Power System Reliability Analysis Considering Protection Failures

Xingbin Yu, *Student Member, IEEE*, and Chanan Singh, *Fellow, IEEE*

***Abstract*—This paper describes power system reliability evaluation including protection system failures. A modified protection system reliability model including two major protection failure modes is established. Protection system failure is the main cause of cascading outages. The mechanism and scheme of protection system have been analyzed on their contribution to the cascading outages after a fault occurs. Non-sequential Monte Carlo simulation approach is used to implement the stochastic properties of component contingency and protection system failure. The whole procedure is verified in the WSCC-9 bus system. BIP (Bus Isolation Probability), LOLP (Loss of Load Probability), and newly introduced EPL (Expected Power Loss) are calculated to demonstrate the vulnerability of a power system under cascading outages.**

***Index Terms*—Power system, Reliability, Protection systems, Rare events, Cascading, Hidden failures.**

I. Introduction

Modern power systems have stepped into the post-restructuring era, in which utility industry as well as ISO are involved. Attention needs to be paid to the reliability study of power systems both in the utility companies and the ISO. Considerable progress has been made in power system reliability modeling and computational methods. In most reliability analysis, protection systems are generally assumed to be perfectly reliable. A study by NERC (North American Electric Reliability Council) shows that protective relays are involved in about 75 percent of major disturbances. Normally power system blackouts result from cascading failures. There are many blackout cases in history such as Northeast blackout on November 9,1965; New York City blackout in July 1977 and Southern Idaho system instability on December 14, 1995. In 1996 alone, WSCC suffered two blackouts, one on July 2^{nd} and another on August 10^{th}. The former was initiated by a flashover near a 345KV transmission line and its protection misoperated and triggered the tripping of two units nearby, which led to parts of WSCC system operating below WSCC Minimum Operating Reliability Criteria. The latter was a false tripping that caused 30,000MW load and 27,000MW generation loss and 7.5 million customers were without power [1]. All these blackouts are related to protection system hidden failures, which remain dormant when everything is normal and are exposed as a result of other system disturbances [2]. There is more and more evidence that protection systems have played a role in the origin and propagation of major power system disturbances. In the deregulated power systems where monetary consequences are involved, the ability to keep the continuity of power supply becomes more significant. Large-scale power system blackout is a rare event. However, when it occurs, the impact on the system is catastrophic [3]. Protection system malfunction plays a significant role in the sequence of events that lead to power system blackouts. However, not much effort has been spent on the study of the cascading events due to protection system malfunction. Therefore it is necessary to develop reliability study methodology concerning the protection system failures.

II. Protection Failure Modes and Cascading Outages

There are two major failure modes of protection system: "failure to operate" and "undesired tripping" [4]. The former one means that when a fault occurs in a power system, the protection system refuses to operate to clear the fault. In practice, phenomenon of stuck breaker is included in this mode. The latter refers to either spontaneous operation in the absence of a fault or trip for faults outside the protection zone.

A cascading outage refers to a series of tripping initiated by one component failure in the system. When a fault occurs, the impact to the system such as over-current or voltage dropping may cause some protection devices to misoperate. As we mentioned before, two types of protection system failures are the major cause of cascading outages. From the viewpoint of real life protection scenario, we know that "Failure to operate" will directly cause at least one bus isolation in the system. "Undesired tripping", however, makes the problem complicated due to various protection system hidden failures [2]. Spectral tripping in the absence of a fault may be remedied immediately by auto-recloser. This situation can be endured and does not have any significant effect on the system reliability. Therefore, it is not within our study scope in this paper. Tripping for faults outside the protection zone is the main cause of the cascading outages.

The authors gratefully acknowledge the support from Texas Advanced Technology Program and Energy Resource Research Program at Texas A&M University.

Xingbin Yu is with the Dept. of Electrical Engineering, Texas A&M University, College Station, TX 77843 USA (e-mail: xingbin@ee.tamu.edu).

Chanan Singh is with the Dept. of Electrical Engineering, Texas A&M University, College Station, TX 77843 USA (e-mail: singh@ee.tamu.edu).

III. MODEL AND ASSUMPTIONS

A. Model

There have been a number of models established to facilitate the reliability evaluation including protection system failures. The model of current-carrying component paired with its associated protection system proposed by Singh and Patton [5] [6] is effective for general reliability analysis. However, it does not differentiate protection failure modes. In this paper, therefore, the model is expanded to include the failure modes of protection system as shown in Fig. 1, where:

State 1: the current-carrying component and the protection system are both good.

