A Risk-Based Decision Approach for Maintenance Scheduling Strategies for Transmission System Equipment

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Abstract--**Cost-effective maintenance scheduling of power system equipment is critical, especially with present economic scenario of power industry. Apart from long-term maintenance policy, asset planners need to come up with revised short term maintenance strategies mainly due to the shrinking budget allocations for various reasons. The problem may be formulated as follows: if it is the same availability of labor crews, and labor hours, and the given budget is constrained, how the maintenance decisions needs to be revised. The problem is particularly prominent if one needs to assign maintenance tasks for part of a system, say a substation with few circuit breakers and transformers. A risk-based decision approach is proposed which suits best this kind of situation. In this approach, the classic definition of 'risk' term is adopted, which is the product of event probability and event consequence. Risk based approaches have been proposed earlier, but this paper differs in the way the 'event probability' and 'consequences' are defined and calculated. Condition monitoring devices can be used to get informed about the equipment condition up to date, which plays major role in this approach. The 'Event probability' is updated after a specified maintenance action and risk is recalculated, and the difference is the direct result of that maintenance activity. The proposed approach is implemented on a set of circuit breakers in a substation.**

Index Terms--**Circuit breakers, condition data, maintenance, risk analysis.**

I. INTRODUCTION

PRESENT economic scenario of power system industry suggests revising maintenance schedules of power system equipment due to limiting budget constraints. Hence there is a great need for developing new maintenance strategies, apart from the existing ones [1]. Reliability centered maintenance strategies and probabilistic maintenance models have been suggested so far trying to optimize the cost of maintenance and reliability [2]-[8]. This paper proposes a risk based approach for maintenance scheduling of circuit breakers. The proposed approach is different from other risk based approaches in the way the risk is being calculated. It utilizes the 'maintenance quantification model' developed earlier to quantify the circuit breaker maintenance [9]-[10].

The paper is organized as follows. Section II discusses the basic concept of risk and how it is being utilized in various areas of power system. Section III discusses the approach of how the event probability is being calculated. Section IV explores the event consequence. An illustration of the proposed approach applied on a set of breakers in a substation is given in section V, followed by conclusions in section VI.

II. CONCEPT OF RISK

This section presents a brief literature about the usage of risk concept, followed by definitions used in this paper. The term 'risk' is very general and can be applied to many areas including finance and power industry. The risk analysis usually includes the process of risk identification, risk management, and hedging, a process of risk mitigation. In finance sectors, risk analysis involves the trade off between the risk and the return. It is used in evaluating the risk associated with bonds, futures, new projects, etc. [11]. The risk concept has been extended to several areas of power industry as well. These areas include but not limited to: energy trading, contracts, operations, bidding, risk based planning, asset management techniques, risk based overload and voltage security assessment, maintenance scheduling of power system equipment, etc [12]-[24]. This paper proposes a risk based approach for maintenance of transmission system equipment such as circuit breakers.

In all of the above references, the underlying quantitative definition of risk associated with an event, is 'the product of probability and consequence of the event'. Following are the definitions used to define the risk in this paper.

Event, E: 'Failure of a component or group of components to operate properly'. Components can be line, breaker or bus bar.

Event probability, p(E): 'Probability that a component or group of components fail to operate properly'.

Event consequence, Con(E): 'Impact of failure of a component or group of components on the system'.

Now, the risk associated with each event is defined as,

$$Risk(E) = p(E) \times Con(E) .$$

Following sections show how to estimate the event probability, consequence and the event risk.

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III. EVENT PROBABILITY

As defined in earlier section, an event includes failure of a component or group of components. In order to evaluate the event probability, it is necessary to estimate the failure probability of all components involved in that event, such as line, breaker and bus bar in the system. The failure probability of line and bus bar is available from the substation reliability data. The focus of this paper is to estimate the failure probability of circuit breaker utilizing the monitored data. This failure probability is different from the failure rate or failure frequency which often used in reliability studies. The failure probability of breaker is treated separately because the focus of this paper is the maintenance scheduling of breakers. A model to quantify the effect of maintenance is developed earlier and used in this paper to estimate the failure probability of a breaker [9].

