Journal of the Korean Institute of Illuminating and Electrical Installation Engineers Vol. 16, No.6, pp. 66~73 November 2002 논문 16-6-9

1차측 환류 다이오드를 제거한 ZVZCS Three Level DC/DC 컨버터에 관한 연구

(A Study on the ZVZCS Three Level DC/DC Converter without Primary Freewheeling Diodes)

배진용 · 김 용* · 백수현 · 권순도 · 김필수 · 계상범
(Jin-Yong Bae · Yong Kim · Soo-Hyun Baek · Soon-Do Kwon · Pill-Soo Kim · Sang-Bum Kye)

요 약

본 논문에서는 1차측 환류 다이오드를 제거한 ZVZCS(영전압 영전류 스위칭) Three Level DC/DC 컨버터에 관하여 논하였다. 제안된 컨버터는 1차측 회로를 Three Level 결선하고, 여기에 위상이동 스위칭 방법을 이용하여, 스위치 전압 스트레스를 저감시킬 수 있으므로, 기존의 Full-Bridge 컨버터에 비하여 스위칭 손실이 적고, 고전압 응용 분야에 적합하다. 기존의 경우 2차측에 한 개의 커패시터와 두 개의 다이오드를 이용한 보조회로를 부가하여, 누설 인덕터와 2차측 보조 커패시터를 이용하여 공진을 일으킴으로써 주 스위치의 영전압 영전류 스위칭(ZVZCS)이 가능하였다. 그러나 새로운 컨버터는 기존의 보조 회로에 결합 인덕터를 추가함으로써, 누설 인덕터, 2차측 보조 커패시터, 2차측 결합 인덕터가 공진을 일으키므로 기존의 경우보다 도전 손실이 저감된 고효율 컨버터를 구현할 수 있다. 또한 1차측 순환 전류의 현저한 감소로 환류 손실이 작아지며, 1차측에 환류 다이오드를 제거한 경제적인 Three Level 컨버터를 구현하였다. 본 논문에서는 제안된 컨버터의 동작원리, 해석 및 특성에 대해서 논하였으며, IGBT를 사용하여 1[kW]급 시작품을 제작, 50[㎑]에서 실험하였다.

Abstract

This paper presents ZVZCS(Zero-Voltage and Zero-Current Switching) Three Level DC/DC Converter without primary freewheeling diodes. The new converter presented in this paper used a phase shift control with a flying capacitor in the primary side to achieve ZVS for the outer switches. A secondary auxiliary circuit, which consists of one small capacitor, two small diodes and one coupled inductor, is added in the secondary to provide ZVZCS conditions to primary switches, ZVS for outer switches and ZCS for inner switches. Many advantages include simple secondary auxiliary circuit topology, high efficiency, and low cost make the new converter attractive for high power applications. Also the circulating current flows through the circuit so that it causes the needless conduction loss to be occurred in the devices and the transformer of the circuit. The new converter has no primary auxiliary diodes for freewheeling current. The principle of operation, feature and design considerations are illustrated and verified through the experiment with a 1[kW] 50[㎑] IGBT based experimental circuit.

Key Words : ZVZCS, Three Level Converter, Coupled Inductor, Without Primary Freewheeling Diodes

1. Introduction

On the design of high frequency switching mode power supplies for high power applications, the conventional full bridge zero-voltage switching switching pulse-width-modulation (FB-ZVS-PWM) converter is considered one of best alternatives. This converter possesses the most

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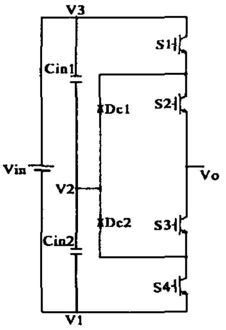
* 주저자 : 동국대학교 전기공학과 부교수
Tel : 02-2260-3720, Fax : 02-2260-3720
E-mail : kyee@dongguk.edu
접수일자 : 2002년 8월17일
1차심사 : 2002년 8월21일
심사완료 : 2002년 9월25일

desirable characteristics of both the hard switching PWM and the soft switching converters, while avoiding their major drawbacks, such as commutation losses in the first group. However, the FB-ZVS-PWM converter is not suitable for high input voltage applications because the total input voltage is applied across its blocking switches and, in many cases, the designer dose not have semiconductors able to block high voltage in high power applications available[1-5]. In order to reduce the voltage stress of the switches, many alternatives have been studied. Among these alternatives are the series connection of switches and the use of three level converters. These converters reduce the voltage stress across the power switch to half of the input voltage[1-5].

