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Reliability Modeling and Structure Importance Analysis of Electric Power Station Distribution Control System

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Abstract: Aiming to the complexity of reliability model of Distributed Control System (DCS), a novel reliability modeling method has been put forward in this study. The method can be employed in many situations, especially in the case of DCS of electric power stations. The traditional reliability principles and the relative definitions of coherent system have been introduced as the foundations. Based on the structural and functional analysis of classical DCS, the overall structure of DCS which are normally seen as a repairable system in the real industrial productive process can been modeled as an un-repairable system according to some proposed approximating conditions. As an example, one whole DCS and its subsystems have been tackled to calculate their reliability indices. At the same time, one type of structure importance of DCS has also been computed based on the model. The values are of significant directive functions for the maintainance schemes of DCS.

Key words: Distributed control system, reliability modeling, structure importance

INTRODUCTION

The Distributed Control System (DCS) is used world wide to control the processes in different fields around us. It is also applied to control both hydraulic and thermal electric power station, petrochemical industry, factories, airplanes and radar system etc. (Damsker, 1991; Hemeida *et al*., 2004). Especially, the DCS has been a necessary constituent component for the productive process control of electric power station (Huang *et al*., 2010; Williams, 1993). Accompanied by the rapid developments of computer, communication and control (3C) technology in recent years, the generator unit capability and thermal parameters have been continuously a considerable increase. Consequently, the demand of DCS reliability is getting higher and higher.

Some researchers have employed different method to improve the stability and safety of DCS. Fang *et al*. (2010) established a novel DCS architecture by optimizing the network of control system and combining a variety of communication mode organically. Object oriented analysis and design method is used to model DCS of power plant and the method can help to find the common cause of failure via FEMA worksheet in order to enhance the reliability (Gawand *et al*., 2010). But because of the numerous components and complex structure of DCS, how to analyze its structure and evaluate quantitatively its reliability, has not yet been reported.

Reliability block diagram tool has been developed to quantify various risks. These works focus mainly on the reliability analysis and availability evaluation for electric power and/or automatic control system etc. (Anthony *et al*., 2013; Gupta and Sharma, 1978; Hajian-Hoseinabadi, 2013; Hajian-Hoseinabadi *et al*., 2012; Kumamoto *et al*., 1977). Some important measures of components in a coherent system have been calculated in order to prioritize components so that, certain measure can be taken for reliability improvement and/or maintenance plan optimization. There are many applications of these methods in a variety of research fields (Barlow and Proschan, 1975; Natvig *et al*., 2011; Vaurio, 2010; Kuo and Zhu, 2012; Wu and Coolen, 2013). Although some scholars have analyzed some sub-systems of DCS such as control cabinet, power supply etc., but how to model the entire DCS system and assess its reliability will encounter some difficulties, for example, the complicated structures and numerous electronic equipments. In this study, which is based on

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the analysis of the system structure, reliability evaluation of DCS has been done according to the hierarchical level of DCS by the reliability block diagram principle and structure importance measures. The results of system reliability indices and component structure importance have been figured out which can be as a scientific evidence to direct the power station engineer's maintenance plans.

MATERIALS AND METHODS

Reliability block diagram model: Reliability Block Diagram (RBD) is a type of logic diagram used to analyze the relation between system and components from the view of reliability. The RBD which is depicted by some rectangles and lines, reflects the character how these components will affect the system function when the failures of components occur. This model has been applied in many aspects (Levitin *et al*., 2013). The often used model includes series, parallels and hybrids which is explained, respectively as follows.

Assume that there are n components which have a reliability:

$$R_i(t),\ (i = 1, 2,\ldots, n)$$

The series system model is presented by Fig. 1.

The series system reliability is defined by the following equation:

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{1}$$

The parallel system model is presented in Fig. 2.

The equation of parallel system reliability can be defined by:

$$R_s(t) = 1 - \prod_{i=1}^{n} (1 - R_i(t)) \tag{2}$$

The hybrid system has two types. One is series-parallel system and the other is parallel-series system.

The series-parallel system consists of n series subsystems which are of parallel structure. One can assume that the i-th subsystem is of m_i same components connected in parallel. Because the component of each subsystem is redundant, this type of system is also named as component redundancy structure whose model is depicted in Fig. 3.

