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A Fault Tolerant Inverter with SCADA Communication Capability for Photovoltaic Applications

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Abstract

In most recent sensitive industrial application of inverters, reliability is a crucial issue to care. Due to development of SCADA system and variety of renewable energy in electrical grids that are mostly scattered in distance, it is necessary to have ability to communicate within industrial control systems and be allowable to be aware of a system condition every moment. Inverters are the core part of the grid-tied PV system. In traditional inverters, just local monitoring of electrical parameters or inverter's condition was available but nowadays operation condition of inverters and more information like status, quantity of input, output, and electrical parameters like voltage, current, power or occurred faults, are available using developed industrial communication protocols. In instructed fault tolerated inverter of this article, a fault is manually simulated and applied in one of the switches. The result is that the damaged element was replaced with a redundant reserved switch and it was identified remotely by control center using IEC60870-5-101. It gives an extra feature to prepare an ideal decision to repair or maintain of that damaged switch. Validation of communication between inverter ad control server is lasted using Fink-WinPP101 software using IEC 60870-5-101 protocol. The proposed strategy is emulated on the 7-level inverter and the tolerance ability and faulty condition report with time tag is proved by using protocol tester software Fink-WinPP101. Experimental and simulation results prove accuracy of the proposed system.

Keywords: Inverter; SCADA; Control center; Fault tolerant

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1. Introduction

Solar energy is converted from sunlight into either directly using photovoltaics (PV), indirectly using concentrated solar power, or a combination. Inverters are one of the power electronic components that their main application in power systems are to convert direct current (DC) to alternative current (AC). Fault issues is one of the most problems that experts should care about in operation, repair and maintain of inverters. Supervisory control and data acquisition (SCADA) is a control system architecture that is developed for transmission of information within a control center and a remote equipment. In instructed fault tolerated inverter of this paper, if a fault occurred in switches the damaged element can be identified remotely by control center using IEC60870-5-101 and prepare an ideal condition for repair or maintaining of that validation of communication between inverter and control server is lasted using Fink-WinPP101

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software using IEC 60870-5-101 protocol. In this section, solar energy, faults in inverters, SCADA, communication proptocols is discussed. In section 2, the proposed system is presented. Simulation and experimental results verifications are discussed in section 3. Finally, the conclusions are stated in section 4.

1.1. Solar energy in electrical grid

Solar energy is the conversion of energy from sunlight into electricity, either directly using photovoltaics (PV), indirectly using concentrated solar power, or a combination. Totally, Photovoltaic cells convert light into an electric current using the photovoltaic effect. It is mostly used in scattered micro grids and is developed is recent decade. Due to the dispersion of these micro grids, there is necessary to have a control center to manage detailed condition of these kind of grids. One of the critical equipment of the solar micro grids is the inverters. Because if abnormal condition occurs to the inverters, the stability of the grid will be disrupted and it may cause huge damages to other equipments of the grid.

1.2. Faults in inverters

In overall definition, inverters are one of the power electronic components that their main application in power systems are to convert direct current (DC) to alternative current (AC). Inverter takes a direct input voltage and turns it to a symmetrical, alternative voltage as an output that has specified amplitude and frequency. While the inverter's output is in one phase, it will appear as a 120V in 60Hz, 220V in 50Hz or 115V in 400Hz frequency. While the inverter's output is in three phases, it will appear as a 220/380V in 50Hz, 120/208V in 60Hz or 115/200V in 400Hz frequency.

The multilevel inverters are power electronic devices that produces various voltage and current waveform in output with using some DC voltage sources and power switches. The desired output voltage is achieved by switching between sources for several modes with different topologies. Most important applications of multilevel inverters are in flexible ac transmission system [1], active filters [2], electric drives [3] and renewable energy systems [4]. The most renowned and basic multilevel inverters are: “Cascaded H-Bridge (CHB), Flying Capacitor (FC) and Neutral Point Clamped (NPC)”[5].

Fault issues is one of the most problems that experts should care about in operation, repair and maintain of inverters. There is no general solution to cover or prevent faults in different circuits, but the solutions provided in several new papers can improve inverter's operation in fault conditions.

Fault may occur in any of the switch, leg, module or system level of an inverter that it has different methods to detect in order to the position. In this paper, the goal is to find a proper way to send the fault alert to control center immediately in order to prevent other equipment's damage

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1.3. SCADA

Supervisory control and data acquisition (SCADA) is a control system architecture that is developed for transmission of information within a control center and a remote equipment. Using SCADA systems will provide more reliability and accuracy in controlling and monitoring the devices. It is suitably used for monitoring and collecting some information of remote equipment installed in solar grids in order to gather data of these devices condition such as inverter’s switches to track the healthy statement of the equipment and to be aware if any abnormal or faulty conditions.

