A Novel Approach for Assessing the Impacts of Voltage Sag Events on Customer Operations

Muhammad Yasir, Shahram Kazemi, *Graduate Member, IEEE*, Matti Lehtonen, and Mahmud Fotuhi-Firuzabad, *Senior Member, IEEE*

***Abstract*—The business activities of the majority of industrial and commercial customers are dependent on some critical equipments that are susceptible to voltage sag events. This paper aims to propose a novel approach to estimate the financial impacts of voltage sag events on customer operations. The proposed technique is based on the event tree method. Using this approach, it is possible to consider the impacts of operational failure of various sensitive equipments, involved in the customer operations, on the financial losses expected from voltage sag events. A quantitative case study is conducted in the paper to illustrate the applicability of the proposed approach.**

***Index Terms*—Event tree, interruption cost, power quality, voltage sags.**

I. Introduction

VOLTAGE sag is one of the most significant power quality issues that can affect the majority of sensitive equipments like personal computers (PC), adjustable speed drives (ASD), programmable logic controllers (PLC), semiconductor devices (SD) and contactors. A voltage sag event is defined as the decrease in the rms value of voltage between 0.1 p.u. and 0.9 p.u. for durations from 0.5 cycles to 1 minute [1]. The number of occurrence of voltage sag events is far more than that of power interruptions. Therefore, for specific customers, the financial losses caused by voltage sag events may even be greater than the cost associated with power interruptions. The increased sensitivity and high costs associated with such events are acting as a driving factor for increasing interest to study and to reduce the effects of voltage sags on customer operations.

The general idea of modeling the voltage tolerance capabilities of sensitive devices for estimating the effects of voltage sags on a given process or customer has already been utilized in some literatures, e.g. [2] and [3]. The approach proposed in this paper use the similar idea for assessing the impacts of voltage sag events on the customer operations. The commonly used technique in the previously developed approaches is a block diagram having series/ parallel combination of equipments for modeling a customer operation. The block diagram method shows the logical connection of the equipments needed to fulfill a specific customer operation or process. Employing this modeling technique for a complex process is bothersome and complicated. If the customer has more than one process, each process should be considered individually, and a separate block diagram has to be established for each customer operation. In addition, when the order in which the operational failures of equipments occur is important, the block diagram method cannot be employed. To overcome these issues, an evaluation approach based on the event tree technique is proposed in this paper. The event tree approach is an inductive method which can provide much detailed results compared to the block diagram approach.

The rest of the paper is organized as follows. In Section II, the general concepts and steps of the proposed evaluation procedure are presented. A typical case study is presented in Section III using the proposed approach. Finally, a conclusion is provided in Section IV.

This work was supported in part by the Fortum Foundation in Finland under Grant B2-11-032.

M. Yasir and M. Lehtonen are with the Department of Electrical Engineering at Aalto University, Espoo, Finland.
(e-mail: muhammad.yasir@tkk.fi, matti.lehtonen@tkk.fi).

S. Kazemi is with the Departments of Electrical Engineering at Sharif University of Technology, Tehran, Iran and Aalto University, Espoo, Finland (e-mail: shahram.kazemi@aalto.fi).

M. Fotuhi-Firuzabad is with the Department of Electrical Engineering at Sharif University of Technology, Tehran, Iran (e-mail: fotuhi@sharif.edu).

II. The Proposed Approach

A. General Concepts

A modular approach has been developed to evaluate the impacts of the voltage sag events on the customer operations. This approach relies on the event tree technique and follows the basic concepts that have already been developed by the authors for reliability assessment of the automated distribution systems, e.g. [4] and [5]. Susceptibility of customer operations against voltage sag events depends on the voltage tolerance capabilities of its equipments against these events. Therefore, different failure modes of the customer equipments during a voltage sag event should be considered in the related analysis. In the proposed approach, the sensitive equipments involved in the customer operations are identified. Normally, the customer operations are carried out based on the sequential operation of a set of these equipments. Therefore, the consequence of operational failures of the identified sensitive equipments on the customer operations is analyzed using the event tree method [6]. Using this approach, various possible consequences of a voltage sag event on the customer operations are identified. By summing up the effects of each voltage sag event, the overall financial impact on the customer due to all voltage sag events is estimated.

