論文 4-6-14

전압조정과 고조파 저감을 위한 배전용 STATCOM 개발

秋 鎭 夫, 全 榮 洙, 尹 鍾 秀, 韓 榮 城, 洪 淳 旭, 李 學 成, 申 熙 昇

A Development of a Distribution STATCOM for Voltage Regulation and Harmonic Mitigation

Jinboo Choo, Youngsoo Jeon, Jongsu Yoon, Youngseong Han
Soonwook Hong, Hahksung Lee, Heeseung Shin

요 약

본 논문에서는 순간전압조정, 역률 보상, 고조파 저감에 대한 배전용 정지형 동기조상기(STATCOM : STATic COMpensator)에 대한 다양한 제어 모드를 제안하고 있다. 이러한 제어 알고리즘의 성능을 검증하기 위해 각 제어 알고리즘을 20kVA의 축소형 STATCOM에 적용하고 간단한 배전계통을 꾸며 시험하였다. 실험결과로부터 제안한 제어알고리즘이 Custom Power 시스템으로 훌륭한 성능을 보임을 확인할 수 있었다. 실제 배전계통에 적용하여 현재 1MVA STATCOM이 성공적으로 운전되고 있다.

ABSTRACT

This paper describes the proposed various control modes of a distribution STATCOM(Static Synchronous Compensator) to provide instantaneous voltage regulation, power factor correction, and harmonics mitigation. To verify the performance of these control algorithms, each one is applied to a 20 kVA STATCOM(a reduced model of a real STATCOM) and tested with a small size distribution system. These experimental results of proposed control algorithms show good performance as a custom power system. For real application to the distribution power grid, 1 MVA STATCOM employing one of these algorithms has been made and is currently on successful commercial operation.

Key Words : STATCOM, Voltage Regulation, Harmonics Mitigation, Power Factor Correction, Voltage Source Converter

1. Introduction

Power utility and customer-side disturbances result in terminal voltage variations, transients, and waveform distortions on the distribution power system. A distribution STATCOM is a fast response, solid state power controller that provides flexible voltage control for power quality improvements at the point of connection to the distribution feeder.[1,2] A distribution STATCOM is an alternating, synchronous voltage source that is shunt connected to the distribution feeder circuit via a tie reactance. It can exchange both reactive and real power with the distribution system by varying the amplitude and phase angle of the voltage source with respect to the line terminal voltage. The result is controlled current flow through the tie reactance between STATCOM and the distribution lines. This enables STATCOM to control the terminal voltage and correct the power factor at substations and customer connection points on the feeder in instantaneous real time. In the distribution system, a STATCOM is commonly operated under voltage regulation control mode to cope with voltage drop and voltage pert urbation mainly incurred by the combination of characteristics of line impedance and load property.[3]

But one of the crucial problems in modern distribution system is the harmonics which are mostly generated by the non-linear loads. The harmonic currents in the distribution network can deteriorate the performance of electric equipment in the industry.[4] So power utility company like KEPCO requires a distribution STATCOM with the function of the harmonics mitigation lately.

This paper describes the proposed various control modes of the distribution STATCOM which include power factor correction, voltage regulation and harmonics mitigation. These control algorithms are tested and evaluated with a reduced scale STATCOM of 20 kVA rating and a small size distribution system with nonlinear loads. These test results verify the performances of the proposed control algorithm for STATCOM in the distribution lines with nonlinear loads.