The maintenance quantification model is shown in Fig. 1. It utilizes the breaker control signal data to estimate the condition of the breaker. Control circuit data is basically a record of wave forms taken from the circuit breaker control circuit by using a portable [25] or on-line recorder [26] and respectively manually or automatically forcing a breaker operation. Signal processing and expert system modules developed in [27] can be used to extract the various features of the waveforms. A maximum of ten such features, also called events, and corresponding signal parameters are defined in Table I. Each of these extracted timing parameters is fitted with probability distribution and failure probability index is defined based on the probability distributions. The distributions and hence the failure probability index is updated using Bayesian approach as the new data comes. If the new data is taken after a maintenance action, any change in the failure probability index can be reported as the result of that particular maintenance action. In this way, the proposed model can be utilized to quantify the effect of maintenance. Readers are advised to go through [27] to know more about breaker control circuit, as well as definition of signal parameters. The model is implemented on data collected on a group of similar circuit breakers at different times, and the updated parameter distributions are shown in Fig. 2 [10].

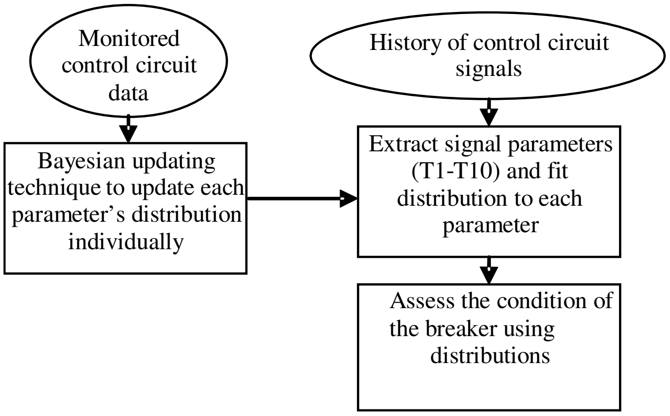


Fig. 1. Maintenance quantification model [9]

TABLE I
WAVEFORM ABNORMALITIES AND SIGNAL PARAMETERS [28]

Event	Event Description	Signal
1	Trip or close operation is initiated (Trip or close initiate signal changes from LOW to HIGH)	T1
2	Coil current picks up	T2
3	Coil current dips after saturation	T3
4	Coil current drops off	T4
5	B contact breaks or makes (a change of status from LOW to HIGH or vice versa)	T5
6	A contact breaks or makes	T6
7	Phase currents breaks or makes	T7
8	X coil current picks up	T8
9	X coil current drops off	T9
10	Y coil current picks up	T10

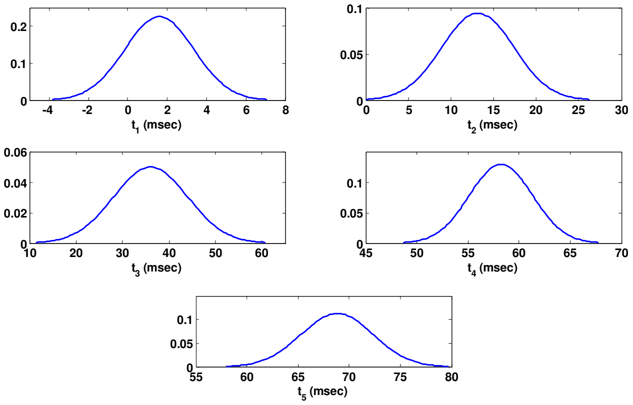


Fig. 2. Updated parameter distributions [10]

First of all, define upper and lower limits for each timing parameter such that if new value of 't_i' falls in this range, then those parts of the breaker which cause the occurrence of time instant 't_i', operate properly. For example, if t_2 falls out of the limits, it means that there is some problem associated with close coil. Table II shows the upper and lower limits of the circuit breaker under consideration. These limits are the expert system settings used in developing automated analysis of CB operation earlier [28]. Fig. 3 shows the probability distribution function of timing parameter t_2, result of Bayesian updating approach. The shaded area between the lower and upper limits is the probability that the breaker will operate properly.

