УДК 697.1
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EXPERT OPINION-BASED POWER SUBSTATION RISK ASSESSMENT FOR PREVENTION OF ACIDENTS

Використання електричної енергії на виробництві пов'язане з виникненням ризиків для здоров'я та життя електротехнічних працівників. У статті викладено метод оцінки домінуючих виробничих чинників, вплив яких може призводити до виникнення неприватних випадків. Статистичні дані про причини нещасних випадків на трансформаторних підстанціях використано як вихідну інформацію методу Analytic Hierarchy Process. Запропонований підхід дає змогу визначити узгодженість експертних рішень. Отримані результати дали можливість ранжувати найбільш суттєві небезпечні та шкідливі виробничі чинники.

Ключові слова: *ризик, нещасні випадки, нечіткі множини, багатокритеріальне ухвалення рішення.*

Использование электрической энергии на производстве связано с возникновением рисков для здоровья и жизни электротехнических работников. В статье изложен метод оценки доминирующих производственных факторов, влияние которых может приводить к возникновению нечастных случаев. Статистические данные о причинах нечастных случаев на трансформаторных подстанциях использована в качестве исходной информации метода Analytic Hierarchy Process. Предложенный подход позволяет определить согласованность экспертных решений. Полученные результаты дали возможность ранжировать наиболее существенные опасные и вредные производственные факторы.

Ключевые слова: *риск, несчастные случаи, нечеткие множества, многокритериальное принятие решения.*

Electricity is a type of energy that creates risks, and its misuse can lead to damage to workers' health as well as to production losses. The present paper proposes an assessment method to determine the significance of factors contributing to the occurrence of accidents in the operation and maintenance of substations. This method is associated with analyzing preselected failure modes using a fuzzy version of the Analytic Hierarchy Process to determine the weights of the considered criteria and the experts involved in the assessment process based on group-based decision-making methods. These methods are used to determine the level of consensus among experts controlled by fuzzy logic procedures. The paper results allow one to identify factors that have a high level of contribution to the accident at power substations.

Keywords: *power substations, electrical accidents, risk assessment, group decision, fuzzy sets, multicriteria decision making, analytic hierarchy process.*

Risk Assessment of Power Substations. The identification and management of the risks related to the processes of electricity generation, transmission, distribution, and consumption is becoming increasingly necessary on the part of the companies involved in these processes. The occurrence of electrical accidents can lead to serious injuries of workers and their deaths. In addition to production losses, the significant costs of litigation and fines imposed by regulatory authorities take place, that negatively influence on the financial health of companies [1]. The assessment of the corresponding risks presents significant difficulties. The lack of statistical and historical data forces specialists to adopt intuitive and empirical decision-making methods using personal judgments [12]. The application of multicriteria group decision making techniques allows one to resolve several complex and conflicting aspects, at least partially. Individual decisions, which are to be aggregated into group decisions, are usually divergent, and appropriate techniques are to be applied to obtain satisfactory solutions. The satisfactory solutions are solutions which are acceptable to all members of the group, due to the rarity of finding a unanimous solution [8].

A method of identification of the most relevant contributing factors proposed in this work has is based on using standardized records and evaluations and wide applications of knowledge, experience, and intuition of experienced experts. Considering this, indices, which are to be used for weighting experts, are the following: practical experience, academic level, professional level, and training in work safety.

Although there exist numerous definitions of the risk concepts, in this study the definition of risk is associated with the combination of the probability of the accident occurrence and the severity of the corresponding potential damage. In [4], a methodology for risk assessment of automation systems of substations is considered, including the calculation of the probability of failure and determination of weights of the risk function using the Analytic Hierarchy Process (AHP). In [3], the risk assessment, involving the probability of electrocution in substations related to grounding systems, is realized. The risk assessment of major accidents in large power plants is an object of consideration in [2]. According to [6], the risk assessment in electrical environments includes a comprehensive analysis of hazards, associated predictable tasks related to them, and protective measures that are necessary to maintain an acceptable risk level. In [5], the risk analysis is performed through the following steps: (1) risk identification; (2) risk analysis; (3) risk assessment; (4) risk management. This model is widely used by large world organizations.

