Electrical Power and Energy Systems 57 (2014) 335–349

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A switchable high-speed fiber-optic ring net topology and its method of high-performance synchronization for large-capacity power electronics system

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ARTICLE INFO

Article history:
Received 18 April 2012
Received in revised form 3 December 2013
Accepted 10 December 2013

Keywords:
Power electronics
Distributed control
High-speed fiber-optic ring net
Switchable topology
Sequence observer
Synchronization

ABSTRACT

With the particularity in the structures of large-capacity power electronics converter devices, the high-speed serial fiber-optic ring net communication control mode has gradually superseded the conventional centralized control mode. However, this fiber-optic ring net cannot accurately synchronize all the nodes in the system easily due to its own network delay and data retransmission, and even the net requires a more complex communication protocol for its operation. To solve these problems, this paper has conducted an investigation into the proposed switchable high-speed fiber-optic ring net, made a simple and feasible communication protocol and presented a method of high-performance synchronization based on the sequence observer. The synchronization method can be used to achieve the synchronization accuracy within 8 ns, thus overcoming the low accuracy and the accumulation of delay errors that exist in the current synchronization methods. As a result, the accurate synchronization of the whole system has been fulfilled. Finally, The results obtained from the data communication and synchronization performance experiments and the system's trial run have verified the correctness, feasibility and superiority both the developed communication protocol and the proposed synchronization method.

1. Introduction

With the development of social economy, more and more capacity is needed to satisfy the demands of the modern power electronics converter systems (PECS), and the high-capacity PECS based on a combination of multiple standard module units or the multiphase-and-multilevel topology has been developed and applied more and more extensively. For conventional small and moderate-capacity power electronic converter devices, with their compact and centralized topology and hardware architecture, the centralized control method is a simple, reliable and practical one. However, for the large-capacity power electronics converter devices, the conventional centralized control method will be challenged by the complex topology of multiphase and multilevel or series–parallel connection as well as by the large-dimension space distribution [1]. As the conventional centralized control structure has lots of point-to-point communication, such problems as low flexibility, poor reliability, uneasy maintainability, long development cycle, and difficult reconfiguration will appear, so that it is difficult to meet the requirements of high reliability, flexibility, simplicity, easy maintenance and reconfiguration of the modern large-capacity PECS. With the advent of power electronics building blocks (PEBB), the conventional centralized control mode tends to be replaced by the distributed control network topology and control mode [2–5] in the high-capacity PECS.

Because large-capacity power electronics devices have distribution characteristics which are apparent in circuit structure, space layout and control function, the distributed control methods will be able to realize the standardization and modulation of the whole converter devices from modules to subsystems which are pluggable, thus improving the redundancy and reliability of the systems. High-speed serial optical fiber communication is a critical technique in performing the complex distributed control, which can fulfill an exchange of all the real-time and non-real-time control data between the master controller and each slave controller (for instance, duty ratio, real-time feedback data, fault states of power devices and operation of the system) so as to completely solve the problems of too many point-to-point control connections and difficult maintenance for the centralized control technology. At present, a lot of Refs. [6–17] have been found to make an extensive study of the high-speed serial fiber-optic communication network topology. For example, the module controller proposed in [6] can perform the inner loop control, and the communication between

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0142-0615/$ - see front matter
http://dx.doi.org/10.1016/j.ijepes.2013.12.012

the outer loop master controller and the module controller can be carried out by means of a single fiber-optic link with 2.5 megabit per second (Mbps). Another high-speed fiber-optic communication network topology, Power Electronics System Network (PESNet), is presented in [7,8], with the rate of communication up to 125Mbps. The PESNet communication network topology is further developed in [9–11], which present a distributed, open control architecture consisting of system layer, application layer, and hardware management layer. The main defects in the single fiber-optic ring net topology are that the whole serial fiber-optic communication ring net is affected by a possible failure in any data channel of the network, and even requires a more complex communication protocol. Aimed at these problems, a dual ring PESNet (DRPESNet) topology is presented in [12], The topology can improve the redundancy and reliability of the communication system, but it will lead to a great increase in cost and a dramatic waste of resources as far as the system is concerned.

The distributed large-capacity PECS with the high-speed fiber-optic ring network topology structure has advantages of simplicity, high flexibility and easy reconfiguration, but the inherent network transmission delay existing in the topology and the retransmission of communication data and command information through each slave node make it difficult for all the nodes to operate synchronously. Besides, the operation of the system requires a more complex communication protocol. Therefore, the simplification of communication protocol and solution to the synchronization of the system have become critical techniques of the high-speed serial fiber-optic ring network topology.