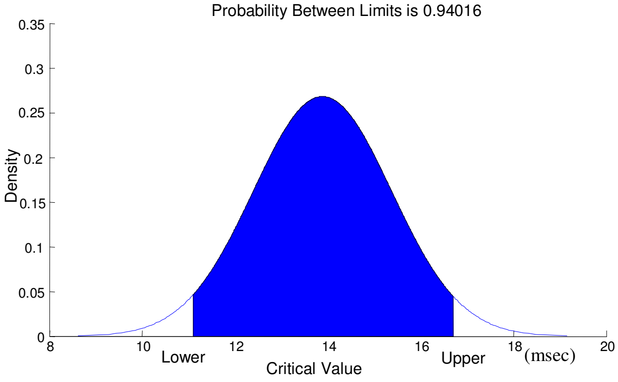


Fig. 3. Updated probability distribution of parameter t_2

TABLE II
TOLERANCE LIMITS NORMAL OPERATION [26]

Event	Lower (msec)	Upper (msec)
t_1	0	5.5
t_2	9.8	16.4
t_3	26	43.4
t_4	49.9	67.5
t_5	62	75.8

In general, probability that breaker operates correctly with respect to 't_i' is define as,

$$p(t_i) = \Pr(l_i \le t_i \le u_i)$$

where, l_i is the lower limit and u_i = upper limit.

For the breaker to operate properly, all of the timings (t_1-t_5) should fall into the specified interval. In other words, if any of these timings fall out side of the corresponding tolerance limits, we can say that the breaker fails to operate properly. This quantity can be defined as, probability that the breaker does not operate properly and is estimated as,

$$p_f(B) = 1 - \prod_{i=1}^{5} p(t_i)$$

Note that this failure probability is different from the failure rate or failure frequency which often used in reliability index. Now, the event probability is computed as the product of failure probabilities of components involved in that event.

IV. EVENT CONSEQUENCE

Consider the example system as shown in Fig. 4. The system consists of a load, generator and three lines protected by breaker-and-half scheme.

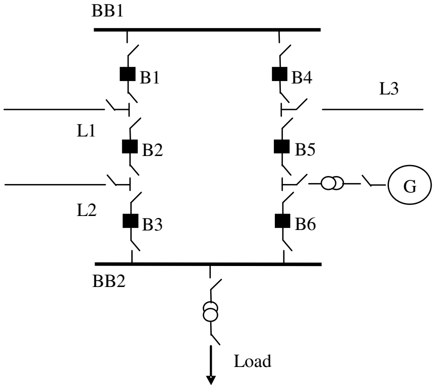


Fig. 4. Breaker-and-half scheme

To illustrate the impact of the event on the system, two different scenarios are considered: single and multiple contingencies. Single contingency involves fault on bus bar, line, or breaker. Multiple contingency involves failure of more than one component.

Consider the single contingency; a fault on bus bar BB2. The breakers B3 and B6 should open to isolate the faulted bus bar. This results in loss of load for the duration until the bus bar is restored. Failure of any of these breakers leads to multiple contingency. If B3 fails to open, B2 and the breaker on the other side of the line L2 will open, resulting in loss of that line. Similarly, failure of B6 results in loss of generator.

Consider the other single contingency, which is a fault on line L2. In this case, breakers B2, B3 and the breaker on the other side of the line will open to isolate L2. Multiple scenarios will occur if any of those breakers fail to open.

In conclusion, for both scenarios, the event consequence term can be divided into four components: (i) loss of load, (ii) loss of line, (iii) loss of generator, and (iv) repair cost.

