A New Approach to PID Controller Design of STATCOM

C. Pang, *Student Member, IEEE*, and M. Kezunovic, *Fellow, IEEE*

***Abstract*—As a common reactive power compensation equipment in power system, the static synchronous compensator (STATCOM) has played a very important role in the stable operation of power system, which requires fast response and well-designed controller. This paper presents a new approach to proportional-integral-derivative (PID) controller design of STATCOM based on root counting and signature theory with the help of computer-aided calculation. The complete coefficient set of stabilizing PID controllers can be found, which is superior to the traditional trial and error method. The performance specification could be considered within the entire stabilizing set to identify the desired values of coefficient gains of PID controller. Case study is implemented to illustrate and verify the feasibility of the proposed approach.**

***Index Terms*—STATCOM control, PID, model based design, root counting, performance specification, cascading event**

I. Introduction

POWER system security and stability are the top priority when operating the electric power system. All the other targets, such as economic dispatch and optimal load flow, are all subject to the requirements of system security and stability. Power systems are exposed to all kinds of disturbances, which may come from bad weather, human errors, equipment malfunction, natural disasters, etc., and some of these disturbances may cause power service interruption. This situation is getting even worse under new market rules introduced by deregulation causing more stressed operation.

Among the disturbances, cascading outage, especially the large-scale cascading outage, draws special attention since it can cause great economic damage to the power system and devastating impact on people’s life. For example, Northeastern System Blackout in 2003 led to the load loss of 61.8GW, which influenced more than 50 million people [1]. The recent research efforts and solutions are aimed at understanding and finding ways to detect, prevent, and mitigate the cascading events. [2-5] A novel interactive scheme of system/local monitoring and control tools for detection, prevention and mitigation of cascading events was recently introduced [6-13]. This scheme can identify the disturbance information and provide control means for preventing further unfolding of the cascading events and keeping the stability of the power system. Another very important approach in to mitigating the cascading event is trying to take some preventive actions before the disturbances happen.

As we all know, the power system stable operation is supported by many control means, such as exciter control system, reactive power compensation, frequency regulation service, etc. Selecting suitable parameters of the controller will improve the control performance and system ability to resist instabilities. Reactive power control is one of the most critical services. Shortage of reactive power will increase the transmission losses, degrade power transmission capability, decrease load end voltage regulation, and increase the chance for the system outages [14]. With the development of power electronics and the increasing power rating achieved by solid-state devices, the Static Synchronous Compensator (STATCOM) has taken the places of the traditional Thyristor-Controlled Reactors (TCR) and Thyristor-Switched Capacitors (TSR) as the reactive power compensation equipment. Thus the continuous reactive power control with fast response is the main requirement for the STATCOM controller [15].

The control of STATCOM has been discussed in many published papers, which includes state feedback control techniques, pole placement method, etc. [16-18]. The ultimate aim is to determine the optimal parameters for the controller by using genetic algorithm, linear quadratic regulator (LQR) method, etc. However, an important method for PID (Proportional-Integral-Derivative) controllers was reported in [19, 20]. In this paper, the new PID controller design and synthesis approach for STATCOM control is introduced based on the root counting and signature theory [21, 22]. This approach can find the complete set of stabilizing PID controllers in the PID coefficients gain space. Once the entire set is found, it will be very easy to solve the performance attainment problems and meet the desired requirements such as guaranteed gain and phase margins, since the performance results can be evaluated by sweeping the PID parameter space under the given plant.

This paper is organized as follows: Section II introduces the overview of STATCOM modeling. The design and synthesis approach for the PID controller is described in detail in Section III. Section IV presents the implementation

This work is supported by Power System Engineering Research Center (PSerc) under the project S-29 tilted “Detection, Prevention and Mitigation of Cascading Events – Prototype Implementations”.

