Loss Minimization by Partial SAZZ for High-Power Chopper

Yukinori Tsuruta^{*a)} Member, Atsuo Kawamura^{*} Fellow

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Loss minimization is vital in high-power choppers for electric drive systems in automobiles. This paper describes the evaluation of partial turn-off behavior in IGBTs (Insulated Gate Bipolar Transistor) by ZVS (Zero Voltage Switching) without over-elimination based on Partial SAZZ (Snubber Assisted Zero Voltage and Zero Current Transition). High power BTB (back to back) experiments using a 90 kW 3-phase interleaved chopper derived the good characteristics of the Partial SAZZ method and compared them with those of the hard switching (Hard SW) method. The total switching loss of the main circuit, which accounted for 48% (674 W) in Hard SW, reduced to 192 W, a 72% reduction, in Partial SAZZ. The Partial SAZZ method obtained the highest efficiency of 97.42% at 30 kW, 1.82% higher than Hard SW (95.6%) and the highest efficiency over the entire power region. This was verified through a load test and loss breakdown of up to 30 kW per phase.

Keywords: power converters for FCEV, soft switching, IGBT, automotive application

1. Introduction

Improvement of efficiency for DC-DC converter has been widely studied in the many fields of industry such as transportation, electric appliance, computer, electric power and high-tech industry. Mainly rapid advances in semiconductor power devices based on hard switching and high frequency have made it possible⁽¹⁾⁻⁽³⁾. However these studies were discussed in comparatively small power region and there were few focused on DC-DC converter by soft switching for high power range in which recent application expanded for electric drive on eco-EV such as Hybrid electric vehicles (HEV), pure electric vehicles (EV) and fuel cell electric vehicles (FCEV) taking the place of conventional vehicles with internal combustion engine (ICE). Recent years improvement of efficiency based on soft switching topology has been mainly discussed aimed for high power range converters⁽⁴⁾⁽⁵⁾. Power rating of DC-DC converter for these electric drives on eco-EV reaches the range beyond 10 and 50 kW and high efficiency DC-DC choppers with 98–99% are reported. Generally these high power DC choppers are designed as multi-phase interleaved converter. J-S Lai reported ultra high efficiency 4-phase buck-boost chopper based on coupled inductors and super-junction MOSFET with 99.2% at 30 kW⁽⁶⁾ and with 99% at 50 kW⁽⁷⁾. B. Eckard also developed 12-phase buck-boost chopper with 97–98% range⁽⁸⁾. Hirakawa reported high efficiency 2-phase buck-boost chopper based on coupled inductors with 98.4% at 42 kW⁽⁹⁾.

The authors have been studying the improvement of efficiency by soft switching topology. C-Bridge switch shown in Fig. 1(a) was proposed⁽¹⁰⁾ with 8 kW, 25 kHz and 96.0%. Later on, Quasi-resonant Regenerating Active Snubber (QRAS) chopper shown in Fig. 1(b) was originally proposed⁽¹¹⁾ to achieve zero current switch (ZCS) turn-on and ZVS turn-off by regenerating the snubber energy to DC reactor divided in two parts to improve efficiency of C-Bridge switch. The efficiency was improved from 96.0% to 97.5% at 8 kW, 25 kHz. The improvement of efficiency was further obtained by SAZZ topology shown in Fig. 1(c)⁽¹²⁾⁽¹³⁾. The efficiency was improved from 97.5% to 99.0% at 8 kW, 25 kHz⁽¹⁴⁾. Moreover the authors have studied 30 kHz prototype model of 3-phase interleaved boost chopper created by SAZZ topology for FCEV high power application from 2007 fiscal year. However following points proved problems of conventional SAZZ method for high power application. 1) Surge voltage across auxiliary switch S_2 appeared big due to high power operation of conventional SAZZ chopper⁽¹⁵⁾. 2) Snubber capacitance tends to be bigger to keep perfect ZVS

Fig. 1. High efficiency soft switching topologies

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a) Correspondence to: Yukinori Tsuruta. E-mail: tsuruta@ynu.ac.jp

^{*} Department of Electrical and Computer Engineering, Faculty of Engineering, Yokohama National University
79-5, Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan

condition during turn-off due to high power operation and total efficiency decreases. Partial SAZZ method that could be revised from conventional SAZZ to minimize total loss⁽¹⁶⁾. In chapter 2 principle of SAZZ chopper, theory of partial soft switching method as Partial SAZZ design and efficiency sensitivity analysis on SAZZ topology will be showed. Test verification by the 30 kHz prototype model chopper will be discussed in chapter 3. Chapter 4 is conclusion.

