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System-Level Vulnerability Assessment for EME: From Fault Tree Analysis to Bayesian Networks—Part II: Illustration to Microcontroller System

Congguang Mao, Flavio G.Canavero, Zhitong Cui, and Dongyuang Sun

Abstract—The vulnerability of microcontroller system against high-altitude electromagnetic pulse (HEMP) is taken as an illustration to demonstrate the assessment methodology based on Bayesian networks (BN). The complete procedure is performed by two steps: the qualitative and the quantitative. The first step focuses on the analysis of three classes of properties, the electromagnetic environment, system function/structure, and their interactions. The primary BN model is built at the end of the first step. The second step investigates the BN nodes and branches one by one, which further implemented through two stages, i.e., the data acquisition and data fusion. The susceptibilities of devises are examined with the pulsed current injection. The responses of the transmission lines to HEMP are computed using the field-line coupling model. Comparing the probability density functions of the electromagnetic stresses and strengths produces the failure probabilities of the interface components. Through two-step analysis, the critical elements and coupling paths are identified and highlighted. After neglecting those unimportant factors, many BN nodes and branches are deleted. Thus, the complexity of assessment is reduced. By assigning the probability values to the simplified BN model, the system failure probability is calculated, which characterizes the system vulnerability against HEMP environment. The illustration validates the rationality and flexibility of the BN assessment methodology.

Index Terms—Assessment, Bayesian networks (BNs), E3, EME, HEMP, IEMI, vulnerability.

I. Introduction

THE objective of vulnerability assessment is to find the potential risk or to authenticate the performance of protective design. As a system of systems or subsystems, the system-level vulnerability is hard to quantitatively characterize.

For the manageable system assessment against high-altitude electromagnetic pulse (HEMP) and high-power electromagnetic environment, one specific standard, IEC 61000-5-9, is published by International Electrotechnical Commission (IEC), and the test procedure is recommended [1]. However, for the larger or more complex system, a unified analysis framework is badly necessary, which can divide the whole system into relatively independent and manageable subsystems. Then the test can be carried out. Unfortunately, no such technique is recommended by the standard. Neither does the characterization parameter of the system-level effects. The assessment methodology based on Bayesian Networks (BN) is built to help to fulfill this mission.

The complete assessment is executed by two main steps: the qualitative analysis and the quantitative calculation. First, the properties of system, electromagnetic environment (EME), and their interactions are analyzed, and the primary BN model is built. Then, the electromagnetic strength of the interface components and their stresses are investigated. At this point, tests play the most important role [2]–[4]. Comparison of these two categories of data produces the failure probabilities of components, which can indicate the sensitivity. After deleting the nodes with no effects, the BN model is simplified. The relative probabilities are assigned to the left nodes and the system failure probability is calculated finally.

These contents are organized as follows. Section II analyzes the interaction of the EME and system, and builds the primary BN model. All the data of threshold and stresses are acquired and processed statistically in Section III. Section IV presents the complete assessment procedure. Finally, Section V discusses the issues need to be done further.

II. System Qualitative Analysis

For the extensive application in industry, the smart control system, composed with the computer and microcontroller, is chosen as the object of investigation. The radiated susceptibility of the microcontrollers and computers are studied individually in [5]–[7]. Here both of the devices are connected. Furthermore, the microcontroller is extended into a macromodel containing several components, every of which stands for one system or subsystem. The system operates in the buildings. The computer is installed in shielding rooms and microcontroller in the equipment box.

In practice, all the possible classes of EMEs could impact the system, such as HEMP, intentional electromagnetic interference (IEMI), high-intensity radio field, etc. Here, for simplicity, only HEMP is considered as one kind of extreme EME. What should

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be noted is that the definition of IEMI in many documents mainly refers to the high-power microwave. Despite of difference at many aspects, it is believed to be similar as far as the assessment procedure is concerned. The early-time HEMP environment is defined in standard [8]: the maximal peak value of the electric field is up to 50 kV/m; the rise time is 2.5 ns, and the half-width at 50% maximum is 23 ns.

In this qualitative analysis, the system function and structure are presented and the fault tree (FT) models are built. Then, the coupling of the system with the electromagnetic pulse (EMP) is analyzed using the electromagnetic topology (EMT). Finally, the BNs model integrates the FT and EMT.

A. System Structure

The controller is designed to execute of the computer commands, which is coded with digital logic. After start or reset, the first series of code is stored in the microcontroller as the command, if the following codes are identical with those stored, the light-emitting diode will be lightened as the indicator, or the indicator will not be lightened.

The mission is executed by three steps: the command emission, transmission, and judgment, which corresponds three hardwares: the computer, transmission interfaces, and microcontroller. Furthermore, the computer subsystem is composed with the host computer and accessories, such as keyboard, display device and mouse, all of which are linked by short cables. The transmission subsystems composed the 232 bus processer, 20 m-long transmission lines, and 485 interfaces integrated circuit (IC), which transform the computer command into microcontroller codes, and the microcontroller is supplied by the direct current to direct current (dc/dc) converter to provide the power of 5 V and reset by the solid-state relay. The whole system is supplied by the commercial grid, whose susceptibility is not concerned in this control system. The components and the functions are corresponding one by one and depicted in Fig. 1(a).

Because three subsystems are in series from the point view of the reliability, each of their failure will lead to the system breakdown, which means they construct the OR-logic in FT model. Similarly, all the components of subsystems are necessary, except that two dc/dc modules are designed as the redundancy. The FT model of system is shown in Fig. 1(b).

