A Quantitative Risk Assessment Methodology of Electric CPS

ZHANG Jiaxi and SONG Yu

School of Control and Computer Engineering, North China Electric Power University, Baoding, China

Abstract: To mitigate the security risk level of CPS (cyber physical power system) and achieve efficient operation of power system, this paper focused on the CPS risk assessment. Based on the study of CPS risk assessment theories and electric CPS security features, this paper analyzed and compared the existing electric CPS risk researches, and found that the limitation was the lack of specific quantitative methods. By introducing the integrated fuzzy risk assessment methodology, a security risk quantitative evaluation methodology of electric CPS was designed. Firstly, a systematic literature review was conducted, and relevant standards were collected; then we used AHP (analytic hierarchy process) to analyze the weights of each parameter; and finally integrated various parameters and calculated the overall risk rating of the system. The data of an electric CPS were used to apply this methodology and the result confirmed the feasibility.

Key words: Electric CPS, risk assessment, TFN, AHP.

1. Introduction

The deep integration of power systems and cyber systems is a major trend in the development of the current electricity system. CPS (cyber-physical systems) integrates computing resources and physical systems, in order to achieve the perception, control and information services of large engineering systems. The CPS used in power systems will effectively realize the intelligent development of systems. However, electric CPS has a high complexity, which is characterized by: (1) The range of information collection is much larger than that of smart grid; (2) Electric CPS communication network is composed of wired and wireless networks; (3) Many distributed computing devices exist; (4) The control center is connected with and directly control a variety of distributed power sources and the load device [1]. Therefore, the risk sources are quite diverse. Depending on the size of risk, we determine the degree of attention, so risk quantification is essential

for decision-making.

With the development of power systems, security issues become more prominent, so the risk assessment of CPS is important. Most of the power system security risk assessment study in Refs. [2-11] to quantify physical and information systems separately. It's lack of systematic quantitative methods, and it's not conducive to the overall decision-making. Therefore, we introduce fuzzy risk assessment methods to systematically analyze the risk of electric CPS.

The paper is organized as follows: Section 2 explains risk analysis of electric CPS; Section 3 contains the integrated fuzzy risk assessment methodology; Section 4 is the conclusion.

2. Risk Analysis of Electric CPS

Power system is a complex system, its supporting environment includes the heterogeneous computer systems in dispatch center at all levels, local area networks and the power system industry extranet, connecting the local area networks [12]. CPS is a binary heterogeneous complex network and its security issues include network security and physical

Corresponding author: Jiaxi Zhang, graduate student, research fields: software engineering, artificial intelligence. E-mail: 283873633@QQ.com.

security, as well as the coupling risk [13]. Given the special nature of electric CPS, considering various factors on physical and cyber layers, we take a thermal power plant as an example. Referring to Ref. [14], Table 1 lists the electric CPS risk assessment parameters, written as C_i .

3. Integrated Fuzzy Risk Assessment Methodology

3.1 TFN

TFN (triangular fuzzy number) is a method to turn uncertain fuzzy linguistic variables into certain values.

If the membership function of fuzzy number A is

$$\mu_A(x) = \begin{cases} \mu_A^L(x), & x \in [a, b] \\ \mu_A^R(x), & x \in [b, d] \\ 0, & x \notin [a, d] \end{cases} \quad (1)$$

In Eq. (1): $\mu_A^L(x): [a, b] \rightarrow [0, 1]$, continuously and strictly increases; $\mu_A^R(x): [b, d] \rightarrow [0, 1]$, continuously and strictly decreases; $a < b < d$ and $a, b, d \in \mathbb{R}$. If $\mu_A^L(x)$ and $\mu_A^R(x)$ are linear functions of Eq. (2), we call A TFN, and record as $A = (a, b, d)$, where a is the value of the lower limit, b is the possible value, d is the upper limit [15].