State 2: the component is good but the protection is at risk for "undesired trip".

State 3: the component is good but the protection is exposed to "failure to operate".

State 4: the component is good and the protection system is being inspected.

Stage 5: the component is failed while the protection system is still under "undesired trip"

State 6: the component is failed but the protection system is good.

State 7: the component is failed while the protection system has experienced "failure to operate".

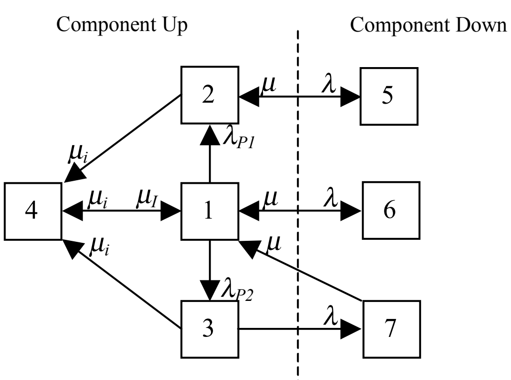


Fig. 1. State transition diagram of a component and its protection system.

B. Notation

μ_i inspection rate of protective system.

μ_I repair rate of protection system.

μ repair rate of component.

λ failure rate of component.

λ_{P1} failure rate of protection system to exposure to "undesired trip".

λ_{P2} failure rate of protection system to state of "failure to operate"

C. Assumptions

1) Failure to operate and undesired trip of the protection system failure do not overlap. That means whenever unrevealed protection failure exists, it will reside either in state 2 or state 3.
2) When component fails, the protection system does not fail.
3) All failures are mutually independent. Failures of the protection system are independent of the failures of the component.
4) Inspection of protection system does not lead to component failure.

Based on this model, we can get protection system failure probability with regard to its inspection. The derived data can be used in our following study.

IV. METHODOLOGY

A. Basic Methodology

As shown in Fig.2, suppose a fault occurs in L-1, normally protection system for this line will operate to clear the fault. L-2 and L-3, sharing the same bus with the faulted L-1, are exposed lines that are at risk to trip also.

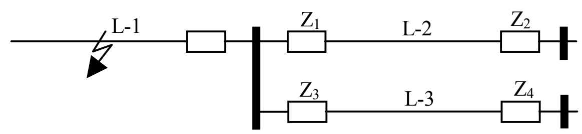


Fig. 2. Sequence of cascading outage

If L-2 trips for its protection system failure, then up to this step the probability of cascading outage can be calculated by:

$$P(cas)=P_f(L\text{-}1) * P_f(Z_1 \cup Z_2) * (1-P_f(Z_3 \cup Z_4)) \quad (1)$$

where

$P(cas)$ probability of cascading outage.

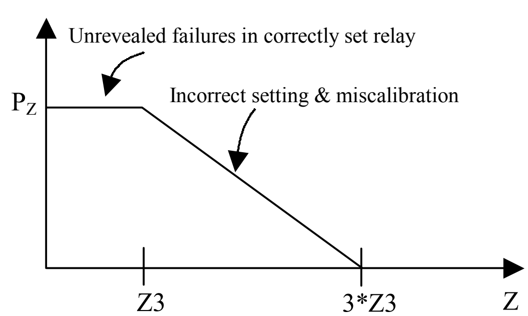
$P_f(L\text{-}1)$ probability of L-1 failure.

$P_f(Z_1 \cup Z_2)$ probability of the union of protection system Z_1 and Z_2 failure

$P_f(Z_3 \cup Z_4)$ probability of the union of protection system Z_3 and Z_4 failure

B. Protection System Failure Properties

Reference [7] proposed hidden failure probability of exposed line tripping incorrectly as a function of impedance seen by the relay. In this paper, we introduce some simplification for the probability properties. For distance protection scheme, property is shown in Fig. 3.

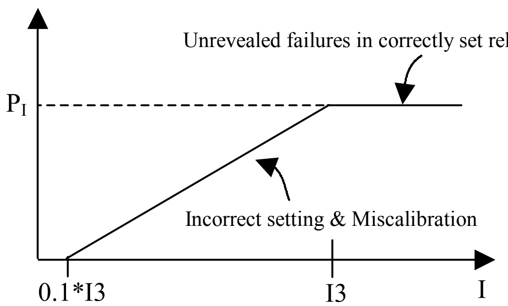


P_Z: Distance protection failure probability
Z3: Impedance zone 3 setting
Z: Impedance seen by relay

Fig. 3. Distance protection failure probability of exposed line

Similarly, we give over-current protection failure probability property as shown in Fig. 4.

