論 文 5-5-5

풍력발전을 위한 이중여자 유도기의 센서리스 제어

金 容 現, 金 一 煥

Sensorless Control of a Doubly Fed Induction Machine for Wind Energy Generation

Yong-Hyun Kim, Eel-Hwan Kim

요 약

이중여자 유도기를 계통선 연계형 풍력발전 시스템에 적용할 때, 고정자는 계통선에 그리고 회전자는 제어 시스템에 연결된다. 이때 고정자에는 일정전압과 주파수가 걸리기 때문에, 고정자측에는 거의 일정한 고정자 자속값을 갖는다. 또한 고정자 자속을 기준으로 고정자 전류와 회전자 전류를 이용하여 슬립각을 추정하고, 이를 이용하여 고정자측에 출력되는 전력을 제어한다. 제안한 알고리즘의 타당성을 검증하기 위해 컴퓨터 시뮬레이션과 실험을 통하여 이를 입증한다.

ABSTRACT

In wind power generating system connected in power grid, the value of stator flux has almost constant because the stator side of doubly fed induction machine(DFIM) is connected to power grid. Using the stator and rotor current, it is possible to estimate the slip angle and rotor speed. A stator flux orientation scheme and rotor slip estimator are employed to achieve control of generating power in stator side. To verify the theoretical analysis, a 5-hp DFIM prototype system and PWM power converter are built. Results of computer simulation and experiment are presented to support the discussion.

Key Words : Power control, Stator flux orientation, Rotor slip estimator

1. Introduction

In wind power generating system, the most important thing is how to capture the maximum wind energy from variable wind speed. Recently, doubly fed induction machine(DFIM) with field orientation control(FOC) is very attractive to the wind power generating system under the variable wind speed because it is effectively possible to improve the capturing wind energy capability[1] [3].

The fundamental feature of a variable speed wind power generating system is that the power processed by the power converter is a fraction of the total system power and the output power must be always maintained at a constant frequency. Using only a small power converter, it is possible to achieve active and reactive power control from cut-in to cut-out speed.

If rotor speed is over synchronous speed, the output power is recovered to power source from power converter connected in rotor side and if not, slip power flow will be reversed. So real generating power is the total of stator and rotor output power.

To achieve the slip power control, a rotor slip angle and synchronously rotating angle are necessary for a variable speed wind power generating system. So we have to find the two kinds of angle. Due to connect the stator of a DFIM to the power grid, stator flux always keeps constant[2]. It is easy to find the synchronously rotating angle by stator flux estimation and the rotor angle if uses a rotor position sensor. But it is not easy to construct the rotor position sensor to large generator shaft with mechanical gear system. This is a big disadvantage. To overcome the former disadvantage, the proposed scheme dose not have rotor position sensor. For finding the information of rotor position, stator flux and slip estimator are applied to the system[3] [5].

With the result of this system, it is possible to provide a convenient regulation of active and reactive power flow between the power grid and the variable speed generator[1]-[3]. In this paper, the concept and implementation of DFIM for a variable speed drive and generating power in stator side without position sensor are proposed. To verify the proposed method, a 5-hp DFIM prototype system and PWM power converter are built. Results of computer simulation and experiment are presented.

2. Operational Principles

2.1 Wind Power Generating Control

Under the variable wind speed, the efficiency of wind power generating system will be low if use the fixed turbine speed system. Because it can not capture the maximum wind energy as shown Fig.1. As illustrated in Fig.1, the output of electrical power is related to the cube of wind speed as follows.

$$P_w = \frac{1}{2} \rho\ C_p A\ v^3 \eta\ =\ k\ v^3 [\mathrm{w}] \qquad (1)$$

where P_w : electrical output power [w]

ρ : air density [kg/m^3]

A : blade area [m^2]

v : wind speed [m/sec]

C_p : tip-speed ratio

η : system efficiency

k : $\frac{1}{2} \rho\ C_p A\ \eta$

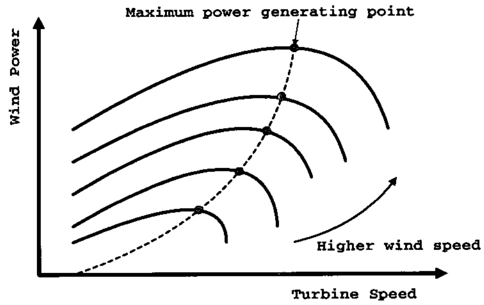

Fig. 1 Wind energy characteristics

In order to capture the maximum power energy, we have to control the system with maximum power tracking point in accordance with variable wind speed as illustrated in Fig.1. DFIM are possible to apply to this system. So this machine has a big advantage in variable wind speed generating system. The major component of this system is a wound rotor induction machine which needs to be excited at both the stator and rotor terminals. It is common practice that the stator winding is connected to the power grid directly. And the rotor winding is connected to the power converter for slip power control in accordance with variable wind speed.