2. The Function of STATCOM

2.1 Voltage Regulation Function

Fig. 1 illustrates a simplified distribution line with STATCOM. In the Fig. 1, E and V represent voltages at bus and load respectively, Z_S and Y_L represent line impedance and load admittance respectively. In Fig. 1 STATCOM is shunt connected to the PCC(Point of Common Coupling) of the distribution line. Fig. 2 illustrates the relation between E and V where $\Delta V'$ denotes voltage drop due to line impedance Z_S. $\Delta V'$ can be shown as equation (1).

$$\Delta V' = I_S R_S + jI_S X_S \qquad (1)$$

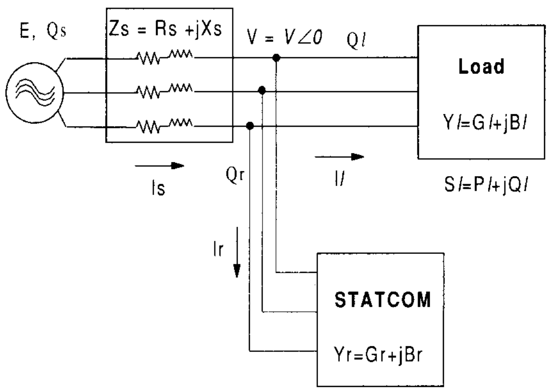


Fig. 1 Simplified distribution system with STATCOM

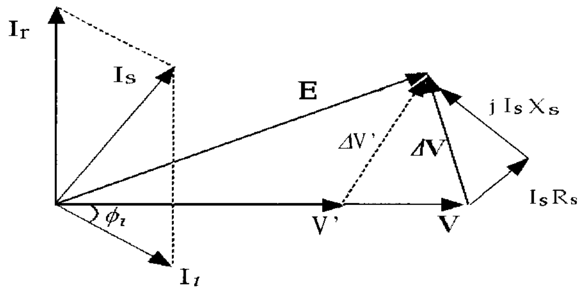


Fig. 2 Phasor diagram with STATCOM

Without STATCOM, the line current I_S is the same as the load current I_L. but in case of STATCOM appliance with voltage regulation control mode, the line current I_S can be obtained the following equation (2).

$$I_S = I_L + I_r \qquad (2)$$

where I_r is the current provided by a STATCOM.

Assuming that magnitude and phase of load current I_L is fixed with respect to the line voltage V, then the line current I_S can be controlled by adjusting the compensation current I_r. If the reactive current I_r of STATCOM is properly controlled, the PCC voltage V can be regulated within pre-defined error boundary.

Fig. 3 illustrate the proposed control block diagram for the voltage regulation represented on d-q frame. In Fig. 3 the voltage error signal enter into PI- controller and the processed signal becomes the current reference one which should provide STATCOM system. The limiter is adopted for anti-windup. The voltage reference and feedback signal are the magnitude of voltage vector.

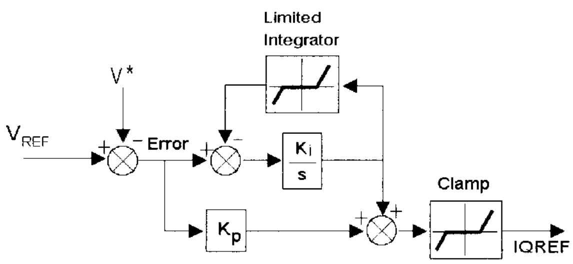


Fig. 3 Control block diagram for voltage regulation

2.2 Power Factor Correction Function

Fig. 4 illustrates the phasor diagram of voltage and current of an arbitrary load and the power factor correction of STATCOM. As shown in equation (3), load current I_L can be decoupled into real part I_R and imaginary part I_X on the complex plan. And power factor Φ_l is determined from the component of load admittance G and B.

$$\begin{aligned} I_L &= V\,Y_L = V\,(G_L + jB_L) \\ &= VG_L + jVB_L \\ &= I_R + jI_X \end{aligned} \qquad (3)$$

