Journal of the Korean Institute of Illuminating and Electrical Installation Engineers Vol. 18, No.1, pp. 142~149 March 2004 **논문** 18-2-20

계통연계 풍력발전시스템의 최대출력제어를 위한 신경회로망 제어기에 관한 연구

(Neural Network Controller of A Grid-Connected Wind Energy Conversion System for Maximum Power Extraction)

노경수* · 추연식
(Kyoung-Soo Ro, Yeon-Sik Choo)

요 약

본 논문은 바람으로부터 최대출력을 추출하기 위해 계통연계 풍력발전시스템의 신경회로망 제어기와 추출된 최대출력을 계통에 전달하기 위한 전력제어기를 제안한다. 유도발전기, 변압기, 정류기 및 인버터 등으로 구성된 제어기를 갖춘 풍력발전시스템의 모델링과 시뮬레이션에 대해 검토하고자 한다. 본 논문에서는 동특성해석을 위해 드라이브 트레인 모델, 유도발전기 모델과 계통접속 모델을 제시한다. 신경회로망 제어기는 풍차날개의 피치각을 제어하여 바람으로부터 최대출력을 추출한다. 피치제어방법은 기계적으로 복잡하지만 제어성능은 스톨제어보다 우수하게 된다. MATLAB으로 수행한 시뮬레이션 결과는 발전기 토오크, 발전기 회전속도, 피치각, 계통으로 주입되는 유효/무효전력 등을 예시하고 있으며 그 결과를 보면 제안된 제어기의 효용성을 입증할 수 있다.

Abstract

This paper presents a neural network controller of a grid-connected wind energy conversion system for extracting maximum power from wind and a power controller to transfer the maximum power extracted into a utility grid. It discusses the modeling and simulation of the wind energy conversion system with the controllers, which consists of an induction generator, a transformer, a link of a rectifier, and an inverter. The paper describes the drive train model, induction generator model and grid-interface model for dynamics analysis. Maximum power extraction is achieved by controlling the pitch angle of the rotor blades by a neural network controller. Pitch control method is mechanically complicated, but the control performance is better than that of the stall regulation. The simulation results performed on MATLAB show the variation of the generator torque, the generator rotor speed, the pitch angle, and real/reactive power injected into the grid, etc. Based on the simulation results, the effectiveness of the proposed controllers is verified.

Key Words : wind energy conversion system(WECS), maximum power, pitch control, D/A inverter

1. Introduction

In recent years, a wind energy conversion system (WECS) is getting the most attention as an environmentally benign technology since it

---

* 주저자 : 동국대학교 전기공학과 조교수
Tel : 02-2260-3346, Fax : 02-2260-3346
E-mail : ksro@dgu.ac.kr
접수일자 : 2003년 9월 29일
1차심사 : 2003년 10월 9일
심사완료 : 2003년 11월 26일

becomes cost-competitive compared to the conventional power generations. The WECS is a system converting the wind turbine's mechanical energy obtained from wind into an electrical energy through a generator and can be categorized by the types of generators used, power control methods, constant or variable speed operation, and methods of interconnecting to the grid. Variable speed operation of a wind turbine is generally more advantageous over constant speed one since variable speed operation is able to trace the maximum power of the wind turbine with wind speed changes.

Many research results have recently been reported on the control of wind turbine generators. A study of the application of induction generators to wind power generation was given in [1] where the effect of induction generator parameters and voltage support requirements for stability under disturbance conditions were studied. Steinbuch applied a linear quadratic optimal control technique to a 310kW horizontal axis WECS with a synchronous generator and DC link [2]. Leithead et al. examined the choice of control objectives together with the influence of the controller on the dynamics of the wind turbine and investigated the requirement of variable pitch control to regulate power generation [3]. Muljadi and Butterfield presented the operation of variable-speed wind turbines with pitch control [4]. Variable speed control has been added to pitch-angle controlled design in order to improve the performance of the system, but the claim that the target power is proportional to the cube of rotor speed is not correct when a pitch angle control is adopted. A fuzzy logic control approach is presented in [5] where the input variables of the control system are the variations of the output power and actual speed of the generator. Based on the generator speed and power output, the fuzzy logic controller adjusts the torque on the shaft to drive the turbine to the desired speed. Chedid et al. presented a model capable of simulating the dynamics of a WECS and compared four control techniques based on conventional and intelligent control schemes [6]. A complete fuzzy logic control based wind generation system is described in [7] where fuzzy logic principles are used for efficiency optimization and performance enhancement control.