$$\mu_A(x) = \begin{cases} \frac{1}{b-a}x - \frac{a}{b-a}, & x \in [a, b] \\ \frac{1}{b-d}x - \frac{d}{b-d}, & x \in [b, d] \\ 0, & x \in (-\infty, a] \cup [d, +\infty) \end{cases} \quad (2)$$

3.1.1 Determining the Quantitative Status Indicator Scoring Models and Membership Functions

Risk assessment includes two aspects, namely the severity and probability. In reality, due to the uncertainty and lack of information, there are certain difficulties to assess these factors. Therefore a lot of evaluation results use linguistic variables, such as high, medium, low. In this study, the qualitative standard uses TFN to express the ambiguity of object. Table 2 describes the qualitative evaluation of systems.

3.1.2 Determining the Qualitative Status Index Memberships

Risk parameter rating is constituted by the linguistic variables, including $V_1, V_2, V_3, V_4, V_5, V_6, V_7$, where, V_1 = quite low, V_2 = very low, V_3 = low, V_4 = moderate, V_5 = high, V_6 = very high, V_7 = quite high. These language variables membership function is defined by TFN, shown as Eq. (3).

$$V_1 = \left(0, 0, \frac{1}{6}\right) \quad \mu_{V_1}(x) = \begin{cases} 1-6x, & 0 \leq x < \frac{1}{6}, \\ 0, & \frac{1}{6} \leq x \leq 1, \end{cases}$$

$$V_n = \left(\frac{n-2}{6}, \frac{n-1}{6}, \frac{n}{6}\right) \quad \mu_{V_n}(x) = \begin{cases} 0, & 0 \leq x < \frac{n-2}{6}, \\ 6x-(n-2), & \frac{n-2}{6} \leq x < \frac{n-1}{6}, \\ n-6x, & \frac{n-1}{6} \leq x \leq \frac{n}{6}, \\ 0, & \frac{n}{6} \leq x \leq 1, \end{cases} \quad (3)$$

$$V_7 = \left(\frac{5}{6}, 1, 1\right) \quad \mu_{V_7}(x) = \begin{cases} 0, & 0 \leq x < \frac{5}{6}, \\ 6x-5, & \frac{5}{6} \leq x \leq 1, \end{cases}$$

$n=2,3,4,5,6$

3.1.3 Establishing Fuzzy Evaluation Matrix

Fuzzy risk evaluation matrix is established by $C_i \times V$. A fuzzy evaluation matrix M (C_1) can be calculated as follows:

$$M(C_1) = \begin{pmatrix} V(s_{11}, l_{11}, 1) & V(s_{11}, l_{11}, 2) & \dots & V(s_{11}, l_{11}, 7) \\ V(s_{12}, l_{12}, 1) & V(s_{12}, l_{12}, 2) & \dots & V(s_{12}, l_{12}, 7) \\ \dots & \dots & \dots & \dots \\ V(s_{18}, l_{18}, 1) & V(s_{18}, l_{18}, 2) & \dots & V(s_{18}, l_{18}, 7) \end{pmatrix} \begin{matrix} C_{11} \\ C_{12} \\ \dots \\ C_{18} \end{matrix} \quad (4)$$

In the same way, we can construct fuzzy evaluation matrix M (C_2), M (C_3), M (C_4) and M (C_5) for risk category C_2, C_3, C_4 and C_5 respectively.

3.2 AHP

The AHP is a good way to solve the problem of multi-parameter decision. Suppose the parent function f is divided into five sub-functions f_1 - f_5 , followed by the corresponding risk weight ω_1 - ω_5 . Specifically, the risk weight steps are as follows:

Table 1 Risk assessment parameters of electric CPS.

