. 4. After a certain speed, the DC link voltage is increased proportionally to the speed, and it becomes a constant at a certain high speed. This DC voltage profile results in an approximately

Fig. 4. DC link voltage profile of chopper-based power train

5–6% driving range extension compared with a non-chopper type power train ⁽⁶⁾.

The two-battery HEECS chopper-based power train has two batteries, and State of Charge (SoC) imbalance occurs without any special control. Thus, a control to improve the SoC imbalance has been proposed by the authors ⁽¹¹⁾⁽¹²⁾.

3.2 Minimum Pulse and Maximum Pulse Width Problem

Due to the nature of the HEECS chopper, there is a problem in the transition operation mode between the duty ratio of zero and a finite minimum value, and between a high duty ratio and unity. A smooth output voltage control of this HEECS chopper is required as shown in Fig. 4, particularly from the constant voltage E_1 to a higher output value or from the high output voltage to the constant voltage $(E_1 + E_2)$.

During this transition, the actual duty ratio should change from zero to a very small value. However, the actual achievable pulse width is equal to the minimum duty ratio, for example, 0.06 times the sampling period, due to the dead time of the actual switching devices. We define this as the hardware minimum one pulse width T_{min} and, correspondingly, the duty ratio for the same is d_{min} . Similarly, we define d_{max} as a possible hardware maximum duty ratio less than unity by one pulse.

The vehicle speed may change in any manner that a driver controls the vehicle speed, thus sometimes a so-called limit cycle may occur if the difference between zero duty ratio and the minimum duty ratio d_{min} is not small enough. To avoid this, a speed dead zone is introduced; however, this dead zone

later shown in Fig. 12, and the chattering frequency is not too large. All the symbols and variables are summarized in Table 2. Introduction of the hysteresis control prevents a frequent transition between the intermittent PDM and the simple duty ratio control, and control stability is improved. Moreover, we confirmed the stability of the total control loop by calculating the transfer function assuming that the plant is of a second order and PWM is a linear function. All poles are located in the left half plane.

4. Verification of Intermittent Pulse Modulation

In this section, the step and frequency response characteristics of the intermittent PDM and simple PWM controls were simulated using PSIM software and verified by several experiments. For the simple PWM control, the following algorithm was employed. When the duty ratio d_{PI} from the PI controller in Fig. 6 is between 0.0 and 0.05, the duty ratio d_{ref} of Fig. 6 is set to 0.0 and when it is between 0.05 and 0.1, it is set to 0.1.

4.1 Simulations of Steady State Operation

4.1.1 Simulation Conditions Figure 8 shows the simulation circuit in which the load is replaced with a pure resistance. The circuit parameters are shown in Table 3⁽⁸⁾. A load resistance of $40\ \Omega$ is assumed as the replacement of a motor load.

The hardware minimum duty ratio d_{min} is 0.06; however, in the actual experiments it was set to 0.1 for safety reasons. Thus, in this study the minimum duty ratio was set at 0.1. The voltage reference was selected to be 113 V ($d = 0.01$). The total number of samples in the averaging was set to 16 ($= n$ in (3) and (4)), and the pattern of intermittent output pulses

was taken from Table 1.

4.1.2 Simulation Results

Figure 9(a) shows simulation results of steady state operation in which the inductor current ripple under the simple PWM control was lower than that under the proposed intermittent PDM control. This is because the switching frequency of the simple PWM (60 kHz) was higher than that of the intermittent PDM (60/16 kHz). Figure 9(b) shows the experimental result of the intermittent PDM. It is observed that the two waveforms of simulations and experiments are very similar under this control. Thus, it is verified that the proposed control is properly implemented in the experiments.

4.2 Simulations of Step Response

4.2.1 Simulation Conditions

The simulation conditions were the same as in the previous section except that the voltage reference was changed stepwise from 112 V ($d = 0.01$) to 127 V ($d = 0.07$), and the resistance value was changed from $4.42\ \Omega$ to $4.28\ \Omega$, simultaneously. This load parameter condition is aimed at replacement of a motor load condition from 23.1 km/h and 137 Nm to 26.9 km/h and 123 Nm, which corresponds to the speed transition of a JC08 mode driving cycle from 1017 [s] to 1018 [s]⁽¹³⁾.

