Analysis of a Communication Network for Control Systems in Nuclear Power Plants and a Case Study

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Abstract: In this paper, a real-time communication method using a PICNET-NP(Plant Instrumentation and Control Network for Nuclear Power Plant) is proposed with an analysis of the control network requirements of DCS (Distributed Control System) in nuclear power plants. The method satisfies deadline in case of worst data traffics by considering aperiodic and periodic real-time data and others. In addition, the method was used to analyze the data characteristics of the DCS in existing nuclear power plant. The result shows that use of this method meets the response time requirement(100ms).

Keywords: DCS, Token Rotation Time, Cycle Data, Acyclic Data, Urgent Data

1. INTRODUCTION

There are many cases in which the communications network of the distributed control system(DCS) accommodates a layer structure according to the applied area, and in such cases, the communications regulations as the IEEE 802.4 token bus regulation[1], IEEE 802.5 token ring regulation[2], and the FDDI regulation[3] usually deal with the middle range, and numerous field buses such as FIP[4] proposed by France, Profibus [5] proposed by Germany, and CAN[6] proposed as a vehicle communications protocol and set as an international standard handles the sensors of the lower layer and the communications of the driver portion. However, when observing the characteristics of each protocol, the division of the middle layer and the lower layer is ambiguous.

However, there are many difficulties in directly applying theses protocols to middle layer communications network of the nuclear power plants DCS. In case of systems concerning safety as the nuclear power plants, network protocols which may guarantee the deadline of the acyclic real-time data should be utilized, or networks which present a method to guarantee the hard real-time must be applied. They must simultaneously be able to present a method to guarantee the transmission of the cyclic real-time data.

In this study, a method to guarantee the deadline of the acyclic real-time data and the hard real-time and the soft real-time of the cyclic real-rime data, subjecting the control network of the KNX-5[7], the prototype of the nuclear power plant DCS proposed by the Electric Power Research Institute. In chapter 2, a method to reinforce the hard real-time communications is proposed, In chapter 3, the real-time characteristics of the proposed method is interpreted, the control system for the nuclear power plants currently running is selected, the number of data and the data characteristics are evaluated, and PICNET-NP is applied to the control system of the nuclear power plant through the proposed method[8]. Finally, chapter 4 displays the conclusion. .

2. REAL-TIME COMMUNICATIONS APPLYING PICNET-NP

2.1 Basic Characteristics of PICNET-NP

The coaxial cable and the twisted-pair cable is utilized as the transmission media. In addition, the fiber optic cable may also be utilized by applying equipment as transceivers. The maximum distance of transmission without using any other extension devices, is 100m for the twisted-pair cable, 500m for the coaxial cable, and 3km when using separated extension devices as repeaters. The transmission rate is 5 Mbits/s. 250 stations may be linked in maximum, and they can be divided into a maximum of 15 groups. One group may be composed of 64 stations in maximum.

2.2 Definition of Data & Stipulation of Length

The frame utilized in the PICNET-NP is discussed here. The discussed frame was selected while considering the data required from the DCS and is used when being applied to the control system of the nuclear power plant in chapter 3.

2.2.1 Structure of the token Frame

A frame which is defined by the IEEE 802.4 token bus size is applied. It is composed of 21 octet and the transmission time of the token frame is 33.6 μ sec.

Preamble	SD	FC	DA	SA	FCS	ED
10	1	1	2	2	4	1

2.2.2 Data Frame

It is composed of (21+L) octet, and its transmission time is $(21+L)\times 8\times 0.2$ μ sec. From this, L, the data part, accommodates different structures according to the characteristics of the data.

Preamble	SD	FC	DA	SA	Data	FCS	ED
10	1	1	2	2	L	4	1

Urgent Data

The data from the non-cyclically occurring events include the time stamp, the e. ID, the e. Data, the Status, and etc.

Hence, it is composed of 10 bytes, and its structure is as the following. Therefore, the length of the frame to transmit the urgent data is 31 bytes, and a period of 31 octet time is consumed.

