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Real-time and Reliability Analysis of FlexRay Bus

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Abstract—Real-time communication system is widely used to smart grid. The real-time performance and reliability are compared between CAN bus and FlexRay bus in theory. Then a steer-by-wire system experimental platform, which using the FlexRay bus, is built to verify the analysis results. The test results show that FlexRay bus has strong real-time performance and high reliability and are more suitable for high-speed, large capacity, strong and highly reliable real-time field bus communication networks. FlexRay bus has a good application prospects in the future smart grid and real-time control network.

Keywords—Smart grid; FlexRay; Real-time communication system; Reliability

I. INTRODUCTION

Smart grid is a kind of vision for the future development of power grid; it is the integration of the information technology and the electric power industry. It focuses on the electricity power system, such as power generation, transmission, distribution, storage and objects, uses digital information technologies and automated control technology to realize two-way information exchange all aspects of the system, and optimizes power generation, transmission and use [1]. This high level of information technology and automation whether it is from the substation automation, power transmission of information, even to the user terminal automation of meter can not do without high-speed, real-time, reliable communications network. In particular, the smart grid statuses monitoring, troubleshooting techniques that require high-speed network communications, a high degree of real-time, reliability, structural flexibility. However, the traditional power industry field bus, such as RS-422/RS-432, CAN, etc. due to their own protocol limitations, they are difficult to meet requirements of the information transmission of the future smart grid, such as the high-speed, certainty and fault tolerance.

FlexRay is a high-speed, strong real-time, highly reliable in-vehicle network communication technology. In automotive-wire system and security control areas, CAN bus is being replaced by FlexRay bus. In the future more and more in-vehicle network and on-site control network, FlexRay will be used partly and replace the CAN bus and get more applications. FlexRay fully meets the network communications development needs of the future smart grid real-time control network, has good application prospects. The present studies on FlexRay mainly focused on two aspects: theoretical

calculation and simulation analysis, and the application in X-By-Wire system [2]. By analyzing the worst response time of the message communication, as well as the failure probability of message transmission under strong electromagnetic interference environment, the reliability and real-time performance of the FlexRay bus can be gotten; then the results were validated by FlexRay bus real-time and reliability test of steer-by-wire hardware-in-loop simulation platform.

II. FLEXRAY REAL-TIME ANALYSIS

FlexRay uses differential transmission mode, communicating through two separate bus, each one of the data rate can be up to 10MBit / s; compared to the CAN protocol, the available bandwidth can be increased by 10 ~ 40 times. The visit method of FlexRay is based on synchronized time base which is automatically created and synchronized by agreement. Time-base accuracy is between 0.5 μ s and 10 μ s [3]. FlexRay provides redundancy and non-redundant communication, communication is carried out by cycle, and its communication cycle primarily includes dynamic segment and static segment. The message transmission in static segment is based on TDMA (Time Division Multiple Access) mechanism, the message transmission delay will be very small, and the message response time is equal to transmission time. The message transmission in dynamic segment is based on FTDMA (Flexible Time Division Multiple Access) mechanism, and the calculation of the message response time can refer to Pop literature [4]. Because the dynamic segment is used to transmission of unexpected messages, so the research is mainly on comparison of the message response time of the FlexRay static segment and CAN bus.

FlexRay static segment message transmission time C_i^F can be calculated as (1).

$$\begin{aligned} C_i^F &= [7 + 1 + 2 + t_d + (8 + S_i) \times (8 + 2)] \tau_{bit} \\ &= (90 + t_d + S_i \times 10) \tau_{bit} \end{aligned} \quad (1)$$

S_m is data length, τ_{bit} is transfer time of a bit. The first three constants in the (1) are related to the frame format: Transmission Start Sequence (5-15 bit); Frame Start Sequence (1 bit); Frame End Sequence (2 byte). Also in front of each data the byte start sequence (2 byte) are added, so each communication bytes occupy 10 bits, t_d is the transmission

delay from the sending nodes to the receiving nodes, it's about 2 to 3 bits.

Because the CAN bus uses event-triggered mechanism, when there are several nodes to apply the bus control, low-priority message will be delayed, the more high-priority messages and be sent more frequently, the longer the low-priority message will be blocked. Worst-case response time of CAN messages can be calculated by the following recursive formula (2) [5] [6]:

$$R_m^{n+1} = C_m + B_m + \sum_{\forall k \in hp(m)} \left\lceil \frac{R_m^n + J_k + \tau_{bit}}{T_k} \right\rceil \times C_k \quad (2)$$

$$= C_m + B_m + I_m$$

B_m is the longest delay time of the message m which might be blocked by low-priority messages; C_m is the longest transfer time for the worst case. $hp(m)$ is the message set which have a higher priority than the message m . The jitter time J_i of the message queue J_k is defined as the time the messages from the production to its success into the CAN bus controller. T_k is the transmission cycle. Formula (2), the initial value is set as $R_m^0 = J_m + C_m$, when $R_m^{n+1} = R_m^n$, the recursive computation end. If $R_m^{n+1} \geq T_m$ or $R_m^{n+1} \geq D_m$ (D_m the time limit of the information m), ahead of the end of the equation, indicating that the message can not be scheduling.