Fig. 3 and Fig. 4 show that the probability of exposed line tripping incorrectly is not simply a fixed value as derived from Markov model in Fig.1. On the contrary, it is also dependent on the fault and operating conditions.



P_I: Over-current Protection failure probability
I3: Over-current Zone 3 setting
I: Current seen by relay

Fig. 4. Over-current protection failure probability of exposed line

C. Assumptions in Calculations

In calculations, we are only concerned about the distance protection zone 3 and over-current zone 3. We choose zone 3 impedance setting as 250% of the line impedance; zone 3 over-current setting as 10% of the rated secondary current of CT (Current Transformer).

Besides the above description, additional assumptions are made as follow:

1) Generator and transformer are treated as one unit whose failure rate is the sum of their individual failure rates.
2) For the initial fault, only first order contingency is considered.

V. Reliability Indices

According to the assumptions made, any system condition with two and more components outage is caused by protection system failure.

In this paper, we calculate

1) BIP (Bus Isolation Probability).

$$BIP=\sum_i I_i / N \tag{2}$$

where i is the element of set of bus isolation.

I_i is the number of system state *i.*

N is the total number of simulations.

Bus isolation is a major disturbance to the power system. BIP shows the weakness of system in which one component outage might result in bus isolation.

In simulation, "bus isolation" is the criterion to stop for a series of outages. This means that as the series of outages progress, it is stopped as soon as a bus is isolated.

2) LOLP (Loss of Load Probability).

$$LOLP = \sum_i L_i / N \tag{3}$$

where i is the element of set of load curtailment.

L_i is the number of system state *i.*

N is the total number of simulation.

Normally power system can withstand one component outage without adequacy and security violation. Based on our assumption, here the LOLP represents the loss of load resulting from protection system failure. Since we are concerned here with loss of load, the series of outages is stopped as soon as a loss of load occurs.

3) EPL (Expected Power Loss)

$$EPL = \sum_i C_i / N \tag{4}$$

where i is the element of set of completion of cascading outages.

C_i is the load curtailment of system state *i.*

N is the total number of simulation.

This index with unit of "MW" can numerically show the impact to the system by cascading outage.

In simulation, no artificial stop criterion for a series of outages is used for calculating this index. The series of outage will keep extending until no more new outage occurs.

VI. Calculation of Reliability

A. Formulation of OPF

In the process of calculating LOLP and EPL, OPF (optimal power flow) is used to determine the occurrence and the amount of load curtailment of the system. OPF formulation is shown as below:

Objective: $$\min \sum_{i=1}^{n} (Load\_Curtailment)_i \tag{5}$$

where $(Load\_Curtailment)_i = P_{di} - P_{li}$

ST:

$$P_{gi} - P_{li} - \sum_{j=1}^{n} U_i U_j (G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) = 0$$

$$Q_{gi} - Q_{li} - \sum_{j=1}^{n} U_i U_j (G_{ij}\cos\delta_{ij} - B_{ij}\sin\delta_{ij}) = 0$$

$i=1,\ldots,n$

$$P_{gi\min} \le P_{gi} \le P_{gi\max}$$

$$Q_{gi\min} \le Q_{gi} \le Q_{gi\max}$$

$i=1,\ldots,n_g$

$$0 \le P_{li} \le P_{di} \qquad i=1,\ldots,n_d$$
$$0 \le Q_{li} \le Q_{di}$$
$$U_{i\min} \le U_i \le U_{i\max} \qquad i=1,\ldots,n$$
$$P_{ij}^2 + Q_{ij}^2 \le S_{ij\max}^2 \qquad ij \in [1,\ldots,n_b]$$

where

n, n_g, n_d, n_b are the number of node, generator node, load node and branch;

P_{gi}, Q_{gi} are the real and reactive output of the generator;

P_{gimin}, P_{gimax} are the min/max real power of the generator;

Q_{gimin}, Q_{gimax} are the min/max active power of the generator;

P_{li}, Q_{li} are the load after rescheduling of generation;

P_{di}, Q_{di} are the actual demand;

U_i is the voltage magnitude;

U_{imin}, U_{imax} are the voltage magnitude limits;

P_{ij}, Q_{ij} are the line flow;

S_{ijmax} is the line flow limit.