Decision Making Procedures. The Decision Making (DM) process is defined, in most cases, as the act of performing the identification, evaluation, comparison, ordering, prioritization, and more rational choice of alternatives [8,11]. In group decision-making, it is necessary to construct a collective opinion of the group based on individual opinions and aggregation of corresponding preferences related to each decision criterion, which simultaneously reflect all the criteria in a global way. In this case, individual ideas become less personal and managerial conflicts are minimized [9]. In the literature, several methods are presented in order to support the experts in the DM processes. In particular, the Analytic Hierarchy Process (AHP) [10,11] has found wide applications. It consists of a structural modeling methodology that, in addition to the qualitative structuring, incorporates a structure of weights [10,11]. In particular, the AHP has been used in [14] to determine values of probability and severity weights, in order to establish the level of risk associated with failures

in aviation systems. In [13], it is proposed to use a fuzzy version of the AHP to determine the weight of experts involved in an accident risk assessment for petrochemical tanks. The fuzzy set-based consensus scheme, proposed in [8,9], uses the concepts of fuzzy preference relations [7]. This scheme makes use of consensus for coordination goals, creating an efficient way to explore the capabilities of each group member in a cooperative work. In the present work, we use trapezoidal fuzzy numbers [8] to better represent human thinking and reduce the subjectivity of responses [9,14]. The applicability and efficiency of the results of [8,9] are demonstrated in [9] on the basis of a case study related to strategic planning in an electric power company.

Results. The proposed method, Analysis of Contributing Factors (ACF), permits one to carry out an evaluation of the systemic aspects responsible for the occurrence of accidents in the operation and maintenance of substations. Decision-making techniques, risk concepts, standards and the mathematical integration and registration of expert's opinions allow the identification and recording of relevant information that may contribute to the accident prevention strategy in power substations.

As a case study, consultations have been realized with five experts with solid experience. These experts have been invited to answer the corresponding questionnaire. Its first part is related to their experience, academic level related to electrical systems and substations, professional level, and training in work safety. The second part is formed by 42 failure modes extracted from the informative Annex F of [6] and adapted for the present research. These modes have been considered as contributing factors in this analysis. Each item has been evaluated by the experts considering the following problem: What are the most relevant contributing factors in the occurrence of personal accidents in power substations? It has been used a linguistic variable with five terms (very little, little, medium, very high, and extremely high). The determination of weights (ω_i, i=1,...,n) of the criteria (C_i, i=1,...,n) which serve for evaluating experts was realized applying results of [9] in accordance with steps given below.

1. Definition of the criteria for evaluating experts. In particular, the following criteria have been included:

- $C1$ – Experience in substations (Years of direct action);
- $C2$ – Academic level in electricity with emphasis on substations (Technical, Graduation, Specialization / Master or Doctorate);
- $C3$ – Professional level in corporation (Intermediary, Senior, Master or Specialist);
- $C4$ – Work safety training (Does not have, Technical, Specialization or Master / Doctorate).

2. Determination of the matrix A (as it is shown in Table 1), according to criteria defined by the moderator, obtaining the weight value ω_i.

3. Determination of the matrix $W = (\omega_i)_{nxn}$.

4. CI consistency test (A, W). The value found for CI (A, W) = 0.0917<0.1. The consistency of matrix A is considered acceptable. In the same way, we define the weights for the following criteria: practical experience, academic level, professional level and training in work safety represented in table I.

TABLE I. MATRIX A, ω_i, and ω_j

CRITERION	$C1$	$C2$	$C3$	$C4$	SUM	ω_i
$C1$	0.5	0.6	0.7	0.9	2.7	0.308
$C2$	0.4	0.5	0.4	0.6	1.9	0.242
$C3$	0.3	0.6	0.5	0.7	2.1	0.258
$C4$	0.1	0.4	0.3	0.5	1.3	0.192
ω_j	0.192	0.258	0.242	0.308		1.00

The weight of each expert (ω_{ei}) is defined according to the following steps:

1. Register the profile of each expert (e) in table III according to questionnaire answered;

2. Determine the values of $C1$ (ω_{e1}, ω_{e2}, ω_{e3}, ω_{e4}, and ω_{e5}) by means of standardization and fuzzy logic (the values of $C2$, $C3$, and $C4$ presented in Table IV are originated from Table II and based on the responses given in Table III; in particular, the values ω_i of Table I are to be multiplied by ω_i of table II, according to the criterion and profile of each expert registered in Table III);