2. The previous Three Level Converter

2.1 The Three Level circuit

Fig. 1 shows the Three Level circuit and the output voltage in switch condition. This circuit consists of four switches, two diodes and two capacitors. Output voltage appears differently in each switch condition [1,2].



Switch condition				Output Voltage (Vo)
S1	S2	S3	S4	
1	1	0	0	V3 (=Vin)
0	1	1	0	V2 (=Vin/2)
0	0	1	1	V1 (=0)

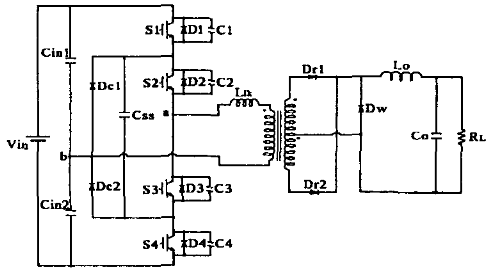
Fig. 1 Three level circuit and the output voltage which it follows in switch condition

2.2 The ZVS Three Level Converter

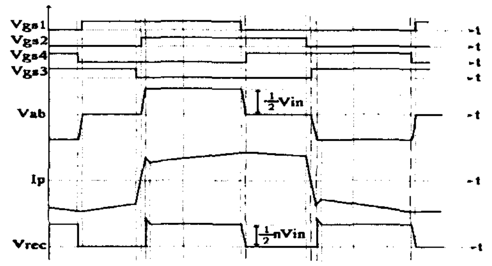
Fig. 2 shows the ZVS Three Level DC/DC converter. In order to achieve ZVS operation for the inner switches S_2 and S_3, the proposed converter uses the stored energy in the leakage inductance of the transformer to charge and discharge the parasitic capacitances C_2 and C_3 at the instant when S_2 is turned off. The parasitic capacitance of the transformer also has to be considered in this process. This stored energy depends on the primary current i_{lk}. For true ZVS operation, the stored energy in L_{lk} has to satisfy the inequality[1,3].

$$\frac{1}{2} L_{lk} I_{lk}^{2} > \frac{4}{3} C_{mos} \frac{V_{in}}{2}^{2} + \frac{1}{2} C_{tr} \frac{V_{in}}{2}^{2} \qquad (1)$$

Where the term 4/3 Cmos is twice the typical non-linear parasitic capacitance of the switch and C_{tr} is the transformer winding capacitance.



(a) Converter circuit



(b) Theoretical waveforms

Fig. 2. The previous ZVS three level converter

In order to ensure the safe ZVS operation, the transformer should be designed to have large leakage inductance or an external inductor should be connected with the transformer in series. But the large leakage inductor or the external inductor results in the high circulating energy so that the conduction loss becomes large during the circulating current mode and the duty ratio loss of the secondary side gets much serious[1,3].

In practice, it is recommended to lose the ZVS condition fro S_2 and S_3 at certain load conditions. In this way, the critical primary current needed to achieve ZVS operation can be abstained from (1) as

$$i_{crit}=\frac{V_{in}}{2}\sqrt{\frac{2}{L_{lk}}\left(\frac{4}{3}C_{mos}+\frac{1}{2}C_{tr}\right)} \qquad (2)$$

Therefore, the ZVS condition is obtained when the load current Iout reflected to the primary side is higher than the critical current, that is;

$$\frac{I_{out}}{n} > i_{crit} \qquad (3)$$

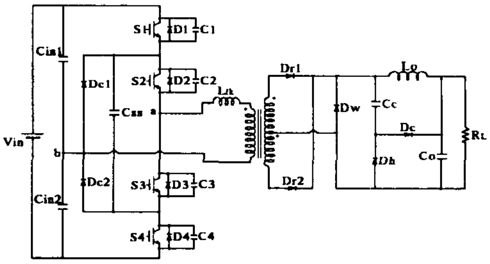
Where n is turns ratio of the transformer

2.3 The ZVZCS Three Level Converter

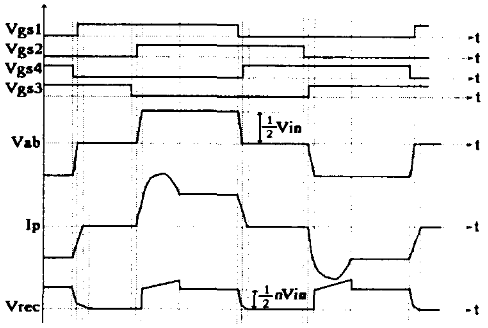
In order to solve the problems, the previous ZVZCS three level converter using secondary auxiliary circuit has been studied and developed. This converter includes the secondary auxiliary circuit, which consist of a small capacitor and two small diodes. Also The converter has wide ZVZCS range, small duty cycle loss, and no severe parasitic ringing exhibited [1,2,4,5].

