Assessing functions of human risk, reliability and error probability

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Abstract. The paper discusses the problem of assessing human risk and reliability as well as a probability of a human error when applied to power systems. The research shows the effect of the human factor on the power system security; this effect is caused by poor (inadequate) maintenance due to human errors and a power system cascade failure. A need for making time-centered human reliability analysis is underlined. The problem is solved using the covariance analysis, i.e. mathematical statistics applied to research in the correlation between sets of independent categorical variables (factors) and independent quantitative variables (covariates). The introduction of covariates is intimated to enable evaluating their influence on the interaction of an independent variable and factors, and, in the course, the greater the influence coefficient for a factor is, the greater influence this factor has on human reliability and still more probable human errors are.

1. Introduction
Judging by the available studies of reliability and safety in industry, in many cases the main focus is made on the reliability of equipment, so the human reliability factor is overlooked (or completely ignored) [1-3]. It is also noted that human errors are quite common in the manufacturing sector, although they do not necessarily lead to disastrous results [4 - 8]. In general, the assessment of the human impact on safety requires analysis and consideration of the human factor and human error [9 - 13].

The standard of the SSSRIEC 62508-2014 (the Russian State Standard Specification, the International Electrical Commission) [14] cites the first manual on system reliability in the part concerning human activities. The standard can be applied in any field of industry where there is man-machine interaction. The standard presents only qualitative methods and a brief review of foreign quantitative techniques. To date, the remaining challenge is to develop manuals on quantitative assessment of the human factor (HF).

A comprehensive procedure for assessing probability of a human error under emergency conditions has been developed [15], which is based on the human reliability analysis methodology taking into account human factors (using a combination of the Weibull distributions functions) and external factors related to the environmental conditions (using a table of factors contributing to the system efficiency (serviceability). The Weibull function enables determining probability of a human error,
taking into consideration the difference between the first hour of the operator’s work and other time periods.

The paper discusses the problem of assessing human risk and reliability as well as a probability of a human error when applied to power systems. The research shows the effect of the human factor on the power system security; this effect is caused by poor (inadequate) maintenance due to human errors and a power system cascade failure. A need for making a time-centered human reliability analysis is underlined.

2. Setting of the problem
Analytic representation [16] is used for risk function:

\[ h(t, Z) = h_b(t) \psi(Z), \quad t \geq 0 \]  

where: \( t \) is time; \( Z = [z_1, z_2, \ldots, z_k] \), \( z_i \ (i = 1, 2, \ldots, k) \) are covariates; \( k \) is the covariates number; \( h_b(t) \) is the basic function characterizing human reliability changes; \( \psi(Z) = \exp(\gamma Z) = \exp \left( \sum_{i=1}^{k} \gamma_i z_i \right) \) is the link function introduced to allow for the impact of covariate \( z_1, \ldots, z_k \) on human reliability; \( \gamma_i \) are weighted coefficients for covariates \( z_i, \ i = 1, 2, \ldots, 5; \ j = 1, 2, \ldots, n \), where \( n \) is the number of cases under consideration. Thus, the algorithm in [16] was generalized for 5 covariates in case of an arbitrary number of covariates.

The influence of covariates is also taken into account: the influence coefficient of each covariate is supposed to be capable of taking one of the three values: 0, 1 or 2. The Weibull distribution is taken for the basic function in accordance with the recommendations presented in [16, 17]:

\[ h_b(t) = \frac{\beta \alpha^{\beta-1}}{\alpha^\beta} e^{-\alpha t} \]  

with parameters of \( \alpha = 200 \) hours; \( \beta = 3 \). It is necessary to evaluate the functions of:

1. A risk for a human being:

\[ h(t, Z) = h_b(t) \psi(Z), \quad t \geq 0 \]  

2. Human reliability:

\[ R_{hp}(t) = \exp \left[ -\int_0^t h(s, Z) ds \right] = \exp \left[ -\int_0^t \frac{\beta \alpha^{\beta-1}}{\alpha^\beta} \exp(\gamma Z) ds \right] \]  

\( R_{hp}(t) \) human reliability function expresses a probability of making no error by a human being up to the moment of \( t \).