In this system, the stator voltage and current have constant frequency while rotor speed is changing by wind speed. And amplitude of stator voltage almost has constant because the stator side is connected to power grid. This means that the stator flux of d and q axis in synchronously rotating reference frame have almost constant and zero respectively. Also, the stator voltage of d axis has almost zero. For field orientation control of this machine, the dynamic equations of a DFIM in synchronously rotating reference frame are as follows.

$$v_{dse}=R_s i_{dse}+\frac{d\lambda_{dse}}{dt}\approx 0 \quad (2)$$

$$v_{qse}=R_s i_{qse}+\omega_e\lambda_{dse} \quad (3)$$

$$\lambda_{dse}=L_s i_{dse}+L_m i_{dre} \quad (4)$$

$$\lambda_{qse}=L_s i_{qse}+L_m i_{qre}\approx 0 \quad (5)$$

The active and reactive power at the stator side can be derived as follows.

$$P_s=\frac{3}{2}(v_{qse}i_{qse}+v_{dse}i_{dse}) \quad (6)$$

$$Q_s=\frac{3}{2}(v_{qse}i_{dse}-v_{dse}i_{qse}) \quad (7)$$

In wind power generating system connected in power grid using DFIM, the level of stator flux remains approximately unchanged, resricted by the constant magnitude and frequency of the line voltage. Therefore, (7) can be expressed as follows.

$$P_s=\frac{3}{2}\left[v_{qse}\left(-\frac{L_m}{L_s}\right)\right]i_{qre}$$
$$=-\frac{3}{2}\frac{L_m}{L_s}v_{qse}i_{qre} \quad (8)$$

Using (1), (2) and (3), (6) can be written as follows.

$$Q_s=\frac{3}{2}\omega_e\lambda_{dse}\left(\frac{\lambda_{dse}-L_m i_{dre}}{L_s}\right) \quad (9)$$

In (9), ω_e and λ_{dse} have almost constant value.

As a result of (8) and (9), we know that it is possible to control the active and reactive power in stator side by controlling essentially decoupled i_{dre} and i_{qre}.

2.2 Slip estimation

In order to control the active and reactive power of DFIM, we need slip angle information for controlling the power converter connected in rotor side. We can be written slip angle as follows.

$$\theta_{sl}=\theta_e-\theta_r \quad (10)$$

where θ_e : Angle of synchronously rotating reference frame.

θ_r : Rotor angle.

To find the θ_{sl}, we need the angle of θ_e and θ_r. In stator flux orientation control, the reference frame rotates synchronously with respect to the stator flux. The stator flux is estimated from the terminal voltages and phase currents as described in the following equations in stationary reference frame.

$$\lambda_{dss}=\int(v_{dss}-R_s i_{dss})dt \quad (11)$$

$$\lambda_{qss}=\int(v_{qss}-R_s i_{qss})dt \quad (12)$$

where R_s : stator resistance.

The flux magnitude and transformation angle can be expressed as follows

$$|\lambda_s|=\sqrt{(\lambda_{dss})^2+(\lambda_{qss})^2} \quad (13)$$

$$\theta_e=\tan^{-1}\frac{\lambda_{qss}}{\lambda_{dss}} \quad (14)$$

If R_s is very small, $R_s i_{dss}$ and $R_s i_{qss}$ can be neglected. So θ_e can be simply derived as follows.

$$\theta_e=\theta_v-\frac{\pi}{2} \quad (15)$$

where θ_v : phase angle of the primary winding voltage.

Fig.2 shows the stator magnetizing current and rotor current phasor with torque angle(δ) and rotor current phasor angle (γ).