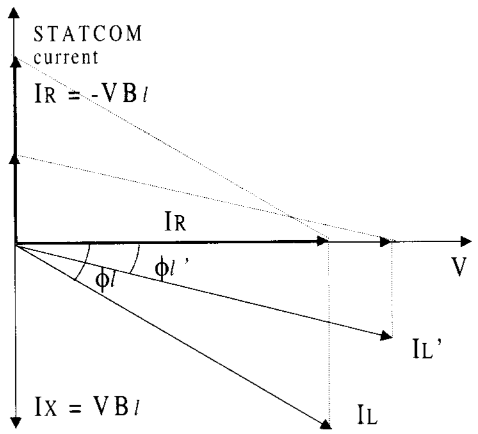


Fig. 4 Phasor diagram of power factor correction

Without STATCOM, we assume that the load consumes inductive current I_L which is exactly the same as the line current I_S ($I_S = I_L$). If the injected current from STATCOM is I_R, then the phasor of the resulting line current I_S becomes in phase with PCC voltage V. Thus as the compensation current of STATCOM increase or decrease, the resulting line current becomes capacitive or inductive one accordingly. In conclusion, with manipulating magnitude of compensating current, the phasor of line current can be controlled arbitrarily. When a capacitive load is applied, the STATCOM should have a capability of providing inductive current in order to achieve power factor correction.

2.3 Harmonics Mitigation Function

The conceptual control block diagram for harmonic mitigation algorithms is illustrated by Fig. 5 The basic idea on harmonic mitigation control is that an AC signal consisting of multi-signals with different frequency is projected onto the rotating frame with specific frequency, then only the specific component of the signal, which has the same frequency of rotating frame, can be represented by a DC value. Other components of AC signal are represented by AC signal on the rotating frame.

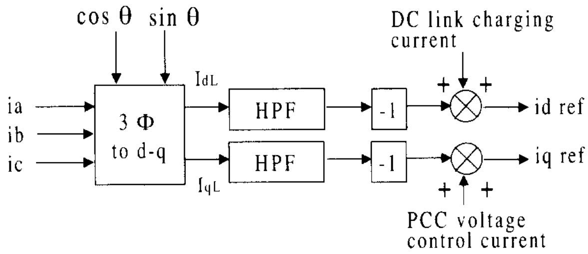


Fig. 5 Harmonic mitigation control

At the first time, the load current is transformed into the rotating frame of base frequency based on d-q transformation. For construction of the reference unit vector the information of PCC voltage is used. If the transformed load current is processed with high pass filter, then harmonic components can be extracted from the load current. The reference current of d-axis is obtained by adding AC components of d-axis to required charging current for maintaining DC link voltage constant. By the similar way the reference current of q-axis is determined by adding AC component of q-axis to the required current for regulating PCC voltage. Comparing with other algorithms this idea has one outstanding feature that the load current is filtered on the rotating frame of basic frequence, DC component can be completely filtered out. As the position of pole of the high pass filter can be placed in the vicinity of the origin, phase delay of AC components can be minimized.

3. Experiment for various control mode of STATCON

Fig. 6 illustrates the single line diagram of the experimental environment used for testing performance of the proposed STATCOM algorithm for various load conditions. Testing hardwares is shown in Fig. 7.