B. Steps of Evaluation Procedure

The evaluation procedure can be conducted according to the following steps:

(1) Sensitive equipments involved in the customer operations are identified. PLC, ASD, PC, SD and contactors are

978-1-4673-1979-9/12/$31.00 É 2012 IEEE

major sensitive devices that may involve in the customer operations.

(2) Susceptibility of the identified sensitive equipments against different voltage sag events is provided. The vulnerability of equipment against voltage sag events can be represented by a characteristic or tolerance curve. The characteristic curve represents the sensitivity of the equipment to voltage sag events in terms of magnitude and duration of the sagged voltage. Typical characteristic curves for PLC, ASD, PC, SD and contactors can be taken from [2], [7]–[10].

(3) The operational failure probabilities of the identified sensitive equipments against different voltage sag events are determined. Usually, the normal distribution probability function is utilized for approximating the malfunction probability of the sensitive equipments. Fig. 1, as an example, shows the operational failure probabilities of a typical PLC for different voltage sag events. The parameters of the normal distribution probability functions have been taken from [11] to deduce this figure.

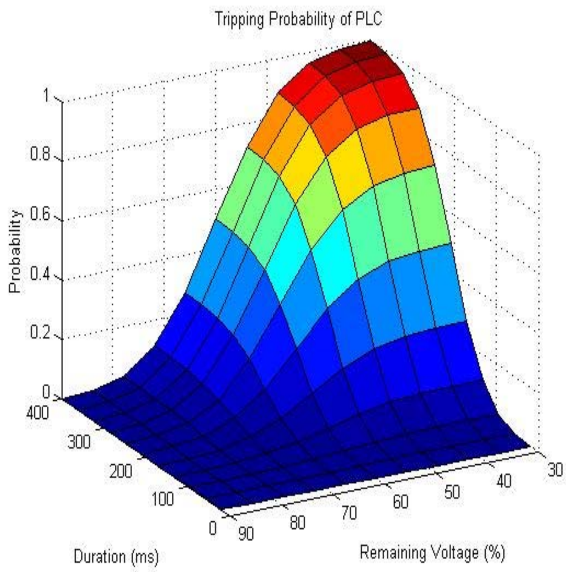

Fig. 1. Distribution of malfunction probability for a typical PLC.

(4) Considering the operational failures of the identified sensitive equipments, an event tree which reflects the customer operations is deduced. Assuming two operational states for each sensitive equipment (one for the normal operating status and the other for operational failure status), there are 2^n possible outcomes for the deduced event tree, where n is the number of sensitive equipments involved in the analysis. For example, in the case of a customer with five sensitive equipments, the deduced event tree contains $2^5 = 32$ outcomes.

(5) For each outcome of the deduced event tree, possible consequences on the customer operations are examined. Each outcome of the event tree can then be assigned by a parameter designated as "impact factor" which shows to what extent the customer operations are disturbed when its sensitive equipments encounter with operational failures. An impact factor should provide an estimate of the financial impact on the customer operations. Therefore, the numerical value assigned to the impact factor can be represented in per unit of the financial impact imposed on the customer due to a momentary power interruption as expressed below:

$$IPF_j = \frac{EOC_j}{MIC}, \tag{1}$$

where:

IPF_j – Impact factor of the event tree outcome number j

EOC_j – Financial impacts on the customer operations corresponding to the event tree outcome number j

MIC – Financial impacts on the customer operations when facing with a momentary power interruption

(6) The deduced event tree is analyzed for any possible modification. It might be possible to combine those event tree outcomes that result in the same impact factor. This will reduce the computational efforts in the next steps.

(7) Statistical data associated with the voltage sags events imposed on the sensitive equipments, during a specific period (e.g. one year), are provided. This data can be derived either using stochastic voltage sag prediction studies or power quality monitoring methods [12], [13] and [14].

(8) Contribution of voltage sag events on the financial losses imposed on the customer operations is determined. To perform this task, for the targeted voltage sag event, the probabilities associated with different states involved in each outcome of the event tree are multiplied by each other. The result is then multiplied by the impact factor corresponding to that event tree outcome (i.e. IPF_j) and MIC. This process is repeated for all the event tree outcomes. Finally, these results are summed up to find the contribution of the targeted voltage sag event on the financial losses imposed on the customer. The following equation can be used for accomplishing this step:

$$VSIP_i = MIC \times \sum_{j=1}^{TNE} \left\{ IPF_j \times \bigcap_{m \in DN_j} f_{u,t}^{m}(U_i, T_i) \times \bigcap_{n \in UP_j} \left(1 - f_{u,t}^{n}(U_i, T_i)\right) \right\} \tag{2}$$

where:

$VSIP_i$ Contribution of the voltage sag event number i on the financial losses imposed on the customer

UP_j Set of sensitive equipments which are in the successful operational status for the event tree outcome number j

DN_j Set of sensitive equipments which are in the operational failure status for the event tree outcome number j

U_i Remaining voltage of the voltage sag event number i

T_i Duration of the voltage sag event number i

$f_{u,t}^{x}(U_i, T_i)$ Operational failure probability of equipment x, when encountering the voltage sag event number i with the remaining voltage equal to U_i and duration equal to T_i

TNE Total number of the event tree outcomes

(9) Overall financial impact on the customer due to all voltage sag events during the study period is estimated by the following equation:

$$VSC = \sum_{i=1}^{TNS} \left(VSIP_i \times VSOR_i \right) \quad (3)$$

where:

VSC Overall financial impact on the customer due to all the voltage sag events

$VSOR_i$ Rate of occurrence of the voltage sag event number i during the study period

TNS Total number of voltage sag events

III. Case Study

The applicability of the proposed approach, for assessing the impacts of voltage sag events on customer operations, is represented here using a typical semiconductor facility. The momentary interruption cost for the semiconductor facility with peak load of 30 MW and service voltage of 161 kV is reported to be around $1,400,000 [15]. In this section, the calculations are performed for specific operations of this facility which are estimated to have load of 500 kW. Out of this 500 kW load, the consumptions of sensitive equipments are assumed to be as shown in Table I.

TABLE I
CONSUMPTIONS OF SENSITIVE EQUIPMENTS (IN PERCENTS OF 500 KW)

PLC	PC	ASD	Contactors
10 %	18 %	65 %	7 %

A. Estimating the Financial Impact of Voltage Sag Events

The proposed evaluation approach is applied to this case study according to the following steps:

(1) Sensitive equipments involved in the targeted customer operations are identified. In this case, PLC, ASD, PC and contactors are assumed to be the sensitive equipments for the targeted customer operations.

(2) Voltage sage tolerance curves and hence the operational failure probabilities are provided for the identified sensitive equipments. The data provided by equipment manufacture and/or achieved by the laboratory tests are the most trusted sources to accomplish this task.

(3) An event tree is deduced and the impact factors are assigned to its outcomes. This case study presents specific operation of the customer and consists of following sensitive equipments PLC, ASD, PC and contactors. In the realistic situation, the failure of any of these sensitive equipments does not have the same effect on the operation. To cater this phenomenon and for accurate and realistic estimation of financial impacts of voltage sag events, impact factors are assigned based on engineering judgment in the absence of detail actual data. For example, it has been shown in the below figure that If there is failure in the contactors due to voltage sags, it will not trip the whole assembly line of the process. It will have certain impact on the process, which in this case, has been assumed to be 30% (meaning that only 30% (of total load) of the process will be effected). Similarly, in case of PC malfunctioning in the event of voltage sags, 80% of the process will be effected.