4.2.2 Simulation Results

Figure 10 shows the simulation results of this step response; it is observed that the peak inductor current in the transient was suppressed more under the proposed intermittent PDM control than under the simple PWM control. However, a slight voltage overshoot occurred under both controls because the PI gain was adjusted to be optimal between $0.1 < d < 0.93$. If a lower PI gain is used, the peak current in the transient can be lower; however, it becomes difficult for the output voltage to follow the reference voltage and the vehicle speed cannot follow the speed refer-

Fig. 8. Simulation circuit of intermittent PDM and simple PWM

Table 3. Specifications of HEECS chopper in simulations and experiments⁽⁸⁾

Maximum output power	10 kW
Switch devices	SiC-MOSFET
Rated output power	5 kW
Switching frequency	60 kHz
Inductance L	78 μ H
Input capacitor C_i	50 μ F
duty ratio reference	d_{ref}
Output capacitor C_o	88 μ F
Input voltage E_1	110 V
Input voltage E_2	240 V
Chopper weight m	5 kg

(a) Simulation Results

(b) Experimental Result (intermittent PDM)

Red line, yellow line, and blue line indicate inductor current, output voltage, and gate signal, respectively.

Fig. 9. Comparison of Intermittent PDM and simple PWM of Steady State

Fig. 10. Comparison of intermittent PDM and simple PWM of step response in simulations

Fig. 11. Small AC signal Bode plot of simple PWM control at different average duty ratio in simulations

ence of the JC08 test cycles. It is also observed that the peak overshoot voltage under the proposed PDM is slightly lower than that of the simple PWM.

Thus, by using intermittent PDM, overcurrent is avoided, and the voltage response is not degraded in the step response.

4.3 Simulations of Frequency Response Characteristics ^{(14)–(16)}

4.3.1 Simulation Conditions Simulation conditions were same as the previous section except for the resistance value, which was set to $40\ \Omega$. This resistance value is aimed at the replacement of a load at 80 km/h and 40 Nm.

To investigate the frequency response characteristics of the proposed intermittent control, the voltage reference is given as a sinusoidal wave with peak amplitude of 4 V and DC average values of 120 V. This is equivalent to an average duty ratio of approximately 0.04. The frequency characteristics (gain and phase) were measured by changing the frequency of the sinusoidal reference wave.

4.3.2 Simulation Results First, Fig. 11 shows a bode plot of simple PWM control simulation results. It is observed that the simple PWM control has a problem around a very

Fig. 12. Small AC signal Bode plot of intermittent PDM and simple PWM control around the duty ratio 0.04 in simulations

Red line and yellow line show inductor current and output voltage.

Fig. 13. Sinusoidal response of intermittent PDM control in experiments

low duty ratio (0.04) as discussed earlier. The simple PWM without dead time in Fig. 11 indicates that the minimum pulse width d_{min} is zero because the no dead time condition results in no limitations to the minimum pulse width as described in Section 3.2. It is observed that the oscillation of the simple PWM with dead time around 100 Hz is suppressed by the simple PWM without dead time.

Second, Fig. 12 shows the comparison of the proposed intermittent control and the simple PWM control around a very small duty ratio ($d = 0.04$). It is observed that the intermittent PDM controller has almost the same characteristics as the PWM for the duty ratio between 0.2 and 0.8 from Fig. 11. Further, by using intermittent PDM, a response that is close to ignoring the switching dead time is obtained. These results demonstrate that the proposed controller guarantees the same frequency response characteristics of the original PWM control over all duty ratios.

4.4 Frequency Response Characteristics in Experiments ^{(6) (15)}

4.4.1 Experimental Conditions The experimental circuit is the same as in section 4.2. The reference DC value is selected to be 120 V and a small AC signal is chosen as 4 V. The average duty ratio d is approximately 0.04.