The structure function of FT is expressed as

$$P(V) = \sum_{i=1}^{3} P_i' = \sum_{m=1}^{4} P_{1,m} + \sum_{n=1}^{2} P_{2,n} + \sum_{k=1}^{4} P_{3,k} \quad (1)$$

where P_i' is the probabilities of three subsystems $C\prime_k$, $k = 1, 2, 3$; $P_{1,m}$, $P_{2,n}$, and $P_{3,k}$ are relatively the failure probabilities of components $C_{i,j}$, $i = 1, 2, 3$, $j = 1, 2, 3, 4$; and probability of the redundant design $P_{3,1} = P_{3,1,1} \cdot P_{3,1,2}$.

B. Coupling Analysis with EMT

The coupling of EME with system is analyzed with the EMT method, which is common for all the categories of EME. The dominant coupling path and victim components will be suggested.
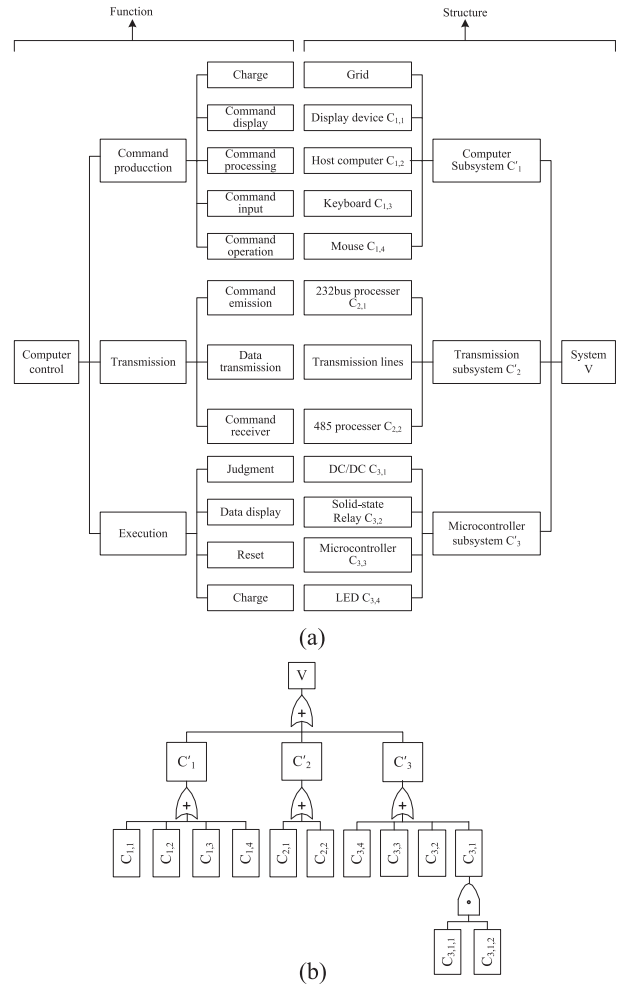

Fig. 1. Function, structure, and FT model of microcontroller system. (a) Function and structure. (b) FT model.

According to the code rules of EMT [9], the exterior and interior building are denoted as V_0 and V_1, and two shielding cavities containing computer and microcontroller are denoted as $V_{2,1}$ and $V_{2,2}$. The components contained in closures are coded similarly as Fig. 2. They are impacted by the field penetrating into cavities. In order to highlight the conducted effects of the transmission lines in V_1, the cables are also coded as L_1, L_2, and L_3. The electromagnetic structure and EMT of the system are depicted in Fig. 3.

Because of the shielding protection of subsystems, the conducted effects will be significant. So the transmission lines between computer and microcontroller are primarily judged to be the critical coupling paths.

C. Primary BN Model of System

The complete process involves two factors: *HEMP* and system (*V*) effects. EMP propagates through the concrete iron building and shielding room or equipment box, and become the ambient environment of system (AEME). Coupling with cables, the free fields induce currents and the electromagnetic stresses (Stres) cause the breakdown of components (Comp), which
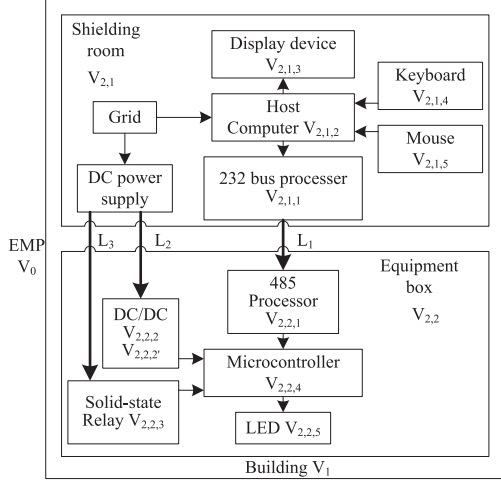
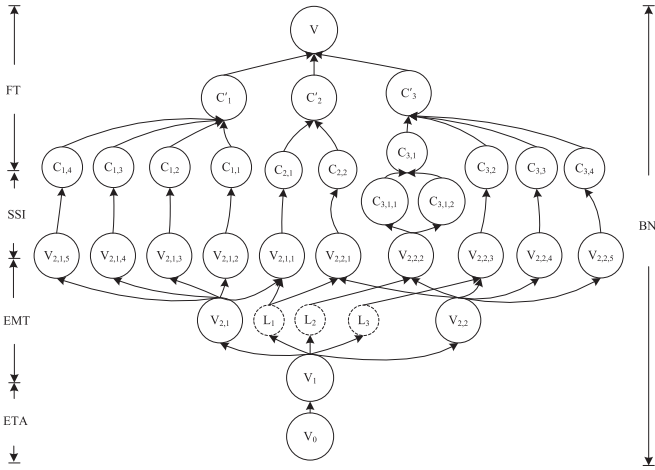Fig. 2.   Electromagnetic structure and EMT of system.

