

RESEARCH ARTICLE

A Novel Communication Method Using PWM and Capture Function of DSP for Parallel Controlled Power Electronics Systems

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ABSTRACT Parallel operation by multiple power converters is typical in microgrids. The communication method for parallel control mainly applies MODBUS RTU (Remote Terminal Unit), and the control performance largely depends on the communication speed. This paper proposes a new communication method that enables fast and accurate communication between master and slave systems combined in parallel using the PWM and capture functions of DSP used as the power converter controller. In the proposed communication method, the transmitting side uses the PWM function of DSP to generate a pulse waveform whose pulse width changes according to the reference command and transmits it to the receiving side. Suppose the capture function of the receiving side DSP is set to the time difference rising and falling edge mode. The set event occurs when the capture signal is detected and initializes the counter value to zero. At this time, it detects the counter signal and receives data. We explain the proposed communication method's principle, characteristics, and noise-canceling method and evaluate the accuracy and stability through data transmission and reception experiments. Finally, three 10kW single-phase electronic loads are connected to the R, S, and T phases to form a three-phase electronic load, and a master and two slaves are designated. The validity of the proposed communication method is verified through the current control response according to the command.

INDEX TERMS Digital signal processor (DSP), electric load, MODBUS, power conversion systems, pulse width modulation (PWM), remote terminal unit (RTU).

I. INTRODUCTION

The increase in the capacity of demand power and the load increases the need for a microgrid system, including a renewable energy source. It is necessary to increase the ability of the power converter to operate the microgrid, but since there is a limit to a single power conversion stack, parallel operation by multiple power converters is common. Communication is essential for the parallel operation of these power converters, and communication speed is the most critical factor in determining the performance [1]–[9].

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Among the communication methods for parallel operation of the power conversion system, the most common communication method is MODBUS communication using RS485. [6] introduced Modbus RTU-based communication system for an adjustable speed drive system. It has some advantages for real-time stability and anti-jamming of the system. Studies on the cyclic redundancy check (CRC) in Modbus RTU and the optimization method in software design and realization show that Modbus RTU is flexible in different applications. However, the communication speed becomes late when it applies to the power conversion systems in parallel because it may also be connected with an industry network based on the Modbus protocol. [7] introduced

the energy management and control subsystem of a grid-connected wind/solar hybrid power system. To control and manage the operation of multi-source, such as power grid, wind turbine generation, PV, storage batteries and loads, and also to acquire data and communicate with others, Modbus RTU was applied, while RS485/TCP converters implement the communication with a computer. Although experiments show that this system can run well, further investigation and experiments are required to optimize the communication between the subsystems. [8] describes an online detector for condition monitoring of switchgear based on Modbus technology. It has a host-and-slave structure. Each slave module is installed on the target switchgear cabinet to monitor all the connected switchgear in the substation comprehensively. Once any potential faults happen, the host can automatically pick the defective switch cabinet out. The overall system is working well; however, communication delays when the communication line is increased. In [9], it introduced EPA and Modbus/TCP industrial Ethernet communication gateway, including the design and implementation of ARM embedded system and $\mu\text{C}/\text{OS-II}$ real-time operating system. The Industrial Ethernet communication gateway can perform bidirectional data transceiving on EPA protocol and Modbus/TCP protocol, which provides a secure, stable, real-time, and flexible solution for process control of power stations. However, it uses the Modbus protocol for communication, which suffers from the late communication speed. The technologies mentioned above use the Modbus protocol, and it is a half-duplex communication method that cannot transmit and receive simultaneously. Therefore, as the number of communication targets increases, the communication period increases, and thus the control speed is limited. The usual method is the 4-wire communication method to overcome this communication speed limitation, but this gives an economic burden when configuring the system when the communication line is extended [10], [11]. Therefore, it is necessary to study the communication method to optimize the speed during parallel operation.

Recently, control methods for a power electronic system to which various communication methods are applied have been introduced [20]–[28]. These communication methods commonly compromise communication speed and economy, and Modbus is an industry-standard. However, in a high-power conversion system composed of a plurality of sub-power converters, developing and applying a communication method to secure faster communication speed, economy, and maintenance convenience is necessary.

This paper proposes a new communication method that enables fast and accurate communication between master and slave systems combined in parallel using the PWM and capture functions of DSP used as the power converter controller. We explain the proposed communication method's principle, characteristics, and noise-canceling process and evaluate the accuracy and stability through data transmission and reception experiments. Experiment results verify the suitability of the proposed parallel operation communication method.