A. *Loss of Load*

The loss of load has a direct impact on customers connected to the system. One way to estimate the impact of loss of load is to use the composite customer damage function (CCDF). It is a measure of the interruption cost for a mix of customers at a bus [29]. The CCDF gives the interruption cost in \$/MW for a particular duration of time. The consequence due to loss of load is computed as:

Con_{load} = Interruption cost (\$/MW)*Loss of load (MW)

B. *Loss of Line*

If a line is out of service, the system configuration is changed. The load flow is recalculated according to the new topology of the system. If the system is secure enough, the power flow is redistributed without overloading the other lines. In this case, loss of line results in switching of one or more components to put the line back in the system. If the system is not secure which means, redistribution of power flow causing any lines to become overload, load curtailment occurs.

The optimal power flow (OPF) is used to estimate the impact of loss of line. The OPF is run without considering the line, and the cost of power generation (\$/hr) is compared with that of the base case. Any additional cost (\$/hr) is the result of loss of line.

The consequence of loss of line due to switching action is computed as:

Con_{line} = Add.cost (\$/hr)*Switching time (hr)

The consequence of loss of line due to load curtailment is computed as:

Con_{line} = Interruption cost (\$/MW)*Loss of load (MW)

C. *Loss of Generator*

When there is a loss of generator, other generators in the system will share the load of the lost generator. There might be additional cost with this situation, if running the other generators is expensive. The impact of this scenario is calculated by running the OPF without considering the generator. Any additional cost (\$/hr) is the impact of loss of that particular generator. The consequence is computed as:

Con_{gen} = Add.cost (\$/hr)*Switching time(hr)

D. *Repair Cost*

This includes the repair/maintenance cost of the components involved in the event. Also, it includes any cost to clear the fault including the labor cost. Following are the costs that are assumed in this study.

The maintenance cost of breaker = $1000.

The repair cost of bus bar and faulted line = $1000 each.

The total consequence is the summation of consequences due to: loss of load, loss of line & generator and repair cost.

$Con(E) = Con_{load} + Con_{line} + Con_{gen} + \text{Repair cost}$

V. ILLUSTRATION

Consider the IEEE 24 Bus Reliability Test System [30] to illustrate the proposed concepts. Fig. 5 shows the substation configuration of bus 16, which has 4 lines protected by breaker and half scheme, a generator of capacity 155MW and a load of 100MW. The substation has a total of 8 breakers (B1-B8), and the objective is to find out which breaker needs immediate attention and how to spend a fixed pool of money towards the maintenance of these breakers. A total of 15, covering all possible scenarios and corresponding definitions are listed in Table III. There are 42 events associated with these 15 scenarios and are given in Table IV. The events include single and double contingencies. The next step is to estimate the probability and consequence of each event and hence risk associated with each event.

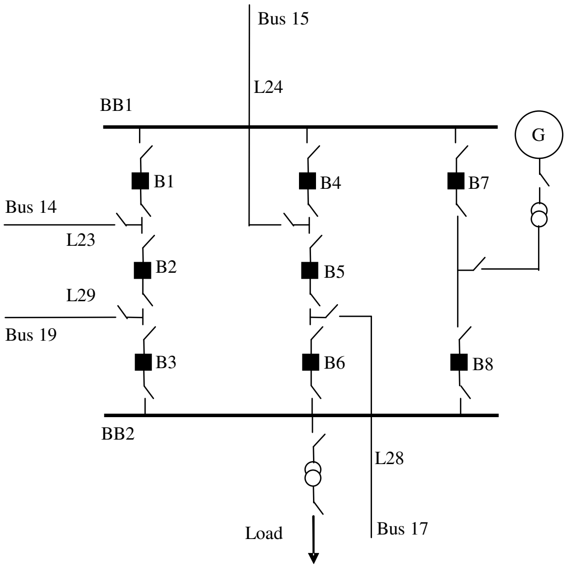


Fig. 5. Station configuration of Bus 16, IEEE RTS [30]

TABLE III
LIST OF SCENARIOS

Scenario #	Definition
S1	Fault on BB1
S2	Fault on BB2
S3	Fault on Line 23
S4	Fault on Line 24
S5	Fault on Line 28
S6	Fault on Line 29
S7	Fault on Generator
S8-S15	Fault on Breakers B1-B8 respectively