1.4. Communication protocol

This section talks about communication structures within inverter and SCADA servers in order to monitor and control the system. This remote controlling method will immediately report the event of fault occurred in system for requesting the proper actions to clear it before damaging other equipment. To do that, first we introduce SCADA and its communication protocols to understand the process.

One of inseparable part of the developed inverters are their connection to a common network consist of different industrial automation equipment and SCADA servers. As we discussed before, we can track quantity of voltage and current, heat and losses in circuit, performance, input, output power, energy usage, healthy state of switches and other relative parameters at every moment with a high speed and accuracy.

1.4.1. IEC 60870

In 1988 to 2003, IEC 60870 appeared according to other existed standards in SCADA communication protocols. This protocol consists of several parts which the 5th part is about its communication protocol and is divided to 5 parts as follows: [6]

5-1: transmission frame of formats

5-2: link transmission procedures

5-3: application service data unit
5-4: application information elements
5-5: application functions

In IEC60870-5 two methods are described for data transmission that the difference is their interface. The first method is described in IEC60870-5-101 and uses serial interface that is appropriate for low bandwidth transmission channel [7].

1.4.2. IEC60870-5-101

This standard uses a 3-level architecture that is called EPA. The familiar OSI architecture and its summarized model (EPA). EPA is suitable for such a system that work in a common network. An additional layer is added in EPA that is called user level. User level provides interoperability between different systems.

So, in conclusion, the completed architecture provided for T101 standard has 4 layers containing user process layer, application layer, data link layer and physical layer that can be implemented in RS232 [8] or RS485 [9] serial port as balanced or unbalanced protocol. The data in this standard is transmitted form of a packet that is created in these levels. There is maximum one application service data unit (ASDU) in each packet. (Note that a packet may have no ASDU). One of the important parts of an ASDU is Type ID which has one octet length. An ASDU with incorrect Type ID is not valid anymore [10]. Fig.1 shows ASDU structure of IEC 60870-5-101 protocol.

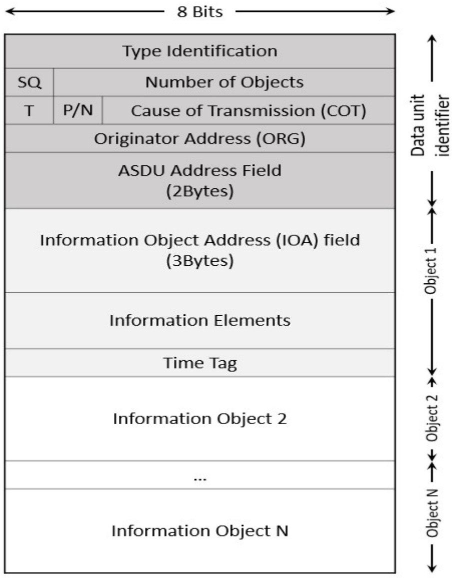

Figure 1 ASDU structure of IEC 60870-5-101 protocol [17].

For example, SCADA systems use Type ID code 31 (Double point information with time tag CP56Time2a) to transmit switch status, or Type ID code 59 (Double command with time tag CP56Time2a) for transmit commands to switches containing time of occurrence, or Type ID code 9 (Measured value, normalized value) for measuring voltage, current, active or reactive power[10]. It is recommended to use the appropriate Type ID code for more compatibility with other systems. In this study, we use standard Type ID code 38 (event of protection equipment with time tag CP56Time2a) to transmit the protective events such as occurring fault in inverters [11]

This standard protocol has several data types to report protective events of faults. Therefore, each power switch of inverter is
supposed as a specific information object of IEC101. In this way, information ans=d status of each switch can be requested by control center. In addition, if a problem occurs in one of the switches, then time, cause and exact position of that can be monitored in SCADA server.