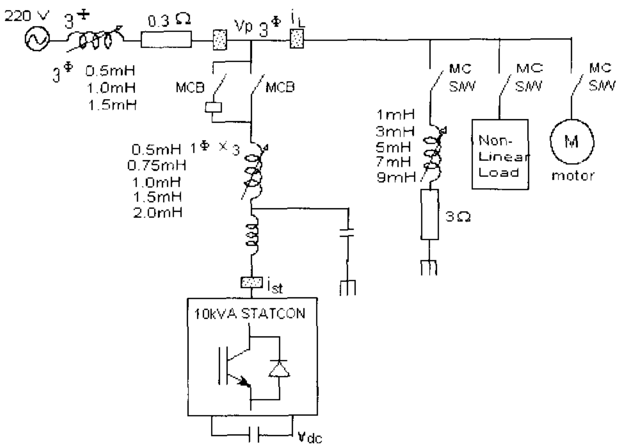


Fig. 6 Single line diagram of testing environment

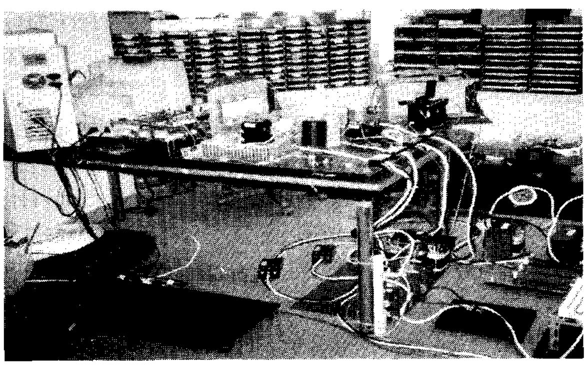


Fig. 7 A Figure of Testing Environment

20kVA STATCOM as a reduced model uses IGBTs as a power switching device and the controller adopts a 32bit floating point 33MHz DSP, hybrid ICs and a specially developed ASIC which covers decoding and PWM pulse generation. The switching frequency is 3060Hz. The distribution network of 3Φ 220V 50kVA is applied as the main power source for the STATCOM. The distribution line impedance is modelled by lumped parameter of resistor and reactor shown in Fig. 7 In this test, three different loads such as linear load, nonlinear load and an equipment for providing flicker source are used. The linear load consists of a resister and reactor combination and the nonlinear load is a combination of 3Φ full bridge diode rectifier and resister, which produces the 5th and 7th harmonic currents. And for a flicker source, A special induction motor is used.

4. Testing Results

4.1 Case 1 : Linear and nonlinear load

This is the case where a distribution network delivers electrical power to a combination of Linear and nonlinear load. Fig. 8 illustrates waveform of voltage(ch1) and line current(ch2) measured at PCC. As clearly shown in Figure, the voltage and current are significantly distorted due to the presence of the nonlinear load. Due to the voltage drop by the line impedance the PCC voltage is about 0.8pu which is much lower than the nominal value, 127V. The voltage THD is higher than 10% and the power factor is about 0.81. Fig. 9 provide with harmonic analysis of the voltage (a), (b) and current (c), (d) in which the left side (a), (c) represent total spectrum and the right one (b), (d) include only harmonic components respectively.

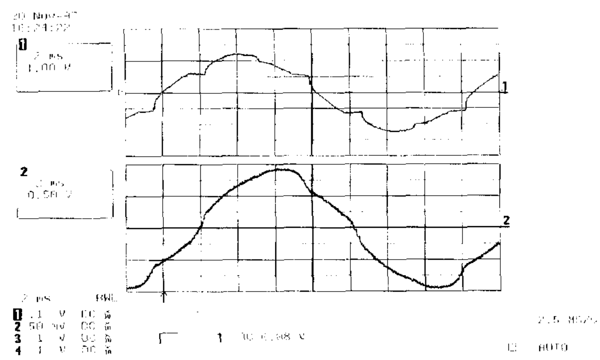


Fig. 8 Phase voltage and current of Case 1

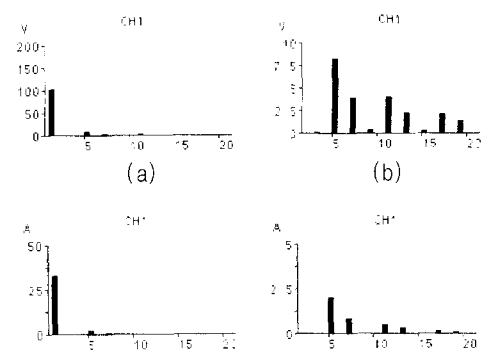


Fig. 9 FFT result of voltage and current for Case 1

4.2 Case 2 : Power factor correction control

This is the case where the proposed STATCOM with power factor correction mode is applied to the network of Case 1. The proposed harmonic mitigation algorithm is embedded in the control loop. As shown in Fig. 10 and 11 with STATCOM the THD of both voltage and current is improved more than 30% compared to Case 1. Also the power factor is regulated within 0.98 in capacitive mode appropriately.