This paper focuses on the controller design and dynamics modeling for a horizontal axis wind turbine with an induction generator and an ac/dc/ac link to a grid. A neural network pitch controller and a power controller are introduced to extract maximum power from wind and transfer the maximum power extracted into the grid. This is achieved by controlling a pitch angle of the rotor blade and firing angles of the inverter switches. Based on the simulation results of the generator torque, the generator rotor speed, the pitch angle, and real/reactive power injected into the grid, etc. for wind speed variations, the effectiveness of the proposed controllers will be verified.

2. Aerodynamic Characteristics

The energy conversion in a wind turbine can be described by the nonlinear equation of (1).

$$P_m = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \tag{1}$$

where $P_m[W]$ is the power captured from wind by the wind turbine, $\rho[kg/m^3]$ is the air density, $A[m^2]$ is the cross-sectional area of the wind turbine rotor, $v[m/\mathrm{sec}]$ is the wind speed, C_p is the power coefficient of the wind turbine, and β is the pitch angle of the rotor blade. And λ is the tip-speed ratio, which is defined by the following equation.

$$\lambda = \frac{\omega_m R}{v} \tag{2}$$

where $\omega_m[rad/\sec]$ is the rotational speed of the rotor, and $R[m]$ is the radius of the rotor blades.

The power captured by the wind turbine depends highly on the C_p for a given wind speed, and the relationship of C_p with λ represents output characteristics of the wind turbine. Fig. 1 illustrates an example of $C_p - \lambda$ characteristic curves for different pitch angles, and the curves were drawn using the following equation [8]

$$C_p = 0.4654\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-20.24}{\lambda_i}} \tag{3}$$

where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

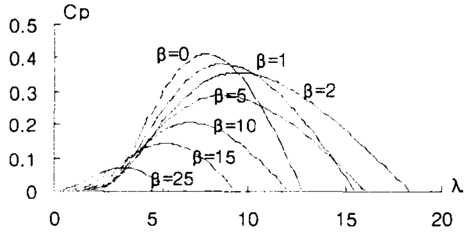

Fig. 1. Characteristic curves of wind turbine for difernt pitch angles

The figure shows power coefficient changes with tip-speed ratio variations for a specified pitch angle and there is one λ value for which the corresponding C_p value is maximized. When the pitch angle increases, the C_p value is reduced, but overall trend of the curve is maintained.

In practice, there exist limits on the wind turbine operation for wind speed variations due to the system's mechanical or electrical limitations. This gives rise to the rotor speed control requirement in order to capture maximum available wind power as well as to protect the rotor and generator facilities from mechanically or electrically overloading at high wind speeds. With taking these limitations into account, Fig. 2 shows the speed control requirement without having the pitch angle adjustments involved. The figure displays the relationships between the rotor power and the wind speed, where vci is the cut-in wind speed [4 m/s], vr is the rated wind speed [13 m/s], and vco is the cut-out wind speed [24 m/s].

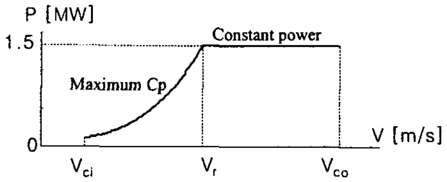

Fig. 2. Power curve of wind turbine considering limitations

3. System configuration and Modeling

Fig. 3 illustrates the block diagram of the wind energy conversion system including two control loops of a neural network (NN) pitch controller and a power controller. The wind turbine's torque is transferred through a gearbox to an induction generator, which is rated with 6-pole, 3.77 [kV] and 1.5 [MW]. An IGBT bridge rectifier rectifies the output power of the induction generator to dc, which is then inverted to 60Hz ac by an inverter and fed to a utility grid through a transformer.