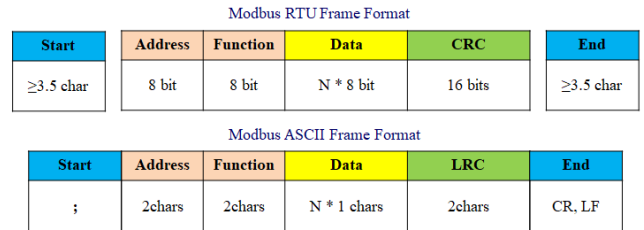


FIGURE 1. MODBUS RTU and ASCII frame.

Section 2 describes the Modbus communication method widely applied to the power conversion system. Section 3 describes the proposed communication method. Utilizing DSP's PWM function and Capture function to enable communication is explained in detail. Also, a method for removing noise from communication data is introduced. Section 4 proves the validity of the proposed communication method experimentally. The primary communication state is verified, and the way of compensating for communication delay is verified experimentally. Finally, by using a three-phase electronic load system, the experiment proves that the master and slave power converters are accurately controlled by the proposed communication method.

II. CONVENTIONAL COMMUNICATION METHOD FOR PARALLEL OPERATION OF POWER CONVERSION SYSTEM

A. MODBUS PROTOCOL

MODBUS is a protocol for client-server communication between devices connected to the network. Since it is connected using a communication line bus or connected in a parallel structure with other types of network devices, it is the most commonly used communication method in the industrial field [12].

The transmission mode of MODBUS is divided into two transmission modes: RTU (Remote Terminal Unit) and ASCII, according to the data encoding method as shown in Fig. 1. In RTU mode, it transmits data in the form of an 8-bit binary. In ASCII mode, communication time is longer than in RTU mode because it divides each character by 4-bit and transmits in the form of two characters. Therefore, ASCII mode is advantageous for communication methods to check errors or view data values, and the industrial field widely uses RTU mode because of its good transmission efficiency.

B. MODBUS FUNCTION CODE

The MODBUS function code is divided mainly according to the data access unit and the read/write function, as given in Table 1.

This paper uses MODBUS RTU communication to acquire analog data values such as power, voltage, current, and resistance of the transmission line and transfer the reference to each master-slave power conversion system. Therefore, the function codes used are 03(0 × 03), 04(0 × 04), 06(0 × 06), and 10(0 × 10).

(0 × 03) Read Holding Registers: As a command to read the read/write-enabled word memory area, the memory allocated

TABLE 1. Classification of MODBUS function.

Function Type	Operation	Function Code
Discrete input	Read Bit Data Area	0x02
Coils	Read/Write Bit Data Area	0x01
Input Registers	Read Word Data Area	0x04
Holding Registers	Read/Write Word Data Area	0x03,0x06,0x10

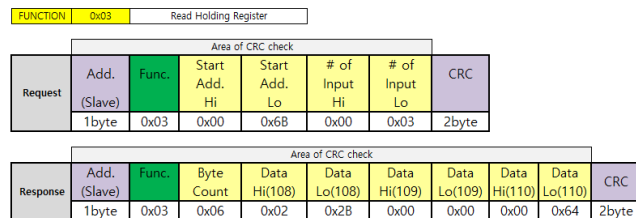


FIGURE 2. Request and response of function code 0 x 03.

to the Read Holding Register represents the memory for module setting (module ID, communication setting, etc.) and output. Read Holding Register should check analog output command status and module communication setting status. The maximum length of register 0 x 03 is 125 words.

(0 x 04) Read Input Register: This is a command to read the word input memory area. To read an analog input, we must use the 0 x 04 function. The Read Input Register memory area is not writable. Be careful if we try to write to the Read Input Register area because data is written to the Holding Register area of the same address. The maximum length of the register is 125 words.

(0 x 06) Write Single Register: This command is used to change data for one word of Holding Register. This function is used when outputting digital output in word units or resetting communication ID.

(0 x 10) Write Multiple Register: Holding Register command is used to change several words simultaneously in the memory area. This function is proper when changing four analog output channels simultaneously. The maximum length of the register is 120 words.

