Journal of the Korean Institute of Illuminating and Electrical Installation Engineers Vol. 21, No.4, pp. 80~87 May 2007

논문 21-4-10

Characteristics of Optical Current Sensors by Sensor Design

Young-Min Kim* · Jung-Hwan Park · Kwang-Sik Lee ·
Jung-Bae Kim · Won-Zoo Park**

Abstract

This paper will suggest that the 1 cross orthogonal loop type sensor improves on the orthogonal loop form sensor-head, which is available a calibration of the linear birefringence, when a fiber optic current sensor was composed. An output characteristics of the 1 cross orthogonal loop form, a general closed loop form, the orthogonal loop form are compared by the IEC(International Electrotechnical Commission) 60044-8 standard, and the state of polarization is compared with three forms.

As a result, when the closed loop form was changed to the orthogonal loop form, retardation decreased 15.3[%]. When the closed loop form was changed to the 1 cross orthogonal loop type, the retardation decreased 33.8[%]. As a result of the Faraday Effect measurement, the 1 cross orthogonal loop form has the highest output characteristic and the lowest error ratio. It met the 0.5 class of the IEC 60044-8 standard.

Thus, in application of the 1cross orthogonal loop form, the possibility to develop high reliability fiber optic current sensors that have a high output and stable error ratio rises is increased.

Key Words : Faraday effect, Optical fiber measurement, Current transformer, Polarization analysis

1. Introduction

Recently, the demand for ultra high voltage power equipment has increased according to the rise of electric power capacity. Therefore, the demand for the conventional current transformer (CT) has also increased. However, the necessity for optic current sensors that use a laser has increased because these solve the problems of the conventional CT which are a large size, heavy weight, and distortion of the output signal due to remaining magnetic saturation. Also, the optic current sensor has the advantages of high insulation, less damage, no inductivity, and stability.

Optic current sensors can be divided by bulk type and optic fiber type in accordance with the medium of the Faraday Effect. For the bulk optical current sensor, although it is highly sensitive due to the high Verdet Constant, it cannot be used for the measurement of wide current regions due to a

---

* Main author : Electrical Engineering at Yeung Nam UniV.
** Corresponding author : Electrical Engineering at Yeung Nam UniV.
Tel : 053-810-3926, Fax : 053-810-4767
E-mail : wzpark@yumail.ac.kr

Date of submit : 2007. 3. 12
First assessment : 2007. 3. 16
Completion of assessment : 2007. 3. 30

limitation in the polarized rotation angle. Fiber optical current sensor, on the other hand, can measure a wide current region with linearity due to a low Verdet Constant. The sensitivity can also be controlled by wrapping in several times around a conductor[1].

The fiber optic current sensor, however, has a linear birefringence because the sensor-head, using an optic fiber that causes retardation between two orthogonal a-linear polarization.

There are several methods for calibrating the linear birefringence of fiber optic current sensors: ① the twisted or spun high-birefringence fiber method, ② a reflection using the Faraday Mirror method, ③ the fiber annealing method, and ④ the orthogonal loop form sensor-head method[2-5].

In this paper, it is, therefore, suggested that a 1 cross orthogonal loop form sensor-head improves on the orthogonal loop type sensor-head, an expensive device, to calibrate the linear birefringence. The state of polarization, an output characteristic of the 1 cross orthogonal loop form with a general closed loop form, and an orthogonal loop form were compared.

2. Theory

2.1 Faraday Effect

The Faraday Effect is a phenomenon in which a shaft of polarized light rotates by the magnitude of a magnetic field when light passes inside a magnetic substance. Here, a optic fiber was used for the Faraday element. In this composition, the rotation angle Φ_F is proportional to the current and the number of times the optical fiber was wound, was based on Ampere's law [1] which is given by

$$\Phi_F = Vn\oint H \cdot dl = VnI \tag{1}$$

Where n is the number of times the optical fiber was wound, I is the current in [A], V is the Verdet Constant in [rad/A] and H is the magnetic field in [A/m].

2.2 Linear birefringence measurement

To calculate the linear birefringence in an optical fiber, it can be assumed that an optical fiber is a phase retarder. If the retardation δ of the phase retarder can be measured, then the linear birefringence of an optical fiber can be measured.