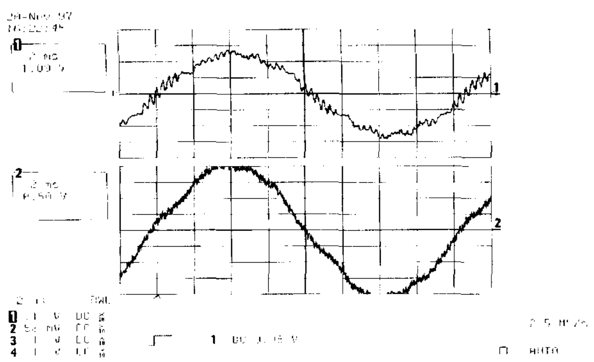


Fig. 10 Phase voltage and current of Case 2

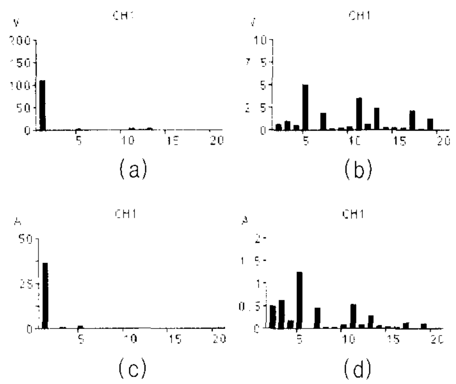


Fig. 11 FFT result of voltage & current for Case 2

4.3 Case 3 : Voltage regulation control

This is the case where the proposed STATCOM with voltage regulation mode is applied to the network of Case 1. The compensator injects capacitive current to maintain the reference PCC voltage, 127V. As the result system maintains a leading power factor of 0.7. Even though here harmonic mitigation algorithm is not embedded, the voltage THD is considerably improved due to the fast control action. Furthermore the current THD is also quitely improved. This is mainly due to the increase of the fundamental component of current under without reduction of absolute magnitude of harmonic current.

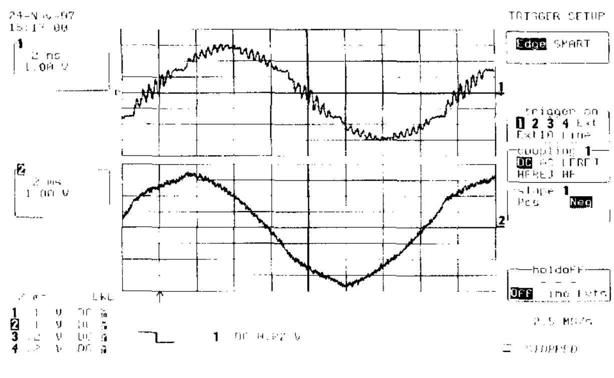


Fig. 12 Phase voltage and current of Case 3

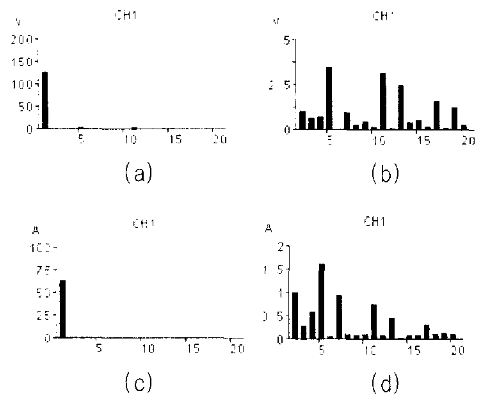


Fig. 13 FFT result of voltage & current for Case 3

Table 1 Summary of Testing Results

	CASE 1	CASE 2	CASE 3
Voltage THD(%)	10.51	6.99	4.84
Phase Voltage(V)	103.29	112.53	127.3
Current THD(%)	7.21	4.55	4.1
Current(A)	33.57	36.58	57.49
Power Factor	0.81	0.978	0.7
kVA(1Φ)	3.47	4.12	7.32