C. Pang and M. Kezunovic are with the Department of Electrical Enginering, Texas A&M University, College Station, TX 77843-3128, USA (emails: pangchz@neo.tamu.edu, kezunoc@ece.tamu.edu)

methodology. Simulation cases and comparative results are shown in Section V. Conclusions are given in Section VI.

II. Mathematical Model of STATCOM

Because of the high dynamic performance, STATCOM has become one of the most effective equipments for reactive power compensation. The compensation does not depend on the common coupling voltage, which makes STATCOM solution attractive due to its advantages: precise and continuous reactive power control with fast response, and minimal interaction with power grid. STATCOM is becoming a predominant new generation devices for flexible AC transmission systems (FACTS).

The mathematical model of STATCOM has been discussed in the literature [14, 15, 17]. Figure 1 shows a typical STATCOM configuration from literature [14]. The DC bus voltage is built up across the DC capacitor. By controlling the fireing command for each of the three-phase bridges, the desired voltage across a bridge will be generated and the current through the line impedance R and L is controlled [14].

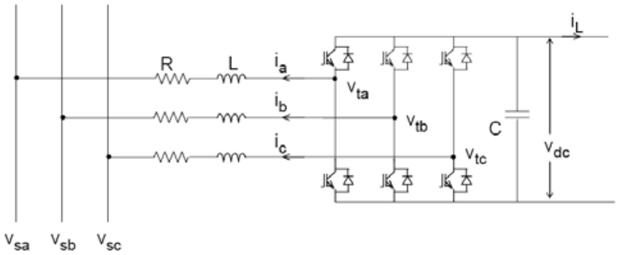

Fig. 1. STATCOM system configuration

STATCOM is a Multiple Input Multiple Output (MIMO) system. Thus a multivariable control approach is needed for the STATCOM control design. Although it is not possible to totally decouple the system variables, there is one powerful tool for studying balanced three phase system, which converts the three phase voltages and currents into orthogonal components in a synchronous rotating frame by Park Transform. The MIMO system will be simplified for the decoupling method. The orthogonal components in the rotating frame are referred to as active and reactive components. The proposed approach for PID controller design and synthesis will be applied for the decoupled control variable.

The mathematical expression of the STATCOM system is given in equation (1) to (4). [14]

$$\frac{di_d}{dt} = -\frac{R}{L} i_d + \omega i_q + \frac{1}{L}\left(V_{td} - V_{sd}\right) \tag{1}$$

$$\frac{di_q}{dt} = -\omega i_d - \frac{R}{L} i_q + \frac{1}{L}\left(V_{tq} - V_{sq}\right) \tag{2}$$

$$\frac{dV_{dc}}{dt} = -\frac{3\left(V_{td} i_d + V_{tq} i_q\right)}{2CV_{dc}} - \frac{i_L}{C} \tag{3}$$

$$Q = \frac{3}{2}\left(V_{sq} i_{sq} - V_{sd} i_{sd}\right) \tag{4}$$

where ω is the angular power frequency, and subscripts d, q represent variables in the rotating coordinate system for the components of direct and quadrature axis, respectively.

Choosing the states x, the inputs u, and the output y by:

$$x = \begin{bmatrix} i_d \\ i_q \end{bmatrix}, \; u = \begin{bmatrix} V_{td} - V_{sd} \\ V_{tq} - V_{sq} \end{bmatrix}, \; y = \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

The equations (1) and (2) can be rewritten to the state space transfer function as the linear system:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \tag{5}$$

where the corresponding coefficient matrices are:

$$A = \begin{pmatrix} -\frac{R}{L} & \omega \\ -\omega & -\frac{R}{L} \end{pmatrix}, \; B = \begin{pmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{pmatrix}, \; C = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

The detailed STATCOM control block diagram is described in literature [17], which includes two control loops in the whole system for the decoupled variable. The new approach will be applied for each variable, which will be discussed later.

III. Design and Synthesis of PID Controller

In this section, we develop the new approach for the PID controller design and synthesis of STATCOM.