2. 3-Phase Interleaved SAZZ Chopper

As a basic concept, to combine advantages of soft switching and plural parallel connections of power converter new three-phase interleaved chopper is created by single basic SAZZ chopper. Comparing with conventional topology, downsizing of input smoothing capacitor due to the reduction of ripple current is expected as advantage of multi-phase topology. At the same time higher efficiency is expected to be obtained by advantage of soft switching topology SAZZ.

2.1 Circuit Topology by 3-phase Interleaved Concept

Figure 2 shows a new three-phase interleaved SAZZ chopper. The main part of the single phase has simple

Fig. 2. Three phase interleaved SAZZ chopper

configuration of 2 switches (S_1 and S_2), 3 diodes (D_2 , D_3 , and D_5), 2 reactors (L_1 and L_2) and 3 capacitors (C_1 , C_2 , and C_3). This configuration retains the desirable properties of the low turn on switching loss and low turn off switching loss so called a “soft switching”.

2.2 Principle of Operation To explain theoretically the operational principles, duty $D=0.5$ is assumed in following explanation. Figure 3 shows the operational waveforms and Fig. 4 shows the equivalent circuits corresponding to 6 operational modes of U-phase on SAZZ topology. Each phase such as U-phase, V-phase and W-phase has 120° phase shift, which is equivalent to a $1/3$ period of operational switching frequency.

1) Mode 1: Pre-turn-on

Main current through main reactor L_1 flows during Mode 6 ($t < -t_2$) shown in Fig. 4(f). At $t = -t_2$ auxiliary switch S_2 turns on earlier than S_1 . Current through auxiliary switch S_2 increase in the loop $(+)C_3-D_5-D_3-S_2-D_2-SL_1-L_2-(+)C_1$ at the rate of $(V_{out}-E_1)t/L_2$. So auxiliary switch S_2 turns on

Fig. 3. Operating waveforms for SAZZ boost configuration

Fig. 4. Equivalent circuits in six operational modes

from zero current. When current through auxiliary switch S_2 reaches load current value I_0 at $t = -t_1$, output diode D_5 turns off due to the reverse recovery of D_5 . Mode 1 ends as shown in Fig. 4(a).

2) Mode 2: Discharging snubber C_2

When D_5 turns off at $t = -t_1$ in Mode 1, main current through main reactor L_1 flows in the loop L_1 - D_3 - S_2 - D_2 - SL_1 - L_2 - L_1 . Simultaneously, at $t = -t_1$ voltage V_{C2} across snubber capacitor C_2 begins to discharge in resonant mode such as sinusoidal wave change from plus to zero. When voltage V_{C2} across snubber capacitor C_2 become zero at $t = t_0$. Mode 2 ends as shown in Fig. 4(b).

3) Mode 3: Turn-on with canceling main current of main switch S_1

When voltage V_{C2} across snubber capacitor C_2 becomes zero at $t = t_0$ in Mode 2, simultaneously, main switch S_1 turns on. I_{L1} keeps constant I_0 due to very short transient period. Since I_{L2} decrease from initial current I_0 in the loop of $(-C_1$ - S_1 - D_3 - S_2 - D_2 - SL_1 - L_2 - C_1 +) shown in Fig. 4(c), I_{S1} ($=I_0-I_{L2}$) increase from zero current. So at $t = t_0$ main switch S_1 turns on in zero voltage and zero current. Store energy of reactor L_2 is under regenerating state as shown in Fig. 4(c). When regenerating current through auxiliary switch S_2 decrease to zero at $t = t_1$, Mode 3 ends.

4) Mode 4: On state

From $t = t_1$ to $t = t_2$ current through reactor L_1 builds up as shown in Fig. 4(d).

5) Mode 5: turn-off of main switch S_1

At $t = t_2$ the voltage across main switch S_1 is snubbed by the capacitor C_2 as shown in Fig. 4(e).

6) Mode 6: off-state

Switches are all in off state as shown in Fig. 4(f).