Fig. 3.   BNs model of system vulnerability against EME.

further result the failure of subsystems (Subs) and finally upset the whole system. Based on the interfering rules of BN [10], structure function is formulated as

$$
\begin{aligned}
P_V(V, \text{EMI}) = \ & P(V|\text{Subs})P(\text{Subs}|\text{Comp}) \\
& \times P(\text{Comp}, \text{Stres})P(\text{Stres}|\text{AEME}) \\
& \times P(\text{AEME}|\text{HEMP})P(\text{HEMP}). \quad (2)
\end{aligned}
$$

This joint probability is a measure of the vulnerable degree of system in HEMP.

Connecting EMT and FT with the causal relationship, i.e., the theory of stress–strength interference (SSI), the primary BN model is built (see Fig. 3). The nodes stand for the free fields, currents, and the concrete structures, i.e., shields, conductors, components, subsystems, and systems. The arrows display the causal dependent relationships from the ambient environments to the stresses and from components to subsystems and final systems. BN reveals all the possible coupling and failure paths. Moreover, two classes of stresses and susceptibilities are also

suggested to be measured or calculated, i.e., the radiated and the conducted.

III. System Quantitative Analysis

Every node and branch in BN, especially the electromagnetic stress (EMS) and the susceptibility of the items, will be checked. Here, three principles will be abided by: 1) to find the maximal EMS; 2) to determine the minimal susceptibility; 3) to process the data with statistical techniques.

A. Radiated EMS and Susceptibility

In this illustration, EMP is the only one class of considered EMI, which means HEMP constitute the total set of EMI. And the interior environment of the building is similar. So

$$
P(\text{HEMP}) = \ P(V_0) = 1 \quad (3)
$$

$$
P(\text{AEME}, \text{HEMP}) = \ P(V_1, V_0) = P(V_1|V_0)P(V_0) = 1. \quad (4)
$$

For the carefully designed concrete iron buildings, the shielding effectiveness (SE) of electric field for HEMP may be up to 40 dB [11]. Considering the windows and doors may deteriorate the shielding ability, the SE reduces to 20 dB. Based on the specifications of shielding room and equipment box, their standard SEs may be up to 80 dB. Similarly, accounting the deterioration and aging, the SE is set to 60 dB. The residual fields, roughly estimating, may be reduced to less than 100 V/m, and the interference thresholds of computer and microcontroller are greater than 1 kV/m [5], [6]. Thus, both of the subsystems are safe against radiated disturbance, i.e.,

$$
P(\text{Comp}|\text{Stres}) = P(\text{Comp} < \text{Stres}) = 0. \quad (5)
$$

B. Conducted EMS and Susceptibility

As we know, the waveform will be distorted somewhat when EMP penetrates into the building. How to predict the interior environment is a time-consuming issue and need to explain specifically. Here, in order to highlight the assessment, this complicated subject is simplified. The incident EMP waveform is still described by the double-exponential function.

Since the signal intensity will decrease after EMP penetrates into the building, the multiconductors are illuminated only with fields of 5 kV/m. Moreover, it is possible for every conductor to be exposed in the electromagnetic wave at its maximal receiving area, so all the conductors are regarded identically and independently. The peak values of the induced currents are taken to denote the EMS. The electromagnetic threshold of the terminal component is defined as the maximal strength to tolerate the EMS.

1) Conducted EMS: Utilizing the Taylor model of transmission line [12], the terminal induced current $I(L)$ of single overhead wire for EMP is calculated, and the maximums of currents $\|I\|_\infty$ are observed as EMS. The parameters in the computation model are as following.
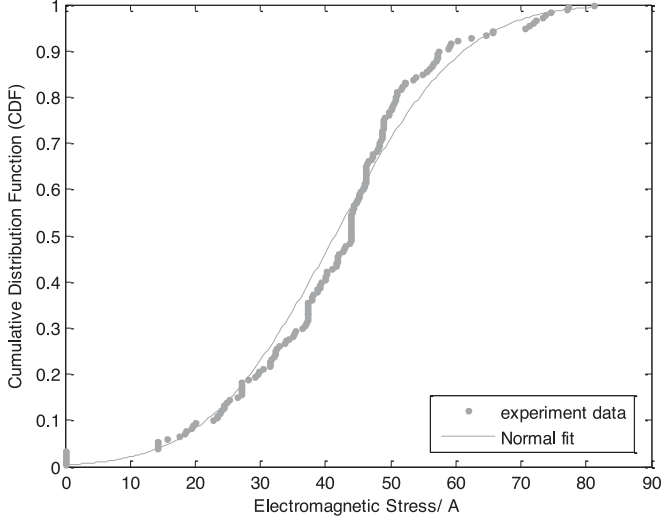
Fig. 4. CPF of EMS at transmission line terminal.