2. Related Studies

In review of some other papers, several features that

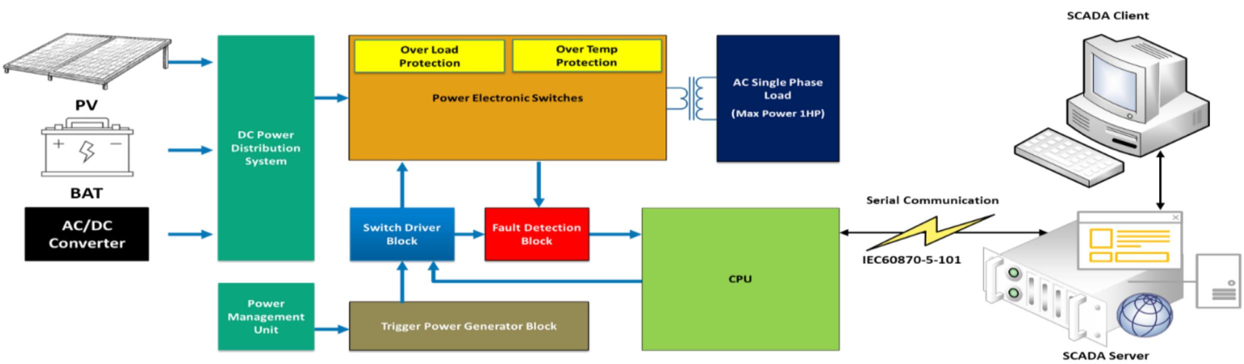

Figure 2 System block diagram

need to be added into SCADA systems can be found. A. M. Grilo et al. identified some features in a SCADA for Monitoring a Critical Infrastructure [12]. M.N. Ashraf et.al shows a new framework of SCADA using LabVIEW for acquising and Managing data. It describes configuration of Remote Terminal Units (RTU) to monitor and transmit real time data over the Intranet[13]. The disadvantage of this idea is using of LABVIEW, because of its unreasonable cost. In [14] a new Fault tolerant control strategy for three-level photovoltaic inverter based on redundant space vectors is proposed. Reference [15] presents novel approach to develop communication system for the SCADA integrated inverter utilizing monitoring and control algorithms via MODBUS TCP/IP protocol over Ethernet. Proposed system in [16] uses Raspberry pi as the controller board and it is enable to remotely collect data using Modbus Protocol.

3.The Proposed System

The designed inverter of this study uses a specific and unique technique to detect several faults such as over voltage faults, over current faults or short/open circuit faults of power switches.

According to fault tolerance ability of the designed multi-level inverter, it can transmit fault report to the upper control center using IEC60870-5-101 communication protocol as it was introduced above. Fig. 2 shows block diagram of the proposed multi-level inverter and communication system.

Central processor of inverter used STM32F103RB ARM Cortex M3 microcontroller and dependent peripherals can manage how to switching and timing operation of switches to be on or off. RS485 serial port used for communication with SCADA server. The speed of communication in half duplex network can be up to 961200bps with SN65HVD75 RS485 transceiver chip. The main sections of this system are power electronic switches, fault detection circuit, and central processor unit (CPU). In power electronic switch used from two simple over load and over temperature protection sensor with related fuse. Comparison of the communication method in this paper and two presented methods in [15-16] is shown in Table I. The communication meyhod in paper has many capabilities (As shown Table 1).

Table 1. Comparison of communication methods

Features	Communication method in this paper	Novel Communication in[15]	IoT based method in [16]
Protocol	IEC60870-5-101	Modbus	Modbus
Data Polling	YES	YES	YES
Event Monitoring	YES	NO	NO
Spontaneous data	YES	NO	NO
SBO Control	YES	NO	NO
Time-Stamp and Time sync	YES	NO	NO
Connection Authorization	NO	NO	NO
Data Class	YES	NO	NO

4. Simulation and Experimental Results

Fig. 3 shows a prototype of constructed inverter for analysis. In faulty conditions as shown in Fig. 4 the procedure of control center is that after received trip or failure reports of every switch, then changing strategy and status of the switches will be reported back to the control center. If the send ASDU had been received correctly, the feedback will be positive. Otherwise, negative feedback will be reported. Negative feedback represents a problem in switches, so a message packet with common structure will be sent to control center immediately using IEC60870-5-101 protocol and RS-485 serial port. This message can be structured considering Fig. 5. The desired response will be sent back from SCADA Master in control center to the user containing the exact part of inverter that has problem and within which activity is occurred.