1) REQUESTS AND RESPONSES IN EACH FUNCTION CODE

Fig. 2 shows each data frame for request and response of the 0 x 03 function code. A data frame is a request to read 3 data starting from address 0 x 6B (decimal number 107). Slave’s unique ID (1Byte), function code (0 x 03), upper 1 Byte (8bit), lower 1 Byte (8bit) of the start address of the data to be read from the slave, the upper 8 bits of the number of data to be read from the start address of the slave memory area. It is defined in the order of CRC (Cyclical Redundancy Checking/2Byte) calculated from the lower 8 bits, the slave ID to the lower 1 Byte of the number of data.

The response frame consists of the slave’s unique ID (1Byte), the function code (0 x 03), the Byte size (0 x 06) of the response data according to the number of three requested data, and the start address of the receiver corresponding to

the start address 0 x 6B of the requested data: 108~110. It responds up to the data value (0 x 02, 0 x 2B, 0 x 00, 0 x 00, 0 x 00, and 0 x 64) stored in the upper and lower 1 Byte of each data up to the address, and the 2 Byte CRC value is calculated from the Byte size of the response data to the lower data of the last address. The data frame for each request and response of function codes 0 x 04, 0 x 06, and 0 x 10 appear similar to 0 x 03.

2) CYCLICAL REDUNDANCY CHECKING (CRC)

Various error detection methods have been studied and applied to reduce the error rate during communication [13]–[19]. Among them, Checksum and CRC Polynomial Code methods are representative. When an error occurs, it is possible to detect what the parity bit cannot detect more efficiently. Most of the parity bits are in the form of NONE in data communication between various peripheral devices in the industrial field, and errors are detected during data transmission/reception through CRC check.

The checksum check method transmits a value that adds the total sum of the bit strings included in the transmitted data and the checksum to become zero. It checks data errors by attaching a checksum bit string of 16 bits to the end of the transmission data string to check whether the data sent from the sending side is precisely the received data when receiving it. CRC (Cyclic Redundancy Code), also called Polynomial Code, is the most representative error detection code used in communication protocols in the industrial field. In general, errors occurring in the network appear in the form of burst errors that occur intensively in a specific bit string. Polynomial Code has a high detection probability of such errors, and CRC-16 is the standard in MODBUS RTU.

The CRC code consists of 16 bits. It is an error detection code to check whether data is transmitted without error during data transmission. It is added to the end of the request data frame, and the calculated CRC value is divided by low/high 1 Byte and delivered to the receiving side. The receiving device that has received the data recalculates the CRC every time. It receives the received data by 1 Byte and compares it with the received value to determine whether there is a reception error.

III. PROPOSED PWM-CAPTURE FUNCTION BASED BIDIRECTIONAL COMMUNICATION

The bidirectional communication proposed in this paper differs from the existing communication method in that it uses the PWM and Capture functions of the DSP (Digital signal processor). Instead of using PWM as a switching signal, it is used to express the size of the data using the width of the pulse, and it is used together with the Capture function to enable bidirectional communication.

A. HOW TO GENERATE PWM IN DSP

The PWM signal consists of duty *D*, frequency *f*, and period *T* to express the width of the pulse, and the magnitude of the

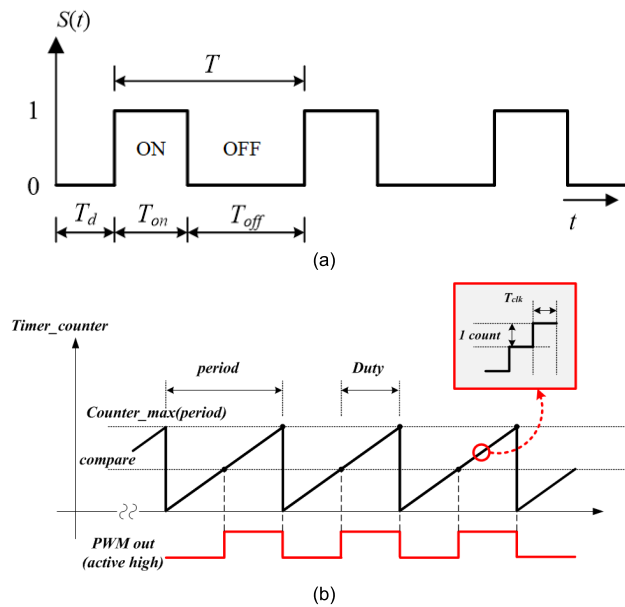


FIGURE 3. PWM signal generation, (a) Configuration of PWM signal, (b) How to generate PWM in DSP.