Fig. 5. Microcontroller subsystem under test.

The incident angle $\psi' \in [18, 90°]$, azimuth angle $\phi' \in [0, 90°]$, and polarizing angle $\alpha' \in [0, 90°]$ are taken as the random variables and sampled with equal step $\Delta = 18°$.

The other parameters are deterministic for the given system: 1) the exciting EMP: $E_0 = 5$ kV/m, $k = 1.3$, $\alpha = 4 \times 10^7$ and $\beta = 6 \times 10^8$; 2) the transmission line: length $L = 20$ m, height $h = 3$ m, radius of perfect conducting wires $a = 1.5 \times 10^{-3}$ m, terminal loads $Z_0 = Z_L = 2\,\Omega$; 3) the lossy ground: conductivity $\sigma_g = 0.01$ S/m, relative permittivity $\varepsilon_{rg} = 10$.

The size of the samples is 180, with maximum 81.2 A, minimum 0 A. The goodness-of-fitting of the distribution function is tested by the Kolmogorov–Smirnov (K–S) test, and the critical value (CV) is 0.10122 at significance level $\alpha^* = 0.05$ [14]. Finally, the statistic of the normal distribution is 0.08405, which is less than CV. Then, the hypothesis that the EMS conforms the normal distribution function $N(\mu, \sigma^2)$ is accepted with the mean value $\mu = 41.419$ A and the variance $\sigma = 15.437$ A. The cumulative distribution function (CDF) is shown in Fig. 4, and the probability density function (pdf) is

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right). \tag{6}$$

2) Conducted Susceptibility: The susceptibility of the port devices (see Fig. 5) are examined by the pulsed current injection (PCI) because of its high efficiency and convenient operation [15], [16]. The current waveform is rectangular with tow parameters: the magnitude and width. The devices are embedded in the system are tested at the operating state. The injection point is just the pin connecting the long line. Before and after every shot, the item and the system functions are checked carefully. The magnitude increases gradually until the device is broken down and the system blacks out. During the process from totally good to totally bad, all the effects phenomena and data are recorded. After the tests of 20 to 30 samples are completed, all the data with the same fault mode are collected. Finally, by
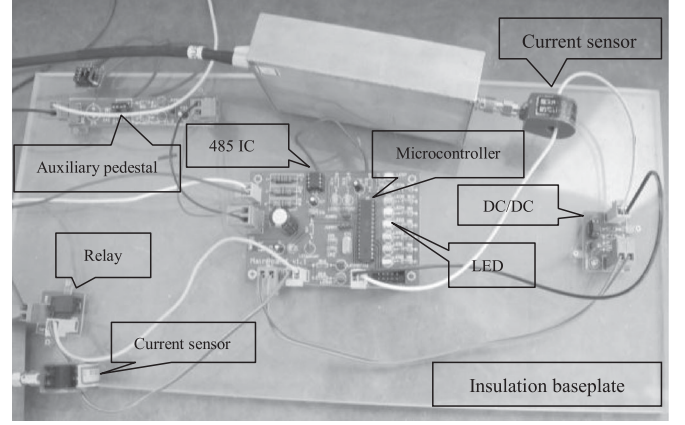
processing these threshold data with the same statistical method as the EMS, the CDF of susceptibility is determined.

For the 485 IC and dc/dc converter, three fault modes are found, the static, soft, and hard. The pulse width cannot cause extra effects. The static damage means that the state parameter of the component has deviated from the rated sets, but no abnormal functions of the system are observed. If the system is malfunctioned by the injected currents and can recover after restarting, the phenomenon is called as the soft interferences. By further improving the magnitude of the exciting currents, the components will be broken down thoroughly, which are named as the hard damage. For the hard fault mode, the system will black out and cannot restore until the collapsed device is replaced.

After statistical processing, the CDFs of 485 IC and dc/dc are founded [see Fig. 6(a) and (b)]. For one device, the static threshold is the lowest and the hard the highest. However, because of the dispersion of the sample data, it is possible for three threshold sets to overlay somewhat.

For the solid-state relay, only the fault of the false trigger is found. During the tests of different pulse widths 0.3, 0.5, 1.0, 5.0, and 10.0 μs, it is obvious that the thresholds vary with pulse widths, tw_c. The five groups of data can all be fitted with normal distribution $N(\mu, \sigma^2)$ [see Fig. 6(c)], and the coefficients μ and σ can be fitted by the exponential polynomial functions (see Fig. 7)

$$\mu(tw_c) = 37.7730 \times e^{(-tw_c/0.2463)} + 4.8577 - 0.2169 \times tw_c \tag{7a}$$

$$\sigma(tw_c) = 1.6291 \times e^{(-tw_c/0.3795)} + 1.0558 - 0.0789 \times tw_c. \tag{7b}$$

Massive calculations indicate that the widths of the response currents $I(L)$ cannot exceed 0.1 μs. So by substituting $tw_c = 0.1\,\mu$s into (7) and (8), the rational distribution function of relay is estimated as normality with $\mu = 30.006$ and $\sigma = 2.2996$. All the distribution functions are listed in Table I.