The incident electric filed component $(E_x E_y)$ appears $(E'_x E'_y)$ by the phase retarder. This relation is represented by the Jones Matrix and is given by

$$\begin{pmatrix} E'_x \\ E'_y \end{pmatrix} = \begin{bmatrix} \exp(j\delta/2) & 0 \\ 0 & \exp(-j\delta/2) \end{bmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} \tag{2}$$

If linearly polarized light with an amplitude $E_0 \exp(jwt)$ is entered into the phase retarder and an analyzer is located with an angle θ_1 for $x-y$, the output light becomes the rotated coordinate system as an angle θ_1. This can be defined as E_{out}. When the linearly polarized light by a polarizer passes through an optical fiber and an analyzer, it can be represented as Equation 3 using the Jones Matrix.

$$E_{out} = \begin{pmatrix} E_X \\ E_Y \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & \sin\theta_1 \\ -\sin\theta_1 & \cos\theta_1 \end{pmatrix} \begin{bmatrix} \exp(j\delta/2) & 0 \\ 0 & \exp(-j\delta/2) \end{bmatrix} \begin{pmatrix} \cos\theta_0 \\ \sin\theta_0 \end{pmatrix} E_0 \exp(jwt) \tag{3}$$

The state of polarization Γ of light that has passed an optical fiber is given by

$$\Gamma = \frac{(|E_X|^2 - |E_Y|^2)}{(|E_X|^2 + |E_Y|^2)} = \cos 2\theta_1 \cos 2\theta_0 + \sin 2\theta_1 \sin 2\theta_0 \cos\delta \tag{4}$$

θ_0 is an angle of the incident polarized light. For a given value of θ_0, Γ will be a maximum when $(\partial\Gamma / \partial\theta_1) = 0$. This leads to the condition.

$$\tan 2\theta_1 = \tan 2\theta_0 \cos\delta \tag{5}$$

P is denoted by the maximum value of Γ using Equation 4 and Equation 5. It is given by Equation 6.

$$P = (\cos^2 2\theta_0 + \sin^2 2\theta_0 \cos^2\delta)^{1/2} \tag{6}$$

The maximum and minimum of P are given by the conditions[6].

$$\begin{aligned} &MAX: P = 1 \; for\; \theta_0 = m(\pi/2),\ m = \text{int}erger \\ &MIN: P = |\cos\delta| \; for\; \theta_0 = (2m+1)(\pi/4) \end{aligned} \tag{7}$$

Here, in the case of θ_0 when the incident polarized light is fixed, the maximum value of Γ and P, can be solved when the maximum and minimum values of the measured values with a rotation of the analyzer are substituted in Equation 4. The minimum value of the values of P, which is repeatedly measured by rotating θ_0 from 0[°] to 90[°], is a retardation δ using Equation 7.

2.3 Linear birefringence & the Faraday Effect

The linear birefringence and the circular birefringence of the Faraday Effect both exist at the same time in an optical fiber. These two states of birefringence are then represented as the superposition. The Jones Matrix of incident light (E_{input}) and output light (E_{output}) for the superposed birefringence is given by [7]

$$\begin{pmatrix} E'_x \\ E'_y \end{pmatrix}_{output} = \begin{pmatrix} A & -B \\ B & A^* \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}_{input} \tag{8}$$

where

$$\begin{aligned} &A = \cos(\phi/2) + j\cos\chi \sin(\phi/2) \\ &B = \sin\chi \sin(\phi/2) \\ &\phi^2 = \delta^2 + (2\Phi_F)^2 \\ &\tan\chi = \frac{2\Phi_F}{\delta} \end{aligned}$$

δ: the linear birefringence; Φ_F: the circular birefringence; ϕ: superposition between the linear birefringence and the circular birefringence

When θ_1 of an analyzer is measured for the x axis, an output of the Jones Matrix is represented as Equation 9.

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix}_{output} = E_{input} \begin{pmatrix} \cos^2\theta_1 & \cos\theta_1 \sin\theta_1 \\ \cos\theta_1 \sin\theta_1 & \sin^2\theta_1 \end{pmatrix} \begin{pmatrix} A & -B \\ B & A^* \end{pmatrix} \begin{pmatrix} \cos\theta_0 \\ \sin\theta_0 \end{pmatrix} \tag{9}$$

After the light is separated into the two vector ingredient $(\theta_1 = \pm 45^\circ)$, which is orthogonal using a PBS(Polarization Beam Splitter), the separated output is given by Equation 10 and Equation 11.

$$J_1 = \frac{J_0}{2}(1 + \sin\chi \sin\phi) \tag{10}$$

$$J_2 = \frac{J_0}{2}(1 - \sin\chi \sin\phi) \tag{11}$$

The output, S, which is computed using Equation 10 and Equation 11, is represented as Equation 12.

$$S = \frac{J_1 - J_2}{J_1 + J_2} = \frac{2\Phi_F}{\phi}\sin\phi \tag{12}$$

In the case of $\phi << 2\Phi_F$, $S \approx \sin 2\Phi_F$ can be approximated. In the case of $\phi >> 2\Phi_F$, however, the linear birefringence has an effect on the output of the optic current sensor as in Equation 12, Fig. 1.