3. Human error probability:

\[ F_{hp}(t) = 1 - R_{hp}(t) \]  

3. Problem solution
Various alternatives are discussed. Alternative 1. For power systems, \( z_i, i = 1, 2, \ldots, 5 \) [18] are considered as covariates characterizing various factors: \( z_1 \) characterizes problem complexity; \( z_2 \)
characterizes environment factors; \( z_3 \) characterizes human knowledge and experience; \( z_4 \) characterizes human psychology; \( z_5 \) characterizes human physical state.

The values of weighted coefficients used for describing the covariates presented above are taken from [19], based on the analytic hierarchy process. Using an expert estimate, five covariates were compared in pairs in their relative importance for a human error probability. And further, their weight could be calculated.

It should be emphasized that:
- within the limits of the algorithm given it is possible to consider, \( i = 1, 2, \ldots, 5 \) covariates for other characterizing factors as well. It is important that the influence coefficients and weighted values should be consistent with these new factors;
- in the examples given below, we assign covariates’ influence coefficients and their weighted values ourselves (when discussing particular cases, the necessary data can be obtained on the basis of expert estimates).

The values of \( \alpha \) and \( \beta \) parameters were borrowed from the primary source [17]. According to [17] the following values were taken: \( \beta = 3 \), \( \alpha = 200 \) hours (they had been obtained using the statistical analysis for the problem discussed in the primary source).

Five covariates characterizing the aforementioned factors, which have various covariates’ influence coefficients and weighted values in the cases discussed, are taken into account in "Alternatives 1 and 2." Since in the general case, as may be supposed, there appears a necessity to evaluate (apart from 5 covariates) the influence of a number of additional covariates \( z_6, z_7, \ldots, z_m \) a specific case with \( m = 8 \) ("Alternatives 3 and 4") was considered as well. Three covariates \( z_6, z_7, z_8 \) were added to the \( z_1, z_2, z_3, z_4, z_5 \) covariates’ set. Let’s assume that they characterize respectively: \( z_6 \) – a possibility for the domino effect occurrence; \( z_7 \) – the existence of corrosion medium; \( z_8 \) – a level of production automation. For a particular problem, all possible covariates’ alternatives should be found out (including with the involvement of experts).

### 3.1. Calculation data

Calculation data for various alternatives and cases is given in Tables 1–4.

#### Table 1. Alternative 1. Case of \( \alpha = 200, \beta = 3, t = (10–60) \) h.

| \( z_i \) \( (i = 1, \ldots, 5) \) covariates | \( i = 1 \) | \( i = 2 \) | \( i = 3 \) | Weighted value of the \( i \)-th covariate in the \( j \)-th case, \( \gamma_{ij} \) |
|---|---|---|---|---|
| \( z_1 \) | 1 | 1 | 1 | 0.27 |
| \( z_2 \) | 0 | 1 | 2 | 0.18 |
| \( z_3 \) | 0 | 1 | 2 | 0.22 |
| \( z_4 \) | 1 | 1 | 2 | 0.15 |
| \( z_5 \) | 0 | 1 | 2 | 0.18 |

Along a horizontal axis, hour (h), while along a vertical axis the name of the function considered \( h(t, Z) \) in the given case are given in all the figures 1 - 15.
Figure 1. Risk functions for a human being in the cases considered – $h(t, Z)$.

Figure 2. Human reliability functions in the cases considered $R_{hp}(t)$.

Case 1: $R_{hp}(t) = \exp \left[ -\int_0^{3t} \frac{3s^{3-1}}{200^3} \exp(0.42200s) \, ds \right]$

Case 2: $R_{hp}(t) = \exp \left[ -\int_0^{3t} \frac{3s^{3-1}}{200^3} \exp(1) \, ds \right]$

Case 3: $R_{hp}(t) = \exp \left[ -\int_0^{3t} \frac{3s^{3-1}}{200^3} \exp(1.73) \, ds \right]$

Figure 3. Functions of a human error probability in the cases considered $F_{hp}(t)$.