3. Sum the individual values ω_e for an expert e to obtain ω_{es};

4. Multiply ω_{es} by 0.2 for obtaining ω_{ies} observing the following correlation:

$$\omega_{ei1} + \omega_{ei2} + \omega_{ei3} + \omega_{ei4} = 1 \quad (1)$$

5. Divide the value ω_{ies} by the sum of all ω_{ies} to obtain the weights ω_{ei} of opinions of the experts.

TABLE II. WEIGHTS OF CRITERIA

CRITERION	TYPE	ωi	CI(A,W)	CRITERION	TYPE	ωi	CI(A,W)
CRITERION	*C1* - EXPERIENCE IN SUBSTATION	0.308	0.092	PROFESSIONAL LEVEL	*C* 3.1 - INTERMEDIARY	0.192	0.092
	C2 - ACADEMIC LEVEL	0.242			*C* 3.2 - SENIOR	0.242	
	C3 - PROFESSIONAL LEVEL	0.258			*C* 3.3 - MASTER	0.258	
	C4 - TRAINING IN WORK SAFETY	0.192			*C* 3.4 - SPECIALIST	0.308	
ACADEMIC LEVEL	*C* 2.1 - TECHNICAL	0.200	0.094	TRAINING IN WORK SAFETY	*C* 4.1 - DOES NOT HAVE	0.183	0.094
	C 2.2 - GRADUATION	0.225			*C* 4.2 - TECHNICAL	0.242	
	C 2.3 - SPECIALIZATION/ MASTER	0.267			*C* 4.3 - SPECIALIZATION	0.275	
	C 2.4 - DOCTORATE	0.308			*C* 4.4 - MASTER/ DOCTORATE	0.300	

TABLE III. PROFILE OF SPECIALISTS

CRITERION	*e*1	*e*2	*e*3	*e*4	*e*5	ωi
C1	15	28	24	25	14	0.308
C2	SPEC/ M.Sc	SPEC/ M.Sc	GRADUATION	SPEC/ M.Sc	GRADUATION	0.242
C3	SENIOR	SENIOR	SENIOR	MASTER	INTERMEDIARY	0.258
C4	DOES NOT HAVE	DOES NOT HAVE	SPEC	DOES NOT HAVE	DOES NOT HAVE	0.192

TABLE IV. WEIGTH OF EXPERTS

CRITERION	ωe1	ωe2	ωe3	ωe4	ωe5
C1 - EXPIRIENCE IN SUBSTATION	0.165	0.308	0.264	0.275	0.154
C2 - ACADEMIC LEVEL	0.064	0.064	0.054	0.064	0.054
C3 - PROFESSIONAL LEVEL	0.080	0.080	0.080	0.067	0.050
C4 - TRAINING IN WORK SAFETY	0.035	0.035	0.053	0.035	0.035
(ωes):	0.344	0.488	0.451	0.442	0.293
(ωies):	0.069	0.098	0.090	0.088	0.059
(ωei):	0.171	0.242	0.224	0.219	0.145

The method discussed in this work is directed at identifying the relevance of failure modes in function of the previously presented problem. The steps are described below as follows:

1. Determination of contributing factors: forty-two items according to table VII have been selected to compose the questionnaire to be answered by the experts;

2. Selection of the five experts (*e*): based on curriculum analysis, mainly considering a solid experience in power substations and effective involvement in activities related to safety in electricity;

3. Evaluation research: the evaluation questionnaire has been structured and submitted to the experts and consolidated using the Google Forms web system (online form to collect information);

4. Achievement of the observance of the necessary level of consensus of the expert *s* in evaluating contributing factors by means of the fuzzy linguistic hierarchy according to [9] and table V;

TABLE V. ASSESSMENT AND CONSENSUS LEVEL

CRITERION	*e1*	*e2*	*e3*	*e4*	*e5*	(*NC*) GROUP
C1	Extremely high	Very high	Very high	Very high	Very high	0.76