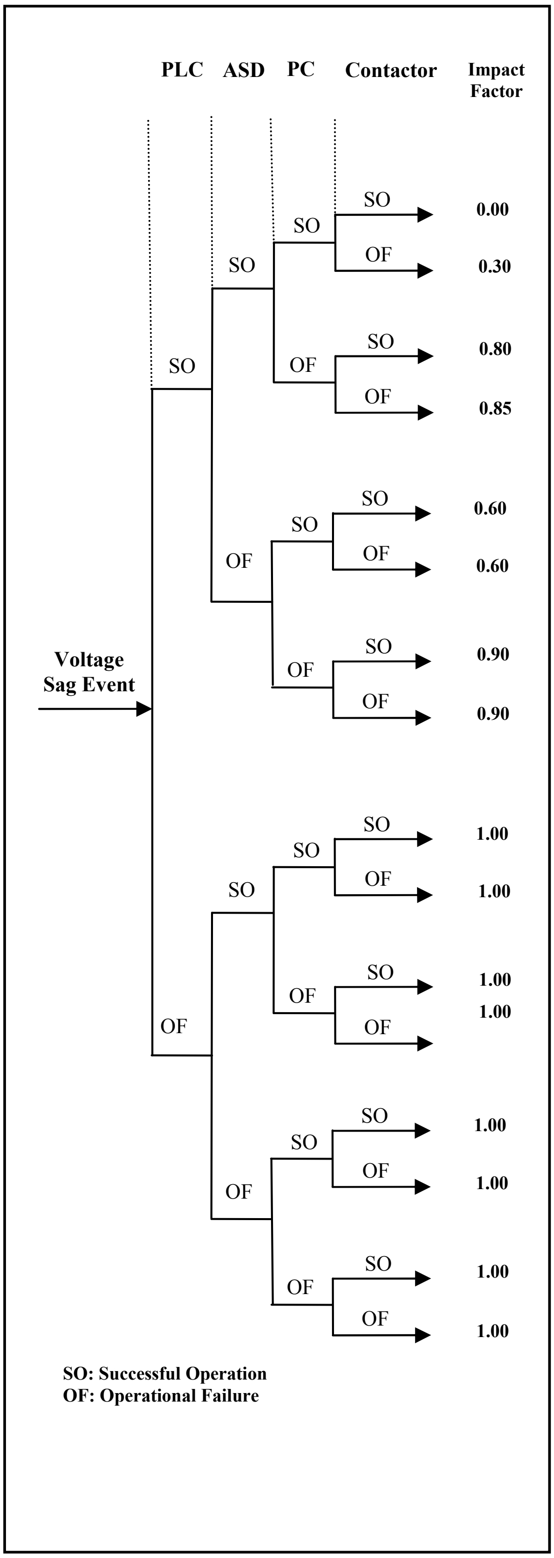

Fig. 2. Event tree diagram deduced for the case study.

(4) Then, the deduced event tree is analyzed for any possible modification. The modified event tree is assumed as shown in Fig. 3. The events having the same impact factors are summed up in one event. This modification helps

in reducing the complexity of the process and also in time savings in performing calculations. It shows that in case of PLC malfunctioning, voltage sag event completely disrupts the whole process.

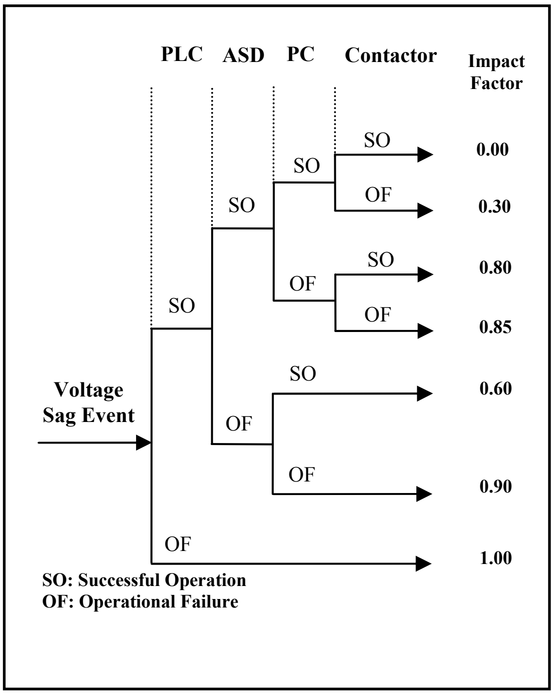

Fig. 3. Event tree diagram deduced for the case study.

(5) A typical voltage sag statistical data based on a large power quality survey conducted in [14] is used in this paper for representing the annual voltage sag events imposed on the facility. The distribution of these voltage sag events are shown in Table II.

TABLE II
ANNUAL DISTRIBUTION OF VOLTAGE SAG EVENTS [14]

Voltage Magnitude	Duration (seconds)				
	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
80-90%	87	4	4	0	2
70-80%	16	2	1	1	0
60-70%	5	5	1	0	0
50-60%	6	2	0	0	0
40-50%	5	2	0	1	0
30-40%	1	1	0	0	0
20-30%	1	0	0	0	0
10-20%	2	1	0	1	0
0-10%	0	1	0	0	0

(6) For each voltage sag event, the probabilities associated with the event tree outcomes are determined. As an example, Fig. 3 shows these probabilities for a sample voltage sag event with the remaining voltage equal to 12 percent of the nominal voltage and the duration of 50 msec.