Dsap	Ssap	Ctrl	ID	Time Stamp	e. ID	e. Data	Status
1	1	1	2	2	1	1	1

Acknowledged Data (ACK)

The frame defined by the IEEE 802.4 token bus size is utilized. It is composed of 3 bytes. Therefore, the length of the frame for ACK transmission of urgent data is 24 bytes, and a period of 24 octet time is consumed.

Cyclic Data

The hard real-time cyclic data and the soft real-time cyclic data have identical structures. The cyclic data is of a structure in which many could be transmitted at once. The cyclic data is composed of the ID, data, and status information. The cyclic data is of a structure in which many could be transmitted at once. The length of one cyclic data is 5 bytes, and the form and structure of the combined cyclic data of as many as k is as the following. Therefore, the length of the frame for the cyclic data transmission including k cyclic data is (21+4+5k) bytes, and a period of (21+4+5k) octet time is consumed.

Dsap	Ssap	Ctrl	#ofData	ID	Data	Status	...	k^{th} cyclic data
1	1	1	1	2	2	1	...	5

Advanced Data

Unlike the urgent data, or the hard and soft real-time cyclic data, this does not have a constant length. However, the size of its maximum frame capable to send at once is limited to 1Kbyte.

Dsap	Ssap	Ctrl	Advanced Data
1	1	1	

2.3 Method of Calculating the Performance of Data Transmission Time

In order to consider the worst situation, the following was presumed. The urgent data uses the L_DATA_ACK primitive of the LLC. The cycles of all cyclic data (hard real-time data, soft real-time data) are the same. Therefore the token rotation time must be guaranteed to be shorter than the given cycle. In addition, the cyclic data utilizes three types of transmission methods, i.e., uni-casting, multi-casting, broadcasting. At this point, when one station undergoes maximum cyclic transmission, (n-1) uni-casting, g times of multi-casting, and one time of broadcasting takes place. Thus, the maximum cyclic transmission frequency is (n+g). figure 1 is displayed by the three methods used for data transmission

① When n・(n+g) b 와 n・(n+g) c is satisfied, TRT is as the following.

TRT = a・(Tu+Tp+Ta+Tp) + n・(n+g)・(Tp + Thoh) + b・Thd + n・(n+g)・(Tp + Tsoh) + c・Tsd + n・{Tt + To}

② n・(n+g) b 와 n・(n+g) c is satisfied, TRT is as the following.

TRT = a・(Tu+Tp+Ta+Tp) + n・(n+g)・(Tp + Thoh) + b・Thd + c(Tp + Tsoh + Tsd) + n・{Tt + To}

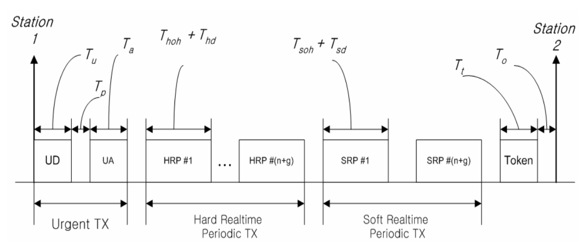
③ n・(n+g) b 와 n・(n+g) c is satisfied, TRT is as the following.

TRT = a・(Tu+Tp+Ta+Tp) + b(Tp + Thoh + Thd) + n・(n+g)・(Tp + Tsoh) + c・Tsd + n・{Tt + To}

④ n・(n+g) b 와 n・(n+g) c is satisfied, TRT is as the following.