A. PID Controller

PID controller is one of the most common controlling devices in the market. Because of its very simple control structure and the linear control methodology, PID control is generically important in many industries and has been widely used in electrical, mechanical, hydraulic, fluidic, and pneumatic systems [21]. It can provide the set point regulation of zeroing error under arbitrary low frequency disturbances, and it owns robust characteristics for those modeling errors. Three term controllers are easier to adjust at the design stage as well as online.

Consider the general feedback system with a PID controller and plant transfer function $G(s)$, which is shown in Figure 2.

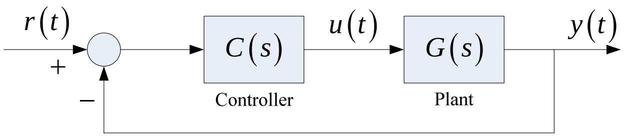

Fig. 2. A feedback system with PID controller

Where $r(t)$ is the reference signal, $u(t)$ is input signal,

$y(t)$ is the output, $C(s)$ is the controller to be designed. For the PID controller, $C(s)$ will be:

$$C(s) = k_p + \frac{k_i}{s} + k_d s \tag{6}$$

where k_p, k_i and k_d are the proportional, integral and derivative gains respectively. In some cases when the error is measured in a noisy environment, a delay part for the transfer function should be considered as:

$$C(s) = \frac{sk_p + k_i + k_d s^2}{s(1+sT)},\ T > 0 \tag{7}$$

where T is usually a small positive value.

The design of PID controller is to determine the values of coefficients k_p, k_i, and k_d, which could make the controller stabilize the given plant. When the controller is used in industries, the performance of the feedback system under the control of the designed PID controller should also be considered. Those parameters should be adjusted so that acceptable performance, such as the rising time, settling time, gain margin, etc. could be obtained. Many controller design methods, such as a model based approach using state space models, state feedback control, and quadratic optimization [23], fixed order controller design in discrete-time system [24], model free synthesis approach based on time series data [25], etc. have been presented in the past years. The tuning methodologies of the PID controller have been developed over the years based primarily on empirical observations and industrial experience.

B. Fixed Order Controllers Design based on Root Counting

Fixed order controller design based on root counting theory is extended from the classical Hermite-Bieler Theorem. The new stabilization algorithm is described in the literature [20-22], which could be used to generate the entire set of stabilizing PID controllers.

Consider the feedback system with PID controller, which is shown in Fig. 2, the plant transfer function $G(s)$ is expressed as:

$$G(s) = \frac{N(s)}{D(s)} \tag{8}$$

where $N(s)$ and $D(s)$ are polynomials in the Laplace variable s. The closed-loop characteristic polynomial is:

$$\delta(s,k_p,k_i,k_d) = sD(s) + (k_i + k_d s^2)N(s) + k_p sN(s) \tag{9}$$

The problem of the PID controller design stabilizing the given plant has been converted to determining the values of k_p, k_i and k_d for which the closed-loop characteristic polynomial is Hurtwitz, which means it has all its roots in the open left half plane (LHP).

The basis idea of the root counting theory is separating the parameters. Define

$$N^*(s) = N(-s) = N_e(s^2) - sN_o(s^2) \tag{10}$$

Then define,

$$\begin{aligned}
\nu(s) &:= \delta(s,k_p,k_i,k_d)N^*(s) \\
&= \Big[s^2\big(N_e(s^2)D_o(s^2) - D_e(s^2)N_o(s^2)\big) \\
&\quad + (k_i + k_d s^2)\big(N_e(s^2)N_e(s^2) - s^2N_o(s^2)N_o(s^2)\big) \\
&\quad + s\Big[D_e(s^2)N_e(s^2) - s^2D_o(s^2)N_o(s^2) \\
&\quad + k_p\big(N_e(s^2)N_e(s^2) - s^2N_o(s^2)N_o(s^2)\big)
\end{aligned} \tag{11}$$