B. Flowchart

Non-sequential Monte Carlo simulation approach is applied to calculate all reliability indices. The sequence of simulation steps is shown in Fig. 5 and Fig. 6.

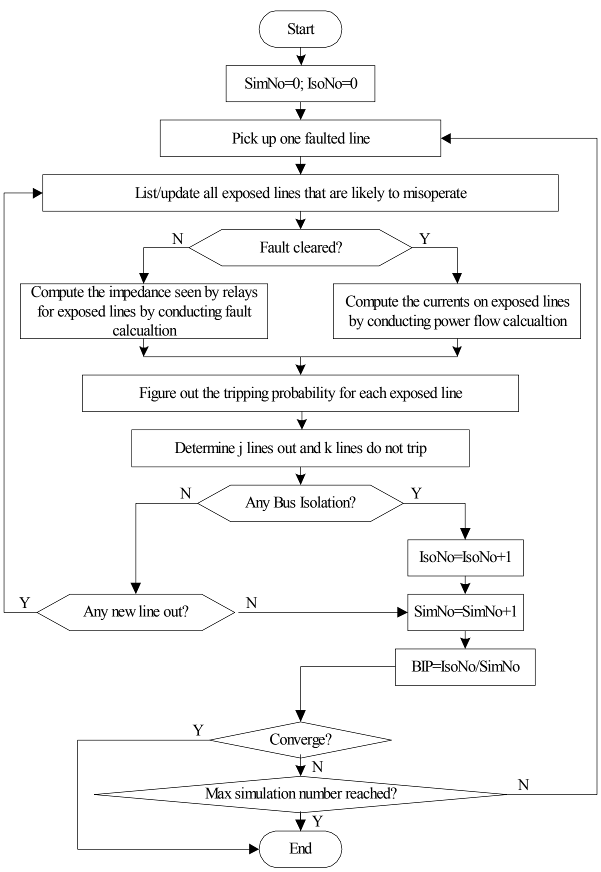


Fig. 5. Flowchart for calculating bus isolation probability

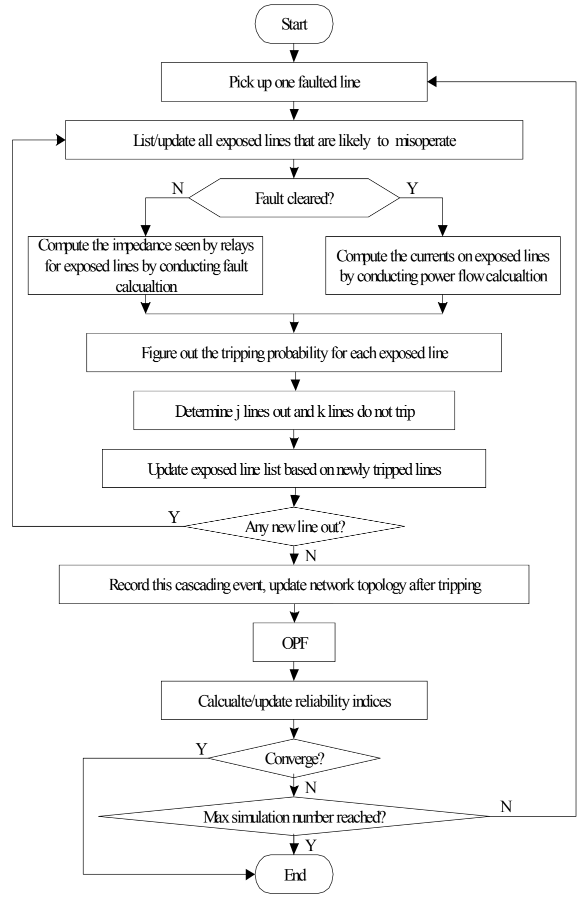


Fig. 6. Flowchart for calculating LOLP and EPL

C. Test System

We use WSCC-9 bus system as the test system (shown in Fig. 7). Because it is not complex, it clearly provides insight into cascading outages.