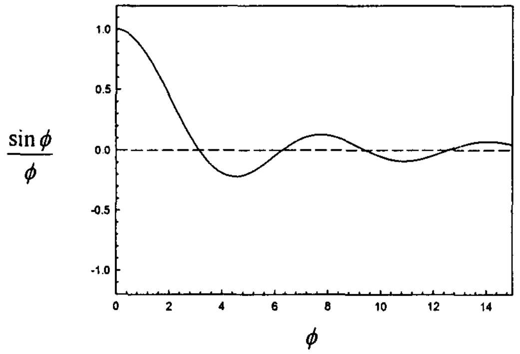


Fig. 1. Output decrease by linear birefringence

2.4 Linear birefringence calibration by figure of the sensor head

The linear birefringence calibration using the orthogonal loop sensor-head is represented as Fig. 2. The calibration method that minimizes the effect of the linear birefringence is winding one optical fiber after the other to a circular frame, which is orthogonal.

The principle of calibration is as following. It can be assumed that a circularly bent optical fiber is a one of two waveplates. These orthogonally arranged circular frames, then, are assumed to be two waveplates. The fast axis and slow axis of an optical fiber change each other because these two waveplates are arranged orthogonally. For the polarized light that entered the optical fiber winding the two orthogonal circular frames undergoes a fast axis and a slow axis. and then the effect of the linear birefringence is counter-balanced.

However, when an optical fiber is wound one after the other to a circular frame that is orthogonal, the figure is not preserved on the cross position due to the use of the optical fiber. A given stress due to the bending of the optical fiber cannot be ignored on the cross position.

Thus, in this paper, the characteristics of the three methods were compared, which are winding an optical fiber by each sensor head as Fig.2. The three methods are: ① the general closed loop, ② the orthogonal loop, and ③ 1 cross orthogonal loop form that is suggested in this paper. The winding method of the 1 cross orthogonal loop form is described as follows.

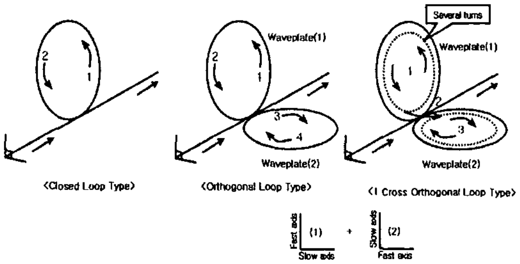


Fig. 2. Scheme of the three sensor-heads

First, an optical fiber is wound several turns on one of orthogonal circular frames, and then is wound for the same number of turns on the other frame. This is the same as the direction of the progress of light of the orthogonal loop form in an optical fiber but the cross position is undergone once.

3. Experiment

3.1 Linear birefringence measurement scheme

An experimental apparatus of the linear birefringence measurement is shown schematically in Fig.3. A 1310[nm] laser diode with 25[mw] was used as the light source. In Fig. 3, the section of the sensor-heads is equipped with each sensor-head type as described in Fig. 2. The closed loop form is used after winding the single mode optical fiber(9/125[μm]) 20 times. The orthogonal loop form and the 1 cross orthogonal loop form are used after winding around an orthogonal circular frame 10 times each.

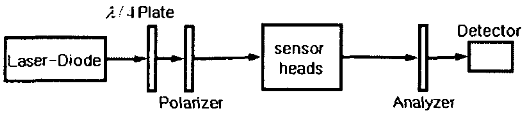


Fig. 3. Diagram of the linear birefringence measurement

The detector consisted of the PIN Photo-Diode (Newport, 818-SL) with a fast response(~0.2[ns]) and the Optical power meter(Newport, 1820-C). The linear birefringence measurement was conducted, in which the angle of the polarizer was fixed after each sensor-head type was equipped, and the maximum and minimum value which was measured by rotating an analyzer were substituted for Equation 4. From this, the state of polarization could be obtained.

3.2 Faraday Effect measurement scheme

The experimental apparatus of the Faraday Effect measurement was same as the apparatus in Fig. 3, but the PBS was used instead of an analyzer to separate the two vector ingredients, which are orthogonal, as in Fig. 4.