3) Probabilities of Devices About Conducted Effects: With the SSI theory, every mode failure probabilities of devices P_F
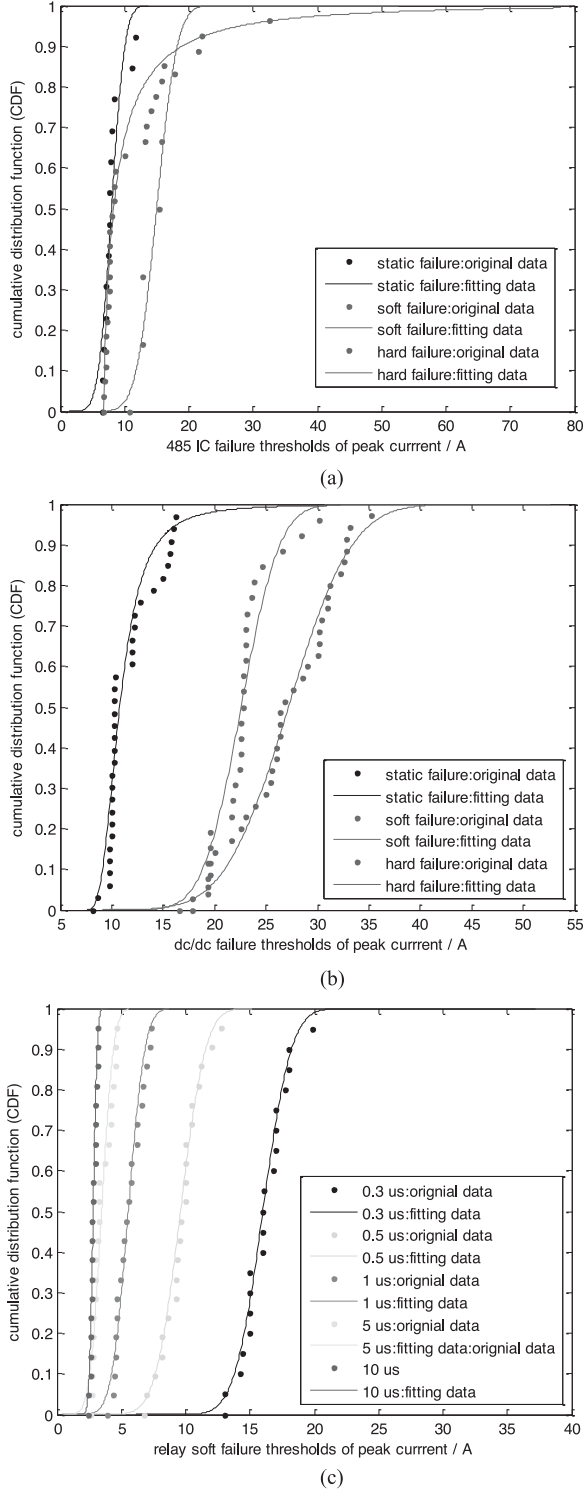
(a)

(b)

(c)

Fig. 6. Failure thresholds of components. (a) 485 IC. (b) dc/dc. (c) Solid-state relay.

are calculated by

$$P_C = P(\text{Comp}, \text{Stres}) = P(y \geq x)$$

$$= \int_{x_{\min}}^{y_{\max}} g(y)dy \int_{x_{\min}}^{y} f(x)\,dx \qquad (8)$$
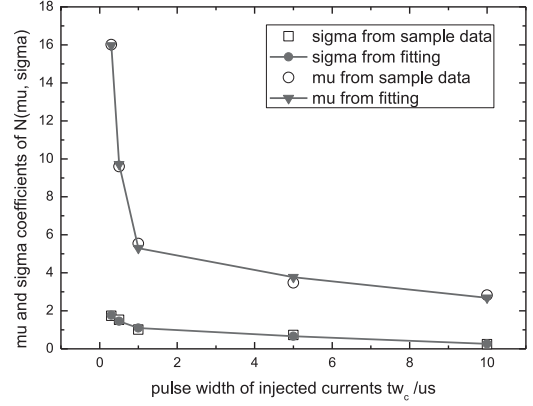

Fig. 7. Parameter fitting of distribution function for solid-state relay.

where Comp stand for nodes $C_{3,3}$, $\{C_{2,2,i}\}$, $\{C_{3,1,i}\}$, and Stres for $\{V_{2,2,i}\}$, $i = 1, 2, 3$; $f(x)$ and $g(y)$ are relatively the pdfs of the thresholds and EMS; $x \in [x_{\min}, x_{\max}]$ and $y \in [y_{\min}, y_{\max}]$ are peaks of the terminal currents $\|I\|_\infty$. The SSI curves of 485 IC, dc/dc and solid-state relay are shown in Fig. 8, and the failure probabilities P_C are listed in Table I.

For the endpoints of $x_{\min}$, $x_{\max}$, $y_{\min}$, and $y_{\max}$, the rule of 3σ for the normal distribution can provide good reference. If $X \sim N(\mu, \sigma^2)$

$$F(\mu - 3\sigma \leq x \leq \mu + 3\sigma) \approx 99.7\%.$$

So for the normal distribution, $[x_{\min}, x_{\max}] = [\mu - 3\sigma, \mu + 3\sigma]$. For other distributions, the endpoints are chosen at the quantiles of 0.15% and 99.85%.