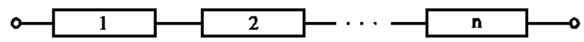

Fig. 1: Series system model

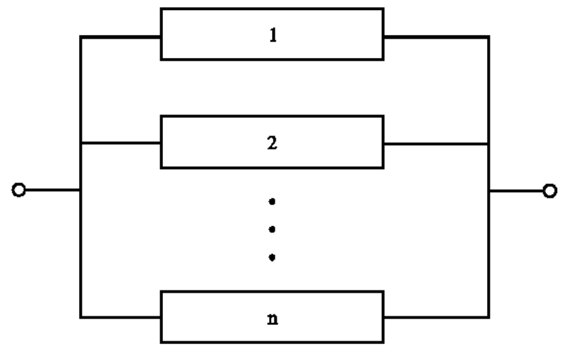

Fig. 2: Parallel system model

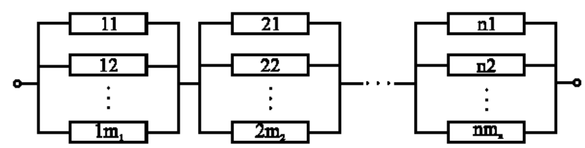

Fig. 3: Series-parallel system model

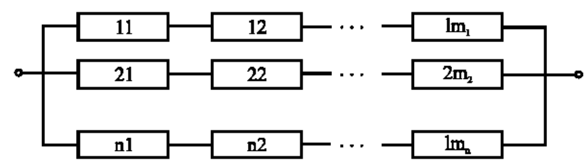

Fig. 4: Parallel-series system model

Let, each component's reliability is $R_{ij}(t) = (1, 2,\ldots, n; j = 1, 2,\ldots, m_i)$, then the series-parallel system's reliability can be represented by the following equation:

$$R_s(t) = \prod_{i=1}^{n} (1 - \prod_{j=1}^{m_i} (1 - R_{ij}(t))) \tag{3}$$

The second type is parallel-series system which is made up of n parallel subsystems each of which include m_i same components connected in series. As long as one subsystem can function well, the whole system will work effectively. So, this kind of system is also named as "System Redundancy Structure" and its structure model is as follows in Fig. 4.

One can set each component's reliability is equal to $R_{ij}(t) = (i = 1,2,\ldots, n; j = 1, 2,\ldots, m_i)$, then the reliability of whole parallel-series system can be described by:

$$R_s(t) = 1 - \prod_{i=1}^{n} (1 - \prod_{j=1}^{m_i} R_{ij}(t)) \tag{4}$$

Coherent system and component importance: Supposing one system includes n components, every component has only two states: Normal and failure. Variable x_i can be denoted the above two states as follows:

$$x_i = \begin{cases} 1 & \text{if i is functioning} \\ 0 & \text{if i is failed} \end{cases} (i=1, \cdots, n) \quad (5)$$

Then, $x = (x_1, x_2, \ldots, x_n)$ express all components states of a system. The system's state can be denoted by the structure function $\varphi(x)$ which can be defined by:

$$\varphi(x) = \begin{cases} 1, & \text{if the system is functioning} \\ 0, & \text{if the system is failed} \end{cases} \quad (6)$$

If $\forall x \le y$, the structure function $\varphi(x) \le \varphi(y)$ is true, then the φ can be named as a monotony structure function or monotony system.

Let the following notation:

$$\begin{cases} (1_i, x) = (x_1, \cdots, x_{i-1}, 1, x_{i+1}, \cdots, x_n) \\ (0_i, x) = (x_1, \cdots, x_{i-1}, 0, x_{i+1}, \cdots, x_n) \end{cases}, \ i = 1, 2, \cdots, n \quad (7)$$

If $\varphi(0_i, x) = 0$, $\varphi(1_i, x) = 1$, then the component i is related to the system. When all the components are related to the system, then the monotony system is named as monotony associated system or coherent system.

Once the system structure φ is ascertained and all the system components have the reliability $p = (p_1, p_2, \ldots, p_n)$, where $p_i = R_i(t)$, the system reliability must be a function h(p). In the absence of component reliability (for example, in the early stages of system development), it may be reasonable to assume that component life distributions are the same. Given the system structure function φ, the importance of component i is called structure importance denoted by $I_\varphi(i)$ (Barlow and Proschan, 1975) whose definition is:

$$I_\varphi(j) = \int_0^1 (h(1_j, p) - h(0_j, p)) \, dp \quad (8)$$

The method is called B-P structure importance which can be used to calculate the component structure importance in a coherent system.