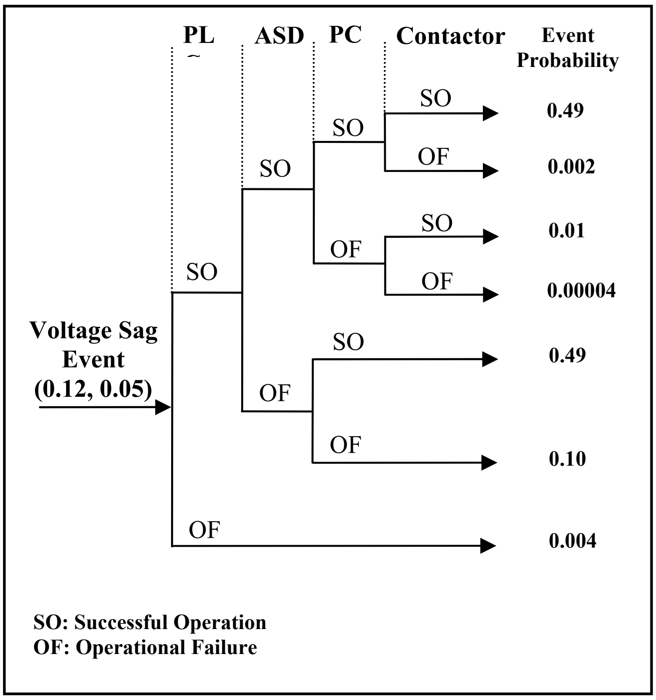

Fig. 4. Probabilities associated with the outcomes of the deduced event tree for a sample voltage sag event.

(7) The contributions of each voltage sag event on the financial losses imposed on the customer operations are determined using (2). Table III shows the contribution of all the voltage sag events, within the specified range, on the financial losses of the target customer operations.

TABLE III
FINANCIAL IMPACT OF VARIOUS VOLTAGE SAGS ON THE CUSTOMER, EUR/YR

Voltage Magnitude	Duration (seconds)				
	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
80-90%	306	179	314	0	348
70-80%	12614	6459	6287	26	0
60-70%	12390	42943	7238	0	0
50-60%	15319	32181	0	0	0
40-50%	45456	33056	0	17152	0
30-40%	16082	16830	0	0	0
20-30%	16414	0	0	0	0
10-20%	19739	17558	0	17568	0
0-10%	0	16931	0	0	0

(8) The overall financial impact of the voltage sag events on the targeted customer operation is estimated using (3). This is equal to the sum of all the contents of Table III. The annual financial impact of the voltage sag events on the targeted facility operation is estimated to be around 353,390 Euro.

IV. Conclusion

This paper proposed a methodology for assessing the impacts of voltage sag events in terms of financial losses on the consumer operations. The proposed approach was based on the event tree method. Compared to the previously developed evaluation techniques, which are mainly based on the block diagram approach, the implementation of the proposed technique is much easier. In addition, the different failure modes of the sensitive equipments and their possible consequences can be taken into account in this approach. The evaluation procedure is generic and can be applied on a variety of the customers.

For demonstration of the proposed technique, a typical case study was discussed in the paper for a semiconductor industry. The financial impacts of various voltage sag events on the facility concerned in this case study were evaluated.

V. References

[1] *IEEE Recommended Practice for Monitoring Electric Power Quality*, IEEE Standard 1159, New York, 2009.

[2] C. P. Gupta and J. V. Milanović, "Probabilistic methods for counting equipment trips due to voltage sags," *in Proc. 9th International Conference on Probabilistic Methods Applied to Power Systems, 11-15 June 2006, KTH, Stockholm, Sweden.*

[3] C. P. Gupta and J. V. Milanović, "Probabilistic assessment of financial losses due to interruptions and voltage sags-part II: practical implementation", *IEEE Transaction on Power Delivery, vol. 21, no. 2, April 2006.*

[4] S. Kazemi, M. Fotuhi–Firuzabad, and R. Billinton, "Reliability assessment of an automated distribution system," *IET Generation, Transmission and Distribution, vol. 1, pp. 223-233, March 2007.*

[5] S. Kazemi, M. Fotuhi–Firuzabad, M. Sanaye-Pasand, and M. Lehtonen, "Impacts of automatic control systems of loop restoration scheme on the distribution system reliability," *IET Generation, Transmission and Distribution, vol. 3, pp. 891-902, October 2009.*

[6] R. Billinton, and R. N. Allan, *Reliability Evaluation of Engineering Systems*, Plenum Press, Second Edition, 1992.