2.3 Principle of Partial SAZZ Operation⁽¹⁷⁾ “Partial SAZZ operation” is method to improve total efficiency of soft switching chopper as proposed in this paper. Snubber capacitor C_2 is charged by current I_{L1} during ZVS turn-off using C_2D_3 snubber shown in Fig. 4(e). Fig. 5 shows principal waveforms of ZVS turn-off without consideration of wiring inductance and tail current. In following approximation, tail current is neglected because it is not published as device data in catalogue. Therefore turn off loss P_{S1_off} during fall time t_f of main IGBT S_1 becomes substantially negligible small according to the increase of turn-off speed of main IGBT S_1 . This justifies the design of decreasing value of capacitance C_2 using C_2D_3 snubber as “partial ZVS turn-off” in order to improve total efficiency reducing loss of the auxiliary circuit. Fig. 6 shows normalized operating area of analysis model of SAZZ chopper shown in Fig. 2. Efficiency sensitivity analysis is calculated at highest loss point A in normalized operating area. Under the condition of this point A, equations of circuit component loss are calculated under Partial SAZZ operation mentioned above. Table 1 shows the definition of symbols regarding loss equations.

In terms of loss factor of IGBT S_1 first equation of total loss P_{S1_total} is derived approximately from

$$\begin{aligned} P_{S1_total} &= P_{S1_on} + P_{S1_on-state} + P_{S1_off} \\ &= V_{S1_CEsat} \times I_{L1_av} \times \left(1 - \frac{E_1}{V_{out}}\right) + \frac{1}{6} I_{off} V_{tf} t_f f \\ &\dots\dots\dots (1) \end{aligned}$$

Fig. 5. Partial soft switching by ZVS turn off

Fig. 6. Normalized operating area

Fig. 7. Sinusoidal approximation of current waveform on auxiliary IGBT S_2

where P_{S1_on} can be neglected by zero voltage and zero current switching (ZVZCS).

Total loss P_{D5_total} of output diode D_5 becomes

$$\begin{aligned} P_{D5_total} &= P_{D5_VF} + P_{D5_rrr} \\ &= V_{D5_VF} \times I_{L1_av} \times \frac{E_1}{V_{out}} + f \times Q_{D5_rrr} \times V_{D5_r} [W] \\ &\dots\dots\dots (2) \end{aligned}$$

By sum of (1), (2) total loss of main IGBT module P_{S1_module} is as follows

$$\begin{aligned} P_{S1_module} &= P_{S1_total} + P_{D5_total} \\ &= V_{S1_CEsat} \times I_{L1_av} \times \left(1 - \frac{E_1}{V_{out}}\right) + \frac{1}{6} I_{off} V_{tf} t_f f \\ &\quad + V_{D5_VF} \times I_{L1_av} \times \frac{E_1}{V_{out}} + f \times Q_{D5_rrr} \times V_{D5_r} [W] \\ &\dots\dots\dots (3) \end{aligned}$$

where S_1 and D_5 are included in one module.

Based on sinusoidal approximation of current waveform shown in Fig. 7, total loss of auxiliary IGBT S_2 P_{S2_total} becomes