4.4 Case 4 : Flicker control mode

This is the case where the proposed STATCOM with voltage regulation mode is applied to the network to see the control performance under flicker environment When large induction motor starts up, the in-rush current should be provided from the distribution network. The voltage dip profile, defined as a deviation from nominal value(1.0 pu), seen at PCC is illustrated by Fig. 14. The maximum voltage dip of 70V is observed in Fig. 14. When the STATCOM is applied to this network, the maximum voltage dip is reduced to 20V as shown in Fig. 15. As clearly seen at Fig. 15, the duration time of transient is also significantly reduced, 0.6 sec to 0.3 sec. This is because the induction motor can start up with full voltage, which is supported by the STATCOM. It, however, shows that a little amount of voltage dip exists with STATCOM. This is due to current limit of the controller for over current protection. The Fig. 16 illustrates the tracking performance of the proposed STATCOM, in which ch2 and ch1 represents reference of reactive current and feedback respectively. The reactive current tracks to the reference very closely. The Fig. 17 and Fig. 18 shows the phase voltage and current profiles.

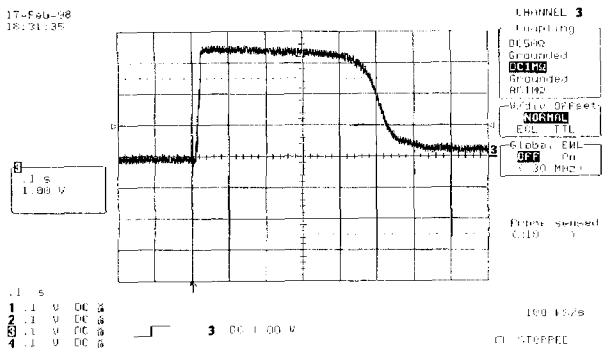


Fig. 14 Voltage Dip Profile Without STATCOM

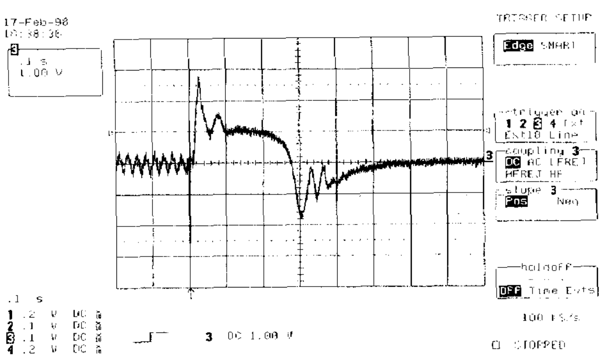


Fig. 15 Voltage Dip Profile With STATCOM

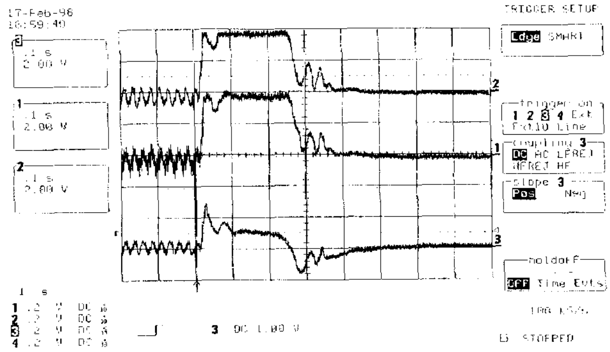


Fig. 16 Tracking Performance of Reactive current

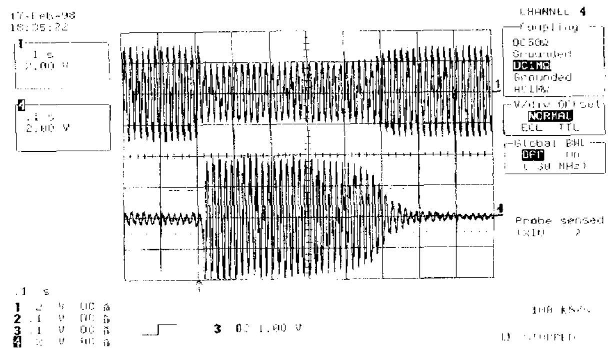


Fig. 17 Voltage and Current Profiles Without STATCOM

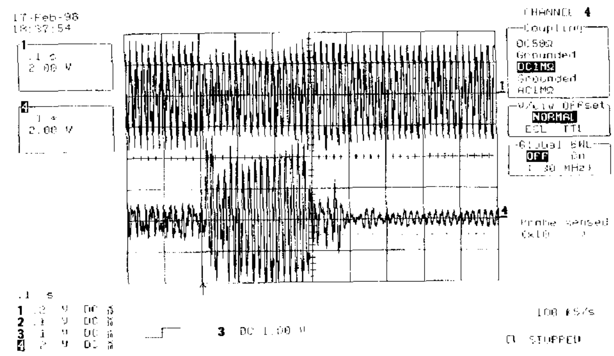


Fig. 18 Voltage and Current Profiles With STATCOM

5. Conclusion

