Implementation of High Speed Control Network with Fail-Safe Control and Communication Cable Redundancy in Modular Multilevel Converter

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Abstract
A simple and fast internal communication system (ring communication network) had been proposed to simplify the wiring system in complex multilevel converter, such as Modular Multilevel Converter (MMC). This paper will present a fail-safe control and communication system for a MMC. A fail-safe control is demanded to ensure MMC continue operating without interruption when a malfunction power switch is detected. On the other hand, if a section of the communication cable breaks, the data transfer will be interrupted. Hence, a communication cable redundancy protocol must be enhanced in a ring control interface to increase the reliability of the MMC.

Introduction
Modular Multilevel Converter (MMC) is gaining popularity with its modular and simple Power Electronic Building Block (PEBB) design. The basic structure and principal of MMC is fully described in [1] and [2]. A PEBB is a fully integrated device with basic components such as power switches, gate drivers, and measurement sensors [3], [4]. Power switches may integrate in different configurations for different applications. Among all, half-bridge configuration is normally used in dc-ac conversion. Whereas, H-bridge configuration which support bidirectional current flows are suitable for ac-ac conversion and motor drive applications.

By reviewing the literatures, we found that the number of PEBBs per phase leg in a MMC may vary from less than ten units [5], [6] to more than hundred units [7]. Siemens had commercialized a MMC with more than 200 units of PEBBs per phase in HVDC application [8]. So the complexity in the conventional star control interface between the controller and the gate drivers will definitely increase proportionally to the increase number of PEBBs in the MMC. A number of wires which are used for switching commands, sensor measurements and fault status will increase drastically for a complex system [9]. As a result, the noise problem may also increase. Therefore a ring control network is preferable in MMC for data communication [10].

A set of basic communication requirements for MMC had been given in [11]. Phase based parallel control ring is preferable to handle a large number of PEBBs in MMC. The one ring per phase monitoring and control will ensure simultaneous operation of all the PEBBs within one phase leg and between each phase.

Fig. 1 outlines a phase based ring communication network in MMC. MMC Master Controller is responsible for executing the MMC control and modulation schemes. Then, the Master Communication Controller (MCC) will pack the generated switching commands into different data packets and scheduling transmission. Each PEBB will own an identical Slave Communication Controller (SCC) to extract the switching commands. Conversely, all sensor measurements and status...
of each PEBB will be packed and transmitted from SCC to MCC. High speed optical fiber cable, which immune electromagnetic noise, is recommended to use as the communication cable in MMC. In this way a series data transmission will take place for information exchange between the MMC master controller and all the PEBBs.

A failure of a MMC may have its root from one or more malfunction power switches on PEBBs. In general, a power switch may suffer from short-circuit fault due to current or voltage stress. In addition, the failure of a gate drive amplifier to trigger the corresponding power switch will result in an open-circuit fault [12]. A reliable MMC should be capable to first detect and identify these fault occurrences. Then, a high-speed bypass switch must be triggered to short out the defective PEBB [8]. Subsequently, redundant PEBBs can be configured for replacement [13] or the system can operate degraded [14].

On the other hand, a broken communication ring will terminate all the data communication between the master controller and PEBBs; this may consequently cause MMC failure. Therefore, communication cable redundancy is essential to increase the reliability of the ring. Data packets will be circulated in both directions (clockwise and counter clockwise) throughout the ring. This is mainly to compensate a SCC failure or a section of optical fiber fault. As long as the defective PEBB can be isolated immediately, the ring may be saved from having fault.

**High Availability MMC**

A MMC may contain a large number of power switches. Each power switch may fail and cause erroneous operation of the MMC. To prevent the failure propagation, fault detection and isolation are the initial steps.

A malfunction power device can be easily identified by monitoring its gate signal and the resultant voltage across the switch. Irrespective to the triggering of a gate signal, a short circuit power switch will always keep approximately zero voltage (the switch turn-on voltage) across it. Whereas, the voltage across an open circuit power switch will remain non-zero value continuously. Most of the gate driver circuits have included power device failure detection. Therefore no additional hardware sensors are necessary.
are required. The gate driver will then softly turn-off the faulty power switch based on its on-board protection scheme. Normally both the upper and lower power switches will be turned off under fault condition. As a result, the MMC operation will be interrupted. An additional high speed bypass switch can be installed parallel with the PEBB to effectively bypass the PEBB when fault occur [8], [15]. With this fail-safe mode, MMC may operate continuously without interruption. The failure of the PEBB is reported to the master controller to kick start the backup system. Fig. 2 draws two potential configurations of a PEBB (half-bridge or h-bridge) integrated together with a bypass switch.