Dcs structure analysis

Approximate conditions: From the point of reliability, any system will be classified into two types: Repairable and non-repairable system. For the repairable system, the reliability analysis must take the component maintenance result into consideration. So, the model of system is complex and the calculation process of indices is also difficult. For the non-repairable system analysis and calculation of reliability is more convenient because the component maintenance can be neglected. But in many actual reliability projects, many systems are repairable. In order to calculate conveniently the actual repairable system can be approximately seen as a non-repairable system based on the following assumptions: (1) The system running conditions are constant, (2) The system is of repair it as good as new.

For the DCS of electric power station, the system running conditions and operation instructions have the rigid criterions and the circumstances always keep cleaning. These situations are in accordance with the first assumption. When the DCS has certain failure, the failed component is always replaced by the new so that the second assumption is also conformed. Based on the above analysis the DCS can be approximately treated as a non-repairable system. Consequently the analysis process will be simplified and the calculation of system reliability and components structure importance can be processed easily.

DCS system structure: For example, one power station No. 1 unit's power is 600 MW and the type of DCS is Siemens T-XP. The system structure has three layers: Field bus layer, redundant plant bus layer and the redundant terminal bus layer. The main equipments include 14 control cabinets, 2 same plant buses, 2 redundant data process units PU, 2 same terminal buses, 4 operator workstations and one engineer workstation. The whole framework of this type DCS system can be depicted by Fig. 5.

The functions of each layer are expressed concisely as follows. The Layer I is responsible for the field data collection and accept the control order from the upper layer in order to finish the control on the important equipments.

Layer II is the middle layer. According the logic functions of production process of power plant, there are 14 control cabinets which are respectively in charge of boiler, turbine and electric equipments etc. On the one hand, according to the control logic which had been preinstalled, the controllers process the inputs data from the field by all kinds of input modules and then send the control instructions to the field equipments by all kinds of output modules so as to accomplish the control over the field equipments. On the other hand, the control cabinets upload the important field data to the data Process Units (PU) taking advantage of the redundant plant bus so that the upper layer can monitor and control the bottom.