TABLE IV
LIST OF EVENTS ASSOCIATED WITH ALL SCENARIO S

Event #	Definition	Event #	Definition
E1	Fault on BB1	E22	Fault on G, B7 fails
E2	Fault on BB1, B1 fails	E23	Fault on G, B8 fails
E3	Fault on BB1, B4 fails	E24	Fault on B1
E4	Fault on BB1, B7 fails	E25	Fault on B1, B2 fails
E5	Fault on BB2	E26	Fault on B1, B4 fails
E6	Fault on BB2, B3 fails	E27	Fault on B1, B7 fails
E7	Fault on BB2, B6 fails	E28	Fault on B2
E8	Fault on BB2, B8 fails	E29	Fault on B2, B3 fails
E9	Fault on L23	E30	Fault on B3
E10	Fault on L23, B1 fails	E31	Fault on B3, B6 fails
E11	Fault on L23, B2 fails	E32	Fault on B3, B8 fails
E12	Fault on L24	E33	Fault on B4
E13	Fault on L24, B4 fails	E34	Fault on B4, B5 fails
E14	Fault on L24, B5 fails	E35	Fault on B4, B7 fails
E15	Fault on L28	E36	Fault on B5
E16	Fault on L28, B5 fails	E37	Fault on B5, B6 fails
E17	Fault on L28, B6 fails	E38	Fault on B6
E18	Fault on L29	E39	Fault on B6, B8 fails
E19	Fault on L29, B2 fails	E40	Fault on B7
E20	Fault on L29, B3 fails	E41	Fault on B7, B8 fails
E21	Fault on G	E42	Fault on B8

The control circuit data is utilized to estimate the failure probability index of each circuit breaker [10]. The estimated failure probability of breakers B4, B5, B6 is 0.3909 and for the remaining breakers is 0.4494. For the purpose of illustration, the bus bar failure probability is assumed to be 0.0005. The reliability data for lines and generator is taken from [31]. Now, the event probability is computed as the product of failure probabilities of components involved in that event. A switching time of 1 hr is assumed for each component in computing the consequence term [31].

A. *Event Risk*

The probability, consequence and risk associated with each event are given in Table V. It is observed from the table that, the risk associated with events which involve faults on breakers, is more significant. This is because of the higher probability of these events compared to other events. The risk levels associated with events, which include faults on lines, are very less. It can be seen from the Fig. 6 that events E30, E42, and E38 possess higher risk in that order, compared to others. Since breakers B3, B6 and B8 are involved in those events, they should be given importance in maintenance planning.

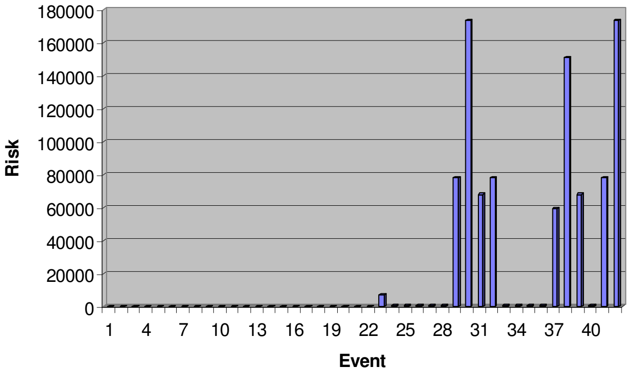


Fig. 6. Risk associated with each event

Further, events E29, E31, E32, E37, E39 and E41 possess significant risk as well. These events involve combination of breakers B2, B3, B5, B6, and B7. This higher risk is because breakers B3, B6 and B8 are involved in those events. This can be verified by looking at the low risk levels of events E28, E36 and E40 that involve breakers B2, B5 and B7 alone respectively. It can be concluded from Table V and Fig. 6 that breakers B3, B6 and B8 are very crucial and needs immediate attentions compared to other breakers.