signal is divided into High(1) and Low(0) PWM pulses.

$$D = \frac{T_{on}}{T} \times 100 [\%] \quad (1)$$

In Fig. 3(a), the duty ratio D represents the signal's ON interval expressed as a pulse in PWM. It means that the magnitude of the signal is significant as the duty ratio D is closer to 100[%]. In this paper, the duty ratio D of the PWM signal is expressed as a counter value for the pulse width using the capture function of the DSP to detect the data size and use it as a reference signal and communication data for control of a parallel-connected power conversion system. As shown in Fig. 3(b), in order to generate PWM, the timer/counter function inside the DSP is used. The pulse width of the PWM signal is adjusted by setting the maximum value (period) and comparison setting value (compare) of the timer.

The maximum counter value set in DSP with a 16-bit timer is 65535 (0xFFFF). Any value between 0 and 65535 can be set as the pulse width period to generate the desired PWM frequency. The timer is reset to zero when the maximum counter value is reached to the set frequency. Repeating this generates a counter value in the form of a triangular wave, as shown in Fig. 3(b). The pulse width (duty ratio, D) that determines the size of the PWM signal is made through the generated counter value corresponding to 0~1500 and the comparison setting value (compare). The PWM output pin maintains Low when the timer counter value is smaller than the comparison setting value. When it is greater than the comparison setting value, it maintains High. According to the PWM generation mode, High and Low signal conditions can be changed.

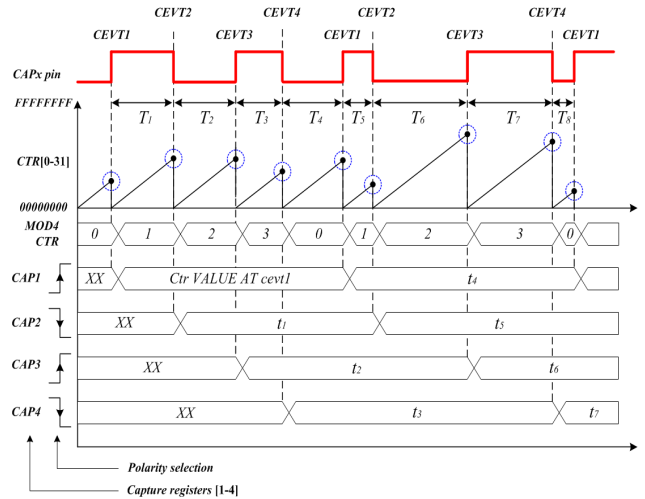


FIGURE 4. Time difference (delta) rising and falling edge mode in eCAP function.

B. SIGNAL DETECTION METHOD USING DSP'S CAPTURE FUNCTION

The capture function of DSP is to detect the time information of the pulse signal. Period (duty) is measured by the time between the edge of the input pulse detected through the counter. Also, by generating an interrupt at the edge of the pulse, it is possible to control it by synchronizing it with the edge of an external signal. eCAP, the Capture function of TI's TMS320F28X series used in this paper, has four modes: Absolute time-stamp rising edge mode, Absolute time-stamp rising and falling edge mode, Time difference (delta) rising edge mode, and Time difference (delta) rising and falling edge mode.

The time difference (delta) rising and falling edge mode shown in Fig. 4 detects both the rising edge and the falling edge of the input signal. Using the counter reset when CEVTx occurs, the period and width of each pulse can be detected. When CEVTx occurs at the edge, the counter is automatically reset to zero, so the period and frequency of each pulse by the capture counter are as follows.

$$\begin{aligned} \text{Duty}_{1(\text{on})} &: \text{Cap}_2 \text{Duty}_{1(\text{off})} : \text{Cap}_3 \\ \text{Duty}_{2(\text{on})} &: \text{Cap}_4 \text{Duty}_{2(\text{off})} : \text{Cap}_1 \\ \text{Period}_1 &: \text{Cap}_2 + \text{Cap}_3 \\ \text{Period}_2 &: \text{Cap}_4 - \text{Cap}_1 \end{aligned} \quad (2)$$

In this paper, the communication data uses the duty corresponding to the PWM pulse's ON interval to control the power conversion system.