The stability of $\delta(s,k_p,k_i,k_d)$ is determined by whether $\nu(s)$ has exactly the same number of closed right half plane (RHP) zeros as $N^*(s)$. By creating the test polynomial $\nu(s)$, the parameter separation has been achieved, where $\delta(s,k_p,k_i,k_d)$ has all three parameters appearing in both the even and odd parts, comparing with $\nu(s)$ that only has k_p appearing in the odd part, and k_i, k_d appearing in the even part. Let $s = j\omega$:

$$\delta(j\omega,k_p,k_i,k_d)N^*(j\omega) = p(\omega,k_i,k_d) + jq(\omega,k_p) \tag{12}$$

where $p(\omega,k_i,k_d) = p_1(\omega) + (k_i - k_d\omega^2)p_2(\omega)$, $q(\omega,k_p) = q_1(\omega) + k_p q_2(\omega)$,

$$p_1(\omega) = -\omega^2(N_e(-\omega^2)D_o(-\omega^2) - D_e(-\omega^2)N_o(-\omega^2))$$

$$p_2(\omega) = N_e(-\omega^2)N_e(-\omega^2) + \omega^2N_o(-\omega^2)N_o(-\omega^2))$$

$$q_1(\omega) = \omega(D_e(-\omega^2)N_e(-\omega^2) + \omega^2D_o(-\omega^2)N_o(-\omega^2))$$

$$q_2(\omega) = \omega(N_e(-\omega^2)N_e(-\omega^2) + \omega^2N_o(-\omega^2)N_o(-\omega^2))$$

The subscript of o and e are the components of odd and even part respectively.

Let $l(N(s))$ and $r(N(s))$ denote the number of roots of $N(s)$ in the open LHP and RHP respectively; let n and m be the degrees of $\delta(s,k_p,k_i,k_d)$ and $N(s)$ respectively. $sgn: R \to \{-1,0,1\}$ is the standard signum function. Since $\nu(s)$ must have exactly the same number of RHP roots as $N^*(s)$, the range of k_p will be determined by satisfying the necessary condition that $q(\omega,k_p)$ has at least β real, nonnegative, distinct roots of odd multiplicity, where

$$\beta = \begin{cases} \dfrac{\left|n-(l(N(s))-r(N(s)))\right|}{2} & \text{for } m+n \text{ even} \\[2ex] \dfrac{\left|n-(l(N(s))-r(N(s)))\right|+1}{2} & \text{for } m+n \text{ odd} \end{cases}$$

By using this root counting theory, the stability condition reduces to:

$$n-(l(N(s))-r(N(s)))=\begin{cases}\{i_0-2i_1+2i_2+\cdots+(-1)^{l-1}2i_{l-1}\\ \quad +(-1)^l i_l\}\cdot(-1)^{l-1}\operatorname{sgn}[q(\infty,k_p)] \\ \quad \text{for } m+n \text{ even} \\ \\ \{i_0-2i_1+2i_2+\cdots+(-1)^{l-1}2i_{l-1}\} \\ \quad \cdot(-1)^{l-1}\operatorname{sgn}[q(\infty,k_p)] \\ \quad \text{for } m+n \text{ odd}\end{cases}$$

In conclusion, the value of k_p will be fixed by choosing from the range of k_p, which is determined by roots counting of $q(\omega,k_p)$. Then for each fixed value of k_p, determining the set of (k_i,k_d) values that simultaneously satisfy the following string of linear inequalities:

$$[p_1(\omega_t)+(k_i-k_d\omega_t^2)p_2(\omega_t)]i_t>0, \forall\, t=0,1,2,\cdots$$

By sweeping k_p over the appropriate ranges, the entire set of stabilizing the plant by the designed PID controller is determined. The detailed proof and formulas of root counting theory can be found in the literature [21].