3. The Proposed Three Level Converter

In this section, the operating principle of the new ZVZCS Three Level converter is presented. The basic operation of the proposed ZVZCS Three Level converter is the same as that of the ZVS Three Level converter, the phase shift PWM control.



(a) Converter circuit



(b) Theoretical waveforms

Fig. 3. The previous ZVZCS three level converter

Fig. 4 shows the proposed ZVZCS Three Level converter without primary freewheeling diodes that employs a coupled inductor and a snubber capacitor to minimize the circulating current and the secondary transient over voltage.

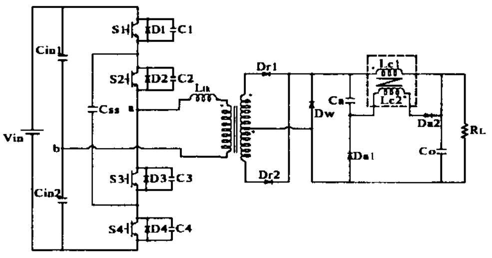


Fig. 4. The proposed ZVZCS three level converter

The previous ZVS Three Level converter has freewheeling diodes on in primary side. The freewheeling diodes give freewheeling root during the circulating current mode. But the proposed converter does not need to do the freewheeling diodes.

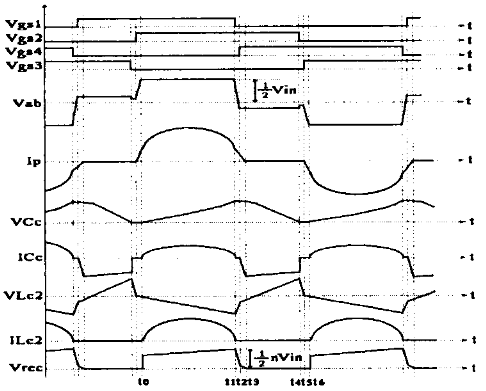
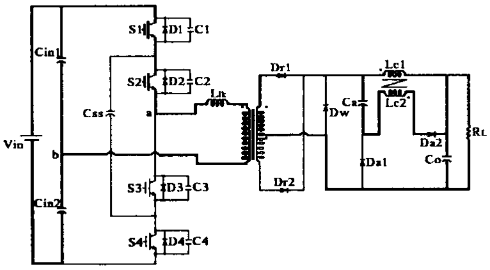
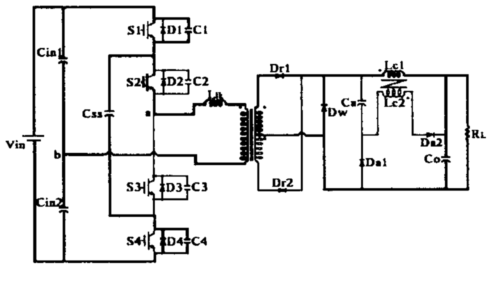


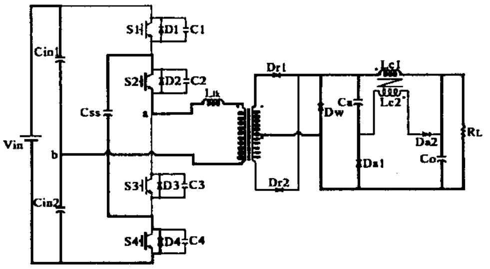
Fig. 5. Theoretical waveforms of the proposed circuit



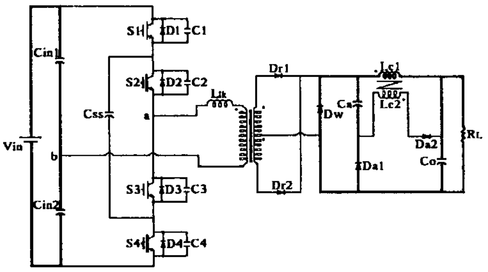
MODE I (t_0~t_1)