C. PROPOSED COMMUNICATION METHOD

In this paper, we propose a communication method using the PWM-Capture function of DSP that can replace the existing MODBUS communication method.

First, the transmitting side generates a pulse waveform whose pulse width is changed according to the reference

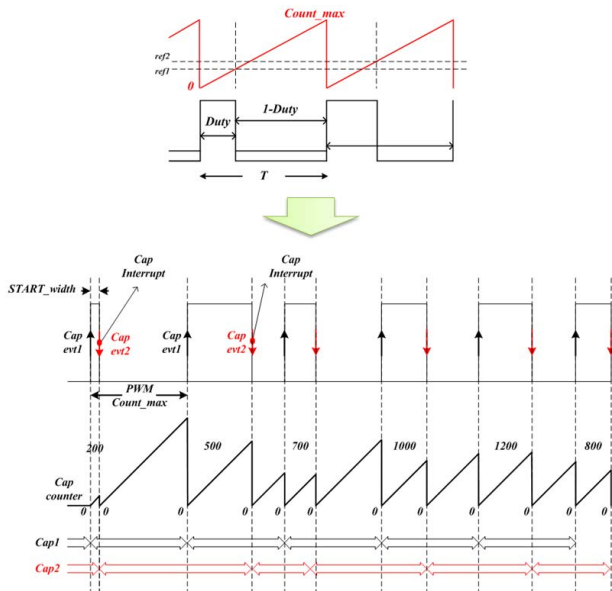


FIGURE 5. Data detection using Capture function according to pulse width change of PWM signal.

command of PWM, and this signal is applied as a capture input signal of the receiving side through a communication line. Suppose the capture function on the receiving side is set to Time difference (delta) rising and falling edge mode. The counter signal is detected while initializing the set event occurrence to zero when the capture signal is detected. In this paper, Capture event 1 and Capture event 2 are applied, event 1 is set to occur at the rising edge of the pulse signal, and event 2 occurs at the falling edge of the pulse signal. Therefore, the Capture counter is reset to zero at the rising edge where the PWM pulse becomes ON and at the falling edge when the PWM pulse becomes OFF. The counter value of the PWM ON section received through the Capture function is determined as (3).

$$PWM_{ON_count} = Cap_2 - Cap_1 \quad (3)$$

Here, Cap_1 and Cap_2 are count_value_register. When the pulse width of the transmitting side defined by (3) is transmitted to the receiving side, the counter value is detected using the capture function of the receiving side, and the detected signal is used as each data for system control. Fig. 6 shows the configuration of bidirectional communication using PWM and Capture functions of DSP. Depending on the number of channels of PWM and Capture, both half-duplex and full-duplex are possible.

Fig. 6(a) shows that half-duplex communication is possible using each PWM-Capture channel of Master and Slave. However, since data transmission and reception are not performed simultaneously, an enable signal is used to distinguish transmission and reception operations. In the case of Fig. 6(b), using two channels of PWM and Capture functions in the Master and Slave, it is possible to implement a full-duplex communication method that can transmit and receive

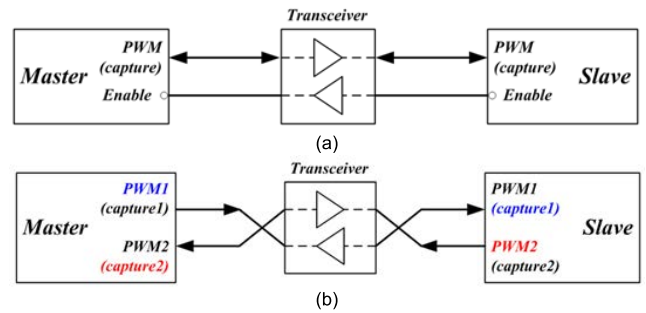


FIGURE 6. Bidirectional communication method using PWM-Capture function, (a) half-duplex, (b) full-duplex.