![Functional block diagram of a Slave Communication Controller couples with a PEBB which can be configured into half-bridge or h-bridge.](image)

**Fail-Safe Mode PEBB Control**

In ring control network, each SCC will contain a FPGA. Two set of logics, namely Control Network Communication Logic and Application Data Processing Logic will be configured into the FPGA. The control network communication logic is responsible for data packaging and provides a finely tuned clock for local application. It is usually developed as an IP (Intellectual Property) Core by industrial network manufactures such as EtherCAT IP Core from Beckhoff [16]. Whereas the Application Data Processing Logic (ADPL) is designed to organize the measurement data and reproduce the switching command for the PEBB [11]. A fail-safe mode PEBB control scheme can then be synthesized as part of the ADPL.

An operating SCC may transition from Normal Operation Mode (NOM) into Fail-Safe Operation Mode (FSOM) in two fault conditions, i.e. PEBB fault or SCC error (Fig. 3). When the gate driver had detected a fault on a power device, it will trigger PEBB error signal (PEBB_err). Besides, in case of communication error found on SCC, the SCC error signal (SCC_Err) will be asserted. For example, if the SCC losses both link on Port 0 and Port 1, the SCC_Err must be pulled high and transfer into FSOM. In fail-safe mode, the bypass power switch (SBP) in Fig. 2) will be turned on immediately. Conversely, other power switches on the PEBB should be turn-off. Fault indication status bits will be asserted and feedback to the master controller. However, SCC

![Fail-Safe Mode PEBB Control Finite State Machine](image)
failure may not be reported in case of link error. Master Communication Controller may recognize the failure SCC from checking the incoming data packets (sensing variables). Missing data packets from a SCC continuously show the communication has been lost. In addition, the link active status bits on neighboring SCCs may help to source out the faulty SCC accurately. This fail-safe mode will last until the next scheduled maintenance service where the faulty devices (SCC or PEBB) are replaced physically.

**Redundant PEBB**

The simple way for a typical fault tolerant method is to duplicate some PEBBs for immediate replacement. Some redundant PEBBs had been proposed to be inserted in each arm to improve the reliability of the converter [13]. These redundant PEBBs will not contribute to produce higher number of voltage level. They are mainly used to ensure the converter remains in normal operation even if one or more PEBBs fail. MMC master controller will instruct the operation of these redundant PEBBs once it receives the PEBB fault indication status bit from SCC.

Although adding redundant PEBBs may increase the cost and size of the MMC, but there are still some proven advantages to employ some of them. First of all, the redundant PEBBs help to offloading other PEBBs. Not all the PEBBs on each arm will be used at every instant, but all of them will be used over a fundamental period based on the voltage balancing algorithm. Therefore, the average switching frequency of a PEBB will be further reduced. In addition these redundant PEBBs help to avoid continuously switching in the same PEBB. This may improve the loss distribution and thermal management in all the PEBBs. Besides, the redundant PEBBs also lower the second harmonics current circulating in the arms of the converter [13]. The required number of redundant PEBBs normally depends on the level of reliability and the acceptable project cost.

**Communication Cable Redundancy**

In the conventional control interface, power switches gating signals and all measurement signals are connected directly from or to the master controller. This control interface is named as star topology where the master controller located as the heart of the network. It provides significant higher degree of redundancy compare to ring control network. One or more signal links failure or devices failure (sensors or power switches) in star topology do not affect the remaining part of the network. Thus, the data communication must be reinforced when replacing the star control network with a ring topology. A link breakage or an SCC failure in ring network may cause the master controller loss communication with other PEBB located after the failure point. Therefore, a duplicate communication path is highly recommended to tolerate with single link or SCC failure in the proposed ring control MMC.

It is shown that EtherCAT performance can fulfill the requirements of minimum cycle time [11] and synchronization jitter [17] as a control network in MMC. Therefore, it is selected as the communication protocol in this application. EtherCAT Master Controller and EtherCAT Slave Controller will be implemented as the control network communication logic inside MCC and SCC respectively.