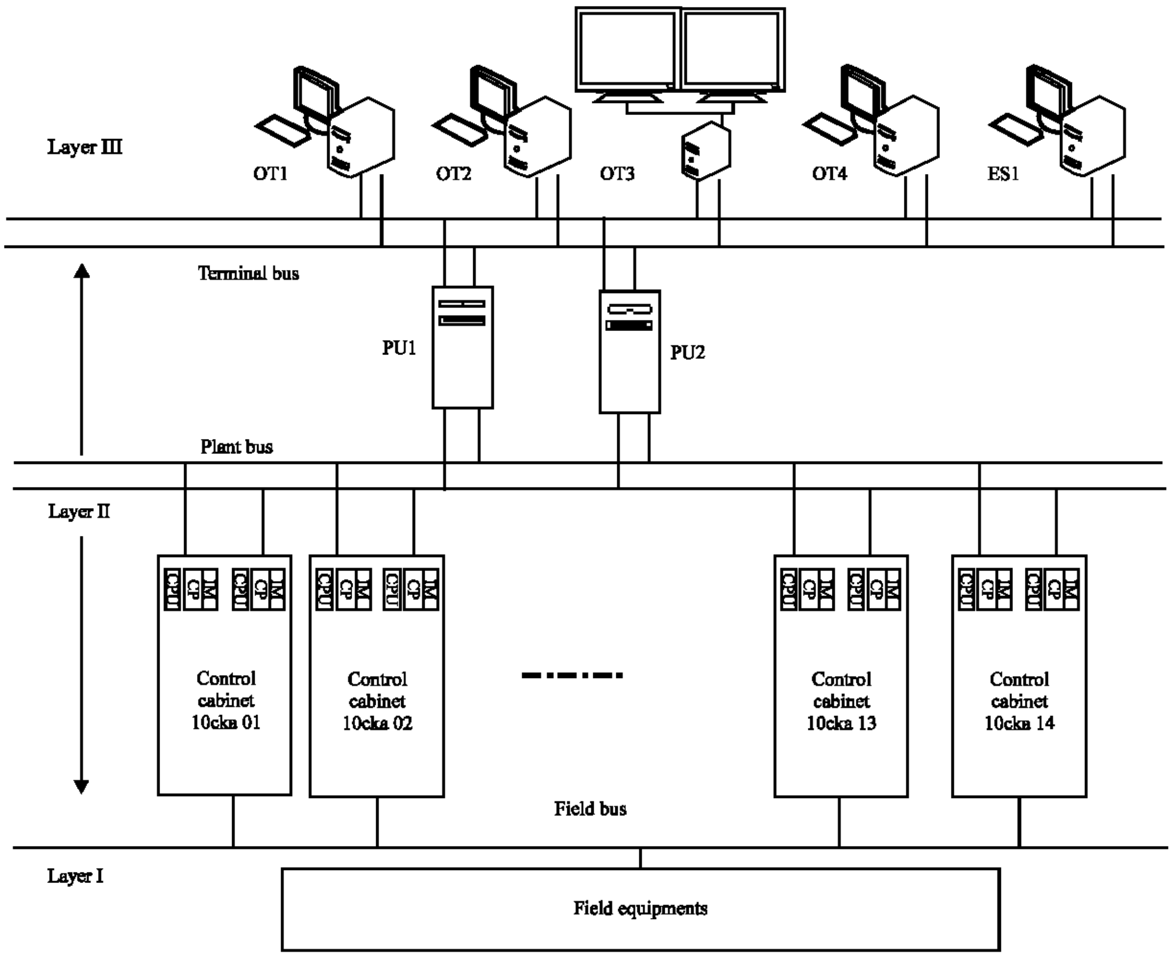

Fig. 5: DCS system framework

The Layer III is the most top layer which is used to monitor and manage the running conditions of DCS by the Engineer Stations (ES) and Operator Terminals (OT). The ES have installed all kinks of functional configuration tools which can configure the control schemes by the offline or online way. The control schemes can be downloaded and installed in the main control modules by the ES which will accomplish the monitoring, adjusting and maintenance for the control schemes at the same time. In addition to the above functions the ES also answer for monitoring the running conditions of system modules and diagnosing the communication failures between the control stations and signal module's failures. The OT is mainly used to observe, handle and manage the DCS and the produce process. Many figures, such as produce flow charts, trend charts, parameters list charts and alarm charts etc., can be displayed on the screens of OT. The manipulation functions include the changing of control loop's running conditions, outputs, setting values and running conditions of much type of equipments that have two values (on or off) conditions like spot touches, relays, fans etc. In addition, the redundant terminal buses improve the reliability of data communication.

RESULTS AND DISCUSSION

Modeling DCS structure: According to the above functional analysis of each layer, every equipment of DCS can be modeled as follows from the view of reliability:

- Because the modeling object is aimed at the DCS, only the equipments above the field bus will be taken into account. Meanwhile, those equipments which can't affect the DCS, such as printer, will be omitted
- Any control cabinet's failure will lead to the DCS failure, so the model of all the control cabinets belongs to series

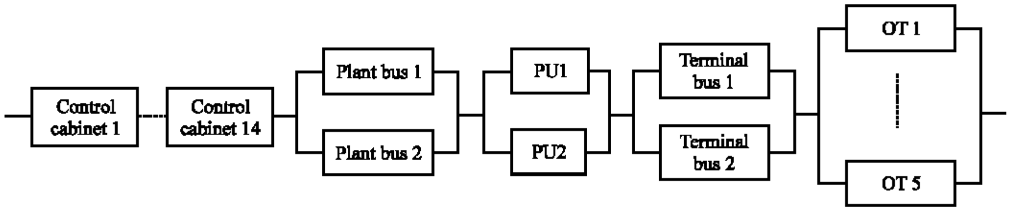

Fig. 6: Distributed control system reliability block diagram

- Data of control cabinets will be transmitted by the redundant plant bus. Once one plant bus failed, the other one will work and the DCS will not be failed. When the both plant buses failed at the same time, the DCS malfunction will arise. So, the model of the two plant buses is parallel
- Data process units PU and terminal buses are also redundantly configured, so both models are parallel
- When the DCS works normally, the ES is seen as an OT by setting an operating password then the ES is equal to an OT. So, the human machine interfaces model, including the ES and the OT, is parallel

According to the above analysis and modeling process, the reliability model of the whole DCS system belongs to one of the hybrid model which is the series-parallel model. As shown in Fig. 3, the reliability block diagram of the DCS system can be depicted by Fig. 6.