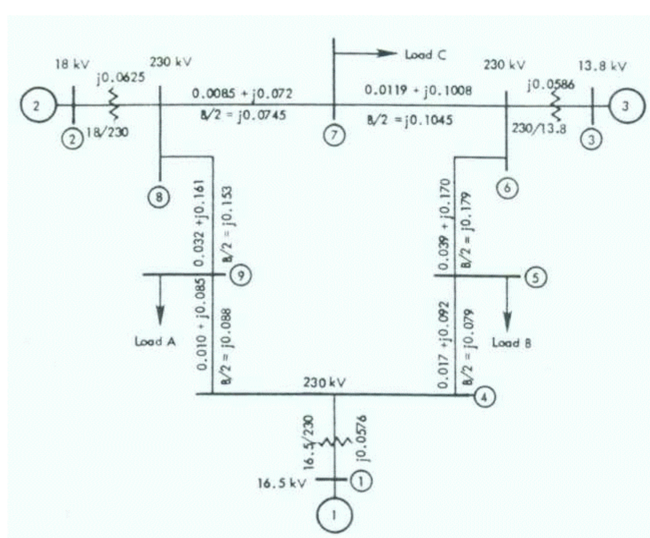


Fig. 7. WSCC-9 bus system

The failure rate and repair rate of each component and protection system are listed in Table I [8] [9].

TABLE I
COMPONENT AND ASSOCIATED PROTECTION SYSTEM DATA

	Component		Protection System			
	λ (1/year)	μ (1/year)	λ_{p1} (1/year)	λ_{p2} (1/year)	μ_i (1/year)	μ_I (1/hour)
T1	9	195	0.08	0.4	4	0.25
T2	9	195	0.08	0.4	4	0.25
T3	9	195	0.08	0.4	4	0.25
L1	10	150	0.08	0.4	4	0.25
L2	10	150	0.08	0.4	4	0.25
L3	10	150	0.08	0.4	4	0.25
L4	10	150	0.08	0.4	4	0.25
L5	10	150	0.08	0.4	4	0.25
L6	10	150	0.08	0.4	4	0.25

T: Transformer L: Line

D. Results

Fig. 8, 9 and 10 show the Monte Carlo simulation process for BIP, LOLP, and EPL respectively.