5. Definition of the most relevant criteria (*C*) according to the decreasing order of weight (PC_i) and the level of consensus (*NC*) represented in table VII. For the calculation of the weight of each criterion (*PCi*) considering the following correlations:

$$PPi = \omega ei \times Pi, i = 1, \dots, 5. \quad (2)$$

$$GP = 0.2 \times \left(\sum_{j=1}^{n} PPi \right), i = 1, \dots, 5, \quad (3)$$

$$PE = \frac{GP}{0.2}. \quad (4)$$

$$PCi = \frac{PE}{\left(\sum_{j=1}^{n} PEi\right)}. \quad (5)$$

The values of P_i vary linearly according to the evaluation of the selected criterion: very little 0.2, little 0.4, medium 0.6, very 0.8 and extremely high 1.

In (2) and (5), *n* represents the number of contributing factors, *GP* and *PEi* are intermediate variables to obtain the value of the contributing factor weight (*PCi*). Table VI presents an example of an evaluation of a criterion considering (2)-(5).

TABLE VI. WEIGHT OF EACH CRITERIA

CRITERION	*P1*	*P2*	*P3*	*P4*	*P5*	*PP1*	*PP2*	*PP3*	*PP4*	*PP5*	*GP*	*PEi*	*PCi*
C1	1	0.8	0.8	0.8	0.8	0.171	0.193	0.179	0.175	0.116	0.167	0.834	0.032

Conclusion. This work has introduced the elements of Decision Making and FAHP in the quantitative evaluation of the relevance of contributing factors in the occurrence of accidents in power substations. The paper results permit one to use the individual experiences within the framework of group decision-making. The corresponding procedures have permitted to identify more accurately the relevance of individual opinions of the experts, valuing their individual knowledge, experience, and intuition and reduce the subjectivity of their estimates. As a result, it has been possible to determine the weights of the considered criterion and use this data to evaluate the relevance of the previously defined contributing factors. The paper results allow one to extract new relevant information. Enables the recording

of a history based on the expert's opinions of a corporation. According to the opinion of the experts it is necessary to observe the questions related to the risk analysis during the accomplishment of activities in power substations. Emphasis should be given on the task risk analysis strategy. It is necessary to adequately carry out the analysis of the risks involved and the establishment of control measures. Among the ten most relevant items, the behavioral aspects stand out. Failures in electrical protection systems also contribute to personal accidents in power substations. Care with electrical installations also deserves a prominent place in this analysis.

TABLE VII. CONTRIBUTOR FACTORS

FAILURE MODES	*Pci*	*NC*
Risk assessment - Does not consider all tasks, hazards, hazardous situations, or combination thereof	0.038	1
Behavioral - Unanticipated tasks	0.038	1
Behavioral - Competency complacency	0.036	0.76
Behavioral - Incentive to circumvent or reduce effectiveness	0.036	0.76
Risk assessment - Work permit system does not exist	0.032	0.76
Installation - Protective system failure	0.030	0.74
Behavioral - Unexpected or unanticipated interaction	0.030	0.74
Installation - Insufficient monitoring, control, or corrective actions, or combination thereof	0.030	0.56
Installation - Depreciation of effect over time	0.028	0.56
Installation - Component(s) failure	0.028	0.56
Maintenance - Inadequate procurement control	0.027	0.72
Communication - Lack of understanding	0.027	0.64
PPE - Worker forgets to use when needed	0.027	0.64
Procedure - Insufficient monitoring, control, or corrective actions, or combination thereof	0.027	0.64
Project - Incorrect calculation (that is, potential energy, toxicity, strength, durability)	0.026	0.7
PPE - Insufficient monitoring, control, or corrective actions or combination thereof	0.026	0.7
Procedure - Inconsistent with the current culture	0.026	0.68
Maintenance - Excessive production pressure	0.026	0.64
PPE - PPE specification inappropriate for the considered hazards	0.026	0.64
Project - Incorrect assembly	0.024	0.7
Procedure - Procedures not current or accessible	0.024	0.7
PPE - Reason for use not understood	0.024	0.7
PPE - Creates barriers to effective completion of the work	0.024	0.6
Management - Insufficient monitoring, control, corrective actions, or combination thereof	0.024	0.6
Procedure - Allows personnel to make the decision to work live without adequate justification	0.024	0.6
PPE - Excessive discomfort	0.023	1
PPE - Perceived invulnerability	0.023	0.7
Procedure - Procedures not current or accessible	0.023	0.52
PPE - Production pressure does not afford time to use or maintain	0.020	0.72
Training - Training not understood	0.020	0.72
Training - Identified hazards not clearly communicated	0.020	0.72
Signaling - Too many warning signs	0.018	0.7
Procedure - Policies and instructions inconsistent	0.018	0.7
Training - Depreciation of effect over time	0.018	0.64
Training - Training material not inclusive of detail regarding how to perform work	0.017	0.7
Training - Training material not current	0.016	0.52
Project - Application of an incorrect construction or manufacturing specification	0.015	0.74
Project - Excessive production pressure	0.014	0.7
Training - Training not consistent with instructions	0.014	0.68
Project - Inadequate procurement control	0.012	0.7
Training - Instructions not consistent with training content	0.011	0.7
Signaling - Content too general (e.g., "Don't touch the live parts; Be careful.")	0.009	0.76