In this figure, torque angle can be described as follows

$$\delta=\tan^{-1}\left(\frac{i_{qre}}{i_{dre}}\right)$$

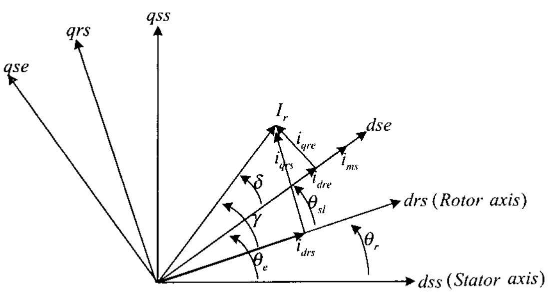

Fig. 2 Space phasor of stator maganetizing current and rotor current

Because the stator side of DFIM is fixed by the network frequency and phase voltage, λ_{dse} and v_{qse} have almost constant value, but λ_{qse} and v_{dse} have almost zero in rotating reference frame. Using (2),(3),(4) and (5), (16) can be derived as follows.

$$\delta = \tan^{-1}\left(\frac{-L_s i_{qse}}{\frac{v_{qse}-R_s i_{qse}}{\omega_e} - L_s i_{dse}} \right) \qquad (17)$$

Also in Fig.2, rotor current phasor angle can be described as follows.

$$\gamma = \tan^{-1}\left(\frac{i_{qrs}}{i_{drs}} \right) \qquad (18)$$

Using (10),(17) and (18), it is possible to estimate the rotor slip angle.

So the estimated slip and rotor angle can be described as follows.

$$\hat{\theta}_{sl} = \gamma - \delta \qquad (19)$$

$$\hat{\theta}_r = \theta_e - \hat{\theta}_{sl} \qquad (20)$$

For a speed control, it is necessary to know the rotor speed which can be obtained by the derivation of $\hat{\theta}_r$. This equation can be described as follows.

$$\hat{\omega}_r = \frac{d}{dt}(\hat{\theta}_r) \qquad (21)$$

The derivation in (21) is solved using a digial high pass filter to eliminate DC offsets.

3. Computer Simulation

To verify the feasibility of the proposed control scheme, computer simulations have been carried out.

A 5-hp DFIM is used in the simulation, and the ratings and parameters of the machine are shown in Table 1. Based on the principle discussed in above section, two control loops are constructed to realize the speed and power generating control as shown in Fig.3. With the PI controller for speed and power control, the sampling periods of current and speed cotrol are 100 μs and 1 ms, respectively.

Fig.4 shows the simulation results of speed control from 1000 rpm to 1800 rpm. In the figure, ω_r, $\hat{\omega}_r$, θ_{sl} and $\hat{\theta}_{sl}$ express the actual speed, estimated speed, actual rotor slip and estimated rotor slip, respectively. From this results, we can know that the estimation of rotor slip by (19) is well done. And Fig.5 shows the stator current in stationary domain and q axis current of rotor in synchronous domain under the same condition in the simulation results of speed control. In Fig.4 and Fig.5, the actual speed and estimated speed of the machine almost overlap. So the proposed estimation method of slip angle and rotor speed in accordance with (19) and (21) is well done.

Table 1 Parameters of model machine

Rated Power	*5 hp*	
Pole Number	*4*	
Jm $[kg-cm^2]$	*0.036*	
	Stator	*Rotor*
Rated Voltage [V]	*220*	*220*
Rated Current [A]	*16*	*11*
Resistor [Ω]	*0.3085*	*0.536*
Leakage inductance [mH]	*0.0022*	*0.0022*
Mutual inductance [mH]	*0.0441*	

Supposing that wind speed is enough to generate the power, Fig.6 shows the process of mode change from motoring to generating by controlling i_{qre} and i_{dre} using (8) and (9). Also, the reference values active and reactive power are ±1500 W and 2800