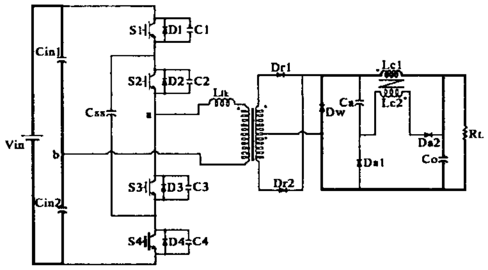
MODE II (t_1~t_2)



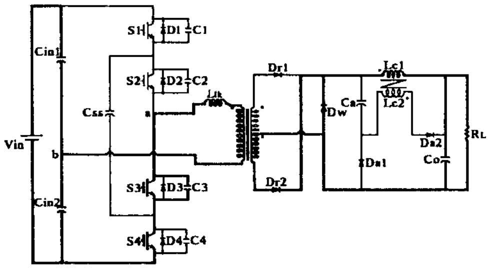
MODE III (t_2~t_3)



MODE IV (t_3~t_4)



MODE V (t_4~t_5)



MODE VI (t_5~t_6)

Fig. 6. Operation mode of the proposed circuit

The steady state operations of the proposed converter are explained under the following assumptions.

- All component and devices are ideal.
- The output filter inductance is large enough to be considered as a constant load current source.
- The output filter capacitance is sufficiently large so that the load voltage can be considered to be constant

The proposed ZVZCS Three Level converter has six operation modes during a half switching cycle. The Theoretical waveforms and the equivalent circuit of each operation mode are shown in Fig. 5 and 6, respectively.

Mode I $(t_0 \sim t_1)$: In this stage, the input power continues delivering to the output. The power is transferred to the load through switches S_1 and S_2, the secondary snubber capacitor(C_a) is charged through the coupled inductor(L_{c2}) and D_{a2}. by the resonance with the leakage inductance(L_{lk}) as shown in Fig. 5. The snubber capacitor(C_a) voltage and current can be obtained as fallows :

$$Vc_a(t)=\left(\frac{V_s}{n}-V_o\right)[1-\cos(\omega_s t)] \quad (4)$$

$$I_c(t)=-\sqrt{\frac{C_a}{L_{lk}}}\left(\frac{V_s}{n}-V_o\right)\sin(\omega_s t) \quad (5)$$

Mode II $(t_1 \sim t_2)$: S_1 is turned off and then the current through the primary charged C_1 and discharges C_4. The primary voltage is linearly decreased and the secondary rectifier voltage is also decreased with the same rate. The primary voltage decreased nearly as follows;

$$V_{ab}(t)=\frac{I_o}{n(C_1+C_4)}t \quad (6)$$

Mode III $(t_2 \sim t_3)$: C_4 is completely discharged, and the switch S_4 turns in with zero voltage. The entire reflected secondary voltage is applied to leakage inductance and the primary current decreases more quickly. The primary current reaches zero at the end of this mode. The rectifier voltage at the end of this mode is define as V_β.

Mode IV $(t_3 \sim t_4)$: The primary current is completely reset and no current flows through the primary. Then C_a supplies the whole load current and, thus the secondary rectifier voltage is decreased quickly. The snubber capacitor voltage is obtained as follows;

$$Vc_a(t)=-\frac{I_o}{C_a}t+V_\beta \quad (7)$$

Mode V $(t_4 \sim t_5)$: At the end of the freewheeling period, S_2 is turned off with complete ZCS, since there is no current in the device. This mode is a dead time between S_2 and S_4.

Mode VI $(t_5 \sim t_6)$: S_3 is turned on. This turn on process is also ZCS, since the primary current cannot be change abruptly due to the leakage inductance. The primary current is linearly increased as follows;

$$I_p=\frac{V_s}{L_{lk}}t \quad (8)$$

The rectifier voltage is still zero. This is the end of an operating half cycle.

4. The Experiment Result

A prototype of the new ZVZCS Three Level DC/DC converter has been implemented to verify the operation principles and performance of the proposed converter.

Table 1 shows specifications and parameters about a prototype of the Three Level converter.