physical layerC1	major architecture factors C11	surrounding architecture environment C111 Storage warehouse and coal pier C112 The main control room C113 Residential building factor C114
	fire management factors C12	Fire alarm systems C121 Flammable gas leak detector C122 Automatic fire extinguishing systemC123 Mechanical exhaust systemC124 Fire truck settingC125 Extinguishing equipment C126 Fire hydrant settingC127 Distance from the local fire brigade C128 Fire water setting C129
	main risk factorsC13	Fuel C131 Boiler systems C132 Turbine generator set C133 Electrical systems C134 Special risk factors C135
	social environment factorsC14	Set of operators on duty C141 Theft factor C142 Public responsibility factor C143 Security situation around the plant C144 Temporary employer's liability factor C145
	secururity managementC15	Safety management C151 Staff safety education C152 Duty system of special operation C153 Duty system of security C154 Regular safety inspections C155 Emergency mechanism C156
	nature environment factorsC16	Geological Environment C161 Hydrological Environment C162 Meteorological environment C163
cyber layerC2	Malicious codeC21	Virus C211 Worms C212 Trojans C213 XSS C214 Hybrid C215
	Hardware failure C22	
	Unwanted accessC23	Fraudulent use of other users C231 Illegal modification of their own user permissions C232 Occupy of two roles C233 Damage of access control systems C234 Not-turned-off interfaces C235 Intercepted and modified during transmission C236 Channel interference of information content C237 The action during very time C238
	Too many service requests C24	Increase in service under normal circumstances C241 Malicious denial of service attack C242
	Data channel failure C25	
	Damage from people C26	
	Users denying operations C27	Users denying specific operation C271 Users denying sending / receiving information C272
	Fake device C28	
	Problematic inputC29	User misuse C291 Malicious input C292 Interaction problem C293

Table 2 Linguistic classification of grades of hazard factors and their corresponding TFNs.

Ranking level	Severity(s)	Likelihood(l)	TFNs
1	Definitely mild	Definitely low	(0.0,0.0,0.1)
2	Extremely mild	Extremely low	(0.0,0.1,0.2)
3	Quite mild	Quite low	(0.1,0.2,0.3)
4	Mild	Low	(0.2,0.3,0.4)
5	Slightly mild	Slightly low	(0.3,0.4,0.5)
6	Moderate	Moderate	(0.4,0.5,0.6)
7	Slightly severe	Slightly high	(0.5,0.6,0.7)
8	Severe	High	(0.6,0.7,0.8)
9	Quite severe	Quite high	(0.7,0.8,0.9)
10	Extremely severe	Extremely high	(0.8,0.9,1.0)
11	Definitely severe	Definitely high	(0.9,1.0,1.0)

(1) Consult experts in the field, compare fl-f5 in pairs based on nine scaling method, and construct judgment matrix Z , shown as Eq. (5).

$$Z = \begin{bmatrix} 1 & z_{12} & z_{13} & z_{14} & z_{15} & \omega_1 \\ z_{21} & 1 & z_{23} & z_{24} & z_{25} & \omega_2 \\ z_{31} & z_{32} & 1 & z_{34} & z_{35} & \omega_3 \\ z_{41} & z_{42} & z_{43} & 1 & z_{45} & \omega_4 \\ z_{51} & z_{52} & z_{53} & z_{54} & 1 & \omega_5 \end{bmatrix} \quad (5)$$

(2) Adopt sum-product method [16] to get eigenvectors of a judgment matrix. Firstly, each column element of Z goes through a normalization process:

$$\bar{z}_{ij} = z_{ij} / \left(\sum_{i=1}^n z_{ij} \right), \quad j = 1, 2, 3, \dots, n \quad (6)$$

Secondly, add the normalized elements of each row:

$$W_i = \left(\sum_{j=1}^n \bar{z}_{ij} \right), \quad i = 1, 2, 3, \dots, n \quad (7)$$

Finally, the vector $W = [W_1, W_2, \dots, W_n]^T$ is normalized, i.e., risk weights:

$$\omega_i = W_i / \left(\sum_{j=1}^n W_j \right), \quad i = 1, 2, \dots, n \quad (8)$$

3.3 Construction of the Overall Risk Assessment Model

In order to assess the system's overall risk, weight of all risk factors, risk categories and their associated parameters have to be considered in the assessment process. Suppose W_i and W_{ij} are the relative weight

of the main risk categories and their associated parameters, $g(s, l)$ is the risk rating of each parameter, determined by s and l from Table 2. Here is the three-step fuzzy evaluation method to obtain the overall risk rating.