Table 2. Alternative 2. Case of $\alpha = 200, \beta = 3, \ t = (10–100) \ h$.

| $z_i$ ($i=1, \ldots, 5$) covariates | Covariates’ influence coefficients in ($j=1,2,3$) cases considered | Weighted value of the $i$-th covariate in the $j$-th case, $\gamma^j$ |
|-----------------------------------|-------------------------------------------------|------------------|
| $z_1$                             | Case 1, $j=1$                                   | 0.2              |
| $z_2$                             | Case 2, $j=2$                                   | 0.25             |
| $z_3$                             | Case 3, $j=3$                                   | 0.3              |
| $z_4$                             |                                                  | 0.2              |
| $z_5$                             |                                                  | 0.25             |
Figure 4. Risk function for a human being – $h(t, Z)$.

Case 1: $h(t, Z) = \frac{3 \cdot t^{3-t}}{200} \cdot \exp(0.7), \ t \geq 0$

Case 2: $h(t, Z) = \frac{3 \cdot t^{3-t}}{200} \cdot \exp(1), \ t \geq 0$

Case 3: $h(t, Z) = \frac{3 \cdot t^{3-t}}{200} \cdot \exp(2.15), \ t \geq 0$

Figure 5. Human reliability functions – $R_{hp}(t)$.

Figure 6. Functions of a human error probability – $F_{hp}(t)$.

Table 3. Alternative 3. Case of $\alpha = 200, \beta = 3, \ t = (0–100) \ h$.

| $z_i$ ($i=1,…,8$) | Covariates’ influence coefficients in ($j=1,2,3$) cases considered | Weighted value of the $i$-th covariate in the $j$-th case, $\gamma_{ij}$ |
|-----------------|---------------------------------------------------------------|---------------------------------------------------------------|
| covariates      | Case 1, $j=1$ | Case 2, $j=2$ | Case 3, $j=3$ |  |
| $z_1$           | 1                | 1                | 1                | 0.21 |
| $z_2$           | 0                | 1                | 2                | 0.14 |
| $z_3$           | 0                | 1                | 2                | 0.19 |
| $z_4$           | 1                | 1                | 2                | 0.10 |
| $z_5$           | 0                | 1                | 2                | 0.12 |
| $z_6$           | 0                | 1                | 2                | 0.07 |
| $z_7$           | 1                | 1                | 2                | 0.09 |
| $z_8$           | 1                | 2                | 2                | 0.08 |
A) \( t = (0–100) \text{ h} \)

**Figure 7.** Risk function for a human being – \( h(t, Z) \).

Case 1: \( h(t, Z) = \frac{3}{200} t^{\beta} \exp(0.48), \ t \geq 0 \)

Case 2: \( h(t, Z) = \frac{3}{200} t^{\beta} \exp(1.08), \ t \geq 0 \)

Case 3: \( h(t, Z) = \frac{3}{200} t^{\beta} \exp(1.79), \ t \geq 0 \)

**Figure 8.** Human reliability functions – \( R_{sp}(t) \).

**Figure 9.** Functions of a human error probability – \( F_{sp}(t) \).

| Table 4. Alternative 4. Case of \( \alpha = 200, \beta = 3 \). |
|---|---|---|
| Covariates’ influence coefficients in \( (j=1,2,3) \) cases | Weighted value of the \( i \)-th covariate in the \( j \)-th case, \( \gamma_{ij} \) |
| **Covariates** | Case 1, \( j=1 \) | Case 2, \( j=2 \) | Case 3, \( j=3 \) |
| \( z_1 \) | 1 | 1 | 2 | 0.2 |
| \( z_2 \) | 0 | 1 | 1 | 0.18 |
| \( z_3 \) | 1 | 1 | 2 | 0.14 |
| \( z_4 \) | 1 | 0 | 2 | 0.12 |
| \( z_5 \) | 0 | 1 | 2 | 0.15 |
| \( z_6 \) | 0 | 1 | 2 | 0.05 |
| \( z_7 \) | 1 | 1 | 2 | 0.07 |
| \( z_8 \) | 1 | 2 | 2 | 0.09 |

A) \( t = (0–100) \text{ h} \)
Figure 10. Risk function for a human being – $h(t, Z)$.