Fig. 7 shows the waveforms of the primary voltage and the current of transformer for previous ZVZCS Three Level converter. A secondary auxiliary circuit, which consists of one small capacitor and two small diode, is added in the secondary to provides ZVZCS

Table 1. Specifications and parameters used in three level converter

Input Voltage	V_{in} = 300 V
Output Voltage	V_{out} = 48 V
Output Power	Pout = 1 ㎾
Switching Frequency	f = 50 ㎑
Transformer	EE5530, N1:N2=26:8
Leakage Inductance	L_{lk} = 8 uF
Input Capacitor	C_{in} = 100uF
Output Capacitor	C_{out} = 1000uF
Flying Capacitor	C_{ss} = 100 uF
Snubber Capacitor	C_a = 0.47 uF
Coupled Inductor	L_o = 38uF
IGBT	SM2GN50N S60 (SAMSUNG)

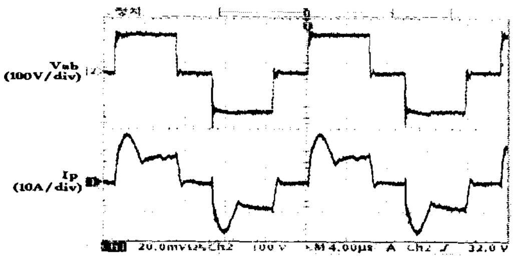


Fig. 7. Waveforms of the transformer voltage and current for previous ZVZCS converter

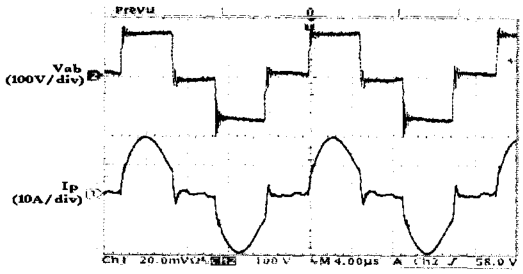


Fig. 8. Waveforms of the transformer voltage and current for proposed ZVZCS converter

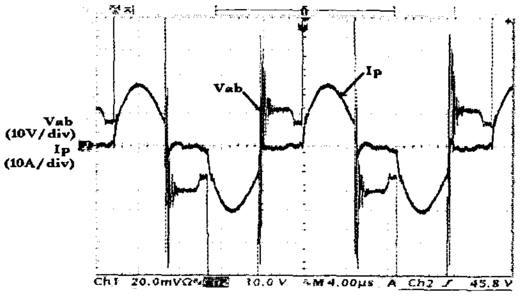


Fig. 9. Waveforms of the transformer voltage and current for proposed ZVZCS converter

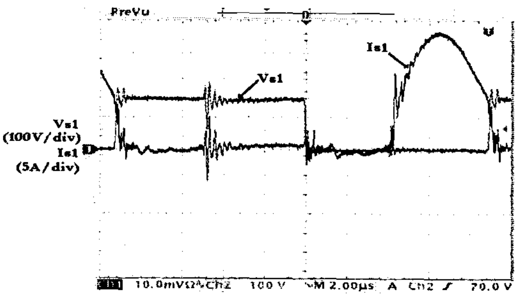


Fig. 10. The ZVS waveforms of switch S1 for proposed ZVZCS converter

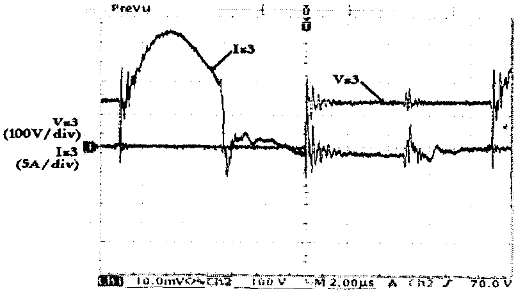


Fig. 11. The ZCS waveforms of switch S3 for proposed ZVZCS Converter

conditions to primary switches with primary freewheeling diodes.

Fig. 8 shows the waveforms of the primary voltage and the current of transformer for proposed ZVZCS Three Level converter. It can be seen the primary current is reduce to zero, during the freewheeling period without primary freewheeling diodes.

Fig. 9 enlarges of the primary voltage of transformer for proposed ZVZCS Three Level converter. During freewheeling mode, The voltage of transformer rises a little, because the circulating current flows through flying capacitor.

Fig. 10 shows the zero voltage turn on waveforms of switch S_1. During the dead time, the voltage of switch S_1 is reduced to zero and the switch S_1 turn on with zero voltage.

Fig. 11 shows the zero current turn off waveforms switch S_3. The current through S_3 is reduced to zero before the turn off gating signal is applied, and the switch S_3 turns off with zero current.