Moreover, the overlaying portion of stress with the thresholds P_t can reflect the threat degree of the coupling paths

$$P(\text{Stres}|\text{AEME}) = P_t = \int_{x_{\min}}^{y_{\max}} g(y)dy. \qquad (9)$$

So the coupling parameters of transmission lines L_1, L_2, and L_3 are assigned as about the maximums of P_t listed in Table I

$$485 \cdot IC : P(V_{2,2,1}|V_1) \approx 0.99 \qquad (10)$$

$$\text{DC/DC} : P(V_{2,2,2}|V_1) \approx 0.98 \qquad (11)$$

$$\text{Relay} : P(V_{2,2,3}|V_1) \approx 0.88. \qquad (12)$$

C. Assessment Result of Whole System Based on BN

It must be pointed that no faults are observed for 232 IC and computer subsystem, which mean they are stronger. After the radiated and conducted effects analysis, all the nodes and branches judged to be safe can be deleted. On the other hand, the component with the multistate faults is extended into three nodes. For example, the node of 485 processor $C_{2,2}$ is extended into $C_{2,2,1}$, $C_{2,2,2}$, and $C_{2,2,3}$. It should also be noticed that two dc/dc converters $C_{3,1,1}$ and $C_{3,1,2}$ are identical, and so do the paths of $V_{2,2,2}$ to $C_{3,1,1}$ and $V_{2,2,2}$ to $C_{3,1,2}$. Thus, the latter can be simplified into one dashed line.

The original BN model of Fig. 3 is modified and shown in Fig. 9, where three salient effect scenarios are displayed. The

TABLE I
THRESHOLDS DISTRIBUTION OF COMPONENTS

Modes	485 IC				DC/DC convertor				Solid-sate Relay		
	pdf	P_C	P_t	P_w	pdf	P_C	P_t	P_w	pdf	P_C	P_t
static	$N(\mu,\sigma^2)\ \mu = 7.9754$ $\sigma = 1.6287$	0.9804	0.9921	$\frac{13}{46}$	Log-Logistic$(\alpha,\beta,\gamma)^2$ $\alpha = 2.9022$ $\beta = 3.1692$ $\gamma = 7.6582$	0.9693	0.9843	$\frac{33}{94}$	–	–	–
soft	$N(\mu,\sigma^2)$ $\mu = 15.0\ \sigma = 2.5036$	0.9506	0.9847	$\frac{6}{46}$	$N(\mu,\sigma^2)\ \mu = 22.592$ $\sigma = 2.8394$	0.9604	0.8813	$\frac{26}{94}$	$N(\mu,\sigma^2)\ \mu = 30.006$ $\sigma = 2.2996$	0.7644	0.8809
hard	Lognormal$(\mu,\sigma,\gamma)^1$ $\mu = 0.53459\ \sigma = 1.565$ $\gamma = 6.679$	0.9442	0.9865	$\frac{27}{46}$	$N(\mu,\sigma^2)\ \mu = 26.783$ $\sigma = 4.8447$	0.8140	0.9693	$\frac{35}{94}$	–	–	–

[1]Lognormal(μ,σ,γ): $f(x) = \dfrac{\exp\left(-\dfrac{1}{2}\left(\dfrac{\ln(x-\gamma)-\mu}{\sigma}\right)^2\right)}{(x-\gamma)\sigma\sqrt{2\pi}}$;

[2]Log-Logistic(α,β,γ): $f(x) = \dfrac{\alpha}{\beta}\left(\dfrac{x-\gamma}{\beta}\right)^{\alpha-1}\left(1+\left(\dfrac{x-\gamma}{\beta}\right)^{\alpha}\right)^{-2}$.

first one is that the EMP (V_0) through building (V_1) propagates to cable (L_1), breaks down 485 IC $(C_{2,2})$ and lead to the failure of transmission subsystem (C_2'). The second one starts from EMP, interrupts the power supply of dc/dc $(C_{3,1})$, and the third is triggering the solid-state relay $(C_{3,2})$. The last two events cause the fault of the microcontroller (C_3'). Considering the effect independence, every scenario can be examined respectively. The structure function (2) is embodied as

$$P_V(V, \text{IEMI}) = P(V_{2,2,1}, V_0)P(C_{2,2}, V_{2,2,1})P(C_2'|C_{2,2})P(V|C_2')$$
$$+ P(V_{2,2,2}, V_0)P(C_{3,1}, V_{2,2,2})P(C_3'|C_{3,1})P(V|C_3')$$
$$+ P(V_{2,2,3}, V_0)P(C_{3,2}, V_{2,2,3})P(C_3'|C_{2,2})P(V|C_3') \quad (13)$$

where $P(V_{2,2,i}, V_0) = P(V_0)P(V_1|V_0)P(V_{2,2,i}|V_1)$, $i = 1, 2, 3$.

The fault of 485 IC and dc/dc converter may be regarded as one set and constituted by three portions: the static, soft, and hard. In FTA, the XOR-logic and noisy-gate can be applied to the multimode failure model [17], whereas the weighted sum approach is used in BN for this multicause to one-result structure [13]. The weight of every portion P_w is measured by the ratio of the sample size of each mode against the total. Taking 485 IC as an example, the sample size of each mode is relatively 13, 6, and 27, then the number of total samples is 46. So the weights $P_w = P(C_{2,2,i}|V_{2,2,1}), i = 1, 2, 3$, are relatively 13/46, 6/46, and 27/46. The weights indicate the occurring possibilities of different modes and are also listed in Table I. Utilizing the total probability formulation, the joint probability of 485 IC

$$P(C_{2,2}, V_{2,2,1}) = \sum_{k=1}^{3} P(C_{2,2}|C_{2,2,k})P(C_{2,2,k}, V_{2,2,1})$$

$$= 0.9804 \times \frac{13}{46} + 0.9506 \times \frac{6}{46} + 0.9442$$

$$\times \frac{26}{46} \approx 0.9347. \quad (14)$$

The same method can be applied to the dc/dc converter

$$P(C_{3,1,1}, V_{2,2,2}) = P(C_{3,1,2}, V_{2,2,2}) = \sum_{i=1}^{3} P(C_{3,1,1}|C_{3,1,1,i})$$
$$P(C_{3,1,1,i}, V_{2,2,2}) \approx 0.9090. \quad (15)$$