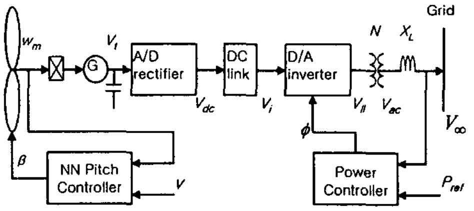

Fig. 3. Configuration of a grid-connected wind energy conversion system

3.1 Drive Train Model

A typical drive train model, as illustrated in Fig 4, primarily consists of a wind turbine, a gearbox, and a generator. The drive train converts the input wind torque into the torque on the low-speed shaft that is scaled down through the gearbox to induce a torque on the high-speed shaft. The dynamics of the rotational system can be simplified by the following equation [5].

$$\left(\frac{J_r}{n^2}+J_g\right)\frac{dw_g}{dt}=\left(\frac{T_r}{n}-T_e\right)-\left(\frac{D_r}{n^2}+D_g\right)w_g \qquad (5)$$

where, w_g is the generator rotor speed (rad/s), n is the gear box turn ratio, T_r is the mechanical input torque to the wind turbine (Nm), T_e is the electromagnetic torque applied on generator shaft (Nm), J_r is the moment of inertia of the wind turbine (kg m^2), J_g is the moment of inertia of the generator (kg m^2), D_r is the turbine friction coefficient (Nm/rad), and D_g is the generator friction coefficient (Nm/rad).

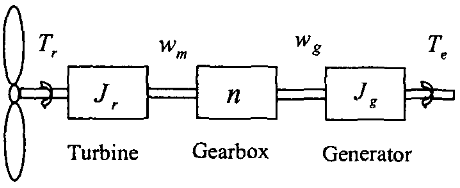

Fig. 4. Schematic diagram of drive train model

3.2 Electrical Generator Model

Recent wind turbines are generally equipped with induction generators because of low costs and simple operation. Because of its rugged construction, the induction generator is inherently a low maintenance machine and has higher expected reliability compared to the synchronous machine.

The modeling of induction generators is expressed with respect to the reference frames that are the axes rotating at synchronous speed [9]. For representation in dynamics study, the stator transients are usually neglected since they are far faster than the rotor ones. Then the stator equations are derived in the algebraic form as follows.

$$v_{ds}=-R_s i_{ds}+X_s' i_{qs}+v_d' \qquad (6)$$

$$v_{qs}=-R_s i_{qs}-X_s' i_{ds}+v_q' \qquad (7)$$

where v_{ds} is the d-axis component of stator voltage, v_{qs} is the q-axis component of stator voltage, R_s is the stator resistance, i_{ds} is the d-axis component of stator current, i_{qs} is the q-axis component of stator current, v_d' is the d-axis voltage behind transient impedance, v_q' is the q-axis voltage behind transient impedance, X_s' represents the transient reactance of the induction generator.

And the dynamic equations for the rotor windings are described as

$$\frac{dv_d'}{dt}=-\frac{1}{T_0'}[v_d'-(X_s-X_s')i_{qs}]+\frac{(w_s-w_g)}{w_s}v_q' \qquad (8)$$

$$\frac{dv_q'}{dt}=-\frac{1}{T_0'}[v_q'+(X_s-X_s')i_{ds}]-\frac{(w_s-w_g)}{w_s}v_d' \qquad (9)$$

where T_0' is the transient open-circuit time constant of the induction generator, X_s is the stator reactance, w_s is the synchronous speed and w_g is the rotor speed.

3.3 Coupling with Grid

As shown in Fig. 3, in order for the induction generator to be interconnected with a utility grid, it is necessary to use an ac-dc-ac conversion scheme since the generator produces a terminal voltage of variable-magnitude and variable-frequency. A three-phase IGBT bridge rectifier converts the terminal voltage to a dc voltage V_{dc}, which can be expressed as follows.

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_t \cos \alpha \tag{10}$$

where V_t is the generator terminal voltage and α is the firing delay angle in the switching of the rectifier. In the paper, the rectifier is not controlled, so the firing angle is assumed to be zero.

Parallel three-phase bridge inverters are used to convert the dc voltage into a 60Hz ac voltage in order to reduce harmonics involved in the inverter output voltage. The magnitude of the inverter output voltage V_{ll} is given by the equation (11).

$$V_{ll} = \frac{2\sqrt{2}}{\pi} \cos(\frac{\pi}{6}) V_i \cos \delta \tag{11}$$

where V_i is the dc link output voltage and δ is the angle at which the inverter switch is on from zero state, thus it can control the magnitude of the inverter output voltage.