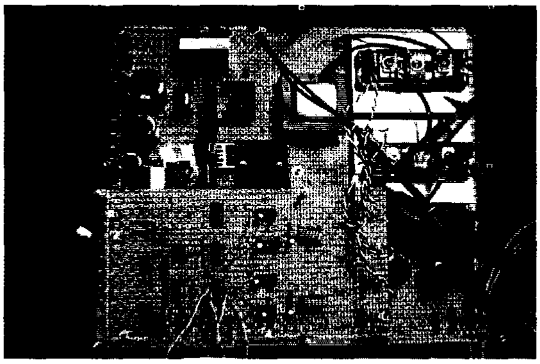


Fig. 12. Manufactured converter

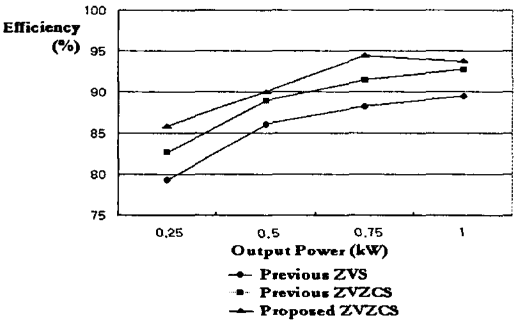


Fig. 13. The compared efficiency

Fig. 12 shows manufactured converter and Fig. 13 shows the compared efficiency obtained from the implemented prototype converter. The efficiency of the proposed ZVZCS Three Level DC/DC converter shows the high efficiency characteristics from light load to the heavy load. The highest efficiency is 94.5% at 0.75[kW] and the efficiency at the full load is 93.7%.

The precious Three Level converter needed the primary freewheeling diodes. But the proposed Three Level converter not needed the primary freewheeling diodes, because of the use of secondary auxiliary circuit to remove circulating current.

5. Conclusion

This paper has presented the ZVZCS Three Level Converter without primary freewheeling diodes. The operation stages and characteristics of the proposed converter were presented. Experimental results from the 1[kW], 50[kHz] prototype converter employing IGBTs were shown to confirm the validity of the proposed scheme. The measured efficiency at full load was 93.7%.

The main features of the proposed converter are as follows

- With no primary auxiliary diodes for freewheeling current, the switching loss is not increased.
- This converter reduces the voltage stress across the main switch to half of input voltage.
- The needless conduction losses during the freewheeling mode can be minimized.
- IGBT can be much effectively used because the influence of the tail current can be ignored.
- The diode(D_a) of the auxiliary circuit is softly commutated and its reverse recovery is minimize.

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◇저자소개◇

배 진 용(裵辰容)
1975년 8월 17일생. 1998년 동국대 전기공학과 졸업. 2002년 동 대학원 전기공학과 졸업(석사). 2002년~현재 동 대학원 전기공학과 박사과정.

김 용(金 龍)
1957년 3월 20일생. 1981년 2월 동국대 전기공학과 졸업. 1994년 2월 동 대학원 전기공학과 졸업(박사). 1995년~현재 동국대 전기공학과 부교수.

백 수 현(白壽鉉)
1947년 5월 2일생. 1972년 한양대 전기공학과 졸업. 1974년 동 대학원 전기공학과 졸업(석사). 1981년 동 대학원 전기공학과 졸업(박사). 1977년~현재 동국대 전기공학과 교수, 전기학회 부회장.

권 순 도(權純道)
1954년 11월 5일생. 1978년 광운대 응용전자공학과 졸업. 1980년 건국대 대학원 전기전자학과 졸업(석사). 1996년~현재 동국대 대학원 전기공학과 박사과정 수료. 1983년~1986 (주)삼성정밀 연구소 자동화 연구실 근무. 1996년 3월~현재 대림대 전자정보통신계열 교수.

김 필 수(金必洙)
1961년 5월 5일 생. 1984년 동국대 전기공학과 졸업. 1986년 동 대학원 전기공학과 졸업(석사). 1994년 동 대학원 전기공학과 졸업(박사). 1992년 3월~1996 2월 충청대학 전기공학과 조교수. 1996년 3월~현재 대림대 자동차과 조교수.

계 상 범(桂尙範)
1966년 1월 21일 생. 1989년 고려대 전기공학과 졸업. 1992년 한국과학기술원 전기 및 전자공학과 졸업(석사). 1992년 ~현재 (주)메디슨 연구소 책임연구원.