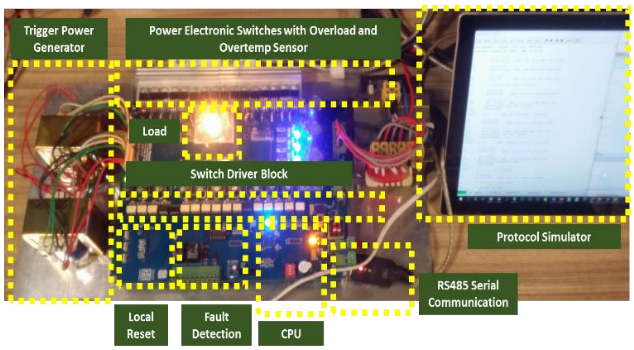

Figure 3 A prototype of constructed inverter for analysis

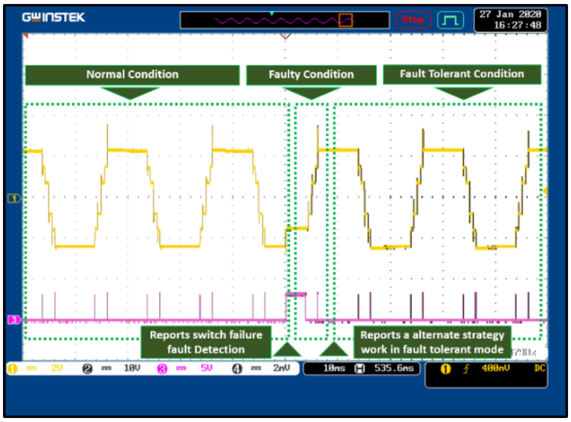

Figure 4 Output waveform of fault tolerant system.

One of the important abilities of T101 is that it can link a time tag to every message packet that shows the exact time of events. Therefore, whenever an event is occurred in system, user is able to check various sequence of events to configure the reason. Below example shows the designed inverter that a fault is forced on it to discover the action and result.

As it is shown in Figs. 5-6 the event is reported to control center immediately from T101 Slave to Master. When information object 2-1-8 of system that represents current of the switch number 2 goes higher that it's limit (the overflow flag is set), the mentioned switch will be damaged and short circuit fault will occur in this case the single point information objects of 2-1-4 turned on and reported as an event. This short circuit fault will be diagnosed immediately in less than half duty cycle and the redundant switch is closing the current loop to provide appropriate potential level at S2 voltage. Therefore, a "Start Protective Event" message will be sent to Master with COT 3 and type ID 39 and user will be aware of the inverter's status. So, the operator can do repair and some preventive actions to compensate the damages and to prevent this kind of events.

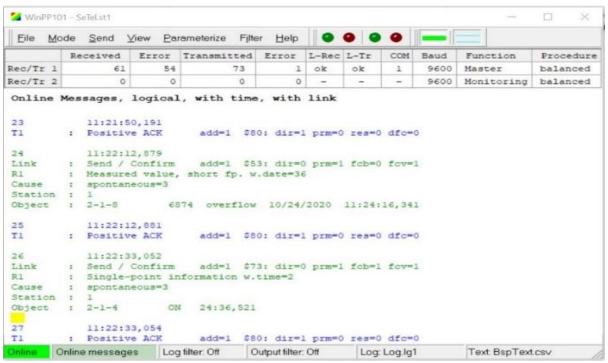

Figure 5 Transmitting Overcurrent event and switch change

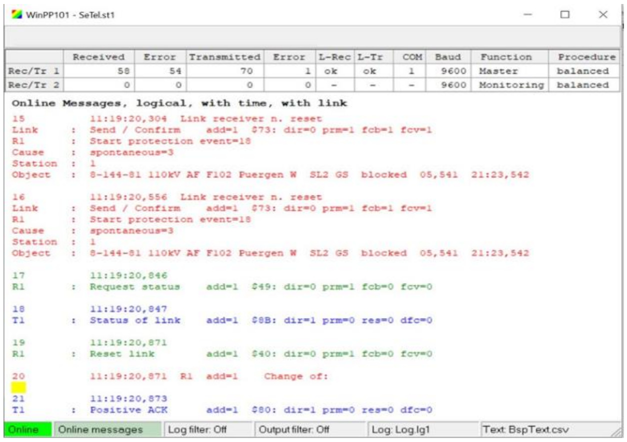

Figure 6 Transmitting start protection event.

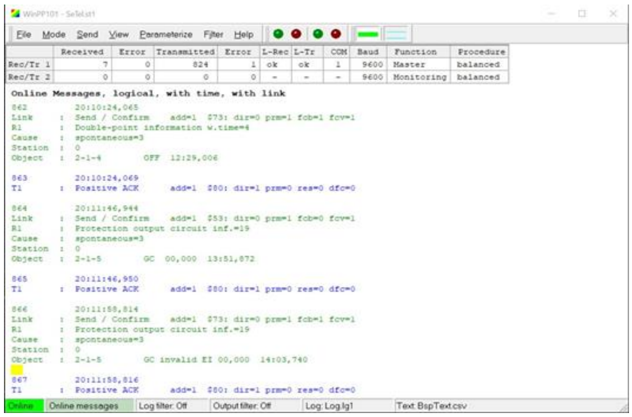

Figure 7 Transmitting a double point binary status using

As shown in Fig. 7 change in switching strategy that is allocated in information object number 2-1-4 with double point type is reported to control center. Double point type tag will use when a binaray status in circuit is highly recommended that reports OFF state with 01, ON state with 10, 00 means indeterminate state and 11 means intermediate state. This kind of additional information is used to prevent mismatch of communication collisions.