Case 1: $h(t, Z) = \frac{3 \cdot t^{3-1}}{200^3} \exp(0.62)$, $t \geq 0$

Case 2: $h(t, Z) = \frac{3 \cdot t^{3-1}}{200^3} \exp(0.97)$, $t \geq 0$

Case 3: $h(t, Z) = \frac{3 \cdot t^{3-1}}{200^3} \exp(1.82)$, $t \geq 0$

Figure 11. Human reliability functions – $R_{hp}(t)$.

Figure 12. Functions of a human error probability – $F_{hp}(t)$.

Figure 13. Risk function for a human being – $h(t, Z)$.

Case 1: $h(t, Z) = \frac{3 \cdot t^{3-1}}{200^3} \exp(0.62)$, $t \geq 0$

Case 2: $h(t, Z) = \frac{3 \cdot t^{3-1}}{200^3} \exp(0.97)$, $t \geq 0$

Case 3: $h(t, Z) = \frac{3 \cdot t^{3-1}}{200^3} \exp(1.82)$, $t \geq 0$

Figure 14. Human reliability functions – $R_{hp}(t)$.

Figure 15. Functions of a human error probability – $F_{hp}(t)$.
3.2. Calculation data analysis

1. Alternative 1 (Table 1) is considered for five covariates \( z_i \ (i=1,...,5) \) with specified (in three cases) influence coefficients of \( z_{ij} \ (j=1,2,3) \) covariates and the corresponding weighted values of \( \gamma_y \).

When a power system operates for \( t = 10–60 \) h, and in accordance with formulas (3)–(5), calculations were made with the parameters’ values of \( \alpha = 200, \beta = 3 \) and functions were plotted (Figures 1–3): the risk function for a human being – \( h(t,Z) \); the function of human reliability – \( R_{hp}(t) \), the function of a human error probability – \( F_{hp}(t) \). Calculations were further made for Alternative 2 (Table 2) with changes in influence coefficients of \( z_{ij} \ (j=1,2,3) \) covariates, corresponding weighted values of \( \gamma_y \) and the period of system operation of \( t = (10–100) \) h (Table 2).

Plots of \( h(t,Z) \), \( R_{hp}(t) \) and \( F_{hp}(t) \) functions are given in Figures 4–6.

It is noted that the functions of a human error probability \( F_{hp}(t) \) by the moment of \( t = 100 \) h were in between 0.2 and 0.65 for the cases considered, and by the moment of \( t = 60 \) h – in between 0.05 and 0.2 (while for Alternative 1 at \( t = 60 \) h, these values ranged from 0.04 up to 0.141). Thus, with the same number of covariates there is a change, small as it is, observed in the evaluation of a human error probability.

2. Provision was made for including three additional covariates \( z_6, z_7, z_8 \) with new influence coefficients’ values of \( z_i \ (i=1,...,5) \) covariates and weighted values of \( \gamma_y \) into Alternative 3 (Table 3). Calculations were made using the values of \( \alpha = 200, \beta = 3 \) for the time of the system operation \( t = (0–100) \) h (Figures 7–9). Another alternative with eight covariates (Alternative 4, Table 4) was also considered: for \( t = (0–100) \) h (Figures 10-12) and for \( t = (0–200) \) h (Figures 13–15).