The redundant design in FTA is described by the AND-logic, whereas in BN it is modeled as the converging structure. Because the simultaneous failure of two converters $C_{3,1,1}$ and $C_{3,1,2}$ can lead to the blackout, they form the certain event of the power failure, $C_{3,1}$. So the conditional probability

$$P(C_{3,1}|C_{3,1,1}, C_{3,1,2}) = 1 \quad (16)$$

and the joint probability

$$P(C_{3,1}, C_{3,1,1}, C_{3,1,2}) = P(C_{3,1,1})P(C_{3,1,2})$$
$$P(C_{3,1}|C_{3,1,1}, C_{3,1,2}), \quad (17)$$

where $P(C_{3,1,1}) = P(C_{3,1,2}) = P(C_{3,1,1}, V_{2,2,2})$. Thus,

$$P(C_{3,1}, V_{2,2,2}) = P(C_{3,1,1}, V_{2,2,2})P(C_{3,1,2}, V_{2,2,2}) \times 1$$
$$= 0.9090 \times 0.9090 \approx 0.8263. \quad (18)$$

Actually, the same result as (18) can be deduced by De Morgan's theorem [18].

$C_{3,1}$ and $C_{3,2}$ constitute the total set of the failure of the subsystem C_3', and considering the importance of the power supply the conditional probabilities

$$P(C_3'|C_{3,1}) = 0.6,\ P(C_3'|C_{3,2}) = 1 - 0.6 = 0.4. \quad (19)$$

Since the failure of C_2' only depends on $C_{2,2}$, the probability

$$P(C_2'|C_{2,2}) = 1. \quad (20)$$

Similarly, the dependant relationships of the total system V and the subsystems C_2' and C_3' can be described as

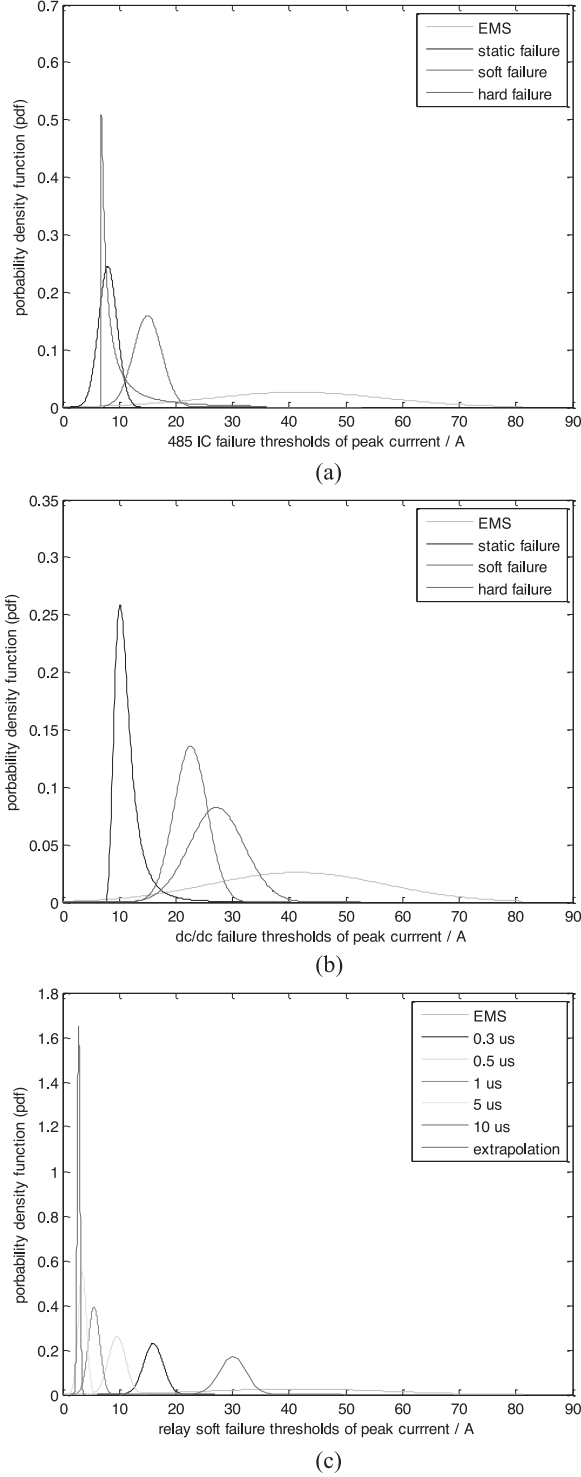$$P(V|C_3') = 0.3, \quad P(V|C_2') = 1 - 0.3 = 0.7. \quad (21)$$

Fig. 8. SSI. (a) 485 IC. (b) dc/dc. (c) Solid-state relay.