Contrast formula (1) and (2), it's not difficult to find that, FlexRay bus using TDMA static scheduling in the static-segment message transmission, there is no conflict, the response time is a constant, cycle jitter is small. The message response time in the CAN bus will gradually increase when high-priority messages with the increase in the number. So CAN-bus load rate should be 20% ~ 30% in most design [7]. Therefore, FlexRay bus has a powerful advantage over CAN bus in system applications which have strict requirements of real-time.

III. FLEXRAY RELIABILITY ANALYSIS

When analyzing the operation status of a real-time system, only concerning about the real-time system is not enough, but should also take full account of its reliability. Real-time communication system is responsible for messages real-time transmission between the nodes, the message from ready to be sent correctly to the receiver, will involve the nodes, bus and time constraints.

Message transmission delay T_D mainly includes three parts: the network transmission delay T_{Net} , node receive delay T_A , as well as the mechanical delay T_M of the implementation of command message [30].

$$T_D = T_{Net} + T_A + T_M \quad (3)$$

For a fixed control algorithm, T_A in the formula (3) is fixed; T_M is different from nodes, for the same node controller is basically fixed, can be available through Matlab / Simulink simulation. Therefore, to get a good security and reliability of the system, the network transmission delay should in the allowed range.

When $T_D > T_{max}$, the system control performance will clearly decline. Thus, adequate safety assurance should meet (4):

$$p(T_D > T_{max}) < p_{max} \quad (4)$$

The probability that the transmission delay T_D is greater than T_{max} is less than $p_{max} = 10^{-9}$ (SIL level) [43].

Then system communication reliability is design as (5).

$$p(T_{Net} > T_{max} - T_A - T_M) < p_{max} \quad (5)$$

For the FlexRay bus systems, the network transmission latency will be small enough to microseconds, so in the case of no electromagnetic interference, using the FlexRay system will have good security. In fact, in practical industrial applications, industrial external EMI environment is very bad, so it requires a combination of Poisson error model [8] with random errors [9] model to study the FlexRay bus system security. Poisson error model is used to calculate the probability of failure of each FlexRay cycle; random error model is used to calculate the probability of error happening, that is, whether there is an error each cycle is random.

In the static segment of FlexRay, messages are transmitted when there is an error, will not automatically be resent. If there is no redundancy in the TDMA cycle, then the messaging process, regardless of one or more errors, the message can not be right to be send, so the message i transmission failure rate equal 1 minus the probability of message transmission with zero errors:

$$p(k \neq 0) = 1 - \frac{e^{-\lambda C_i} (\lambda C_i)^0}{0!} = 1 - e^{-\lambda C_i} \quad (6)$$

As redundant features of the dual-channel FlexRay bus, the introduction of redundancy β , assuming that the message I transmitted in the channel A and channel B, and the close proximity of the two channels, while subject to the same error model of interference; at this point $\beta = 2$, when the single-channel transmission $\beta = 1$.

Therefore, a single message transmission on the FlexRay bus, the probability of failure to re-record is (7).

$$p_i^{fail_Flex} = (1 - e^{-\lambda C_i})^\beta \quad (7)$$

Taking into account the FlexRay message redundancy β will be able to take a larger value. Such as: FlexRay adoption of dual-channel transmission, in order to increase reliability of transmission, in the TDMA cycle, using a dual redundant transmission message, at this time $\beta = 4$.

According to formula (7), the probability of message being damaged in each FlexRay cycle can be got, if each cycle, the probability is same, then, the probability of message being destroyed in n consecutive FlexRay cycles is (8).

$$p = (1 - e^{-\lambda C_i})^{n\beta} \quad (8)$$

When the FlexRay bus is in outside interference, the network transmission delay consists of two parts, one for n consecutive cycles $n * T_C$ interfered with errors, and the other for the FlexRay message transmission delay.

$$T_{Net} = n * T_C + T_w \quad (9)$$

Assumption that the system is $T_{max} = 20ms$, $T_A = 0.2ms$, $T_M = 1.4ms$ and $T_C = 5ms$, $T_w = 0.017ms$. According to Formula (5) and formulas (9), the maximum continuous interference FlexRay bus cycle number allowed by the system can be drawn: $n = 3$.