EtherCAT employs the Ethernet MAC (Media Access Control) frame structure [18]. Each outgoing Ethernet frame will first be duplicated and then forwarded out simultaneously via the MCC ports. One frame will depart via primary port (Port_P), passed through all SCCs and get back through secondary port (Port_S) as illustrated in Fig. 1. At the same time, the identical telegram will be transmitted from Port_S and forwarded through the ring in the opposite directions. Both frames must eventually return back to the EtherCAT Master Controller as a kind of response frame. EtherCAT Master Controller only supports single fault tolerant, in case of a SCC failure or a single optical fiber fault, the ring network will transform into dual line topology. All others SCC are still accessible by the master controller.
Basically, a unit of SCC reserves two ports (Port_0 and Port_1). Each of them holds a pair of Receiver (Rx) and Transmitter (Tx) interfaces. When the data frame entering Port_0, it will be routed to EtherCAT Processing Unit (EPU). EPU will extract or insert data from or into the frame rapidly and send the frame to the neighbor SCC. The telegram travels through EPU is called “Processing Path”. In contrast, a duplicate telegram will enter a SCC via Port_1 receiver. This frame will be directly sent to Port_0 transmitter without any processing. This forwarding path is mainly designed as a redundant path. Fig. 4 (a) draws the processing and forwarding path within three SCCs. Assume SCC_j, SCC_p, and SCC_k are part of the complete ring shown in Fig. 1.

When a fault occur in SCC_j (Fig. 4 (b)), the SCC located just before the fault occurrence (SCC_i) will automatically short-circuit the Rx and Tx interface in Port_1. A returned path is created for directing the frame traveling back to the master controller. On the other hand, the SCC situated right after the fault occurrence (SCC_k) will close Port_0. The duplicated telegram will now be diverted into EPU for processing. After processing, the telegram will be transmitted to the next SCC following the processing path until it finally returns to the master controller. In case of communication cable fault occurs between SCC_j and SCC_k, both frames will be transmitted in the same way. Port_1 in SCC_j is closed to send back the data frame while Port_0 of SCC_k is short circuit to transfer the duplicated frame into the processing path (Fig. 4 (c)). So the data exchange between the master controller and each PEBB is maintained.

![Fig. 4: EtherCAT Communication Cable Redundancy](image)

(a) normal operation, (b) SCC fault, (c) link fault
Experimental Results

An experiment has been set up to evaluate the proposed fail-safe mode PEBB control and the EtherCAT communication cable redundancy. Fig. 5 draws the simple control ring with a MCC and three units of SCC couple with PEBB. The MCC currently consists of an Industrial PC (IPC) from National Instruments couple with a Real-Time Ethernet Port multiplier (CU2508). CU2508 is demanded to support the combination of cable redundancy and Distributed Clock (DC) for synchronization management [16]. TwinCAT network card driver is installed in the IPC to support the redundancy as a software solution. On the other hand, the Piggyback Controller Board FB1130 is integrated as the SCC with EtherCAT Slave Controller IP Core downloaded into its onboard Xilinx Spartan XC3S1200E FPGA. Ethernet cables are used as the communication cable to form the ring. Half-bridge power module will be used in parallel with a high speed bypass power switch (SBP). Assume that the PWM signals to the upper switches (S1) of each PEBB are the same with 10 kHz switching frequency. The lower switches (S2) always complement to the upper switches. Two investigations will be carried out. Firstly a test will be focused in SCC to examine the fail-safe mode PEBB controller under Power switch fault and SCC fault. Then a system level test will be performed to monitor the EtherCAT communication behavior during a SCC fault and a section of Ethernet cable fault.

Experiment 1: Fail-Safe Mode PEBB Control

Fig. 6 shows the experiment result during Normal Operation Mode. NOM signal is HIGH with no errors detected. When the synchronization (Sync) signal asserted, a PWM signal will be reproduced [11] and triggered S1. S2 will also receive the complementary gating signal at the same time. To demonstrate a power switch fault is detected, PEBB_ERR signal is pulled HIGH as shown in Fig. 7. The operating mode is now transition to Fail-Safe Operation Mode (FSOM arises). Despite of the PWM signal, the S1 and S2 are both pulled low with the assumption that the gate driver will in charge to perform its soft turn-off protection scheme. Fig. 8 shows the zoom in view of Fig. 7, where the bypass switch (S_BP) is trigger ON within 20 ns after the PEBB_ERR signal arises.

Fig. 5: Experiment set up for ring communication control with three units of Slave Communication Controller (SCC) couple with PEBB.