4.4.2 Experimental Results Fig. 13 shows the small signal sinusoidal response of the chopper output voltage.

Figure 14 compares the frequency characteristics of the simulation and experimental results when the duty ratio is

Fig. 14. Small AC signal Bode plot comparison of experiments and simulations around the average duty ratio 0.04

Fig. 15. Voltage ripple comparison of intermittent PDM and simple PWM control (Experiments)

The ratio reference value of dB is voltage ripple of the simple PWM control ($f = 1$ Hz).

very low ($d = 0.04$). The two sets of data match very well. Moreover, the frequency response at duty ratios between 0.2 and 0.8 in the simulations of Fig. 11 and in the experimental intermittent curve of Fig. 14 are very similar. These figures indicate that the proposed intermittent control makes the total frequency response of the output DC voltage PI controller more stable.

Figure 15 shows the voltage ripple frequency characteristics of the small AC reference when the duty ratio is very low ($d = 0.04$). This figure indicates that the ripple generated by the sudden change in the duty ratio around a very low duty ratio value is less in the proposed intermittent control than in the pure PI control. The effect of the proposed approach is apparently superior to the pure PI, in which the attenuation of the ripple is about 4 dB, particularly around a frequency of 100 Hz.

Therefore, it was confirmed that voltage ripple and current ripple were reduced by the proposed method, and the proposed voltage controller has almost the same frequency characteristics for all duty ratios.

5. Experiments of Driving Range Extension based on Proposed Intermittent Pulse Density Modulation Control⁽⁶⁾

5.1 Steady State Efficiency Map The steady state efficiency map of the proposed chopper-based power train was

measured by using the motor test bench. We compared the efficiency of the power train of the proposed control with the non-chopper type.

The output voltage command of the HEECS chopper was changed according to (5) as a function of the motor speed v [km/h] and the non-chopper power train was always equal to $E_1 + E_2$.

$$V_{HEECS} = \begin{cases} E_1 & (v \leq 22.7) \\ 4.1875v + 15 & (v > 22.7) \end{cases} \dots\dots\dots (5)$$

Measurements were taken from 10 km/h to 80 km/h by 10 km/h steps and -60 Nm to 60 Nm by 10 Nm steps. Each overall efficiency η_{HEECS_total} and $\eta_{non-chopper_total}$ is expressed as

$$\eta_{HEECS_total} = \frac{\omega_m T_m}{P_1 + P_2}, \dots\dots\dots (6)$$

$$\eta_{non-chopper_total} = \frac{\omega_m T_m}{V_{inv} I_{inv}}, \dots\dots\dots (7)$$

where, ω_m , T_m , V_{INV} , and I_{INV} represent the motor angular velocity, the motor torque, the input voltage, and current of the inverter, respectively.

Figures 16(a) and (b) show efficiency maps of the non-chopper power train and the chopper-based power train. The figures show that the HEECS chopper-based power train has wider high efficiency area. Because inverter switching loss is proportional to the input voltage, the inverter efficiency is improved by changing the input voltage almost proportionally to the motor speed. Thus, the total efficiency of the HEECS chopper-based power train is also improved compared with the non-chopper type in all speed and torque domains.

5.2 Driving Range Extension based on Proposed Intermittent Pulse Density Modulation Control Energy consumption was measured in the driving mode test cycles⁽¹³⁾ by using the motor test bench, and the total energy was compared between the HEECS chopper-based power train and the non-chopper type power train⁽⁶⁾. The proposed intermittent PDM made it possible to run these kinds of driving test cycles. Without this control, overcurrent protection sometimes occurred, and the test cycles were often interrupted. The results are summarized in Table 4. Two types of driving mode tests were employed for this study: JC08 mode, 10–15 mode, WLTC low mode, and WLTC middle mode. The proposed power train saves approximately 5.3% energy in the JC08 mode, 6.3% in the 10–15 mode, 6.4% in the WLTC low mode, and 1.9% in the WLTC middle mode compared with the non-chopper power train. These results imply that the proposed DC voltage control is more effective for driving in the city than driving on the highway.