TABLE V

EVENT PROBABILITY, CONSEQUENCE AND RISK

Event #	Probability, p(E)	Consequence, Con(E)	Risk, R(E)
E1	0.0005	1000.00	0.50
E2	0.000225	2464.31	0.55
E3	0.000195	1994.07	0.38
E4	0.000225	2463.32	0.55
E5	0.0005	386000.00	193.00
E6	0.000225	387337.70	87.03
E7	0.000195	387054.40	75.64
E8	0.000225	387000.80	86.95
E9	0.000494	1464.31	0.72
E10	0.000222	2464.31	0.54
E11	0.000222	2936.04	0.65
E12	0.000429	994.07	0.42
E13	0.000168	1994.07	0.33
E14	0.000168	2985.22	0.50
E15	0.000442	1103.12	0.48
E16	0.000173	2985.22	0.51
E17	0.000173	387054.40	66.87
E18	0.000416	2832.30	1.17
E19	0.000187	2936.04	0.54
E20	0.000187	387337.70	72.41
E21	0.0400	1463.32	58.53
E22	0.0180	2463.32	44.33
E23	0.0180	387000.80	6966.01
E24	0.4494	1464.31	658.06
E25	0.2020	2936.04	593.08
E26	0.1757	2945.98	517.60
E27	0.2020	3969.82	801.90
E28	0.4494	1936.04	870.05
E29	0.2020	387627.00	78300.64
E30	**0.4494**	**386337.70**	**173620.18**
E31	0.1757	387694.90	68118.00
E32	0.2020	387675.50	78310.45
E33	0.3909	994.07	388.58
E34	0.1528	2985.22	456.14
E35	0.1757	2926.90	514.25
E36	0.3909	1985.22	776.02
E37	0.1528	387194.70	59163.34
E38	**0.3909**	**386054.40**	**150908.68**
E39	0.1757	387111.00	68015.40
E40	0.4494	1463.32	657.61
E41	0.2020	387000.80	78174.16
E42	**0.4494**	**386000.80**	**173468.77**

B. *Risk Reduction*

The risk associated with each event can be reduced by using maintenance actions. One can come up with better maintenance policies based on the reduction in risk of each maintenance activity. Again, the risk reduction can be captured by the maintenance quantification model proposed in section III. The model quantifies the effect of maintenance and captures the reduction in failure probability of breaker, and hence the reduction in risk. The risk reduction is computed as,

$$\Delta Risk(E) = \Delta p(E) \times Con(E) .$$

An illustration is presented on how the risk reduction can be computed and used for planning purposes. Using the probabilistic methods, it is possible to predict the future data point with some confidence level and hence the event probability and risk level. Fig. 7 shows the reduction in risk level with each event for the data under consideration [10].

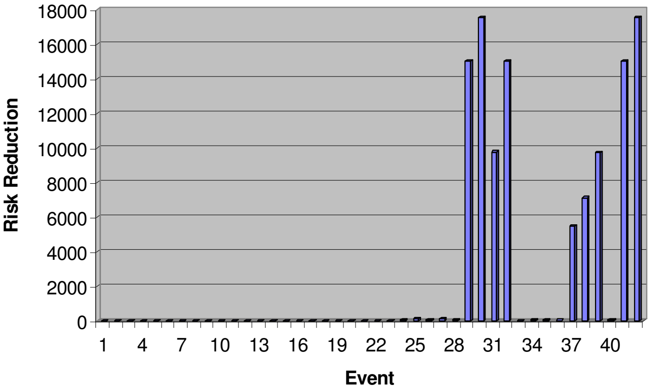


Fig. 7. Risk reduction with each event

It is interesting to note from the Fig. 7 that the amount of risk reduced by maintaining the breaker B6 is less compared to breakers B3 and B8. The breakers B3 and B8 can be given more importance than B6, if one wants to spend money according to the reduction in risk level. For the test system under consideration, it can be concluded from Figs. 6 and 7 that, breakers B3 and B8 are more important followed by B6 than others and should be given priority in budget allocation.

This study can be extended by formulating an optimization problem with objective being the risk reduction, and incorporating the cost of monitoring process and several maintenance actions as additional constraints.