IV. Implementation of Statcom Control System

A. Implementation Approach for PID Design

The PID design approach based on the root counting is aimed at single-input single-output. However, STATCOM control system requires the multivariable control approach because of the MIMO characteristic. As mentioned in Section II, Park transform is used to decouple the multivariable system. Park transform is a very powerful tool in power system analysis. It can convert the three phase voltages and currents into orthogonal components in a synchronous rotating frame. Those orthogonal components are fixed to the rotor and are only related with active and reactive power respectively, which is shown in equation (13):

$$\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} = P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{13}$$

where i_a, i_b, and i_c are the currents for three AC phase respectively;

i_d and i_q are active and reactive components in the rotating frame;

P is the Park transform matrix:

$$P=\frac{2}{3}\begin{bmatrix} \cos(\omega t) & \cos\left(\omega t-\frac{2}{3}\pi\right) & \cos\left(\omega t+\frac{2}{3}\pi\right) \\ -\sin(\omega t) & -\sin\left(\omega t-\frac{2}{3}\pi\right) & -\sin\left(\omega t+\frac{2}{3}\pi\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Thus the control design problem will be greatly simplified using this decoupling processing. Literature presents the detail mathematical model for decoupling [15]. The new design approach presented in this paper can be used for each decoupled component.

Root counting theory provides a feasible way to get the entire set of controls for stabilizing the system. This method highly depends on the computer aided design. With the mature development of computer techniques, it will be much easy to implement the design. Once the entire stabilizing set has been determined, the extra requirements such as guaranteed rising time, settling time, overshoot, gain and phase margins can be easily obtained.

B. Performance Requirements for STATCOM Controller

STATCOM is an important part of the Flexible AC Transmission System (FACTS) solution, which is used to improve power system stability [26, 27]. It is widely used for voltage regulation by injecting or absorbing system reactive power. Thus the STATCOM controller is required to maintain the output voltage or current tracking via regulation of input components. The desired dynamic performances for STATCOM controller design include less oscillation, smaller overshoot, and shorter settling time. The control strategy focuses on performance requirements for each of the decoupled components.

In this paper, the performance requirements are considered in proposed PID controller design method, which includes rising time, settling time, overshoot, gain and phase margins. After the entire set for the stabilizing system based on root counting and signature theory is obtained, the quantity values of each performance specifications will be calculated point by point in the entire set. The comparison criterion is created according to the performance requirements of PID controller design. All the points whose performance meets the criterion will be recorded. Thus by sweeping point by point, the subset within which the points satisfy the performance requirements will be obtained.

V. Case Study Simulation

In order to verify the proposed approach, a Matlab model for simulating the system shown in Fig. 2 is built to test this design method. The chosen system parameters are listed below, which came from [14]:

Line resistance $R=2m\Omega$

Line inductance $L=400\mu H$

Frequency $f=60Hz$

Therefore the corresponding coefficient matrices for the state space transfer function are:

$$A=\begin{pmatrix} -5 & 376.99 \\ -376.99 & -5 \end{pmatrix}, \quad B=\begin{pmatrix} 2500 & 0 \\ 0 & 2500 \end{pmatrix},$$

$$C=\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

The proposed PID controller design approach is tested by the Matlab model for STATCOM. Root counting theory is used for each of the decoupled components. We take the controller for the variable i_d as the example. Fig. 3 shows the entire stabilizing set of PID controller. Any point within the obtained set refers to one PID controller, whose coefficients values are $\left(k_p, k_i, k_d\right)$. This PID controller can stabilize the studied STATCOM. Fig. 4 shows an example for STATCOM unit step response for stabilizing and un-stabilizing PID controller which come from the point of inside and outside the stabilizing set respectively.