$$P_{S2_total} = P_{S2_on} + P_{S2_on-state}$$

Table 1. Definition of symbols

E_1	Input DC power source voltage	T_{period}	Period
V_{out}	Output voltage	V_{tr}	Voltage of snubber C_2 at $t=tr$
L_1	Inductance of main reactor	t_c	Charging time of snubber C_2
L_2	Inductance of auxiliary reactor	t_f	Fall time of IGBT S_1
C_2	Capacitance of snubber capacitor	t_r	Rise time of IGBT S_2
C_3	Capacitance of output smoothing capacitor	t_{rr}	Reverse recovery time
R_L	Load resistance	ω_0	Resonant angular frequency
P_{out}	Output power	η	Efficiency
I_{off}	Peak current of I_{S1} at turn-off of S_1	D	Duty
$V_{D\#-VF}$	Forward voltage drop of diode $D_\#$	f	Switching frequency
$V_{S\#-CESat}$	Saturation C-E voltage of switch $S_\#$	$I_{D\#-t\#}$	Current of diode $D_\#$ at $t=t\#$
$I_{S\#}$	Current of switch $S_\#$	I_0	Initial value of current I_{S1} at S_1 turn on
$I_{S\#-t\#}$	Current of switch $S_\#$ at $t=t\#$	$V_{S\#-CESat}$	Corrector-Emitter saturation voltage of $S_\#$
$P_{S\#-off}$	Turn off loss of IGBT $S_\#$	$V_{D/S\#-VF}$	Forward on voltage of reverse parallel diode of $S_\#$
$P_{S\#-on-state}$	On-state loss of IGBT $S_\#$	$V_{D/S\#-r}$	Reverse voltage of $S_\#$
$P_{S\#-total}$	Total loss of IGBT $S_\#$	I_{L1-av}	Average current of reactor L_1
$P_{S\#-module}$	Total loss of $S_\#$ module (IGBT $S_\#$ and anti-parallel diode of $S_\#$)	$Q_{D/S\#-trr}$	Recovery charge of reverse parallel diode of $S_\#$
$P_{D/S\#-VF}$	Forward on state loss of anti-parallel diode of $S_\#$	P_{SL1}	Core loss of saturable reactor SL_1
$P_{D/S\#-trr}$	Recovery loss of anti-parallel diode of $S_\#$	$P_{L\#}$	Total loss of reactor $L_\#$
$P_{D/S\#-total}$	Total loss of anti-parallel diode of $S_\#$	$V_{D\#-VF}$	Forward voltage of diode $D_\#$
T_0	Time width of current flow of S_2	$Q_{D\#-trr}$	Recovery charge of diode $D_\#$
$P_{D\#-on-state}$	On-state loss of $D_\#$	$P_{D\#-trr}$	Recovery loss of diode $D_\#$
$P_{D\#-total}$	Total loss of $D_\#$	$V_{D\#-VF-t\#}$	Forward voltage of diode $D_\#$ at $t_\#$
P_{SAZZ}	Total loss of SAZZ chopper	$di/dt_{t\#}$	Decrease rate of current per unit second at $t_\#$

$$= \frac{1}{6} I_{S2-11} (V_{out} - E_1) t_r f + \frac{2}{\pi} V_{S2-CESat} I_{S2-22} \frac{T_0}{T_{period}} [W] \quad (4)$$

where peak current I_{S2-22} of current I_{S2} is as follows

$$I_{S2-22} = I_{L1-av} \frac{0.6}{0.8} + (V_{out} - E_1) \sqrt{\frac{C_2}{L_2}} \quad (5)$$

Total loss of auxiliary diode D_2 $P_{D2-total}$ is as follows

$$P_{D2-total} = P_{D2-on-state} + P_{D2-trr} \\ = \frac{2}{\pi} V_{D2-VF} \times I_{D2-22} \times \frac{T_0}{T_{period}} + f \times \frac{-di/dt_{A}}{-di/dt_{typ}} \\ \times Q_{D2-trr-yp} \times E_1 \quad (6)$$

By similar approximation total loss of snubber diode $P_{D3-on-state}$ is expressed by

$$P_{D3-on-state} = \frac{2}{\pi} V_{D3-VF-22} \times I_{D3-22} \\ \times \frac{T_0}{T_{period}} + \frac{2}{\pi} \times V_{D3-VF-jc} \times I_{off} \times \frac{t_c}{T_{period}} [W] \quad (7)$$

Total loss P_{SAZZ} is given by (3), (4), (6), (7)

$$P_{SAZZ} = P_{S1-module} + P_{S2-total} + P_{D2-total} + P_{D3-total} \\ + P_{SL1} + P_{L1} + P_{L2} \quad (8)$$

Total efficiency η is calculated by

$$\eta = \frac{P_{out}}{P_{out} + P_{SAZZ}} = \frac{30kW}{30kW + P_{SAZZ}} [\%] \quad (9)$$

2.4 Efficiency Sensitivity Analysis Table 2 shows normal parameter for sensitivity analysis at point A. Efficiency sensitivity by shifting C_2 parameter $\pm\Delta C_2$ from normal value of snubber capacitance C_2 in Table 2 is calculated. Figure 8 shows result of efficiency sensitivity analysis by change of resonant snubber C_2 . Normal value $0.05 \mu F$ of snubber capacitance C_2 is approximately optimum and highest efficiency is obtained. Figure 9 shows result of efficiency sensitivity analysis by shifting L_2 parameter $\pm\Delta L_2$ from normal value of auxiliary inductance L_2 in Table 2. Normal