Based on the analysis, three causal scenarios of effects are characterized quantitatively, i.e.,

$$P(V|V_{2,2,1}) = P(C_{2,2},V_{2,2,1})P(C'_2|C_{2,2})P(V|C'_2)$$
$$= 0.9347 \times 1 \times 0.7 \approx 06543 \qquad (22)$$

$$P(V|V_{2,2,2}) = P(C_{3,1},V_{2,2,2})P(C'_3|C_{3,1})P(V|C'_3)$$
$$= 0.8263 \times 0.6 \times 0.3 \approx 0.1487 \qquad (23)$$
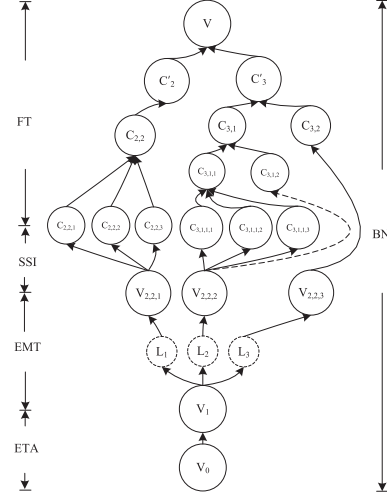

Fig. 9. Modified BN model.

$$P(V|V_{2,2,3}) = P(C_{3,3},V_{2,2,3})P(C'_3|C_{3,3})P(V|C'_3)$$
$$= 0.7644 \times 0.4 \times 0.3 \approx 0.0917. \qquad (24)$$

Finally, the final system failure probability

$$P(V, \text{IEMI}) = \left(\sum_{i=1}^{3} P(V_{2,2,i}, V_0)P(V|V_{2,2,i}) \right)$$
$$= 1 \times (0.99 \times 0.6543 + 0.98 \times 0.1487 + 0.88$$
$$\times 0.0917) \approx 0.8742. \qquad (25)$$

This indicates that the system is susceptible to HEMP at the possibility of 87.42%. With the qualitative and quantitative analysis, the critical items and coupling paths are determined.

IV. SYSTEM-LEVEL ASSESSMENT PROCEDURE

For the distribution system, the evaluation data are usually obtained by means of the local tests. All the results of judge and analysis can be further examined by completed system-level illumination test, if possible and necessary. The illumination test close to reality is recommended to check thoroughly the susceptibility of systems or subsystems [1], [4], [16]. In this case, the assessment above can serve as the preanalysis.

On the other hand, accounting for the cost and practical limits, it is impossible for the system-level illumination to inspect all the uncertain parameters. Generally, only the most significant and measurable effects are checked. Then, such illuminations become the sampling of all the possible cases in assessment.

In order to put emphasis on the assessment methodology, some details are reduced in this example if only the necessary data, although rough, is obtained. For instance, there will be resonance when EMP penetrates into buildings, which can change the wire response and the probability distribution function. To improve the assessment precision, the neglected factors can be restudied and more accurate coupling model should be adopted. It must be noticed that the physical mechanism is essential in the modeling and data acquisition.

The system-level assessment is time consuming and costly. So it will be better that the assessment is carried out from roughly to precisely. This means at the first step, the most significant properties are chosen to analyze the risk. If it indicates that there could be potential threats, more detailed investigation is performed, or it is not necessary to continue the following investigation. Through the repeated iteration, the weaknesses and significant interfering paths are cognized from vague to clear.

The completed assessment procedure is summarized as follows:

1) To define the EMEs.
2) To analyze the system function and determine the critical components for missions.
3) To clarify the propagation path of electromagnetic energy from exterior to interior for given category of EMI.
4) To draw the BN model in detailed.
5) To pick out those critical components on the interfering paths.
6) To carry out the local tests and calculation to estimate the EMS and thresholds.
7) To calculate the failure probabilities of components.
8) To highlight the susceptible items and dominant coupling paths and simplify the BN model.
9) To illuminate the whole system or subsystems and prove the results of analysis, if it is feasible.
10) To promote the assessment accuracy, increase the samples and consider more factors and repeat 3)–9).
11) To present the primary assessment conclusion.
12) To consider other kinds of EME, repeat the procedures of 1)–11).
13) To conclude the system-level vulnerability against EME.

V. DISCUSSION AND CONCLUSION

The microcontroller system is taken as an object to perform the complete vulnerability assessment. The vulnerability is characterized by the joint probability of system failure and EMI. All the activities, involving the analysis, computation, tests and data statistical processing, are integrated into one framework built based on BN. The assessment procedure is summarized and presented.

The EME effects are formulized as one causal scenario and all the factors of environment, coupling, component susceptibility, system constitution, and vulnerability are characterized with the marginal, conditional, or joint probabilities. The failure probability can reflect the environment threat or risk. The main coupling path and weak element can provide the suggestion for protective design and illumination test of the entire system.

This primary application indicates that the BN methodology is of the definite physical and statistical foundation. They are helpful to model, acquire data, and finally quantify the system effects.

This illustration also points out the important subjects necessary to further study 1) aiming the distributed systems EME effects, such as the grid and communication networks, the BN model of the system reliability should be built; 2) every assessment step, such as system modeling, data acquisition and statistical processing, can bring the uncertainty to the final result. The uncertainty source need to be clarified and limited to improve the assessment accuracy; 3) the consistency and completion of the data from all kinds of approaches is critical for the reliable assessment conclusion.

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