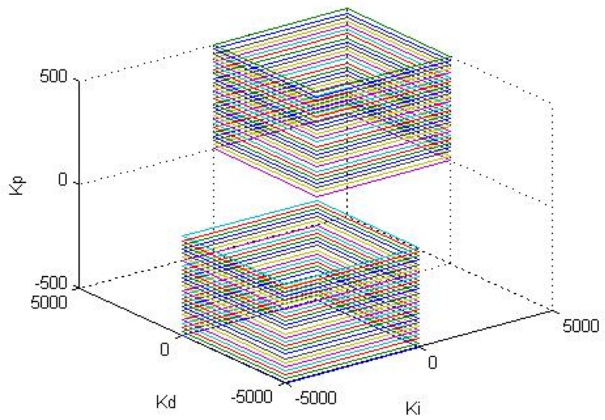

Fig. 3. The Stabilizing set of $\left(k_p, k_i, k_d\right)$values

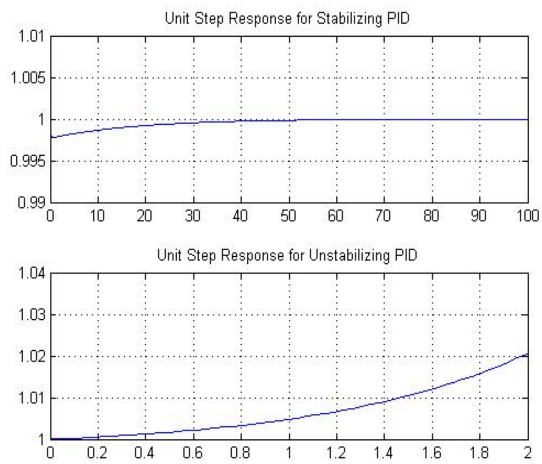

Fig. 4. The unit step response for stabilizing and un-stabilizing PID Controller

Stabilizing the plant is the necessary requirement for PID controller design. The performance attainment problems are also very important, especially in industry application. As we mentioned before, one the entire stabilizing set of the coefficients of PID controller has been obtained, the performance test can be implement for each of the point. The performance specification can be added to the PID controller design. Table I shows the six sets of PID controller coefficients for the case study.

The unit step response for each of the PID controllers is shown in Fig. 5. They exhibit different performance although all of them can stabilize the studied plant of STATCOM. For example, in some cases we hope to get the PID controller with overshoot less than 0.05%. Fig. 6 shows the results of the overshoot for the set of six PID controllers. Under this requirement, PID 2, 3, 4 and 5 are satisfied. PID 3 has the best overshoot performance among these PID controllers.

TABLE I
PID CONTROLLER COEFFICIENTS

	PID 1	PID 2	PID 3	PID 4	PID 5	PID 6
K_p	496.164	496.164	496.164	273.657	273.657	7.673
K_i	168.44	44.3262	26.5957	79.7872	186.170	8.8625
K_d	100.806	52.4294	52.4294	100.806	52.4294	100.806

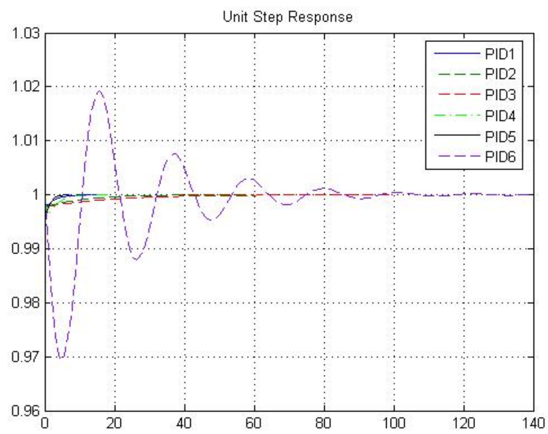

Fig. 5. Unit step response for each PID controller of i_d

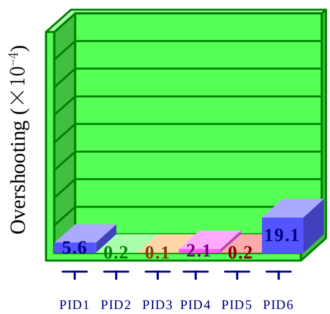

Fig. 6. The performance of overshooting of each PID controller

VI. CONCLUSION

STATCOM has become one of the most important equipments for the reactive power compensation. Fast response controller with well-designed coefficients for the STATCOM control will improve the stability of power system operation and decrease the possibility of blackouts happening, which will be beneficial for preventing cascading events.