The DCS system can be divided into 5 subsystems based on Fig. 6. The 5 subsystems are respectively control cabinet subsystem, plant bus subsystem, process unit subsystem, terminal bus subsystem and the operator terminal subsystem. According to each subsystem's reliability model, the reliability equation can be figured out.

The reliability of control cabinet subsystem can be marked as $R_{cab}(t)$ whose equation is:

$$R_{cab}(t) = R_{cab1}(t)*R_{cab2}(t)*\cdots*R_{cab14}(t) = \prod_{i=1}^{14} R_{cabi}(t) \quad (9)$$

Alike, the other subsystem's reliability of plant bus, process unit, terminal bus and operator terminal can be respectively expressed by the following:

$$R_{pb}(t) = 1 - \prod_{i=1}^{2}(1 - R_{pbi}(t)) \quad (10)$$

$$R_{pu}(t) = 1 - \prod_{i=1}^{2}(1 - R_{pui}(t)) \quad (11)$$

$$R_{tu}(t) = 1 - \prod_{i=1}^{2}(1 - R_{tui}(t)) \quad (12)$$

$$R_{os}(t) = 1 - \prod_{i=1}^{5}(1 - R_{osi}(t)) \quad (13)$$

Using Eq. 9-13, DCS reliability can be figure out:

$$R_{dcs}(t) = R_{cab}(t)*R_{pb}(t)*R_{pu}(t)*R_{tu}(t)*R_{os}(t) \quad (14)$$

Component importance of DCS system: Because of the complexity of DCS structure, analysis and calculation of components importance will be valuable for the improvement and enhancement of DCS system reliability. The B-P method will be adopted in order to calculate quantitatively the component's importance when the reliability of component can not be ascertained.

As for control cabinet subsystem, once the importance of the first control cabinet has been calculated, the others will have the same results because they have the same structure. For the first control cabinet, we have the following:

$$\begin{cases} h(1_{cab1}, p) = p^{13}*(1-(1-p)^2)^3*(1-(1-p)^5) \\ h(0_{cab1}, p) = 0 \end{cases} \quad (15)$$

From Eq. 8 and 15, the importance of the first control cabinet will be calculated as following:

$$I_{\varphi}(cab1) = \int_0^1 (h(1_{cab1}, p) - h(0_{cab1}, p))\,dp \approx 6.97\% \quad (16)$$

Because the plant bus, process unit and terminal bus have the same structure, they have the same importance. Once one component's importance has been figured out, the others will be gotten. Taking the plant bus I for an example, following equation can be obtained:

$$\begin{cases} h(1_{pb1}, p) = p^{14}*(1-(1-p)^2)^2*(1-(1-p)^5) \\ h(0_{pb1}, p) = p^{15}*(1-(1-p)^2)^2*(1-(1-p)^5) \end{cases} \quad (17)$$

From Eq. 8 and 17, the importance of plant bus I can be obtained as follows:

$$I_\varphi(pbl) = \int_0^1 (h(1_{pbl}, p) - h(0_{pbl}, p))\, dp \approx 0.4\% \quad (18)$$

As for the operator terminal subsystem, when the first operator terminal's importance was ascertained the other four will have the same result because they have the same structure. We can get the first operator terminal's function as following:

$$\begin{cases} h(1_{OT1}, p) = p^{14}*(1-(1-p)^2)^3 \\ h(0_{OT1}, p) = p^{14}*(1-(1-p)^2)^3*(1-(1-p)^4) \end{cases} \quad (19)$$

From Eq. 8 and 19, the importance of operator terminal I can be gotten as following:

$$I_\varphi(OT1) = \int_0^1 (h(1_{OT1}, p) - h(0_{OT1}, p))\, dp \approx 0.00139\% \quad (20)$$

The importance of every type component had been listed in Table 1.

It was found that the control cabinet subsystem is the most important. Based on the conclusion the control cabinet subsystem should be as the key component to improve the DCS reliability.