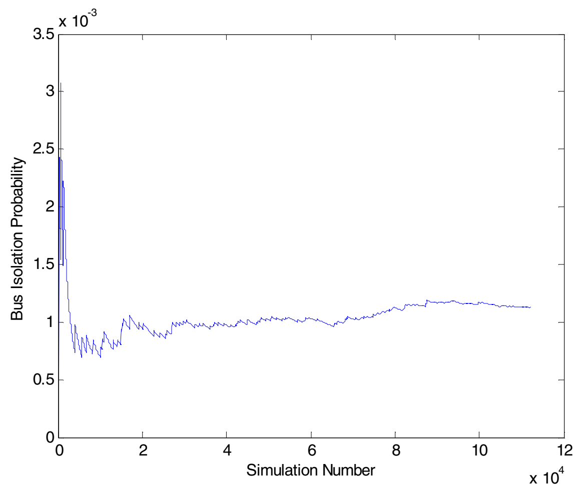


Fig. 8. Bus isolation probability by Monte Carlo simulation

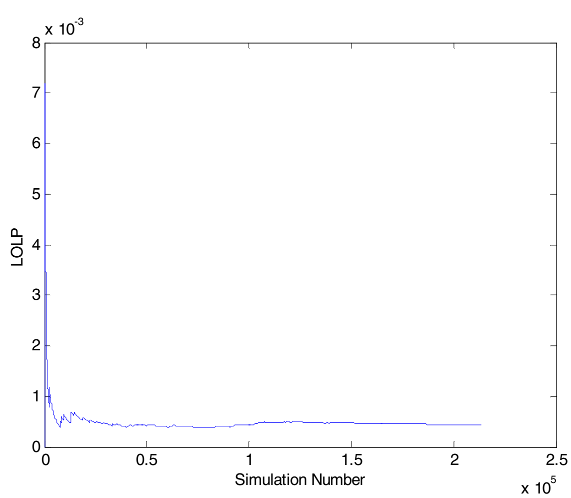


Fig. 9. LOLP by Monte Carlo simulation

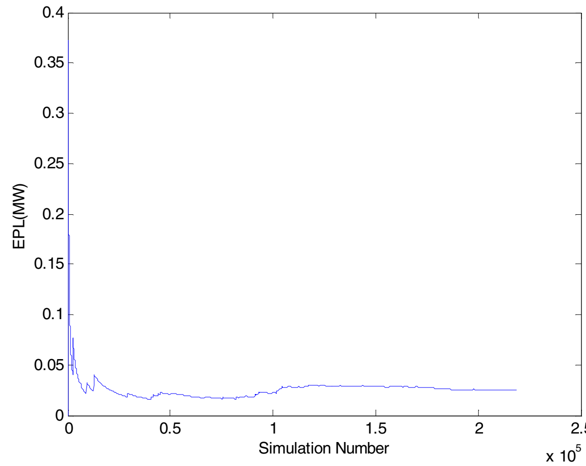


Fig. 10. EPL by Monte Carlo simulation

The final results are shown in Table II

TABLE II
SIMULATION RESULTS

BIP	LOLP	EPL (MW)
0.00113	0.000426	0.0254

All these results are the system-wide reliability indices and represent the degree of vulnerability and load curtailment under cascading outages in a particular power system.

Monte Carlo simulation takes much longer time to converge than other reliability assessment methods. However, it can handle sophisticated stochastic process problem in a more realistic manner.

VII. CONCLUSION AND FUTURE WORK

In this paper, a more explicit model of component paired with protection system is established to include two types of protection failures. Base on this model, a Monte Carlo simulation approach is developed to simulate system behavior under cascading outages. Besides common reliability indices such as LOLP, one new index (EPL) is introduced to depict the severity of the impact by cascading outages.

Different power systems may have different reliability indices due to their different network topologies, installation capacities, and protection devices/scenarios.

Protection failures are rare events in power system. This can be noticed by the long simulation time to converge. Some variance reduction technology could be applied to reduce simulation time.

The methodology presented in this paper will be validated in a larger test system that closely represents real power system.

VIII. References

[1] West Systems Coordinating Council Final Report, *August 10th 1996 event*, Oct. 1996

[2] A. G. Phadke, and J. S. Thorp, "Expose hidden failures to prevent cascading outages," *IEEE Computer Application in Power,* pp. 20-23, Jul. 1996.

[3] S. Tamronglak, S. H. Horowitz, A. G. Phadke, and J. S. Thorp, "Anatomy of power system blackouts: preventive relays strategies," *IEEE Trans. Power Delivery*, vol. 11, pp. 708-715, Apr. 1996.

[4] C. Singh, and A. D. Patton, “Models and concepts for power system reliability evaluation including protection-system failure,” *Int. J. Elect. Power and Energy Syst*. vol. 2, No. 4, pp. 161-168, Oct. 1980.

[5] C. Singh, and A. D. Patton, “Protection system reliability modeling: unreadiness probability and mean duration of undetected faults,” *IEEE Trans. Reliability*, vol. R-29, pp. 339-340, Oct. 1980.

[6] C. Singh, and A. D. Patton, “Supplement to [5],” *NAPS document* No. 03662-C, 8 pages, 1980.

[7] K. Bae, and J. S. Thorp, “An importance sampling application: 179 bus WSCC system under voltage based hidden failures and relay misoperation,” in *Proc. 1998 System Science, Thirty-first Hawaii International Conf*., vol. 3, pp. 39-46.

[8] G. M. Huang, and Y. Li, “Power system reliability evaluation including transient faults,” in *Proc. 2001 NAPS*, pp.559-563.

[9] S. T. J. A. Vermeulen, H. Rijanto, and F. A. Van der Duyn Schouten, “Modelling the influence of preventive maintenance on protection system reliability performance,” *IEEE Trans. Power Delivery*, vol. 13, Oct. 1998

IX. Biographies

Xingbin Yu received his B.S. and M.S. in E.E. from Shanghai Jiao Tong University, Shanghai, China, in 1988, 1993 respectively. In 2001, he joined Texas A&M University power group to pursue his Ph.D. under the guidance of Dr. Singh in the area of power system reliability analysis with focus on the deregulated environment. Mr. Yu is a student Member of IEEEis

Chanan Singh is Regents Professor and Department Head of Electrical Engineering, Texas A&M University. He received the 1986-87 Haliburton Professorship, and the 1992-1993 Dresser Professorship. He also served as Director, NSF Power System Program, for the year 1995-96. Dr. Singh is a senior TEES Fellow at Texas A&M University, Fellow of IEEE, and recipient of the IEEE 1998 Distinguished Power Engineering Educator Award. In 1997, he was awarded a DSc. by the University of Saskatchewan for his research contribution.