The inverter output voltage is raised to the grid level by a pad-mounted transformer. The real power supplied to the grid can be computed as

$$P_{ac} = \frac{|V_{ac}||V_{\infty}|\sin \phi}{X_L} \tag{12}$$

where V_{ac} is the ac voltage behind the transformer, V_{∞} is the reference grid voltage, X_L represents the interconnecting line reactance, and ϕ determines the phase angle between the ac voltage behind the transformer and the reference grid voltage.

4. Models of controllers

4.1 Neural Network Pitch Controller

The purpose of this controller is to capture the wind energy as much as possible below the rated wind speed and to maintain the rated power above the rated wind speed by adjusting the pitch angle of the rotor blades. According to Fig. 1, the power coefficient and the turbine's tip-speed ratio are strongly influenced by the blade pitch angle and their relationships are nonlinear.

Variable pitch control on wind turbines is introduced to prevent overload as the wind speed rises above the rated, which causes the turbine regulated to spill the excess power in the wind. Adjusting the blade pitches provides fast modification of the turbine power by capturing less power from the wind at higher wind speed than the rated.

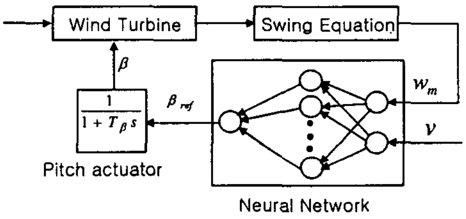

Fig. 5. Model for neural network pitch controller

Fig. 5 illustrates a model of such a pitch controller that incorporates a multi-layer perceptron-type neural network. Highly nonlinear characteristics of Fig. 1 match very well to neural network applications. The neural network has two inputs, 38 neurons in a hidden layer and one output. The number of neurons in the hidden layer was determined by trial and error to minimize the training error. The neural network, using wind speed v and rotor speed w_m as inputs, generates the desired pitch angle β.

The back-propagation learning algorithm is used since the back-propagation algorithm offers an effective approach to the computation of gradients and hence a relatively efficient training of multi-layer NNs. The wind speed values range from 4m/sec to 24m/sec and the rotor speeds range from 0.975rad/sec to 1.935rad/sec. The neural network so designed is able to produce a pitch angle for any value of wind speed and rotor speed in the range [vci ··· vco].

When the incoming wind speed exceeds the rated, the turbine power should be controlled to its rated power by adjusting the turbine blade's pitch angle β. This mechanism can be accomplished by an electro-mechanical actuator, which can be modeled as follows.

$$\frac{d\beta}{dt} = \frac{1}{T_\beta}(\beta_{ref} - \beta) \qquad (13)$$

where T_β is the actuator's time constant.

4.2 Power Controller

The objective of the power controller is to control the inverter in order to transfer the maximum power extracted from wind into the grid. Fig. 6 illustrates a model of the power controller using a PI controller for inverter switching control.

The power controller adjusts the angle ϕ in equation (12) so that the inverter output power follows the generator output power, which is the power extracted from the wind as much as possible by the NN pitch controller. From Fig. 6, the dynamics of the power controller can be described as following.

$$\frac{d\Delta c}{dt} = K_{Ib}(\Delta P_{ref} - \Delta P_{ac}) \qquad (14)$$

$$\frac{d\Delta V_\phi}{dt} = \frac{1}{T_\phi}[K_\phi(\Delta c + K_{Pb}\Delta P_{ref} - K_{Pb}\Delta P_{ac}) - \Delta V_\phi] \qquad (15)$$

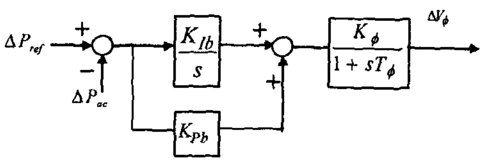

Fig. 6. Model of power controller for inverter swiching

5. Simulation and Discussions

The models of the wind energy conversion system and the controllers presented in the previous two sections are given in the forms of differential and algebraic equations. This section verifies the performance of the proposed controllers by looking into the response of the closed-loop system to a wind speed variation. Randomly varying wind speed data are shown in Fig. 7, where the wind turbine is subject to wind speeds above the rated (13m/sec) up to about 25 seconds. Data about the WECS used in this work are given in the Appendix.