Modeling of control cabinet: From Table 1, it can be found that the importance of control cabinet is approximate up to 98%. So, improving the control cabinet's importance will be significant for improving the DCS importance. The components of control cabinet should be further analyzed.

Every control cabinet is composed of several components such as power supply, cooling fan, Distributed Process Unit (DPU), DPU rack, some Input or/and Output (I/O) modules, I/O rack. In sake of the control cabinet's safety and reliability, the power supply and DPU are configured as redundancy. The reliability model of those two components is parallel. The other components are series model because if any one of them failed the control cabinet will fail. The whole control cabinet subsystem's reliability model should be the series-parallel of the hybrid and its structure model can be shown in the Fig. 7 as follows.

Table 1: Component importance of Distribution Control System (DCS)

Components	Counts	Single importance (%)	Sum (%)
Control cabinet	14	6.97	97.58
Plant bus	2	0.4	0.80
Process unit	2	0.4	0.80
Terminal bus	2	0.4	0.80
Operator terminal	5	0.00139	0.00695

Every component's reliability of the control cabinet subsystem can be calculated by the B-P method according to the Fig. 7.

As for the cooling fan, we have the equation:

$$\begin{cases} h(1_{fan}, p) = p^3*(1-(1-p)^2)^2 \\ h(0_{fan}, p) = 0 \end{cases} \quad (21)$$

Combining Eq. 8 and 21, the cooling fan's structure importance can be calculated by:

$$I_\varphi(fan) = \int_0^1 (h(1_{fan}, p) - h(0_{fan}, p))\, dp = 37/168 \approx 22.02\% \quad (22)$$

Because the DPU rack, I/O rack and I/O module have the same structure, their structure importance is as same as the cooling fan.

As for the redundant DPU and power supply, because they have the same structure, their importance is as same as power supply 1. For power supply 1, we have the following:

$$\begin{cases} h(1_{power}, p) = p^4*(1-(1-p)^2) \\ h(0_{power}, p) = p^5*(1-(1-p)^2) \end{cases} \quad (23)$$

Combining Eq. 8 and 23, the power supply's structure importance can be calculated by:

$$I_\varphi(power) = \int_0^1 (h(1_{power}, p) - h(0_{power}, p))\, dp = 5/168 \approx 2.98\% \quad (24)$$

The result of every component's importance can be listed in the Table 2 in order to find out which one has the most importance.

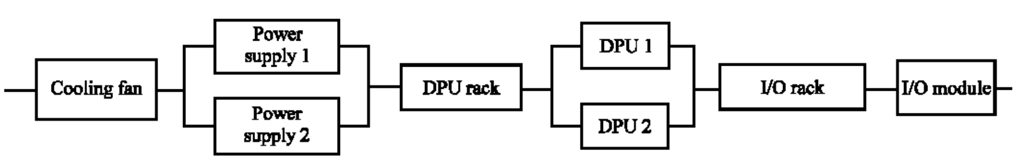

Fig. 7: Control cabinet reliability block diagram

From the Table 2, it can be seen that the cooling fan, DPU rack, I/O rack and I/O module have the more importance than the others. Although power supply and the DPU are also very important in the control cabinet subsystem, their structure importance is not very high because their structures have been configured as redundancy. Based on the above analysis, the maintenance engineers should be put more inspection on the components that have the more importance so as to assure the DCS working well.

Reliability calculation of control cabinet: Based on the above discussion, the control cabinet subsystem should be as the key part for the maintenance engineer. Taking a power plant's control cabinet subsystem for an example, its component's failure rates are listed in Table 3.

Note that every control cabinet has the different I/O module count as their function is respectively different.

In order to calculate conveniently, for every control cabinet the count of I/O module can be approximately equal to 20.

According to Fig. 7, the control cabinet's reliability equation can be listed as follows:

$$R_{cab}(t) = R_{fan}(t) * (2R_{power}(t) - R^2_{power}(t)) * R_{D\_rack}(t) * (2R_{DPU}(t) - R^2_{DPU}(t)) * R_{IO\_rack}(t) * R_{IO}(t) \quad (25)$$

The distribution type of every kinds of component can be seen as exponential distribution. The Eq. 25 can be rewritten as the following:

$$R_{cab}(t) = e^{-8*10^{-6}t} * (2 * e^{-8.3*10^{-6}t} - e^{-16.6*10^{-6}t}) * e^{-6.234*10^{-6}t} * (2 * e^{-5*10^{-6}t} - e^{-10*10^{-6}t}) * e^{-4.1644*10^{-6}t} * e^{-5*10^{-6}t} \quad (26)$$

The reliability curve of control cabinet can be depicted as by the Eq. 26.