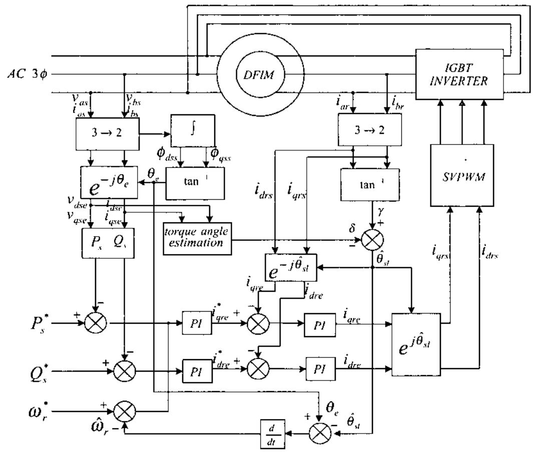

Fig. 3 Schemetic diagram of the proposed control system

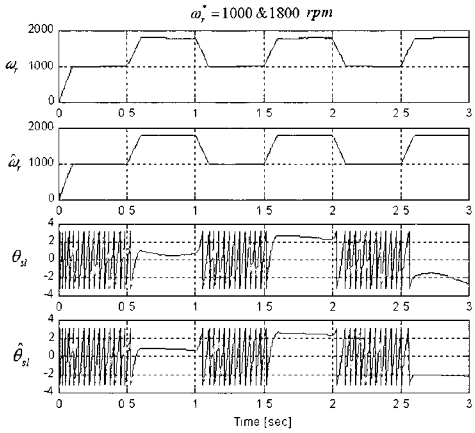

Fig.4 Estimated speed and slip angle

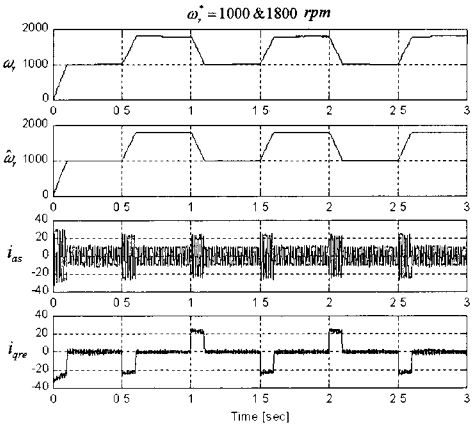

Fig.5 Step speed control

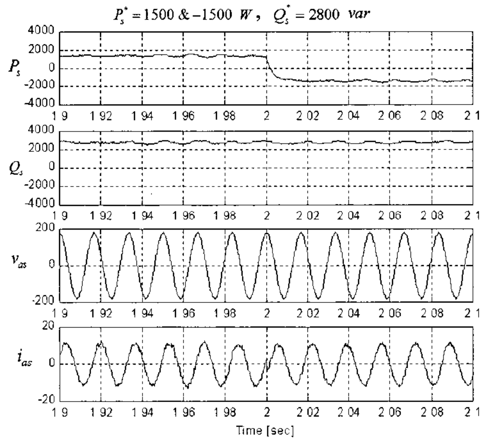

Fig. 6 Power control from motoring to generating mode

var, respectively. Using the (6) and (7), the reference values of i_{qse} and i_{dse} are 5.56 A and 10.4 A, respectively. So the peak reference value of the phase current should be $11.9(=\sqrt{5.56^2+10.4^2})$ A. As seen in the figure, the peak value of the phase current is close to the reference value.

To verify the operating mode change, a step power change is commanded from motoring to generating state at t=2 sec. As seen in the figure, the phase current of the stator lags the phase voltage within 90° before t=2 sec. After t=2 sec, the differences of phase angle between the phase voltage and current is greater than 90° . This means that the system operates well from motoring to generating mode, that is in the generating mode when P_s is negative.

Fig.7 shows the simulation results of the active power control for verifying the characteristics of step response. The reference value of active power before t=2 sec is -500 W, the reference is -1500 W after that time.

As mentioned before, the peak values of phase current should be 10.55 A and 11.78 A, respectively. As seen in Fig.7, the actul value of the current is close to the references. And the differences of phasor angle between phase voltage and current in stator side is greater than 90° . So the system is in generating mode. But the reactive power Q_s is not