Then, the actual FlexRay bus system failure probability is as (10).

$$p(n > 3) = 1 - \sum_{k=0}^3 p(n=k) = (p_i^{fail-Flex})^4 = (1 - e^{-\lambda C_i})^{4\beta} \quad (10)$$

For the CAN bus system, the probability that the message is missing in cycle can be obtained by Poisson error model based on fault tree iteration. The same as before, assuming that CAN message transmission cycle is 5ms, in the same way, the number of a continuous loss number of CAN cycles is not greater than 3. Then, based on the CAN bus system, the probability of system failure is as (11).

$$p(n > 3) = 1 - \sum_{k=0}^3 p(n=k) = (p_i^{fail-CAN})^4 = (p_i^{fail-CAN})^4 \quad (11)$$

When $\lambda = 50$, respectively, compare the failure probability based on CAN bus and FlexRay bus in steer-by-wire system. The results are shown in Table I. CAN-bus baud rate is 250Kbps, and increase the number of frame and the bus load. FlexRay bus baud rate is 10Mbit/s, $C_i = 17\mu s$.

TABLE I. SYSTEM FAILURE PROBABILITY COMPARISON

CAN Bus		FlexRay Bus		
Load Rate	Reliability	One-channel $\beta=1$ Reliability	two-channel $\beta=2$ Reliability	Dual-channel $\beta=4$, dual message redundant reliability
12.8%	1.384×10^{-24}	5.211×10^{-13}	2.716×10^{-25}	7.374×10^{-50}
38.4%	6.691×10^{-18}			
51.2%	6.862×10^{-13}			
64%	4.912×10^{-9}			

It's easy to see that: using CAN bus network system, the message response time, with the increasing of the number of high-priority messages, load rate, the message delay are gradually increasing, and the system's reliability is getting

worse. The use of the FlexRay bus, the network reliability of the system does not increase with the change of bus bandwidth utilization. For the single-channel FlexRay bus system, the reliability should be less than the low-load rate of CAN bus system. This is because the low-load rate of CAN bus system, the message delay is very small, when the bus error occurs, the message can be re-sent immediately after the error frame, so the single message frame loss probability is very small. In the FlexRay bus system without message redundancy, when an error occurs, the cycle message is discarded, and waits until the next cycle will be able to be sent, so the probability of message transmission in FlexRay bus system exceeding the maximum allowed range will be increased significantly. However, when using dual-channel FlexRay bus mechanism, the addition of redundant units, will enhance the reliability of FlexRay bus. In addition, FlexRay bus can also use data redundancy in a cycle, which also led to further improve the reliability of FlexRay bus, relatively speaking, if CAN-bus also use data redundancy, that is, reducing the message transfer cycle, will increase the network load, but reduces the reliability of the bus.

IV. EXPERIMENTAL VERIFICATION

Figure 1. Steer-by-wire system

As shown in Figure 1, a Steer-by-wire experimental platform is built based on FlexRay, which is composed of the steering wheel system, steering system, and the control system. The steering wheel system is used to pass the driver's steering intention to the front wheels controller FW_ECU by the FlexRay bus, and in accordance with steering algorithm to implement steering; the same time, the steering wheel according to the implementation results, provides the driver a sense of the appropriate road feel information. Steering system is used to the implementation of steering, send the implementation result by the FlexRay bus back to the steering wheel controller HW_ECU, in order to provide road feel. Controller system is mainly for sensor data collection and transmission of data by the FlexRay bus, when the transmission destination node receiving data, according to certain algorithms to do data processing, output the calculation results.

As shown in Figure 2, it is the change of the steering wheel angle and the road feel current in the 40km / h speed. It shows that road feel current follow well with front-wheel angle.

Figure 2. The change of the steering wheel angle and the road feel current in the 40km / h speed.

Figure 3. Road feel current following with the steering wheel angle

In figure 3, curves were road feel current changes when the speed is 40km / h, 80km / h, 100km / h. It shows that the system can simulate well the road feel information.

Figure 4. Gaussian noise injection

Figure 5. System performance under the Gaussian noise 0.75V

As shown in figure 4, a Gaussian noise generator is directly inserted into the FlexRay network. The injection point is in one of the ends of the bus, and the amplitude of the Gaussian noise changes in 100mv~1.5v. The figure 5 shows the test result when the system was added 0.75V Gaussian noise and worked

in single-channel FlexRay bus, about 22.7s later, the bus was out of sync, and the steering system stopped working. If the FlexRay working in dual channel, the noise only interfaced the A-channel, didn't produce any effect on other performances except the reliability. The test result is shown in Figure 5.

Figure 6. System performance in dual-channel

V. CONCLUSIONS

The paper analyzed the performance of real-time and reliability of the promising FlexRay bus and currently the most widely used CAN bus in theory; and applied the FlexRay bus in a distributed steer-by-wire system to further verified FlexRay bus Strong real-time and high reliability. As a combination of high-speed, deterministic communication time, dual-channel redundancy and flexible topology and other outstanding features of a bus, FlexRay bus will be more suitable for high-speed, large capacity, strong and highly reliable real-time field bus communication networks; It will become the future mainstream technology to replace the CAN field bus control system, will become the development of industrial automation field bus technology, but also could be the new field bus adopted in the future smart grid condition monitoring, energy information transmission, power grid operation and integrated management system.

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