This paper presents a development of distribution STATCOM for specific application. Especially harmonic mitigation algorithm is presented for incorporation into controller for improvement of its performance. This algorithm is embedded for controller with various control modes; voltage regulation, power factor correction and flicker compensation. 20kVA STATCOM is manufactured and tested in reduced modeled distribution network under various load conditions. Testing results show that the proposed algorithm has outstanding features in harmonic mitigation, power factor control application. Furthermore it successfully cope with severe flicker environment. For real application to the distribution grid, 1MVA 22.9kV class STATCOM has been established and is now under commercial operation for justification of performance.

Reference

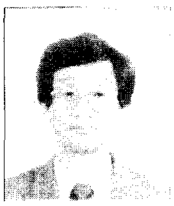
[1] Colin Schauder, Harshad Mehta, "Vector Analysis and Control of Advanced Static Var Compensators", IEEE Proceedings, Vol. 140, No. 4, July 1993

[2] Schauder, C. D., et al., "Development of a 100 MVAR Static Condenser for Voltage Control of Transmission Systems," IEEE Trans. on Power Delivery, Vol. 10, No. 3, July 1995

[3] T. J. E. Miller, "Reactive Power Control in Electric Systems", John Wiley & Sons, Inc. 1982

[4] Fang Zheng Peng "Application Issues of Active Power Filters", IEEE Industry Magazine, September 1998

저 자 소 개



추진부(秋鎭夫)

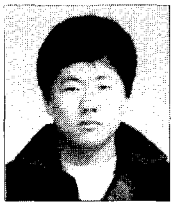
1950년 1월 7일생. 1977년 서울대 전기공학과 졸업. 1987년 동 대학원 석사학위. 1994년 동 대학원 전기공학 박사학위. 현재 한국전력공사 전력연구원 수석연구원.

전영수(全榮洙)

1960년 2월 9일생. 1983년 성균관대 전기공학과 졸업. 1999년 충남대 전기공학 석사학위. 현재 한국전력공사 전력연구원 선임연구원.

윤종수(尹鍾秀)

1968년 5월 30일생. 1993년 경북대 전기공학과 졸업. 1996년 동 대학원 전기공학 석사학위. 현재 한국전력공사 전력연구원 일반연구원.

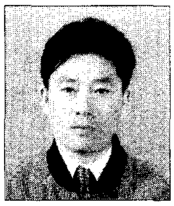


한영성(韓榮城)

1967년 11월 4일생. 1990년 한양대 전기공학과 졸업. 1992년 동 대학원 전기공학 석사. 현재 (주)효성 중공업연구소 책임연구원보.

홍순욱(洪淳旭)

1964년 2월 1일생. 1987년 연세대 전기공학과 졸업. 1989년 미주리주립 대학원 전기공학 석사학위. 1991년 동 대학원 전기공학 박사학위. 현재 (주)효성 중공업연구소 수석연구원보.



이학성(李學成)

1957년 9월 27일생. 1981년 서울대 전기공학과 졸업. 1983년 동 대학원 석사학위. 1992년 USC 전기공학 박사 학위. 현재 (주)효성 중공업연구소 수석연구원.

신희승(申熙昇)

1953년 8월 26일생. 1975년 서울대 전기공학과 졸업. 현재 (주)효성 중공업연구소장.