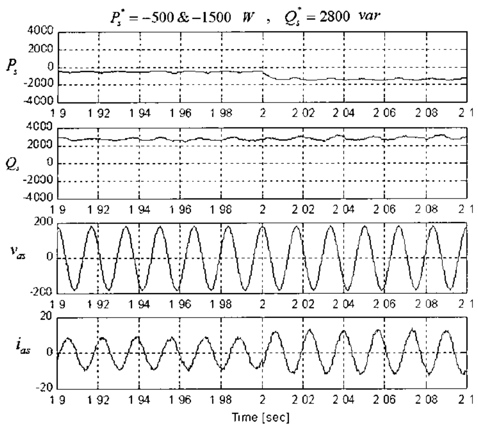

Fig. 7 Active power control

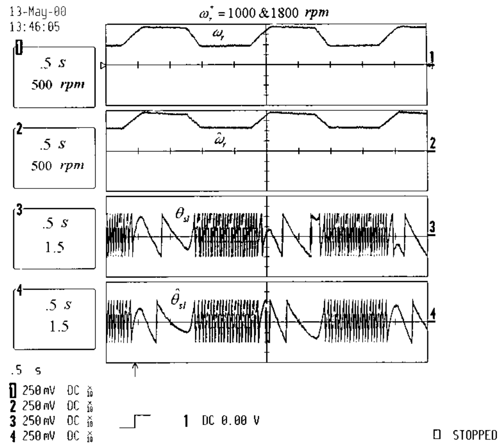

Fig. 9 Estimated speed and slip angle

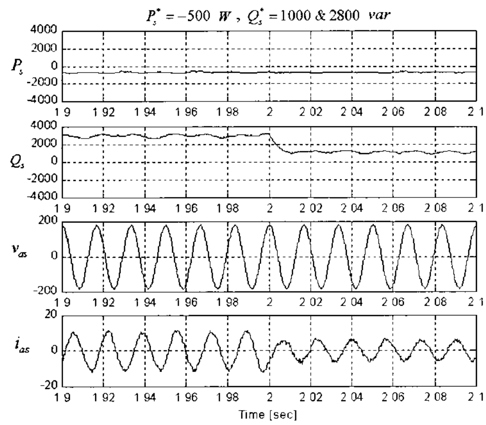

Fig. 8 Reactive power control

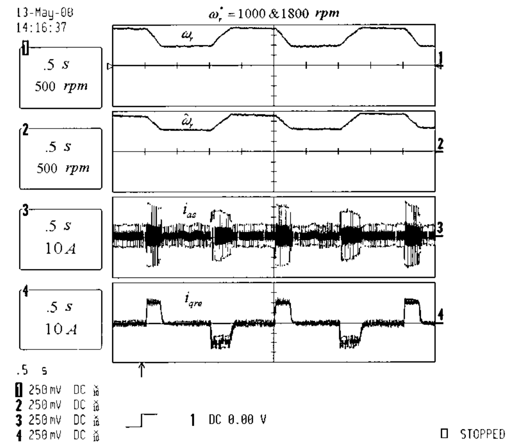

Fig. 10 Step speed control

affected at all when the transition of active power occurs. Fig.8 shows the simulation results of reactive power control. The reference value of reactive power before t=2 sec is 2800 var, the reference is 1000 var after that time. As seen in the figure, the differences of phasor angle between phase voltage and current is greater than 90° . The peak value of the phase current is close to the reference value. The value of acive power P_S keeps constant when the transition of reactive power occurs. The results shown in Fig.6, Fig.7 and Fig.8 indicate that decoupled active and reactive power control have been effectively achieved.

4. Experimental Results

To verify the effectiveness of the proposed control algorithm, a 5 hp prototype system was implemented in the laboratory. The experimental works were carried out with the proposed control scheme. A IGBT PWM inverter and TMS320C31 DSP system are connected to the rotor side. While controlling the PI controller for current and speed loop, the sampling times are 100 μs and 1 ms, respectively. Fig.9 and Fig.10 show the experimental results of speed, slip and current in the same operating condition on Fig.4. As seen in the figure, the actual and estimated values have almost same. While accelerating and reducing speed, the q axis current of rotor in synchronously rotating reference