This paper presents a new approach for PID controller design of STATCOM, which is based on root counting and signature theory. This approach can locate the complete set of stabilizing PID controllers in the PID coefficients gain space, $\left(k_p, k_i, k_d\right)$, and any point within this set exhibits an ability to stabilize the studied STATCOM system. The performance attainment problems will be easily solved after the entire stabilizing set is found. The desired coefficient set of PID controller for satisfying the performance requirements of STATCOM could be identified by sweeping the part of entire set, which includes overshoot, rising time, settling time, gain and phase margins. Case study has been implemented based on the Matlab simulation. The test results verified the feasibility of the proposed approach.

VII. Acknowledgment

Gratefully acknowledge the contributions of Dr. S.P. Bhattacharyya from Texas A&M University for the root counting and signature theory insight.

VIII. References

[1] U.S.-Canada Power System Outage Task Force, “Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations”, April 5, 2004, Available: http://www.nerc.com

[2] Q. Chen, K. Zhu, J.D. McCalley, "Dynamic decision-event trees for rapid response to unfolding events in bulk transmission systems", in Proc. of IEEE 2001 Power Tech Proceedings, Vol. 2 , Sept 2001

[3] B.A. Carreras, V.E. Lynch, I. Dobson, "Dynamical and probabilistic approaches to the study of blackout vulnerability of the power transmission grid", in 2004 Proc. of the 37th Annual Hawaii International Conference on System Sciences, Jan. 2004, pp. 55 - 61

[4] J.C. Tan, P.A. Crossley, P.G. McLaren, "Application of a wide area backup protection expert system to prevent cascading outages", IEEE Transactions on Power Delivery, vol. 17(2), April 2002, pp. 375 - 380

[5] D. C. Elizondo, J. de La Ree, A. G. Phadke, S. Horowitz, “Hidden failures in protection systems and their impact on wide-area disturbances”, in Proc. of IEEE 2001 PES Winter Meeting, Jan/Feb 2001, Vol. 2, pp. 710 – 714

[6] H. Song, M. Kezunovic, “A Comprehensive Contribution Factor Method for Congestion Management”, in 2004 Proc. of IEEE PES PSCE, Oct 2004

[7] H. Song, M. Kezunovic, "A New Analysis Method for Early Detection and Prevention of Cascading Events," Electric Power Systems Research, Vol. 77, Issue 8, Pages 1132-1142, June 2007

[8] M. Kezunovic, C. Pang, "Improved Transmission Line Protection During Cascading Events," CIGRE B5 Colloquium, Madrid, Spain, October 2007.

[9] M. Kezunovic, C. Pang, J. Ren, Y. Guan, "New Solutions for Improved Transmission Line Protective relay Performance Analysis," The 14th Mediterranean Electrotechnical Conference-MELECON 08, Ajaccio, France, April 2008.

[10] N. Zhang, H. Song, M. Kezunovic, "New Monitoring and Control Scheme for Preventing Cascading Outage," North American Power Symposium NAPS 2005, Ames, Iowa, October 2005.

[11] N. Zhang and M. Kezunovic, "A Real Time Fault Analysis Tool for Monitoring Operation of Transmission Line Protective Relay," Electric Power Systems Research Journal, Vol. 77, No. 3-4, pp. 361-370, March 2007

[12] Nan Zhang, M. Kezonovic, “Coordinating fuzzy ART neural networks to improve transmission line fault detection and classification,” IEEE PES General Meeting, San Francisco, June 2005.