Fig. 6: SCC reproduces PWM signal periodically for half-bridge power module during Normal Operation Mode (NOM) (40 µs/div)
With communication cable redundancy, SCC should continue to produce the correspondence gating signals to its PEBB even if it lost one of the links. Fig. 9 and Fig. 10 prove that SCC continues to operate in NOM state when one of the Ethernet cable is disconnected. However when SCC losses both links it may define as SCC’s fault. Assume that a SCC has lost a link, namely Link0. Unfortunately after some time, it lost the second link (Link1) as shown in Fig. 11. When the SCC detected it lost both of the links, Links_ERR signal is pulled HIGH within 20 ns (Fig. 12). Since communication cable fault is not as critical as power switch fault; the PEBB should complete the executing PWM cycle. The SCC_ERR signal will arise on the next assertion of Sync signal to bring the state machine into Fail-Safe Operation Mode (FSOM). The zoom-in view in Fig. 13 shows that the S_BP is turned on within 20 ns after the Sync signal asserted.

![Fig. 7: Power switch fault (PEBB_ERR) had been detected (40 µs/div)](image7)

![Fig. 8: Zoom in view of Fig. 7 (20 ns/div)](image8)

![Fig. 9: Disconnect Ethernet cable from Port 0 to demonstrate link 0 is lost on a SCC (40 µs/div).](image9)

![Fig. 10: Disconnect Ethernet cable from Port 1 to demonstrate link 1 is lost on a SCC (40 µs/div)](image10)
Experiment 2: EtherCAT Communication Cable Redundancy

Two fault scenarios (SCC fault and link fault) will be created to evaluate the EtherCAT communication cable redundancy. Fig. 14 captures three PEBBs operate in NOM state where Port_0 and Port_1 in each SCC are healthy (PEBB*_Link0/1_Lost are tied to LOW). In order to demonstrate SCC failure, Ethernet cables on Port_0 and Port_1 of PEBB2 will be disconnected to break the ring. Fig. 15 shows the PEBB2_Link0_Lost and PEBB2_Link1_Lost assert and the bypass power switch (S_BP) is turned on to short out PEBB2. Although the control ring is broken, PEBB1 and PEBB3 continue receive switching pattern without any interruption. Conversely the link lost status update from PEBB1 (PEBB1_Link1_Lost) and PEBB3 (PEBB3_Link0_Lost) may notify the MCC regarding the failure occurred in PEBB2’s SCC.

Fig. 13: Links_ERR arises when both link 0 and link 1 are lost on a SCC (40 µs/div)

Fig. 14: All the PEBBs operated in normal operating mode (40 µs/div)
Fig. 16 demonstrates the communication cable fault happens in between PEBB2 and PEBB3. When the ring breaks (PEBB2_Link1_Lost and PEBB3_Link0_Lost arise), all the PEBBs continue to operate normally.

Fig. 16: A section of communication cable failure in between PEBB2 and PEBB3 (40 µs/div)

Fig. 15: PEBB2’s Slave Communication Controller (SCC) failure (40 µs/div)

Conclusion

Modular Multilevel Converter (MMC) always consists of a number of Power Electronic Building Block (PEBB). PEBB is an integrated device with basic components such as power switches and gate driver. By using the conventional control interface, each PEBB may require a few wires to receive and transmit the switching commands and sensing measurements from/to the master controller. A ring control network will reduce the complexity in wiring for MMC. In ring topology, switching commands and sensing measurements will be packed in data frame and transmitted to/from PEBB. So each PEBB will couple with a Slave Communication Controller (SCC) which has an FPGA for handling the data exchange.

This paper has described a fail-safe control for MMC. A high speed PEBB bypass control scheme can then be embedded inside the FPGA. When the SCC receives a power device failure signal, it will quickly bypass the defective PEBB within 20 ns. The PEBB fault status will then be packed and sent to the master controller on the subsequent telegram. Once the master controller receives the fault status, backup solution will be initiated. With redundant PEBBs in the ring, the MMC may continue to operate in a fail-safe mode without interruption.

Communication cable redundancy is highly demanded in ring control interface for a MMC. This protocol reserves a backup ring for data communication. In case of a single SCC fault or a section of link failure, SCCs located after the failure point are still accessible by the master controller through the redundant ring. EtherCAT cable redundancy protocol has been reviewed and evaluated. The results prove that EtherCAT manages to tolerate a single fault.
References