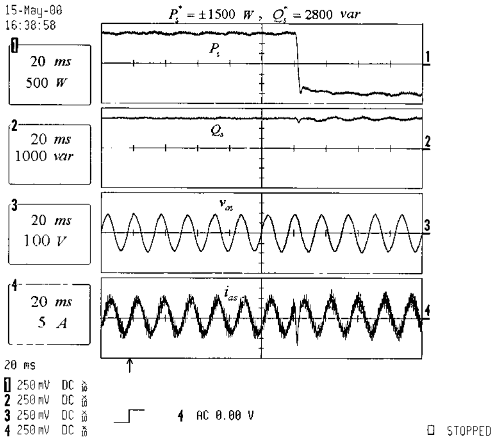

Fig. 11 Power control from motoring to generating mode

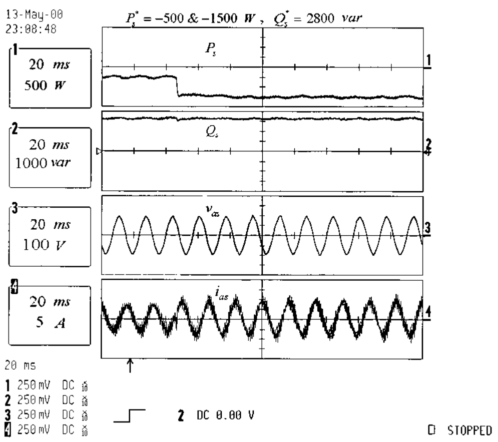

Fig. 12 Active power control

frame has − and + value. This means that the proposed control algorithm is well done by controlling i_{qre} and i_{dre} with PWM inverter system connected in rotor side.

To verify the characteristics of operation mode change from motoring to generating, Fig.11 shows the experimental results of active power control by controlling i_{qre} and i_{dre} with PWM inverter system connected in rotor side. Under the same condition values of computer simulation, the reference values of active and reactive power are ± 1500 W and 2800 var, respectively. So the peak reference value of the phase current should be 11.9 A. As seen in the figure, the actual peak value of the phase current is close to the reference value.

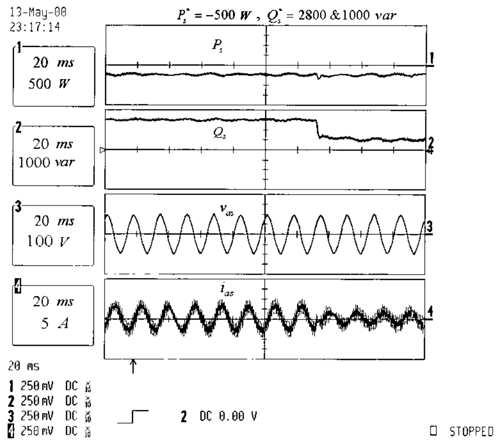

Fig. 13 Reactive power control

Also the phase current of the stator lags the phase voltage within 90° before at t=0.12 ms. After at t=0.12 ms, the difference of the phasor angle between the phase voltage and current is greater than 90° . This means that the system operates from motoring mode to generating mode. In that time, active power $P_s$is from positive to negative.

Fig.12 shows the experimental results of the active power control for verifying the characteristics of step response. The reference values of active power are −500 W and −1500 W. But the reactive power value has constant, that is 2800 var. As mentioned in simulation results, the peak values of phase current should be 10.55 A and 11.78 A, respectively. As seen in the figure, the actul value of the current is close to the reference. And the difference of phasor angle between phase voltage and current in stator side is greater than 90° . So the system is in generating mode. But the reactive power Q_s has almost the same value like simulation results in Fig.7.

Fig.13 shows the experimental results of reactive power control. As seen in the figure, the difference of phasor angle between phase voltage and current is greater than 90° . The reference values are 2800 var and 1000 var. As seen in the figure, the active power P_s keeps almost constant, that is −500 W. And the peak value of phase current is close to the reference value when the transition of reactive power occurs. The system is still in generating mode while reactive power change occurs. From the all of experimental results, it is obvious that the control performances are very good. So the proposed control scheme is very useful for wind power generating system without position sensor.

5. Conclusion

A speed drive and power generating control in stator side of a doubly fed induction machine without rotor position sensor have been proposed in this paper. To show the validity of the proposed control scheme, the comparative simulations and experiments were carried out based on stator flux and rotor slip estimation. Computer simulation and experimental results are shown in excellent agreement. Therefore, it can be expected that the proposed control scheme can be applied to the high performance applications in variable speed wind power generating system.

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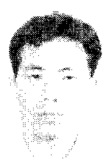
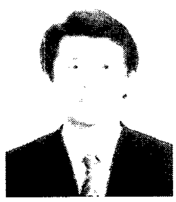
저 자 소 개



김용현(金容現)

1973년 3월생. 1997년 제주대학교 전기공학과 졸업. 현재 제주대학교 전기공학과 석사과정.



김일환(金一煥)

1962년 3월 29일생. 1985년 중앙대 학교 전기공학과 졸업. 1987년 동 대학원 전기공학과 졸업(석사). 1991년 동 대학원 전기공학과 졸업 (박사). 1995년 ~ 1996년 미국오하이오 주립대. Visiting Scholar. 현재 제주대학교 전기전자공학부 교수. 당 학회 학술위원.