5. CONCLUSION

Due to the importance of being aware of the solar grid conditions and its important equipment such as inverters, a multi-level inverter with fault tolerance ability to find a proper way to send the fault alert to control center immediately in order to prevent other equipment's damage is proposed in this paper. A fault condition was manually applied to the instructed inverter. Due to the ability of fault tolerant, the fault on switch S2 was occurred and the redundant switch was replaced. The main feature that is focused in this paper is that the inverter sends this event immediately using IEC60870-5-101 standard protocol with time tag CP56Time2a that accurate in millisecond time stamp. Each switch of the inverter is considered as an information object; therefore, the health status of switches can be requested by the control center. IEC 60870-5-101 Slave has an ability to send all status cyclically by using information object type and COT1 every 20 second to the control center. So, the user in the control center will be aware of all faulty conditions and do recommended actions in order to prevent other equipment damages. The above strategy is emulated on the 7-level inverter designed in this paper and the tolerance ability and faulty condition report with time tag is proved by using protocol tester software Fink-WinPP101.

REFERENCES

1. Sotoodeh, P., Miller, R. D., Design and implementation of an 11-level inverter with FACTS capability for distributed energy systems, IEEE J. Emerg. Sel. Top. Power Electron., 2014, **2**:87-96.
2. Can, E., Novel high multilevel inverters investigated on simulation," Electr. Eng., 2017, **99**: 633-638.
3. Hagiwara, M., Hasegawa, I., Akagi, H., Start-up and low-speed operation of an electric motor driven by a modular multilevel cascade inverter, IEEE Trans. Ind. Appl., 2013, **49**: 1556-1565.
4. Xiao, B., Hang, L., Mei, J., Riley, C., Tolbert, L. M., Ozpineci, B., Modular Cascaded H-Bridge Multilevel PV Inverter with Distributed MPPT for Grid-Connected Applications, IEEE Trans. Ind. Appl., 2015, **51**:1722-1731.
5. Malinowski, M., Gopakumar, K., Rodriguez, J., Perez, M. A., A survey on cascaded multilevel inverters, IEEE Transactions on Industrial Electronics. 2010, **57**: 2197-2206.
6. EN 1991-1-5, Eurocode 1: Actions on structures - Part 1-5: General actions - Actions on structures exposed to fire, Eurocode 1, 2002.
7. Kang, D. J., Robles, R. J., Compartmentalization of protocols in SCADA communication, Int. J. Adv. Sci. Technol., 2018, **8**:27-36.
8. Santos, J. P., RS232, in Tecnologias de Accionamento e Comando 2010/2011, 2010.
9. Frenzel, L. E., RS-485, in Handbook of Serial Communications Interfaces, 2016.
10. Clarke, G., Reynders, D., Wright, E., Practical Modern SCADA Protocols: DNP3, 60870.5 and Related Systems. 2004.
11. Bailey, D., Wright, E., Practical SCADA for Industry, Elsevier Sci., 2003.
12. Grilo, A. M., Chen, J., Diaz, Garrido, M., D., Casaca, A., An integrated WSAN and SCADA system for monitoring a critical infrastructure, IEEE Trans. Ind. Informatics, 2014, **10**:1755-1764.
13. Ashraf, M. N., Bin Khalid, S. A., Ahmed, M. S., Munir, A., Implementation of Intranet-SCADA using LabVIEW based data acquisition and management, in ICC2009 - International Conference of Computing in Engineering, Science and Information, 2009.
14. Zhang, X., Wang, F., Ji, W., Qiao, S., Cao, Y., Fault tolerant control method for three-level photovoltaic inverter based on redundant voltage space vector, in Chinese Control Conference, CCC, 2017.
15. Galketiya, T., Kahahena, J., Chandran, J., Kavalchuk, I., Novel communication system for SCADA tied smart inverter for Vietnam, in Proceedings of 25th Asia-Pacific Conference on Communications, APCC 2019, 2019.
16. Deenadayalan, K. D., Jayanthy, S., Arunraja, A., Selvaraj, S., IoT based Remote Monitoring of mass Solar Panels, in Proceedings of the International Conference on Electronics and Sustainable Communication Systems, ICESC 2020, 2020.
17. Medina, V., Gómez, I., Dorronzoro, E., Oviedo, D., Martín, S., Benjumea, J., Sánchez, G., IEC-60870-5 application layer for an open and Flexible Remote Unit, in IECON Proceedings (Industrial Electronics Conference), 2009.