6. Conclusion

A novel intermittent pulse density modulation method is proposed for the two-battery HEECS chopper, in which the pulse density is intermittently controlled so that the average duty ratio is equal to a reference value. The step response was simulated using the intermittent PDM and the inductor current was observed to be suppressed compared with the simple PWM control. The frequency characteristics were also measured for the HEECS chopper, and we confirmed that the total frequency characteristics of a PI controller are approximately

Fig. 16. Comparison of efficiency measurement data in motor test bench

Table 4. Experimental results of energy consumption in the several kinds of test cycle

		Power train type	Energy consumption [Wh]	Energy consumption per 1 km traveling [Wh/km]	Reduction ratio [%]
Test cycle	JC08	Non-chopper	251.3	30.7	-
		Two-battery HEECS	232.8	29.1	5.3
	10-15	Non-chopper	123.5	29.6	-
		Two-battery HEECS	115.7	27.8	6.3
	WLTC Low	Non-chopper	91.9	29.7	-
		Two-battery HEECS	86.0	27.8	6.4
	WLTC Middle	Non-chopper	155.5	32.7	-
		Two-battery HEECS	152.7	32.1	1.9

unchanged over the whole duty ratio range. Moreover, the voltage ripple is decreased. Using the proposed control, four driving cycle tests were performed in the motor test bench, and approximately 6.3% of energy savings was confirmed for the 10–15 driving mode cycle test.

References

- (1) Y. Ikezawa, H. Fujimoto, Y. Hori, D. Kawano, Y. Goto, M. Tsuchimoto, and K. Sato: "Range Extension Autonomous Driving for Electric Vehicles Based on Optimal Velocity Trajectory Generation and Front-Rear Driving-Braking Force Distribution", *IEEJ J. Industry Applications*, Vol.5, No.3, pp.228–235 (2016)
- (2) A. Kawamura, G. Guidi, S. Tsutsuki, Y. Watanabe, Y. Tsuruta, and N. Motoi: "Experimental Data Analysis on Total Driving Performance of Series Chopper Based EV Power Train", Annual Conference of the IEEE Industrial Electronics Society (IECON), pp.1348–1353, Melbourne (2011)
- (3) K. Aoyama, N. Motoi, Y. Tsuruta, and A. Kawamura: "High Efficiency Energy Conversion System for Decreases in Electric Vehicle Battery Terminal Voltage", *IEEJ J. Industry Applications*, Vol.5, No.1, pp.12–19 (2016)
- (4) M. Pavlovsky, Y. Tsuruta, and A. Kawamura: "Bi-directional buck/boost dc-dc converter with ultra high efficiency based on improved SAZZ topology", Proc. of Energy Conversion Congress and Exposition, ECCE 2009, pp.1783–1790 (2009)
- (5) Y. Hosoyamada, M. Takeda, T. Nozaki, N. Motoi, and A. Kawamura: "High Efficiency Series Chopper Power Train for Electric Vehicles Using a Motor Test Bench", *IEEJ Journal of Industry Applications*, pp.460–468 (2015)
- (6) A. Tamura, K. Kobayashi, Y. Tsuruta, K. Kojima, H. Obara, and A. Kawamura: "Range Extension of Electric Vehicles by Two Battery HEECS Chopper based Power Train", ECCE2017-CINCINNATI-OHIO, pp.4488–4492, Cincinnati, Ohio, USA (2017)
- (7) S. Tenner, S. Guthrie, and W. Hofmann: "Loss Minimization of Electric Drive Systems Using a DC/DC Converter and an Optimized Battery Voltage in Automotive Applications", Vehicle Power and Propulsion Conference, pp.1–7 (2011)
- (8) Y. Tsuruta and A. Kawamura: "Principle verification prototype chopper using SiC MOSFET module developed for partial boost circuit system", IEEE Energy Conversion Congress and Exposition (ECCE), pp.1421–1426 (2015)
- (9) F. Xue, R. Yu, and A. Huang: "Fractional converter for high efficiency high power battery energy storage system", 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, pp.5144–5150 (2017)
- (10) R.M. Button: "An advanced photovoltaic array regulator module", IECCE 96. Proceedings of the 31st Intersociety Energy Conversion Engineering Conference, Washington, DC, pp.519–524 (1996)
- (11) T. Umihara, A. Tamura, T. Ishibashi, and A. Kawamura: "Proposal of SoC balancing methodology in 2 battery HEECS Power Train for Electric Vehicle", Proceedings of the Annual Conference of IEEJ, 4-087, Fukuoka, Japan (2018)
- (12) T. Umihara, A. Tamura, T. Ishibashi, and A. Kawamura: "Proposal of Soft SOC Balancing Method to Two Battery HEECS chopper used for EV Power Train", IECON2018, Washington D.C., USA (2018)
- (13) TRIAS (Traffic Safety and Nuisance Research Institute's Automotive Type Approval Test Standards) 5-10-2008", Ministry of Land, Infrastructure, Transport and Tourism.
- (14) A. Tamura and A. Kawamura: "Proposal of High Bandwidth Frequency Voltage Control for EV Power Train by Two Battery HEECS Chopper", IEE-Japan Industry Applications Society Conference, 4-7, Hokkaido, Japan