For a continuously varying wind speed, the power output of the wind turbine generator will be changing accordingly. The variations of the generator torque, generator rotor speed, generator terminal voltage, pitch angle, power coefficient, and real and reactive power injected to the grid are illustrated from Fig. 8 to Fig. 14, respectively. At wind speeds above the rated, those variables are kept around the rated values owing to the pitch angle controller as shown in Fig. 11. Then the power coefficient reduces to reject the excess energy in the wind and that is shown in Fig. 12.

On the other hand, at wind speeds below the rated, those variables follow the trend of the wind speed to produce the optimal power. Fig. 9 shows a relatively smooth variation since the large inertia of the mechanical system prevents the system from following the high wind speed fluctuations.

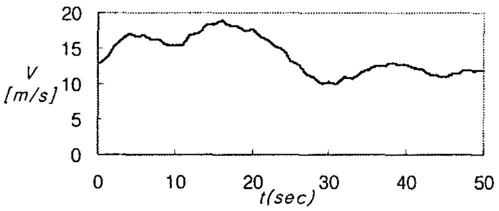

Fig. 7. Wind speed

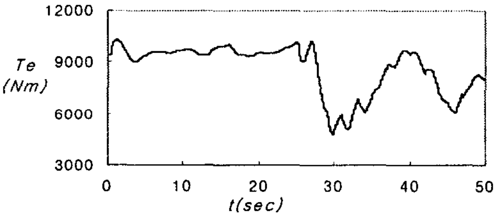

Fig. 8. Variation of generator

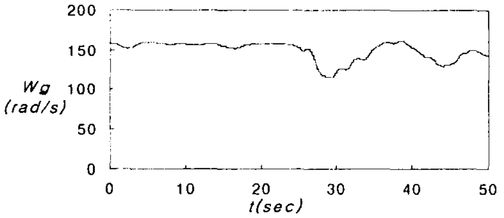

Fig. 9. Variation of generator rotor

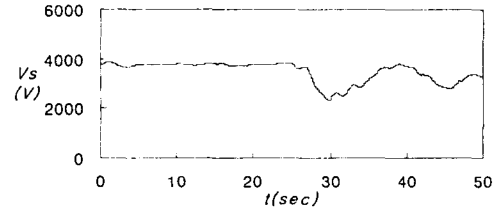

Fig. 10. Variation of generator terminal

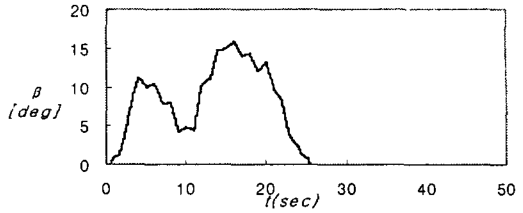

Fig. 11. Variation of pitch

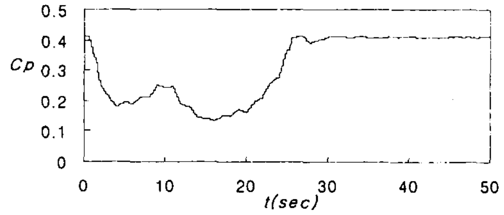

Fig. 12. Variation of power

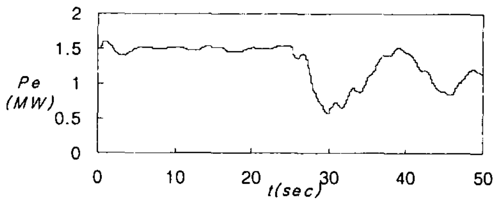

Fig. 13. Variation of real power injected to the grid

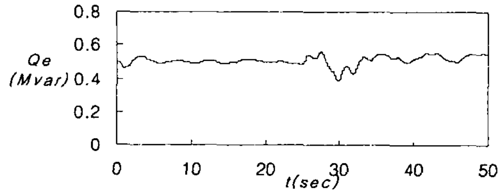

Fig. 14. Variation of reactive power injected to the grid

Fig. 10 shows the variations of the generator terminal voltage, which is not maintained at constant value due to the adoption of an induction generator. The simulation results show that the neural network pitch controller and the power controller work well in the whole region of wind speed. And the proposed controllers achieve the following two goals;

a) During low wind speeds, the wind turbine generator is operated at constant power coefficient.

b) At high wind speeds, the controllers operate the wind turbine to produce constant power.