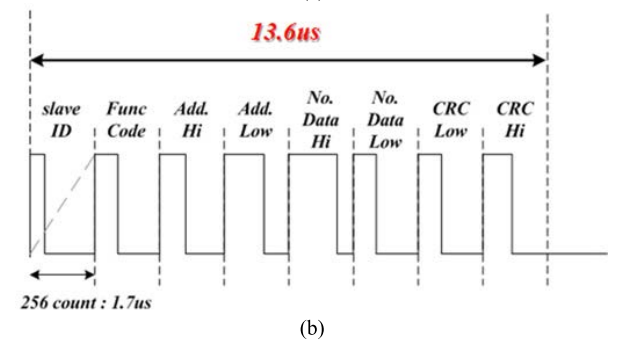
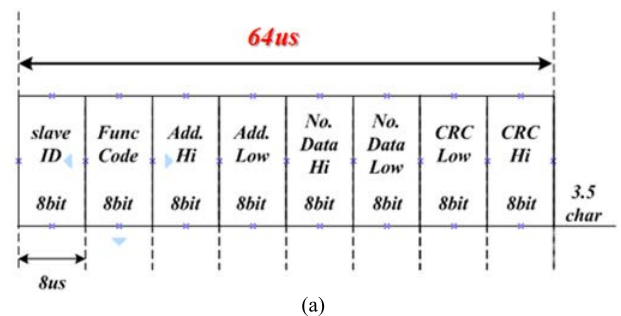


FIGURE 7. Comparison between MODBUS data frame and the proposed data frame, (a) MODBUS protocol data frame, (b) proposed PWM-Capture protocol data frame.

simultaneously. In this case, there is no need for an enabled signal to distinguish between transmission and reception.

The MODBUS communication method will be described based on TMS320F28335, TI's DSP mainly used for power conversion systems. The clock speed of the TMS320F28335 is 150MHz. At this time, the data transmission speed of MODBUS can be used up to 1Mbps.

Fig. 7(a) shows the function code's data frame specification to read the receiving side's data in the general MODBUS method. The 8-bit data required from Slave ID to CRC Hi is 8 data. If this is expressed as a PWM signal for PWM-Capture communication, it can be expressed in Fig. 7(b). When using the CPU clock of 150 MHz, the counter value for 8-bit data transmission is 256. As shown in Fig. 7(a), when the same type of communication frame as the MODBUS protocol is applied, the data transmission rate is about 64 μ s. If this is transmitted in the form of a PWM signal expressed

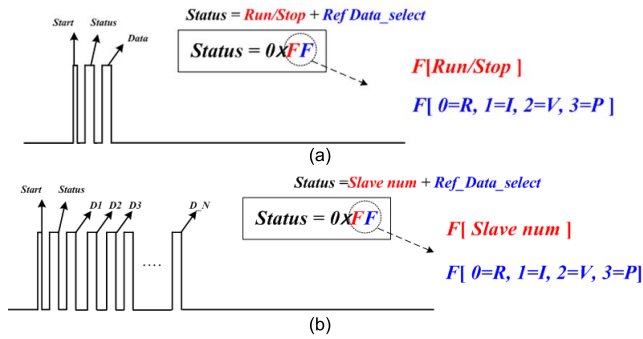


FIGURE 8. Data frame of the proposed communication method, (a) Broadcast, (b) Slave designation method.

in 256 counter values with 8-bit data based on the system clock of 150 MHz, about 13.6 μ s of data transmission time is required, as shown in Fig. 7(b). The data transfer speed is about 4.7 times faster. This relationship reveals several conditions:

- (1) Counter max value of PWM signal = Data resolution = Maximum value of actual communication data to be expressed through PWM
- (2) Resolution changes with DSP clock speed and PWM frequency
- (3) Minimum counter value for generating 8-bit data = 256
- (4) When the transmission data increases, the time difference increases due to the transmission speed
- (5) Resolution changes with DSP clock speed and PWM frequency

If PWM data resolution is applied based on the MODBUS data transfer rate (maximum 1 Mbps), it can be applied up to 10 bits, four times 8 bits. That is, up to a data signal having a data resolution of 1024 can be applied. Compared to the existing 8-bit data method, it has a data margin of 2 bits. It will be used as dummy data for compensating for an error value of communication data due to noise caused by disturbance and impedance of the communication line.

D. DATA GENERATION METHOD USING THE PROPOSED PWM-CAPTURE FUNCTION

The communication protocol using the PWM-Capture function proposed in this paper is divided into two data transmission methods. One is a broadcast method in which the same data is transmitted to controlled slaves connected in parallel. The other is data transmitted by designating each slave when the number of slaves has a value of 16 or less.

Fig. 8(a) shows a broadcast data frame that transmits the same reference data in a batch for parallel control of slaves. It transmits the control command to the slaves operated parallel with the same value. The first information of the data frame is a start bit for detecting the start of transmission data. Since MODBUS is asynchronous communication, for the data transmitted from the Master, the slave must distinguish the data's beginning and end. A pulse having a constant width is used as a start signal to indicate the start of a data frame.