VI. CONCLUSION

A risk based approach for maintenance scheduling of circuit breakers is proposed. The quantitative definition of risk, which is the product of failure probability and consequence, is adopted in this work. This work is different from other risk based approaches in the way the probability and consequences are calculated. A maintenance quantification model for circuit breaker is used to estimate the failure probability of breaker which is utilized to estimate the event probability. The consequence due to loss of load, line and generator along with repair cost are considered. The proposed approach is implemented on a group of breakers in a substation. It has been shown that the approach can differentiate the importance of the breakers in the context of particular consequences, and hence the investment in the breaker maintenance can be prioritized to reduce the risk.

VII. REFERENCES

[1] IEEE/PES Task Force on Impact of Maintenance Strategy on Reliability of the Reliability, Risk and Probability Applications Subcommittee, "The present status of maintenance strategies and the impact of maintenance on reliability", *IEEE Trans. Power Systems*, vol. 16, no. 4, pp. 638- 646, November 2001.

[2] J. Endrenyi, and S. H. Sim, "Availability optimization for continuously operating equipment with maintenance and repair", in Proceedings of the Second PMAPS Symposium, California, September 1988.

[3] J. Endrenyi, G. J. Anders, and A. M. Leite da Silva, "Probabilistic evaluation of the effect of maintenance on reliability- An application", *IEEE Trans. Power System*, vol. 13, no. 2, pp. 576-583, May 1998.

[4] Panida Jirutitijaroen, and Chanan Singh, *"Oil-immersed Transformer Inspection and Maintenance: Probabilistic Models"*, in Proc. 2003 North American Power Symposium Conf., pp. 204-208.

[5] Panida Jirutitijaroen, and Chanan Singh, "The Effect of Transformer Maintenance Parameters on Reliability and Cost: A Probabilistic Model" , Electric Power Systems Research, Volume 72, Issue 3, 15 December 2004, Pages 213-22.

[6] Satish Natti, Panida Jirutitijaroen, Mladen Kezunovic, and Chanan Singh, "Circuit breaker and transformer inspection and maintenance: probabilistic models", *8th International Conference on Probabilistic Methods Applied to Power Systems*, Iowa State University, Ames, Iowa, September 2004.

[7] Satish Natti, Mladen Kezunovic, and Chanan Singh, "Sensitivity analysis on the probabilistic maintenance model of circuit breaker", *9th International Conference on Probabilistic Methods Applied to Power Systems*, Stockholm, Sweden, June. 2006.

[8] Lina Bertling, Ron Allan, Roland Eriksson, "A reliability-centered asset maintenance method for assessing the impact of maintenance in power distribution systems*", IEEE Trans. Power Systems*, vol. 20, no. 1, pp 75-82, February 2005.

[9] Satish Natti, and Mladen Kezunovic, "Transmission system equipment maintenance: on-line use of circuit breaker condition data", IEEE PES General Meeting, Tampa, Florida, June 2007.

[10] Satish Natti, and Mladen Kezunovic, "Model for quantifying the effect of circuit breaker maintenance using condition-based data", *Power Tech 2007*, Lausanne, Switzerland, July 2007.

[11] Smart, Megginson, and Gitman, "*Corporate Finance,*" 2nd ed. Thompson South-Western.

[12] R. Bjorgan, C. Liu, and J. Lawarrée, "Risk assessment in energy trading", *IEEE* Trans. *Power Systems*, vol. 18, no. 2, pp 503-511, May 2003.

[13] R. Bjorgan, C. Liu, and J. Lawarrée, "Financial risk management in a competitive electricity market", *IEEE* Trans. *Power Systems*, vol. 14, no. 4, pp 1285-1291, November 1999.

[14] M. Denton, A. Palmer, R. Masiello, and P. Skantze, "Managing market risk in energy", *IEEE* Trans. *Power Systems*, vol. 18, no. 2, pp 616-623, May 2003.

[15] E. Ni, P. B. Luh, and S. Rourke, "Optimal integrated generation bidding and scheduling with risk management under a deregulated power market", *IEEE* Trans. *Power Systems*, vol. 19, no. 1, pp 600-609, February 2004.