[13] M. Kezunovic, B. Perunicic, and J. Mrkic, “An Accurate Fault Location Algorithm Using Synchronized Sampling,” Electric Power Systems Research Journal, Vol. 29, No. 3, pp. 161-169, May 1994.

[14] W. Ren, et al. “A Multivariable Control Method in STATCOM Application for Performance Improvement,” Industry Applications Conference, vol. 3, pp. 2246-2250, 2005

[15] L. xing, “A Comparison of Pole Assignment and LQR Design Methods for Multivariable Control for STATCOM,” MSc. Dissertation, Florida State University, 2003

[16] P. Garcia-Gonzalez, A. Garcia-Cerrada, “Control System for a PWM-based STATCOM,” IEEE Trans. on Power Delivery, vol. 15, no. 4, pp. 1252-1257, Oct. 2000.

[17] V. Blasko. V. Kaura, “A New Mathematical Model and Control of a Three-Phase AC-DC voltage Source Converter,” IEEE Trans. Power Delivery, vol. 12, no. 1, pp.116-123, Jan. 1997.

[18] P. Rao, M. L. Crow, Z. Yang, “STATCOM Control for Power System Voltage Control Application,” IEEE Trans. on Power Delivery, vol. 15, no. 4, pp. 1131-1317, Oct. 2000.

[19] Darbha, S. Pargaonkar, S. Bhattacharya, S.R. , A linear programming approach to the synthesis of fixed structure controllers. In Proceedings of the 2004 American Control Conference, vol. 5, pp. 3942 –3949.

[20] G. J. Silva, A. Datta and S. P. Bhattacharyya, “New Results on the Synthesis of PID Controllers,” *IEEE Transactions on Automatic Control*, Vol. 47, No. 2, 241-252, February 2002.

[21] Ho, M. T., Datta, A., and Bhattacharyya, S. P. Structure and Synthesis of PID Controllers. Springer - Verlag, London, UK, 2000.

[22] Keel, L. H., and Bhattacharyya, S. P. A generalization of Mikhailov’s criterion with applications. In Proceedings of the 2000 American Control Conference (Chicago, IL, June 2000).

[23] R. E. Kalman, “On the general theory of control systems,” Proceedings of the 1st IFAC World Congress, Mosvow, USSR, 1960.

[24] W. M. Haddad, H.H. Huang, and D. S. Bernstein, “Robust stability and performance via fixed-order dynamic compensation: the discrete-time case,” IEEE Control systems Magazine, vol. 26, pp. 80-91, February, 2006.

[25] U. S. Park and M. Ikeda, “Data-based stability analysis for linear discrete-time system,” Proceedings of the 43rd IEEE Conference on Decision and Control, Atlantis, Bahamas, December 14-17, 2004.

[26] L. Chun, et al., “Ruled-based control for STATCOM to increase power system stability”, IEEE Proc. On PowerCon, vol 1, pp. 372-376., Beijing, China, 1998.

[27] A. Ghafouri, et al., “Fuzzy Controlled STATCOM for improving the power system transient stability,” in Proc. of 39th North American Power Symposium, 2007. NAPS’07, pp. 212-216.

IX. Biographies

Chengzong Pang (S’07) received his B.S and M.S. degrees in electrical engineering from North China Electric Power University, China in 2000 and 2003, respectively. Since Aug. 2006, he has been with Texas A&M University pursuing his Ph. D. degree. His research interests are power system analysis, protection, stability and control.

Mladen Kezunovic (S’77, M’80, SM’85, F’99) received his Dipl. Ing. Degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. Dr. Kezunovic’s industrial experience is with Westinghouse Electric Corporation in the USA, and the Energoinvest Company in Sarajevo. He also worked at the University of Sarajevo. He was a Visiting Associate Professor at Washington State University in 1986-1987. He has been with Texas A&M University since 1987 where he is the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to control, protection and power quality monitoring. Dr. Kezunovic is a registered professional engineer in Texas, and a Fellow of the IEEE.