Step 1, the overall risk assessment of C1 is shown as Eq. (9).

$$\begin{aligned} & (R(1,1), R(1,2), R(1,3), R(1,4), R(1,5), R(1,6), R(1,7))_{1 \times 7} \\ & = (W_{11}, W_{12}, W_{13}, W_{14}, W_{15}, W_{16}, W_{17}, W_{18}) \times M(C_1)_{8 \times 7} \end{aligned} \quad (9)$$

where, $R(1, n) = \sum_{k=1}^8 W_{1k} \times V(s_{1k}, l_{1k}, n)$ for $n = 1, 2, \dots, 7$

$R(1) = (R(1,1), R(1,2), R(1,3), R(1,4), R(1,5), R(1,6), R(1,7))$ is expressed as the overall risk assessment of C1 in the first step. Similarly, $R(2)$, $R(3)$, $R(4)$ and $R(5)$ are the overall risk vectors of C2, C3, C4 and C5 in the first step.

Step 2, as shown in Eq. (10):

$$\begin{aligned} & (R(1), R(2), R(3), R(4), R(5), R(6), R(7)) \\ & = (W_1, W_2, W_3, W_4, W_5)_{1 \times 5} \times (R1 \ R2 \ R3 \ R4 \ R5)^T \end{aligned} \quad (10)$$

where, $R2(n) = (R(1), R(2), R(3), R(4), R(5), R(6), R(7))$.

Step 3, by using the gravity method the final overall risk rating is defuzzificated:

$$Rate = \sum_{n=1}^7 V_G(n) \times R2(n) \quad (11)$$

Specifically, the integrated fuzzy risk assessment method of electric CPS includes:

(1) Determine the power system to be evaluated, functionally decompose it, and collect relevant parameters;

(2) Calculate the risk level of each sub-parameter. First, express severity s and likelihood l by TFN and multiply them to get the risk level g ;

(3) Use AHP to analyze parameter weights. Firstly, based on nine scaling method to build judgment matrix Z , then use sum-product method to calculate feature vectors, normalize them to get risk weights W ;

(4) Construct a risk assessment hierarchy table, consider the various risk levels and weights to get the overall risk assessment vector by fuzzy evaluation matrix, defuzzificate them and obtain specific values.

4. Case Study

We take a CPS system in a thermal power plant as an example to evaluate quantitative risk. Referring to classification of parameters in Table 1, firstly we use the nine scaling method to evaluate weight of risks,

and by building z -matrix, using the method in section 3.2, we get their own weight. Table 3 lists the risk weights of the first layer's parameters.

$$Z = \begin{bmatrix} 1 & 3 & \omega_1 \\ 1/3 & 1 & \omega_2 \end{bmatrix} \quad (12)$$

According to the Eq. (17), using sum-product method, we get $\omega_1 = 3/4$, $\omega_2 = 1/4$. Similarly, the other parameters of the weight distribution are shown in Table 4.

We take C111 as an example, referring to Table 2, and its rating of severity is 8, the TFN is (0.6, 0.7, 0.8); Possibility rating is 4, and the TFN is (0.2, 0.3, 0.4). According to equation 6 g is obtained (s, l) = (0.12, 0.21, 0.32). According to the Eq. (7), through defuzzification, we get $\tilde{g}_i = 0.217$. Likewise other risk ratings are shown in Table 5.

Table 3 Risk weights in case scenario.

Parameters of first layer	C1	C2
C1	1	3
C2	1/3	1

Table 4 Weight distribution of each parameter.