The Mean Time Between Failures (MTBF) of control cabinet is:

$$MTBF = \int_0^{\infty} R_{cab}(t)dt = 36588 \quad (27)$$

In Fig. 8 the data point A shows the reliability of control cabinet when it runs about 100 days (also 2400 h). The reliability value is approximate upto 95%. The data point B shows that the reliability is only 38.74% when the control cabinet runs for a period of MTBF. According to the previous discussion the control cabinet's structure importance is near upon 98%, in order to assure the DCS work well, consequently the inspection interval for control cabinet should be less than 100 days and its reliability can reach to 95% or even more.

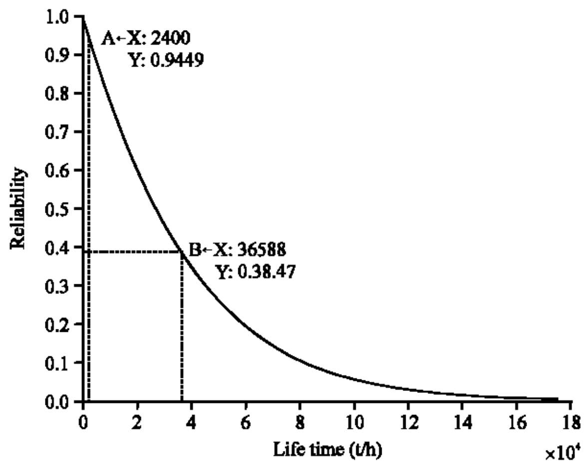

Fig. 8: Control cabinet subsystem reliability curve

Table 2: Component importance of control cabinet subsystem

Components	Counts	Single importance (%)	Sum (%)
Cooling fan	1	22.02	22.02
Power supply	2	2.98	5.96
DPU rack	1	22.02	22.02
DPU	2	2.98	5.96
I/O rack	1	22.02	22.02
I/O module	1	22.02	22.02

Table 3: Component failure rate of control cabinet

Components	Counts	Failure rate (fit)
Cooling fan (λ_{fan})	1	8000.0
Power supply (λ_{power})	2	8300.0
DPU rack ($\lambda_{D\text{-}Rack}$)	1	6234.8
DPU (λ_{DPU})	2	5000.0
I/O rack ($\lambda_{IO\text{-}Rack}$)	1	4164.4
I/O module (λ_{IO})	20	5000.0

The DCS have been constituted of a number of components and wires and their structures are very difficult for modeling and reliability prediction. Lu and Dong (2009) have designed a new Ethernet bus interface controller used in the input/output subsystem of nuclear power plant and evaluated its reliability by the Relex tools. Lapp *et al.* (2010) and Muda and Shakaff (2002) have designed a fault-tolerant architecture for real-time DCS and improved the reliability of the DCS. But the quantitative index of whole reliability of DCS and its structure importance have not yet been reported in the previous studies.

In this study the approximate conditions, by that an actual repairable system can be seen as a non-repairable, had been put forward. It will benefit to model the DCS system. Meanwhile, the structures and functions of DCS system had been analyzed.

Using the reliability block diagram, the reliability model of DCS system had been first build according to the analysis. The component's structure importance had been calculated quantitatively according the B-P method and the results can be as the scientific evidence for the maintenance engineer. They can plan the key subsystem which should be given more inspection than others in order to improve the whole reliability of DCS and make sure the normal productive process of electric power plant.

CONCLUSION

The results also showed that control cabinet subsystem have the higher importance. Then the reliability model of control cabinet subsystem had been modeled. At the same time, the components' structure importance of control cabinet subsystem had been also calculated. Because the control cabinet subsystem has the more importance, its reliability had been depicted. According to the reliability curve the maintenance engineer can schedule the inspection interval scientifically. The components importance of the control cabinet provides scientific evidences of which components should be spent more care than others.

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