Table 2. Normal parameter for sensitivity analysis

Parameter	Symbol	unit	A
Input voltage	E_1	[V]	0.277*
Output voltage	V_{out}	[V]	1.0*
Operating frequency	f	[kHz]	30.0
Rise time of IGBT S_1	t_r	[ns]	100
Saturation C-E voltage of switch S_2	$V_{S2-CESat}$	[V]	1.75
Forward voltage drop of diode D_1	V_{D1-VF}	[V]	2.6
Recovery charge of reverse parallel diode of S_1	$Q_{D/S1-trr}$	[nC]	2.287
Capacitance of snubber capacitor	C_2	[μF]	0.05
Duty	D		0.5
Inductance of auxiliary reactor L_2	L_2	[μH]	0.45
Rise time of IGBT S_1	t_r	[ns]	100
Saturation C-E voltage of switch S_1	$V_{S1-CESat}$	[V]	1.6
Fall time of IGBT S_1	t_f	[ns]	100
Peak current of I_{S1} at turn-off of S_1	I_{off}	[A]	212.5
Average current of reactor L_1	I_{L1-av}	[A]	170
Forward voltage of diode D_2	V_{D2-VF}	[V]	4.5
Recovery charge of diode D_2	$Q_{D2-trr-tsn}$	[nC]	28
Resonant angular frequency	ω_0		6.67e+6

*normalized voltage=(voltage/rated output voltage)

Fig.8. Efficiency sensitivity by change of resonant snubber C_2 Fig. 9. Efficiency sensitivity by change of resonant L_2

value $0.45 \mu\text{H}$ of auxiliary inductance L_2 is considered nearly optimum. Total inductance of auxiliary circuit depends on the fixed structure of wiring method. Since value of inductance L_2 is hard to vary freely, as a result of analysis, it is considered that resonant L_2C_2 parameter optimized is approximately $L_2 = 0.45 \mu\text{H}$ and $C_2 = 0.05 \mu\text{F}$.

3. Experimental Results

3.1 Back to Back Test System for High Power Chopper Experiment was performed by back to back test system shown in Fig. 10. Figure 10 shows 60 kW back-to-back (BTB) converter test setup. Only one chopper unit of 30 kW per phase was operated as tested converter at operating frequency of 30 kHz. Verification was under 30 kW at input 200 V/output 400 V at 30 kHz. In the input side 2 DC power sources APL-II #1 and #2 with 10 kW are operated in master-slave run. The output power of tested converter is regenerated back through DC power controller (60 kW Power Adjustment Controller: PAC). The description on exterior of 90 kW prototype is omitted due to industrial secret.

Fig. 10. Back to Back test system for high power chopper

(a) Conventional Hard SW

(b) Partial SAZZ

Fig. 11. Turn-off loss of main IGBT S_1 when 30 kW

3.2 Comparison of Turn off Switching Loss with Hard SW

The waveforms are obtained under switching frequency $f_s = 30 \text{ kHz}$, the output power $P = 30 \text{ kW}$, boost mode: $V_{in} = 200 \text{ V}$, $V_{out} = 400 \text{ V}$. The comparison of turn-off experimental waveforms is shown in Fig. 11. Figure 11(a) shows conventional Hard SW, Fig. 11(b) shows Partial SAZZ. By means of partial ZVS total turn off loss of main switch S_1 decrease 304.5 W (Hard SW) $\rightarrow 147.3 \text{ W}$ (Partial SAZZ) with 51.6% reduction. The first half of ZVS turn off decrease 222.6 W (Hard SW) $\rightarrow 69.9 \text{ W}$ (Partial SAZZ) with 68.6% reduction. Tail loss in the second half decrease 81.9 W (Hard SW) $\rightarrow 77.4 \text{ W}$ (Partial SAZZ) with 5.5% reduction. Comparing Partial SAZZ to Hard sw, the first half of ZVS turn off loss can be reduced. Total turn-off loss reduces 87% from 304.5 W (Hard SW) to 147.3 W (Partial SAZZ).

3.3 Comparison of Efficiency with Hard SW

The efficiency measurement was carried out by comparing between conventional Hard SW and Partial SAZZ through 1-30 kW at 200 V/400 V at 30 kHz by Hioki digital power meter 3193, clamp on unit: 9602 + current sensor: 9278 200 A. Figure 12 shows the result of efficiency measurement for the complete load range. As can be seen, at 30 kW Partial SAZZ was 1.82% higher than Hard SW, from 95.6% to 97.42%.