TRT = a・(Tu+Tp+Ta+Tp) + b(Tp + Thoh + Thd) + c(Tp + Tsoh + Tsd) + n・{Tt + To}

If Tp = 10, Tt = 33.6, To = 40 is applied to the structure of the data above, Thoh = 25 (octet time) = 40, Tsoh = 25 (octet time) = 40, Tu = 31 (octet time) = 49.6, Ta = 24 (octet time) = 38.4 is true. When applying these values to the cases 1, 2, 3, and 4, TRT can be found.



n : total number of stations
a : total number of acyclic realtime data
b : total number of hard realtime cyclic data
c : total number of soft realtime cyclic data
g : total number of defined groups in communications network
T_u *: transmission time of acyclic realtime data*
T_a *: acknowledge/response transmission time of acyclic realtime data*
T_{hoh} *: transmission time of hard realtime cyclic data overhead*
T_{soh} *: transmission time of soft realtime cyclic data overhead*
T_{hd} *: transmission time of hard realtime cyclic*
T_{sd} *: transmission time of soft realtime cyclic*
T_t *: transmission time of token*
T_p *: blank time between transmission frames*
T_o *: interval time needed for token transmission*

Figure 1. Three Methods Used for Data Transmission

3. CASE STUDIES

3.1 Token Rotation Time

It is the period between when a token is sent to the next station and when it is receive again. If the token rotation time is definite, the transmission of the cyclic data could be easily created. However, the token rotation time in the token bus network is generally not fixed. Therefore, there is difficulty in the cyclical data transmission. In this study, a method to maintain a token rotation time under a certain limit is proposed.

If there were no transmitted data, the token would solely rotate in the network. In this case, the transmission time is 33.6 μsec. In addition, there is time consumed additionally, other than the actual transmission time, while the token is transmitted. This time differs according to the number of stations or the distance between the stations etc., but about 40 μsec is usually sufficient. Therefore, when there are n stations, the TRT is n(33.6+40). When there are 32 stations, it is 2.46 msec, and when there are 10, it is 0.74 msec. The MAC variables, which concern the transmission may be set by the user, are THT, TRT4, TRT2, and TRT0. Thus, the variables are set according to the communications capacity of respective stations. These variables determine the real-time communications characteristics of IEEE 802.4, so how the values of these variables are set determine the performance of the PICNET-NP communications.

THT Determination

THTi is the THT of station number i. The THT of each station is determined by the urgent data and the hard real-time cyclic data. ***THTi*** is calculated as the following. In this case, frames for the urgent data and the cyclic data are captured as many as possible, so the overhead which may occur during transmission can be disregarded.

$$\boldsymbol{THTi} = ai\,(T_u + T_p + T_a + T_p) + (n+g)(T_p + T_{hoh}) + bi\ T_{hd} \quad (1)$$

3.2 Data Analyzation of the Nuclear Power Plants Control System

Based on the functions of the Control System of the Nuclear Power Plants, the analogue contact point, the digital contact point, and etc., the data which shall be applied in the digital communications were analyzed[9]. The results are adjusted on table 1, classified by the type of data. The number of data marked on table 1 is the analysis of every data which could occur in the nuclear reactor control systems. Therefore, it is the number of data per one rotation of the token in the worst case. In addition, in one rotation of the token, the data of the worst case must not occur twice or more. The length of the frame is identical according to the system, but the size of the frame differs according to the communications service, in other words, the urgent, cyclic, and advanced data. The data value varies in by the situation, but the form of the data is uniform.

Table 1. Data number of the Nuclear Power Plant Control System.

Data / System	Urgent Data	Hard realtime cyclic data	Soft realtime cyclic data
RRS	22	13	5
RPCS	20	15	0
PPCS	19	3	11
PLCS	17	5	5
FWCS	36	24	88
SBCS	48	16	83
CEDMCS	87	120	118
합계	249	196	310

3.3 Application of PICNET-NP on the Nuclear Power Plant Control System

The existing nuclear power plant control systems did not use digital communications networks, but were employed by directly connecting point-to-point. Due to this, the system became overly exaggerated in size, high in expense of setting, and its conservation and repair became difficult. If the PICNET-NP is applied to this control system, it could be as the form in figure 2.