Acknowledgements. The Electrical Engineers Adalton Sérgio Oliveira, Bruno Mazzini Muniz, Eduardo Antônio de Castro, Richard Nixon Buter and Roberto Márcio Moraes for the technical contribution. This work has been supported by the Brazilian agency CAPES.

REFERENCES

1. Brenner, B. C. (2013). Improving workplace electrical safety through self-assessment. In: IEEE. Electrical Safety Workshop (ESW), IEEE IAS. [S.l.], p. 163_166.

2. De Siqueira, I. P.; De Souza, B. A. (2010). Risk assessment of major accidents in large electric power plants Transmission and Distribution Conference and Exposition, 2010 IEEE PES,1-7.

3. Dimopoulos, A. et al. (2012). Proposal for probabilistic risk assessment in grounding systems and its application to transmission substations. IEEE Transactions on Power Delivery, IEEE, v. 27, n. 4, p. 2219_2226.

4. Guo, J. et al. Security risk assessment and weaknesses identification of the substation automation system. In: IEEE. Power System Technology (POWERCON), 2014 International Conference on. [S.l.], 2014. p. 1881_1888.

5. ISO, (2009). ISO 31000 2009 - Risk management, International Organization for Standardization, ISO, English.

6. NFPA, (2015). NFPA 70E: Standard For Electrical Safety In The Workplace, National Fire Protection Association (NFPA), English.

7. Orlovsky, S. (1978), Decision-making with a fuzzy preference relation. Fuzzy sets and systems, Elsevier, v. 1, n. 3, p. 155167.

8. Pedrycz, W.; Ekel, P.; Parreiras, R. (2011). Fuzzy multicriteria decision-making: models, methods and applications. John Wiley & Sons.

9. R.O. Parreiras, P.Ya. Ekel, J.S.C. Martini, and R.M. Palhares, A flexible consensus scheme for multicriteria group decision making under linguistic assessments, Information Sciences, vol. 180, no. 7, 2010, pp. 1075-1089.

10. Saaty, T. L. (1999). Decision making for leaders: the analytic hierarchy process for decisions in a complex world. [S.l.]: RWS publications.

11. Saaty, T. L.; Peniwati, K. (2013). Group decision making: drawing out and reconciling differences. [S.l.]: RWS publications.

12. Siqueira, I. P. de; Souza, B. A. de. (2010). Risk assessment of major accidents in large electric power plants. In: IEEE. Transmission and Distribution Conference and Exposition, 2010 IEEE PES. [S.l.], p. 1_7.

13. Zhang, J.; Fan, J.; Zhang, L. (2009). The application of fuzzy decision-making in the solving of petroleum and petrochemical accident probability. In: IEEE. Fuzzy Systems and Knowledge Discovery, 2009. FSKD'09. Sixth International Conference on. [S.l.], v. 7, p. 386391.

14. Zhao, Y.; Jiao, J.; Zhao, T. (2014) A synthetic risk assessment model based on ahp. In: IEEE. Reliability and Maintainability Symposium. [S.l.], 2014. p. 1-6.