2nd layer	w	3rd layer	w	2nd	w	3rd	w
C11	0.0503	C111	0.055	C16	0.0956	C161	0.648
		C112	0.564			C162	0.122
		C113	0.118			C163	0.229
		C114	0.263			C211	0.047
		C121	0.149			C212	0.142
		C122	0.089			C213	0.093
		C123	0.213			C214	0.228
C12	0.1595	C124	0.042	C21	0.2100	C215	0.490
		C125	0.087			C231	0.140
		C126	0.104				0.098
		C127	0.108				0.118
		C128	0.056				0.042
		C129	0.128				0.203
		C131	0.11			C236	0.104
C13	0.4187	C132	0.386	C23	0.3022	C237	0.087
		C133	0.388			C238	0.184
		C134	0.08			C241	0.381
		C135	0.039			C242	0.619
		C141	0.491			C24	0.1192
		C142	0.232				
				C25	0.0181		

(table 4 continued)

2nd layer	w	3rd layer	w	2nd	w	3rd	w
C14	0.0555	C143	0.092	C26	0.0523		
		C144	0.138			C271	0.524
		C145	0.047	C27	0.1287	C272	0.476
		C151	0.424	C28	0.0231		
		C152	0.255			C291	0.129
		C153	0.031	C29	0.0643	C292	0.633
C15	0.2204	C154	0.052			C293	0.238
		C155	0.150				
		C156	0.088				

Table 5 Risk ratings

Risk	s	l	Rating	Risk	s	l	Rating
C111	8	4	0.217	C156	4	4	0.097
C112	4	3	0.067	C161	3	3	0.047
C113	5	3	0.087	C162	6	3	0.107
C114	6	4	0.157	C163	3	3	0.047
C121	8	3	0.147	C211	6	4	0.157
C122	6	3	0.107	C212	4	2	0.037
C123	4	3	0.067	C213	7	2	0.067
C124	9	3	0.167	C214	5	3	0.087
C125	5	4	0.127	C215	5	3	0.087
C126	8	4	0.217	C22	6	3	0.107
C127	4	3	0.067	C231	6	4	0.157
C128	5	3	0.087	C232	4	4	0.097
C129	6	4	0.157	C233	3	3	0.047
C131	3	3	0.047	C234	5	3	0.087
C132	5	4	0.127	C235	7	3	0.127
C133	9	3	0.167	C236	3	3	0.047
C134	3	3	0.047	C237	6	3	0.107
C135	4	3	0.067	C238	5	4	0.127
C141	7	3	0.127	C241	6	4	0.157
C142	6	3	0.107	C242	7	2	0.067
C143	5	4	0.127	C25	3	3	0.047
C144	8	4	0.217	C26	5	3	0.087
C145	6	4	0.157	C271	9	3	0.167
C151	3	3	0.047	C272	6	3	0.107
C152	5	3	0.087	C28	5	4	0.127
C153	9	3	0.167	C291	4	4	0.097
C154	6	3	0.107	C292	3	3	0.047
C155	5	4	0.127	C293	6	3	0.107

Risk rating of C111 is 0.217, and according to the Eq. (3), its corresponding membership of seven qualitative scales are $V1 = 0$, $V2 = 0.70$, $V3 = 0.30$, $V4 = 0$, $V5 = 0$, $V6 = 0$, $V7 = 0$ respectively. Similarly, we get collection of memberships of C112-C114, so to build $M(C11)$ matrix:

$$M(C_{11}) = \begin{bmatrix} 0 & 0.70 & 0.30 & 0 & 0 & 0 & 0 \\ 0.60 & 0.40 & 0 & 0 & 0 & 0 & 0 \\ 0.48 & 0.52 & 0 & 0 & 0 & 0 & 0 \\ 0.06 & 0.94 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{matrix} C_{111} \\ C_{112} \\ C_{113} \\ C_{114} \end{matrix} \quad (13)$$