The output of the optic current sensor is measured from 200[A] to 1400[A] at every 100[A] increase. The signal processing module conducts a signal processing that process two output signals from the PIN Photo-Diode using the LabVIEW commercial program and a 16 bit DAQ-board.

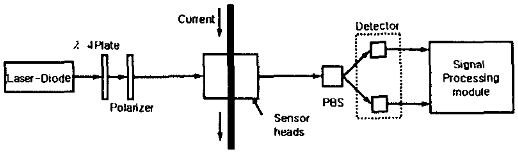


Fig. 4. Diagram of the Faraday Effect measurement

3.3 Adaptive signal process

The signal processing method was used as in Fig. 5.

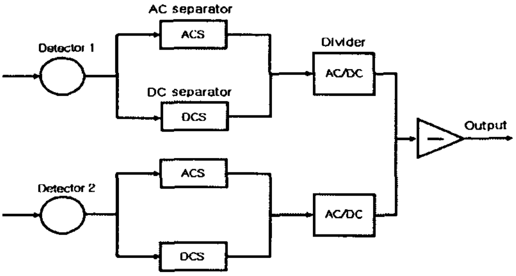


Fig. 5. Diagram of signal processing

Each AC and DC ingredient could be detected in two signals of the PBS. These were then divided each by the AC and DC ingredient to remove the fluctuation of the state of polarization by the fluctuation of light source intensity and noise in the optical circuit as in Equation 13. Then, a stable output signal can be obtained to remove the function of noise in the optical circuit as well as the fluctuation of the light source intensity[8].

$$\frac{AC_a}{DC_a} = -\sin 2\phi \, \frac{2n_1(t)}{J_1 e(t)} \qquad \frac{AC_b}{DC_b} = \sin 2\phi \, \frac{2n_2(t)}{J_2 e(t)}$$

$$\begin{aligned} &S_{out} = \frac{AC_a}{DC_a} - \frac{AC_b}{DC_b} = -2\sin 2\phi + \frac{2[J_2 e(t) n_1(t) - J_1 e(t) n_2(t)]}{J_1 J_2 e(t)} \\ &J_1 \approx J_2 = J_0 \qquad n_1(t) \approx n_2(t) = n(t) \\ &S_{out} \approx -2\sin 2\phi \end{aligned} \tag{13}$$

4. Results

4.1 Comparison of linear birefringence measurement

Each linear birefringence was measured after equipping three sensor forms at the sensor-heads shown in Fig. 3. The polarizer angle was fixed θ_0 and the maximum and minimum values, which were measured by rotating an analyzer, were substituted for Equation 4. From this, the state of polarization was obtained.

The θ_0 was measured repeatedly from 0[°] to 90[°], 10[°] increments. The calculated state of polarization was minimized at 45[°]. At this time, the retardation δ was assumed from a measured minimum value of the state of polarization and Equations 6 and 7.

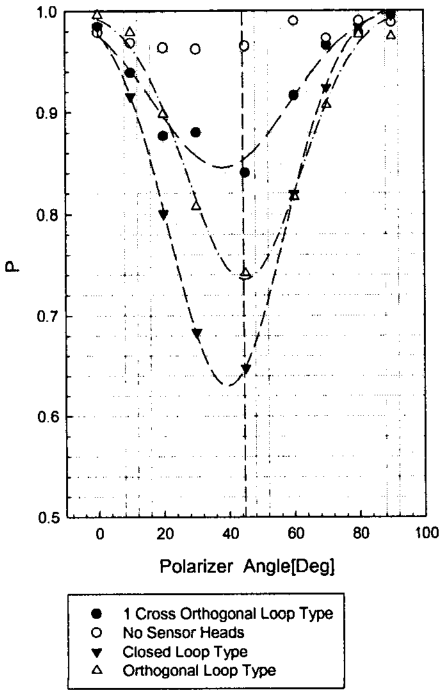


Fig. 6. Comparison of the linear birefringence of each sensor-head

First, the result of the linear birefringence measurement is shown in Fig. 6. In the case of the absence of sensor-heads, a retardation of 15.1[deg] existed due to the inherent anisotropy structure in the optical fiber. The closed loop form had 49.6[deg], the orthogonal loop 42.0[deg], and the 1cross orthogonal loop 32.8[deg].