The effect of covariates’ addition and redistribution of weighted coefficients in the course can be traced when comparing the data given in Table 5. Judging by the data in Table 5 (the bottom row), when a power system operates for a time period of \( t = 100 \) hours for Alternative 4 in cases 1, 2 and 3, the human error probability \( F_{hp}(t) \) is equal respectively to 0.207, 0.28 and 0.54.

That is, the difference is negligible in the first two cases (with five covariates), and with three new covariates added, the human error probability increases from 0.207 up to 0.54, so that the difference is 2.6 times (and for Alternative 2–3 times). As for the reliability function \( R_{hp}(t) \), for Alternative 4 its value decreases from 0.793 in the first case up to 0.462 in the third case, and in Alternative 3 the value decreases from 0.818 up to 0.473.

| Alternatives | Values of functions for various \( t, \) h | Reliability, cases | Error probability, cases |
|--------------|-----------------|------------------|------------------------|
|              | 1               | 2                | 3                      | 1              | 2              | 3              |
| 1            |                |                  |                        |                |                |                |
| 4            | 0.99998        | 0.99978          | 0.99995                | 1.199-10^{-5} | 2.16-10^{-5}  | 4.56-10^{-5}  |
| 8            | 0.99990        | 0.9982           | 0.996                  | 9.599-10^{-5} | 0.00017        | 0.00036        |
| 10           | 0.99981        | 0.99662          | 0.993                  | 0.00019        | 0.00034        | 0.0007         |
| 50           | 0.977          | 0.959            | 0.915                  | 0.0232         | 0.0413         | 0.085          |
| 100          | 0.829          | 0.7136           | 0.490                  | 0.1709         | 0.286          | 0.51           |
| 2            |                |                  |                        |                |                |                |
| 4            | 0.999984       | 0.99997          | 0.99993                | 1.599-10^{-5} | 2.16-10^{-5}  | 6.88-10^{-5}  |
| 8            | 0.99987        | 0.99982          | 0.9994                 | 0.00013        | 0.00017        | 0.00055        |
| 10           | 0.99975        | 0.99966          | 0.9989                 | 0.00025        | 0.00034        | 0.001          |
| 50           | 0.969          | 0.959            | 0.874                  | 0.0308         | 0.041          | 0.126          |
4. Future work
Further investigations in modeling human behavior in stress situations for various fields of industry are necessary. There is an urgent need in developing an algorithm based on this methodology and its software for critical infrastructures used for various purposes. Further investigations and a complete implementation of the methodology proposed in different critical infrastructures sector are planned.

5. Conclusion
1. The well-known approach was generalized on the basis of the covariance analysis (when applied to power systems) in case of an arbitrary number of covariates.
2. When considering the correlation between sets of independent categorical variables (factors) and independent quantitative variables (covariates) for various alternatives and cases (relative to the number of covariates, their influence coefficients and weighted values), it was possible to plot functions of risk, human reliability and a probability of his error.
3. Introduction of covariates to the discussion and generalization in case of an arbitrary number of covariates make it possible to evaluate their effect (and the factors consistent with them) on evaluating the functions of risk, human reliability and a probability of human errors.
4. The plots made on the basis of the calculation data for various alternatives and cases clearly demonstrate that the greater the influence coefficient for a covariate is and the greater its weighted value, the greater effect the corresponding factor has on the human reliability, his risk and still more probable human errors are.
5. The effect of the number of covariates considered and redistribution of their weighted contributions on human reliability and a probability of human errors can be judged about by the calculation data for cases with five and eight covariates.
6. The value of the reliability function $R_{hp}(t)$ for Alternative 4 significantly decreases on completing 100-hour operation of a system from 0.793 in the first case up to 0.462 in the third case (for Alternative 3 it decreases from 0.818 up to 0.473). The difference in values $F_{hp}(t=100)$ is not that great for a probability of human errors in the first two cases (Alternative 1), but with the introduction of three new covariates (Alternative 4) the value of $F_{hp}(t=100)$ significantly increases from 0.207 up to 0.54, so that the difference is 2.6 times (and for Alternative 2–3 times).

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