[16] E. O. Crousillat, P. Dörfner, P. Alvarado, and H. M. Merrill "Conflicting objectives and risk in power system planning", *IEEE* Trans. *Power Systems*, vol. 8, no. 3, pp 887-893, August 1993.

[17] C. J. Andrews, "Evaluating risk management strategies in resource planning", *IEEE* Trans. *Power Systems*, vol. 10, no. 1, pp 420-426, February 1995.

[18] G. J. Anders, J. Endrenyi, and C. Yung, "Risk-based planner for asset management", *IEEE Comput. Applicat. Power,*, vol. 14, no. 4, pp 718-723, October 2001.

[19] Y. Dai, J. McCalley, and V. Vittal, "Annual risk assessment for overload security", *IEEE* Trans. *Power Systems*, vol. 16, no. 4, pp 616-623, November 2001.

[20] M. Ni, J. McCalley, V. Vittal, and T. Tayyib, "On-line risk based security assessment", *IEEE* Trans. *Power Systems*, vol. 18, no. 1, pp 258-623, February 2003.

[21] H. Wan, J. McCalley, and V. Vittal, "Risk based voltage security assessment", *IEEE* Trans. *Power Systems*, vol. 15, no. 4, pp 1247-1254, November 2000.

[22] G. C. Contaxis, S. D. Kavatza, and C. D. Vournas, "An interactive package for risk evaluation and maintenance scheduling", *IEEE* Trans. *Power Systems*, vol. 4, no. 2, pp 389-395, May 1989.

[23] Y. Jiang, M. Ni, J. McCalley, T. Van Voorhis, "Risk-based resource optimization for transmission system maintenance," *IEEE Trans. Power Systems*, vol 21, no. 3, pp 1191-2000, August 2006.

[24] A. D. Janjic, and D. S. Popovic, "Selective maintenance schedule of distribution networks based on risk management approach", *IEEE* Trans. *Power Systems*, vol. 22, no. 2, pp 616-623, May 2007.

[25] L. T. Rumfield "Circuit Breaker Diagnostic Response Testing Using the RTR-84 Response Time Recorder," presented at the Sixty-First Annual International Conference of Doble Clients, June, 1994.

[26] M. Kezunovic, G. Latisko, N. Ved, "Real-time monitoring and assessment of circuit breaker operations for diagnostics and control applications", *EPRI Substation Equipment Diagnostics Conference XIII,* New Orleans, Louisiana, March 2005

[27] M. Kezunovic, Z. Ren, G. Latisko, D. R. Sevcik, J. Lucey, W. Cook, E. Koch, "Automated monitoring and analysis of circuit breaker operations", *IEEE Trans. Power Delivery*, vol. 20, no. 3, pp 1910-1918, July 2005.

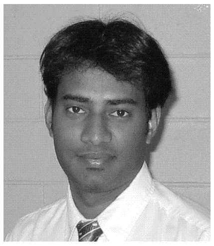
[28] Christopher Donald Nail, "Automated Circuit Breaker Analysis", M.Sc. Thesis, Dept. of ECE., Texas A&M University, College Station, TX, 2002.

[29] R. Billinton, and W. Li, "*Reliability Assessment of Electric Power Systems using Monte Carlo Methods*", Plenum Press, New York, 1994.

[30] Reliability test system task force of the application of probability methods subcommittee, "IEEE reliability test system," *IEEE Trans. Power App. Syst.*, vol. PAS-98, pp. 2047–2054, Nov./Dec. 1979.

[31] Reliability test system task force of the application of probability methods subcommittee, "IEEE reliability test system - 1996," *IEEE Trans. Power Systems.*, vol. 14, no. 3, pp. 1010–1020, August 1999.

VIII. BIOGRAPHIES



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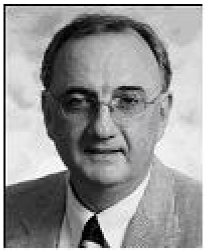

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