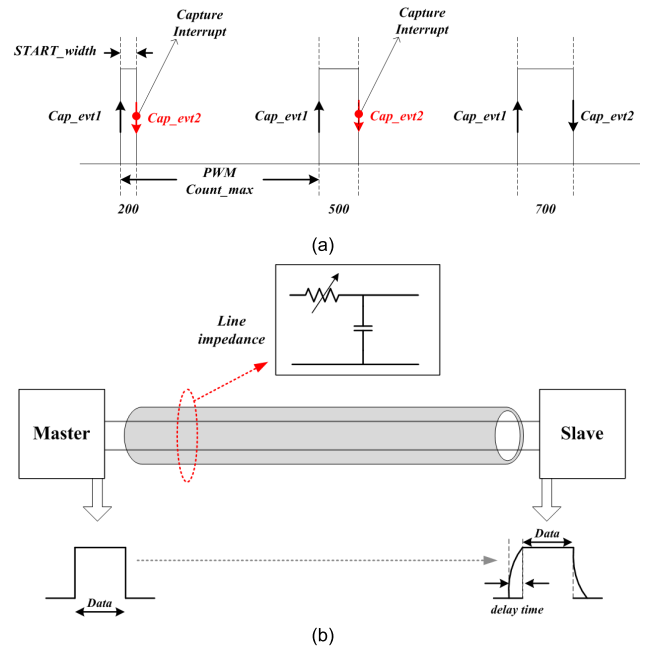


FIGURE 9. Data transmission using PWM-Capture function, (a) PWM signal for data frame transmission, (b) Effect of communication line impedance.

The second data frame is Status information for the operation status of the slave. It is data information for the classification of Run-Stop status and current, voltage, resistance, and power commands. The command data type is sent to distinguish the control data command sent from the Master. The third data represents the actual command data to be controlled by the slave. In this way, a frame with three pieces of data information can transmit information that is at least 2.5 times higher than that of the existing MODBUS protocol data frame.

Fig. 8(b) shows the data frame for transmitting the command to a specific slave among the slaves operated in parallel. The first data is the start bit, as shown in Fig. 8(a). The second status data is the status information of the slave for parallel control and indicates the ID (Adress) of the designated slave and the operation command of the slave. It is data information for classifying the type of command to be transmitted. Then, the actual command data corresponding to each slave is transferred for parallel operation.

Fig. 9(a) shows the PWM signal for data frame transmission in an ideal condition where noise does not occur. If the communication line becomes long, a signal delay, as shown in Fig. 9(b), occurs due to the line impedance of R and C of the line, which causes an error in the pulse width.

A start bit is used to solve this problem. As shown in Fig. 10, if the pulse width of the first start bit is set to 200 when transmitting data from the Master to the slave, all data transmitted after the start bit includes the start bit count value of 200. The receiving side receives data from the communication line, including a specific delay value. When the pulse data is transmitted from the Master to the slave, the received data is expressed as data having a pulse width of

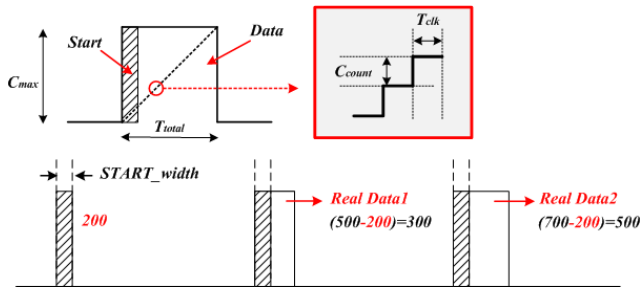


FIGURE 10. Actual valid data, including start counter value.

200, 500, and 700, respectively. Except for the counter value of 200 corresponding to the start bit, the remaining values, 300 and 500, become actual valid data. These values become the actual command and accurate data for control. When configuring the master and slave systems, since all communication data uses the communication line of the site built, all data is affected by the same communication line impedance. Data delay occurs in the data transmission/reception process due to line impedance, as shown in Fig. 9(b), and appears in the same form in all data. When the receiving side removes the counter value corresponding to the start bit, the offset value for data delay is included. Therefore, the remaining data also has a valid data value in which the offset value for the line impedance is compensated.

$$T_{total} = T_{clk} \times C_{max} \tag{4}$$

$$C_{max} = 2^{(Bit_{R_data} + Bit_{dummy_data})} \tag{5}$$

Here T_{total} is one cycle of communication data. T_{clk} is PWM and Capture counter clock. C_{max} is PWM counter max. Bit_{R_data} is the number of valid data bits. Bit_{dummy_data} is the number of dummy data bits.