6. Conclusion

Since wind speed varies over a large range, a variable speed wind power generation system is useful in maximizing the power extraction of a wind turbine. This paper presents a modeling and simulation of a variable speed wind energy conversion system and controllers. A neural network is adopted to control the pitch angle of rotor blades since the Cp-λ characteristics with respect to pitch angle variations are highly nonlinear. A power controller is to transfer the maximum power generated to the utility grid. Examining the operational characteristics of the wind turbine, the advantages of the variable speed mode of operation were highlighted. Based on the simulation results, we came to the following conclusions:

1) In the lower wind speed region, maximum power coefficient operating mode is adapted.

2) In the higher wind speed region, the power coefficient was kept at a lower value to reject the excess energy in the wind and the output power is kept nearly constant.

References

[1] K. Rajendiran, W.W. Keerthipala and C.V. Nayar, "PSCAD/EMTDC Based Simulation of A Wind-Diesel Conversion Scheme", IEEE Power Engineering Society Winter Meeting, 2000, pp. 505-510.

[2] M. Steninbuch, "Optimal Multivariable Control of a Wind Turbine with Variable Speed", Wind Engineering Vol. 11, No. 3 1987, pp. 153-163.

[3] W. E. Leithead, S. de la Salle and D. Reardon, Role and Objectives of Control for Wind Turbines, IEE Proceedings-C, Vol. 138, No. 2, March 1991, pp 135-148.

[4] E. Muljadi and C.P. Butterfield, "Pitch-Controlled Variable Speed Wind Turbine Generation", IEEE Transactions on Industry Applications, Vol. 37, No. 1, Jan./Feb. 2001, pp. 240-246.

[5] Z. Chen and M. Mccormick, A Fuzzy Logic Controlled Power Electronic System For Variable Speed Wind Energy Conversion Systems, IEEE Transactions on Power Electronics, No. 475, September 2000, pp 114-119.

[6] R. Chedid and F. Mrad, "Intelligent Control of a Class of Wind Energy Conversion Systems", IEEE Transactions on Energy Conversion, Vol. 14, No. 4, December 1999, pp. 1597-1604.

[7] M.G. Simoes et al., "Fuzzy Logic Based Intelligent Control of a Variable Speed Cage Machine Wind Generation System", IEEE Transactions on Power Electronics, Vol. 12, No. 1, January 1997, pp. 87-94.

[8] S. Heier, Grid Integration of Wind Energy Conversion Systems, John Wiley & Sons, 1998.

[9] P. Kundur, Power system Stability and Control, McGraw-Hill, 1993

[10] E.S. Abdin and W. Xu, "Control Design and Dynamic Performance Analysis of a Wind Turbine-Induction Generator Unit", IEEE Transactions on Energy Conversion, Vol. 15, No. 1, March 2000, pp. 91-96.

[11] M.R. Patel, Wind and Solar Power Systems, CRC Press, 1999.

[12] E. Muljadi et al., "Variable Speed Operation of Generators with Rotor-Speed Feedback in Wind Power Applications", Journal of Solar Energy Engineering, Vol. 118, November 1996, pp. 270-277.

Appendix

Wind turbine rating	1.5 [MW]
Maximum power coefficient	0.41
Radius of the rotor	32 [m]
Rated wind speed	13 [m/s]
Cut-in wind speed	4 [m/s]
Cut-out wind speed	24 [m/s]
Generator pole number	6
Air density	1.035 [kg/m3]

◇저자소개◇

노경수 (盧炅洙)

1963년 3월 27일생. 1985년 서울대 공대 전기공학과 졸업. 1987년 동 대학원 전기공학과 졸업(석사). 1990년 동 대학원 전기공학과 박사과정 수료. 1997년 미국 Virginia Tech 전기공학과 졸업(공박). 현재 동국대학교 전기공학과 조교수.

추연식 (秋淵植)

1975년 8월 18일생. 2001년 동국대 전산통계학과 졸업. 2003년 동 대학원 전기공학과 졸업(석사). 현재 삼성전자 DS총괄 SYS.LSI사업부 연구원.