[7] *IEEE Recommended Practice for Evaluating Electric Power System Compatibility With Electronic Process Equipment*, IEEE Standard 1346-1998, May 1998.

[8] ITI (CBEMA) Curve (Revised 2000), [online]. Available: http://www.itic.org/clientuploads/Oct2000Curve.pdf

[9] Specification for semiconductor processing equipment voltage sag immunity, SEMI F47-0200 [online]. Available: http://f47testing.epri.com/f47abstract.html

[10] P. Pohjanheimo, "A probabilistic method for comprehensive voltage sag management in power distribution systems," Ph.D. Dissertation, Department of Electrical Engineering, Aalto University School of Science and Technology, Espoo, Finland, 2003.

[11] X. Xiao, Xuna Liu, H. Yang "Stochastic estimation trip frequency of sensitive equipment due to voltage sag", in *Proc. IEEE Asia Pacific Conference, December 2008.*

[12] Math H. J. Bollen, *Understanding Power Quality Problems: Voltage Sags and Interruptions*, New Jersey, USA, IEEE Press, 1999.

[13] P. Heine, "Voltage sags in power distribution networks," Ph.D. Dissertation, Department of Electrical Engineering, Aalto University School of Science and Technology, Espoo, Finland, 2005.

[14] Roberto Chouhy Leborgne, "Voltage sag characterization and estimation," Licentiate Dissertation, Department of Energy and Environment, Division of Electrical Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 2005.

[15] "Technical and Economic Considerations for Power Quality Improvements," Final Report, EPRI 1005910, Palo Alto, CA, 2001.

VI. Acknowledgment

The first author thanks the Department of Electrical Engineering at Aalto University for the financial support provided by SGEM project. The second author gratefully acknowledges the financial support received from the Fortum Foundation under Grant B2-11-032.

VII. Biographies

Muhammad Yasir received the B.Sc. Degree (Honors) in Mechatronics and Control Engineering from University of Engineering and Technology, Lahore, Pakistan. He has recently graduated with M.Sc. Degree in Electrical Engineering with majors in Power System in Aalto University (formerly Helsinki University of Technology), Espoo, Finland, where he also worked as research assistant. His main interests are power quality and voltage sag analysis.

Shahram Kazemi (SM'09) received the B.Sc. Degree (Honors) in Electrical Engineering from University of Hormozgan, Bandar-Abbas, Iran in 2002, and the M.Sc. Degree (Honors) in Electrical Engineering from Sharif University of Technology, Tehran, Iran in 2004. From 2003 to 2006, he has been with Niroo Consulting Engineers Co., Tehran, Iran, as a senior researcher. He has recently completed the Ph.D. and D.Sc. Degrees in Electrical Engineering respectively at Sharif University of Technology,Tehran, Iran and Aalto University, Espoo, Finland. His main research interest is the reliability evaluation of smart distribution grids.

Matti Lehtonen received the M.S. and Licentiate Degrees in electrical engineering from Aalto University School of Science and Technology (formerly Helsinki University of Technology), Espoo, Finland, in 1984 and 1989, respectively, and the D.Sc. Degree from the Tampere University of Technology, Tampere, Finland, in 1992. Since 1987, he has been with VTT Energy, Espoo, and since 1999, he has been with the School of Electrical Engineering at Aalto University, where he is a Professor of IT applications in power systems. His main activities include earth fault problems, and harmonic related issues and applications of information technology in distribution automation and distribution energy management.

Mahmud Fotuhi-Firuzabad (SM'99) obtained the B.Sc. and M.Sc. Degrees in Electrical Engineering from Sharif University of Technology and Tehran University in 1986 and 1989 respectively and M.Sc. and Ph.D. Degrees in Electrical Engineering from the University of Saskatchewan, Canada, in 1993 and 1997, respectively. Dr. Fotuhi-Firuzabad worked as a postdoctoral fellow in the Department of Electrical Engineering, University of Saskatchewan from Jan. 1998 to Sept. 2000, where he conducted research in the area of power system reliability. He worked as an assistant professor in the same department from Sept. 2000 to Sept. 2001. Presently, he is a professor and Head of the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran. Dr. Fotuhi-Firuzabad is a member of center of excellence in power system management and control. He serves as the Editor of the IEEE Transactions on Smart Grid.