3.4 Comparison of Total Loss Breakdown with Hard SW

All waveforms of all power devices separately measured for each switching states were analysed to obtain loss breakdown by each circuit topologies. On state loss was measured by high precision differential amplifier Lecroy DA1855A, probe Lecroy DXC100A and digital oscilloscope Lecroy WAVEPRO 950. Figure 13 shows total loss breakdown by circuit topologies. Total main circuit switching loss decreases 674.2 W (Hard SW) $\rightarrow 191.8 \text{ W}$ (Partial SAZZ)

Fig. 12. Efficiency characteristics versus output power

Fig. 13. Total loss breakdown by circuit topologies

Fig. 14. Loss breakdown comparison of main switch S_1 between Hard SW and partial SAZZ Fig. 15. Loss breakdown comparison of output diode D_5 between Hard SW and partial SAZZ

with 71.6% reduction. Auxiliary circuit based on Partial SAZZ topology operates minimum just before turn-on during switching operation of main switch S_1 . As a result of comparison of main circuit switching loss between Hard SW and Partial SAZZ, efficiency improvement by 1.82% between Hard SW and Partial SAZZ proved to be mainly due to 61.2% (299.6 W) reduction of switching loss with main switch S_1 , 27.8% (135.9 W) reduction of recovery loss with output diode D_5 and 11% (54 W) reduction of unknown factor loss.

Figures 14 and 15 show the evidence of this findings mentioned above. Turn-on loss of main switch S_1 decreases 153.7 W (Hard SW) $\rightarrow$ 11.3 W (Partial SAZZ) with 92.6% reduction of 142.4 W as shown in Fig. 14(a), (b). Turn-off loss of main switch S_1 decreases 304.5 W (Hard

SW) $\rightarrow$ 147.3 W (Partial SAZZ) with 51.6% reduction of 157.2 W as shown in Fig. 14(c), (d). Total reduction of switching loss with main switch S_1 is 299.6 W. Recovery loss of output diode D_5 decreases 212.4 W (Hard SW) $\rightarrow$ 76.5 W (Partial SAZZ) with 64.0% reduction of 135.9 W as shown in Fig. 15(c), (d). Unknown factor loss decreases 309.27 W (Hard SW) $\rightarrow$ 255.54 W (Partial SAZZ) with 17.4% reduction of

53.73 W as shown in Fig. 13. Moreover as a result of breakdown measurement, total auxiliary circuit loss of 41.3 W by Partial SAZZ is mainly composed of auxiliary switch S_2 of 18 W and snubber diode D_1 loss of 23 W.

4. Conclusion

In this paper 2 types of circuit topologies such as Hard SW

and Partial SAZZ, are compared as high power chopper. Soft switching can principally reduce switching loss with conventional Hard SW. However the increase of auxiliary circuit loss in order to obtain function of soft switching formula impedes loss reduction as expected. As shown, Partial SAZZ topology is effective to reduce IGBT turn off loss at fairly high power range operation. Significant contribution in high power boost chopper is partial soft switching method by ZVS without over-elimination. As can be seen, at 30 kW Partial SAZZ was 1.82% higher than Hard SW, from 95.6% to 97.42% and was higher efficiency over whole power region. Optimization of LC parameter, reliability and efficiency on Partial SAZZ topology were confirmed.

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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 Lecturer (Non-Full-time). His research interests are high-frequency converter, soft-switching converter and chopper for EV drive system.

Atsuo Kawamura (Fellow) was born in Yamaguchi, Japan, in December 1953. He received the B.S.E.E., M.S.E.E., and Ph.D. degrees in electrical engineering from the University of Tokyo, Tokyo, Japan, in 1976, 1978, and 1981, respectively. In 1981, he was with the Department of Electrical and Computer Engineering, University of Missouri, Columbia as a Postdoctoral Fellow, where he was an Assistant Professor from 1983 to 1986. Since 1986, he has been with the Division of Electrical and Computer Engineering, Yokohama National University, Yokohama, Japan, where he was first an Associate Professor and later became a Professor in 1996. His research interests include power electronics, digital control, electric vehicles, robotics, train traction control, etc. Dr. Kawamura is a member of the Institute of Electrical Engineers of Japan (IEE of Japan), Robotics Society of Japan, and several other organizations. He was the conference Chairperson of IPEC-Sapporo-ECCE-Asia in 2010. He received the IEEE IAS Transactions Prize Paper Award in 1988, the Prize Paper Award of IEE of Japan in 1996, IEEE IES Transactions Best Paper Awards in 2001 and 2002, and EPE-PEMC Award in 2008.