The synchronization methods have been discussed widely in [7–26]. A synchronization method based on PESNet fiber-optic ring net has been analyzed in [7–10], with the synchronization accuracy of 40–80 ns. A communication network topology based on the data source switched by hard-switch is proposed in [17], and the synchronization delay between two nodes is reported to be 60 ns. All the delays between nodes must be predicted and preset in the system configuration by these synchronization methods. But in fact, the delay of data passing through each node are variable. Consequently, some errors in the delay setting will lead the whole system to low accuracy of synchronization. As for the existing errors, a time-stamping-based synchronization method is proposed for a cascaded ring topology in [18–20]. This method can accurately calculate the delay of a message passing through each node. The accuracy of synchronization between two nodes is found to reach 10 ns. But while the nodes increase in number, the accuracy will decreases because of the accumulation of errors caused by signal jitter. Nevertheless, this method is the best of all the ones that refer to synchronization performance mentioned in the present literatures.

To sum up, there are a couple of problems with the existing methods for synchronization in the high-speed serial fiber-optic ring net, such as the system's low synchronization accuracy and the accumulation of errors from synchronization delay due to the retransmission of commands and data as well as the nonsynchronous clock relationship between nodes. To deal with these problems, a switchable high-speed fiber optic ring net topology is present in [27] by the research group of which the author is a member. This paper, with the topology as an object of study, has analyzed the operating mode of the topology, established two synchronous delay models for the topology, developed a simple and feasible communication protocol and further proposed a high-performance synchronization method based on the sequence observer. The method adopts the high-speed processing clock with 250 MHz to sample and process the high-speed serial sequence in the 125 Mb/s communication net with the help of the sequence observer, and then uses the high-speed clock with 125 MHz to generate the synchronization flag signals according to the detected synchronization command sequences and the delay between nodes in the network. Because of the high-speed clock with 125 MHz used in the sequence observer, the maximum drift error of clock phase is 8 ns after digital processing. As the synchronous commands and control data of the system need not be retransmitted and decoded through any node, the accumulation of system signal jitters and drift errors can be solved. Thus, the synchronization accuracy between any two nodes in the whole network can be kept within 8 ns to achieve the accurate synchronization of the whole system. The experiment results prove the communication protocol and the high-performance synchronization method to be correct and feasible.

This paper is organized into seven sections. Section 2 is concerned with the composition and operating principle of the distributed control structure of the large-capacity power electronic converter system based on high-speed fiber optic ring network communication. Section 3 deals with the operating mode and synchronization delay of the conventional high-speed fiber-optic ring net and points out the problems with the conventional synchronization method. Section 4 makes an analysis of the switchable high-speed fiber-optic ring net topology mentioned in [27] and develops a simple and feasible communication protocol according to the characteristics of the topology. Section 5 introduces the synchronization delay model in using the synchronization method of conventional serialized/deserialized conversion in the switchable high-speed fiber-optic ring net topology and refers to the advantages and disadvantages of the synchronization method. Section 6 provides a high-performance synchronization method based on the sequence observer for solving the problems in Section 5, establishes its synchronization delay model and describes its implementation in detail. Section 7 are concerned with experiments and results. Section 8 makes a summary of what has been done and achieved in the paper.

2. The distributed control structure of the large-capacity power electronic converter system based on high-speed fiber optic ring network communication

The large-capacity power electronic converter device has such apparent distribution characteristics in circuit structure, space layout and control function that it will need the distributed control technologies which are real-time and sophisticated. What is shown in Fig. 1 is the topology of the 20 MW fifteen-phase propulsion converter for ship propulsion. It is characterized by standardization, modularization and distributivity in circuit structure and function. Moreover, the power capacity is so large that the distribution characteristics of the module units are obvious in space layout. Practically, the space which the entire circuit occupies is about 21 cubic meters [29].

For the 20 MW fifteen-phase propulsion converter shown as Fig. 1, a switchable high-speed fiber-optic ring net topology is presented in [27], as shown in Fig. 2. The control structure for the topology consists of a master controller and eighteen slave controllers. The output phase unit and brake unit of each inverter are incorporated into a slave node. There are eighteen slave nodes altogether in the system. Each slave node is fitted with a slave controller. The whole control network forms a ring net with the rate of communication as 125 Mb/s through a single optical fiber. The PECL fiber-optic transceivers with the rate of 155 Mb/s suiting the industrial standard are used in the fiber-optic transceiver module to meet the requirements of communication rate of 125 Mb/s.

The whole control network is divided into two operating modes: the bus-like communication operating mode and the feedback acknowledgment operating mode. The field-bus-like communication mainly refers to the way in which the master controller