These results include the retardation of each sensor-head and the inherent retardation in the optical fiber. Thus, the state of polarization of the orthogonal loop form increased more due to a decreased retardation than the closed loop form, but was lower than the 1 cross orthogonal loop form because the optical fiber of the orthogonal loop underwent stress due to a more cross position than the 1 cross orthogonal loop type during the repeated winding of the optical fiber.

4.2 Comparison of Faraday Effect characteristics

Fig. 7 shows the output and linearity due to the Faraday Effect of each sensor-head of the optic current sensors.

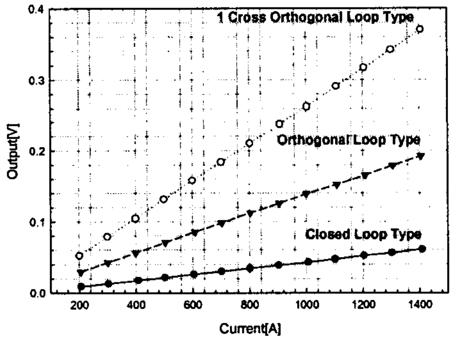
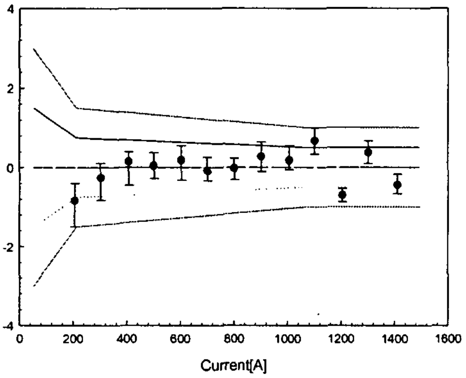
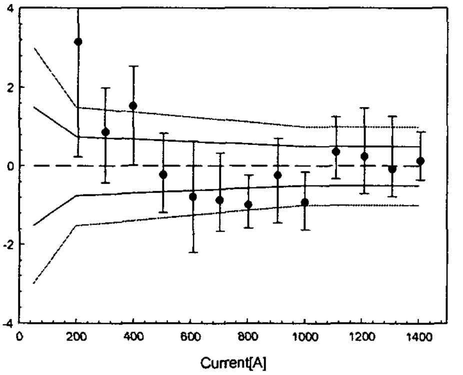


Fig. 7. Comparison of the Faraday Effect of each sensor-head

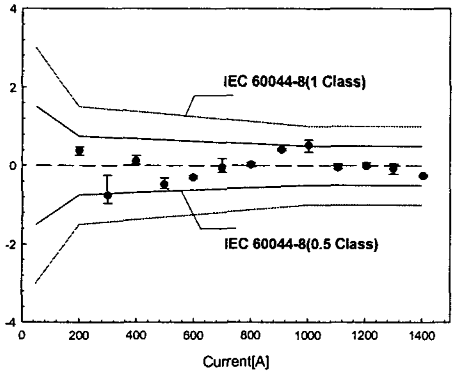
Each sensor-head is equipped at the sensor heads as in Fig. 4. A signal processing method was processed by Equation 13 using the LabVIEW commercial program. Each output was measured 10 times and the average was taken.



(a) Closed Loop



(b) Orthogonal Loop



(c) 1 Cross Orthogonal Loop

Fig. 8. Comparison of the error ratio of each sensor-head

The 1 cross orthogonal loop form, which had the lowest effect of linear birefringence, had the highest output and linearity. Also, in Fig. 7, it is shown that the Faraday Effect was decreased by increasing the linear birefringence as in Fig. 1 and Equation 12.

The (a), (b), and (c) of Fig. 8 show the results of an error ratio between the linear fitting and the output of each sensor-head using Equation 14. Output was due to the inducement of the Faraday Effect from the current as in Fig. 4. The error bars for the error ratio were determined by the standard deviation of the measurement through 10 repeated measurements.

This was then compared with the 1 Class and 0.5 Class standard of IEC 60044-8 that describes the standard of the electronic current transformers[9]. An outside guideline is 1 Class, while an inside guideline is 0.5 Class, as in Fig. 8. In (a), the closed loop form, there is a stable output characteristic at 1 Class. However, it has a lower output than the others as in Fig. 7. Section (b), the orthogonal loop form, has a higher error ratio than the others because the many cross positions of the optical fiber induce linear birefringence. Section (c), the 1 cross orthogonal loop form, is more stable than the others and meets the characteristics for the 1 and 0.5 Classes.

$$E[\%] = \frac{I_{out} - I_P}{I_P} \times 100 \qquad (14)$$

where I_{out}: the output of the optic current sensor, I_P: Linear Fitting value

5. Conclusion

In this paper, it was suggested that the 1 cross orthogonal loop sensor-head improves on the orthogonal loop sensor-head. The 1 cross orthogonal loop form was compared with the closed loop and the orthogonal loop forms.