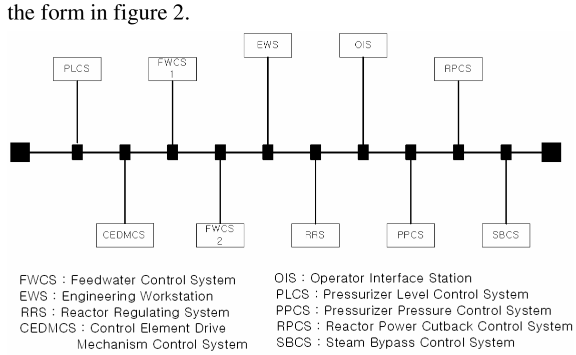


Figure 2. Network of Control System

When observing figure 2, systems as the Engineer Workstation(EWS), which could additionally create designing materials and programs concerning process control and supervising control, Operator Interface Station(OIS), by which the operator could serve functions as controlling and supervising the whole system, and etc. are connected to the network. Other systems could be considered as a part of the process control unit(PCU). Whether the PICNET-NP is suitable as a digital communications network of the nuclear power plant control system was evaluated with the data materials gained from table 1.

The response time actually required in the nuclear power plant slightly differs according to its running devices. However, it is displayed in the Report of the Korean Nuclear Reaction Technology of the Next Generation that the response time between the systems(PCU and PCU) is 100ms-250ms, and the response time between the PCU and the OIS is 250ms-500ms[10].

In order to consider the worst situation through the data, the following was presumed. The urgent data uses L_DATA_ACK primitive of LLC. The cycles of all cyclic data(hard real-time data, soft real-time data) are identical. Therefore, the token rotation time must be guaranteed to be shorter than the given cycle. In addition, the cyclic data is to use three transmission methods, i.e., uni-casting, multi-casting, broadcasting. Hereunto, when one station undergoes maximum cyclic transmission, uni-casting of (n-1), g times of multi-casting, one broadcasting takes place. Therefore, the maximum cyclic transmission frequency is (n+g). In addition, when applying T_p = 10μs, T_t = 33.6μs, T_o = 40μs, to the data structure above, T_{hoh} = 25(octet time) = 40μs, T_{soh} = 25(octet) = 40μs, T_u = 33(octet time) = 52.8μs, T_a = 24(octet time) = 38.4μs is true. When applying these values to equation (2), the TRT in the worst case can be found, and this value becomes TTRT4. Through the method of calculating the performance of the data transmission time, the target token rotation time(TTRT4) is as the following.

If there are 10 stations, 6 groups, 249 urgent data, 196 hard real-time cyclic data, and 310 soft real-time cyclic data, it is classified as case 4.

$$\textbf{\textit{TTRT4}} = 249(0.0528 + 0.01 + 0.0384 + 0.01) + 196(0.01 + 0.04 + O.008) + 310(0.01 + 0.04 + 0.008) + 10(0.0336 + 0.04) = 57.773\text{ms} \quad (2)$$

.

Therefore, it could be concluded that when the network system of figure 2 gives and receives the data of table 1, a transmission shorter than the maximum 57.773 msec could be guaranteed. This verifies that the system sufficiently satisfies the required response time of a nuclear power plant, which is a minimum of 100msec. In addition, it is displayed above that the PICNET-NP could guarantee the minimum cycle of the calculated TTRT4.

Therefore, the cyclic transmission of the soft real-time cyclic data of more that the gained TTRT4 is also guaranteed.

4. CONCLUSION

In this study, the required terms of the nuclear power plant DCS control network were evaluated, and a real-time communications method using the proposed PICNET-NP was suggested. By applying the proposed method, it was verified that the acyclic real-time data, the hard real-time of the cyclic real-time data, and the soft real-time deadline could be satisfied even in the worst data traffic situation. In order to simulate the proposed method, a control system of a nuclear power plant currently running was selected. The number of data from the control system of the designated nuclear power plant and the data characteristics were analyzed, and as a result to calculating the target token rotation time(TTRT4) of the worst situation, it satisfied the response time of 100ms required in the nuclear power plant.

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