Then, risk matrix and $M(C11)$ are multiplied to

obtain the weighted risk rating of category C11:

$$R(11) = [0.055 \ 0.564 \ 0.118 \ 0.263] \times M(C_{11}) \\ = [0.411 \ 0.573 \ 0.017 \ 0 \ 0 \ 0 \ 0]_{1 \times 7} \quad (14)$$

Similarly, we construct $M(C_{12})$, $M(C_{13})$, $M(C_{14})$, $M(C_{15})$, $M(C_{16})$, and calculate to get $R(12)$, $R(13)$, $R(14)$, $R(15)$, $R(16)$:

$$\begin{aligned} R(12) &= [0.298 \ 0.647 \ 0.031 \ 0 \ 0 \ 0 \ 0]_{1 \times 7} \\ R(13) &= [0.253 \ 0.750 \ 0 \ 0 \ 0 \ 0 \ 0]_{1 \times 7} \\ R(14) &= [0.226 \ 0.732 \ 0.041 \ 0 \ 0 \ 0 \ 0]_{1 \times 7} \\ R(15) &= [0.519 \ 0.481 \ 0 \ 0 \ 0 \ 0 \ 0]_{1 \times 7} \\ R(16) &= [0.675 \ 0.324 \ 0 \ 0 \ 0 \ 0 \ 0]_{1 \times 7} \end{aligned} \quad (15)$$

Next, the weight matrix W_{li} is multiplied by a matrix of risk ratings, so to get the risk rating of C1:

$$R(1) = [0.0503 \ 0.1595 \ 0.4187 \ 0.0555 \ 0.2204 \ 0.0956]_{1 \times 6} \times \\ \begin{bmatrix} 0.411 & 0.573 & 0.017 & 0 & 0 & 0 & 0 \\ 0.298 & 0.647 & 0.031 & 0 & 0 & 0 & 0 \\ 0.253 & 0.750 & 0 & 0 & 0 & 0 & 0 \\ 0.226 & 0.732 & 0.041 & 0 & 0 & 0 & 0 \\ 0.519 & 0.481 & 0 & 0 & 0 & 0 & 0 \\ 0.675 & 0.324 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{6 \times 7} \\ = [0.366 \ 0.624 \ 0.008 \ 0 \ 0 \ 0 \ 0]_{1 \times 7} \quad (16)$$

In the same way, we get

$$R(2) = [0.396 \ 0.597 \ 0 \ 0 \ 0 \ 0 \ 0]_{1 \times 7} \quad (17)$$

Finally, integrate C1 and C2, and we get the overall risk rating:

$$\begin{aligned} R2(n) &= [0.75 \ 0.25]_{1 \times 2} \times \\ &\quad [0.366 \ 0.624 \ 0.008 \ 0 \ 0 \ 0 \ 0 \\ &\quad 0.396 \ 0.597 \ 0 \ 0 \ 0 \ 0 \ 0]_{2 \times 7} \\ &= [0.374 \ 0.617 \ 0.006 \ 0 \ 0 \ 0 \ 0]_{1 \times 7} \end{aligned} \quad (18)$$

Using the gravity method to process defuzzification, we get integrated fuzzy risk assessment level.

$$\begin{aligned} ARI &= 0.374 \times 0.0556 + 0.617 \times 0.1667 + 0.006 \times \\ &\quad 0.3333 + 0 \times 0.5 + 0 \times 0.6667 + 0 \times 0.8333 + 0 \times \\ &\quad 0.9444 = 0.126 \end{aligned}$$

Therefore, the risk rating of this electric CPS system is 0.126. Referring to definition of qualitative indicators in section 3.1, it's between V1 (quite low) and V2 (very low).

5. Conclusion

Based on fuzzy set theory and AHP, this paper

presents a quantitative risk assessment methodology of electric CPS. Through the analysis of risk sources of electric CPS, we take various parameters of CPS into account to evaluate the overall security risk. At last, we use case studies to verify the validity of the method. This approach promotes the change of risk control of electric CPS from afterwards to beforehand, which is of some significance to the smart grid construction.

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