(2017)

- (15) A. Tamura, T. Ishibashi, and A. Kawamura: "Frequency Characteristic of Output Voltage Control by Introducing of Intermittent Pulse Density Modulation for Two Battery HEECS Chopper", IEE-Japan Industry Applications Society Conference, 4-5, Yokohama, Japan (2018)
- (16) A. Tamura, T. Ishibashi, T. Umihara, Y. Tsuruta, H. Obara, and A. Kawamura: "Intermittent Pulse Density Modulation of Two Battery HEECS Chopper for Electric Vehicles", IECON2018, Washington D.C., USA (2018)

Ayataro Tamura (Student Member) received the B.E. degree in electrical and computer engineering from Yokohama National University, Japan, in 2017. He is currently working toward the M.E. degree. He has been with the Kawamura Laboratory at Yokohama National University since April 2016. His research interests include power electronics especially electric vehicle power train.

Takayuki Ishibashi (Student Member) received the B.E. degree in electrical and computer engineering from Yokohama National University, Japan, in 2018. He is currently working toward the M.E. degree. He has been with the Kawamura Laboratory at Yokohama National University since April 2017. His research interests include power electronics and electric vehicle.

Takuro Umihara (Student Member) is currently working toward the B.E. degree in electrical and computer engineering from Yokohama National University, Japan. He has been with the Kawamura Laboratory at Yokohama National University since April 2017. His research interests include power electronics and electric vehicle.

Yukinori Tsuruta (Member) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Yokohama National University, Yokohama, Japan, in 1975, 1977, and 2006, respectively. From 1977 to 2003, he was with Toshiba Corporation, Tokyo, Japan, working with the Design and Development Section of Power Converter Equipment as a Specialist Engineer in the Fuchu Works. He is currently with Yokohama National University as a Postdoctoral Fellow and a government-industry-academia collaboration researcher (Non-Full-time). His research interests are SiC converter for EV drive system and renewable energy generation system.

Hidemine Obara (Member) received the Ph.D. degree in electrical and electronics engineering from Chiba University, Japan in 2015. From Oct. 2015 to Mar. 2016, he was a postdoctoral researcher in Tokyo Metropolitan University. Since Apr. 2016, he has been with Yokohama National University as an assistant professor. His research interests include circuit topology, system integration, and implementation for multi-level power converters. Dr. Obara is a member of IEEE and IEE of Japan.

Atsuo Kawamura (Fellow) received the Ph.D. degree in electrical engineering from University of Tokyo in 1981. He then spent five years at University of Missouri-Columbia as a faculty member. Then he joined Yokohama National University in 1986, and now is a Professor. His research interests are in the fields of power electronics, digital control, electric vehicles, train traction control and robotics. He received Transaction Paper Award from IEEE in 1988, 2001, and 2002. Also, he received Award from IEEJ of Japan in 1996. Dr. Kawamura is an IEEE and IEEJ Fellow.