As a result, when the three types of sensor-heads were compared, the 1 cross orthogonal loop had the highest state of polarization than the others. When the closed loop was changed to the orthogonal loop, retardation decreased 15.3[%]. When the closed loop was changed to the 1 cross orthogonal loop, retardation decreased 33.8[%].

Also, when the output characteristics and the error ratio between sensor-heads were compared, the 1 cross orthogonal loop form had an error ratio within a maximum of 1.5[%] and a minimum of 0.5[%] due to the high state of polarization. This meets the criteria of the 0.5 Class standard of IEC 60044-8. When an optical fiber is wound onto two orthogonal circular frames, the cross position gives a stress that induces the linear birefringence to the optical fiber.

Thus, the 1cross orthogonal loop type sensor-head could be applied to the fiber optic current sensor in other to develop a highly reliable fiber optic current sensor.

References

〔1〕 G. D'Antona, M. Lazzaroni, R. Ottoboni, C. Svelto, "C current-to-voltage transducer for industrial application", IMTC '03. Proceedings of the 20th IEEE, Vol.2, 20-22, May 2003.

〔2〕 R. Ulrich and A. Simon, "Polarization optics of twisted single-mode fibers", Appl. opt, vol. 18, No. 13, pp. 2241-2251, 1979.

〔3〕 D. Tang, A. H. Rose, G. W. Day, and S. M. Etzel, "Annealing of linear birefringence in single-mode fiber coils: application to optical fiber current sensors", J. Lightwave Technol.,vol. 9, no. 8, pp.1031-1037, 1991.

〔4〕 N. C. Pistoni and M. Martinelli, "Polarization noise suppression in retracing optical fiber circuits", Opt. Lett., vol. 16, no.10, pp. 711-713, 1991.

〔5〕 A. Papp and H. Harms, "Magnetooptical current transformer 2 :Components", Appl. Opt., vol. 19, no. 22, pp. 3729, 1980.

〔6〕 A. M. Smith, "Polarization and magnetooptic properties of single-mode optical fiber", Appl. Opt.,vol. 17, No.1, 1978.

〔7〕 W. J. Tabor, F. S. Chen, "Electromagnetic propagation through materials possessing both faraday rotation and birefringence: experiments with ytterbium orthoferrite", Appl. Phy., vol. 40, no. 7, 1969.

〔8〕 Y. M. Kim, J. H Park, S. W. Jee, K. S. Lee, J. B. Kim, W. Z. Park, "A comparison of signal processing Technigues in optical current sensor for GIS", KIIEE, vol. 20, no. 9, pp.103, 2006.

〔9〕 IEC60044-8, "Instrument transformers-Part 8: Electronic current transformers", 2002.

Biography

Young-Min Kim

Born Sep 15th, 1979. Graduated from the Electrical Engineering Department of Yeung Nam Univ with a Bachelors degree. Is currently a Master's level student of Electrical Engineering at Yeung Nam UniV.

Jung-Hwan Park

Born July 23rd, 1978. Graduated with a Bachelors degree from the Electrical Engineering Department of Yeung Nam Univ. Is currently, a Master's level student of Electrical Engineering at Yeung Nam Univ.

Kwang-Sik Lee

Born Oct 20th, 1948. Graduated with a Bachelor's degree from the Electrical Engineering Department of Yeung Nam Univ. Received a Ph.D from Yeung Nam University. Was a guest professor of at the Nagoya Institute of Technology. Is currently a professor in the Electrical Engineering Department of Yeung Nam University and is the president of the Korean Institute of Illumination and Electrical Installation Engineers.

Jung-Bae Kim

Born Oct 12th, 1966. Graduated with a Bachelor's degree from the Electrical Engineering Department of Han Yang Univ. Received a Ph.D from Kyushu University. Is currently, the General Manager of the Hyosung Corporation.

Won-Joo Park

Born March 14th, 1954. Graduated with a Bachelor's degree from the Electrical Engineering Department of Yeung Nam Univ. Received a Ph.D in Engineering from Kyushu University. Is currently a professor of the Electrical Engineering Department of Yeung Nam University and is the editorial chairman of the Korean Institute of Illumination and Electrical Installation Engineers.