E. DATA NOISE-CANCELING PROCESS

Fig. 11 shows the noise-canceling technique by removing dummy data to secure data reliability. The counter value of the PWM pulse width to secure the actual 8-bit data is 256, which represents the minimum counter value that can be used in an ideal state without noise. Compared to general MODBUS, the data transmission speed of the proposed method is about 4.7 times faster, and it has a time margin of 2-bit. Based on the data transfer rate of the same time, the data value by the pulse width can have a data value of 10 bits, so the lower 2 bits can be used as dummy data and removed.

Fig. 11 shows the operation flow for securing reliable transmission/reception data through the 2-bit dummy data canceling method. The maximum counter value and time using the valid data and the number of dummy data bits are the same as (4) and (5).

Fig. 12 shows the transmission/reception data according to the half-duplex during master and slave communication. It indicates that data transmission/reception is alternately performed between the Master and the slave using the enable signal. Missing data due to communication errors causes

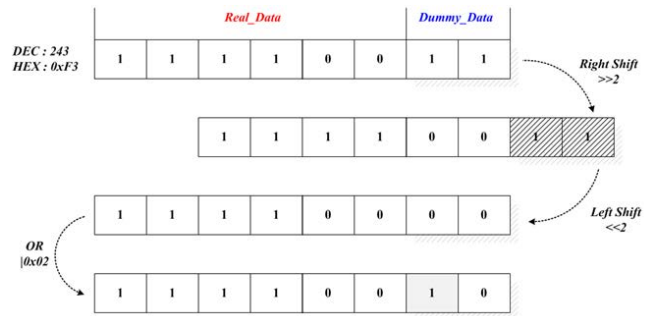


FIGURE 11. Data noise-canceling technique.

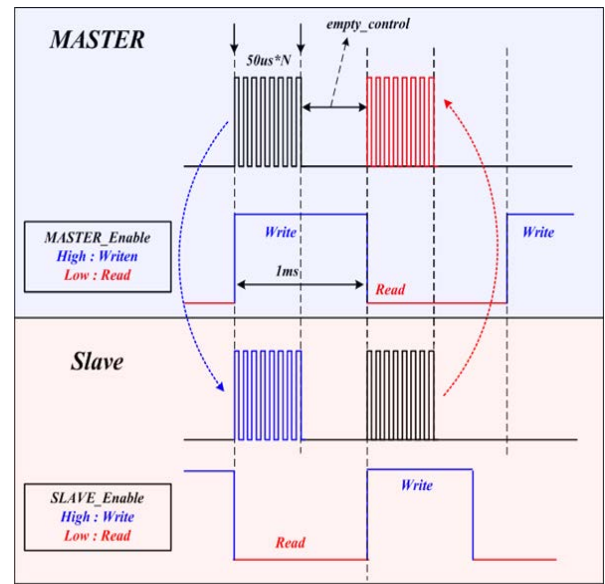


FIGURE 12. Master-slave transmit/receive data timeline.

communication timeouts. In this case, the communication speed can be adjusted by adjusting the empty time.

IV. EXPERIMENT RESULTS AND DISCUSSION

A. VERIFICATION OF COMMUNICATION METHOD BETWEEN MASTER AND SLAVE

To verify the communication method between the Master and the slave, the proposed method’s data transmission/reception function is verified using the data frames of the existing MODBUS Protocol: 0×04 (Read Input Register) and 0×10 (Write Multiple Register).

Fig. 13(a) results from data transmission/reception using the function code of 0×04 when the Master requests 1 data. Fig. 13(b) results from data transmission/reception using the function code of 0×04 when the Master requests 2 data.

Fig. 14 shows the transmission/reception result using the data frame of the MODBUS 0×10 function code. Fig. 14(a) shows the response of the slave when 3 data is sent from the Master. Fig. 14(b) shows the response of the slave when 10 data is sent from the Master. Fig. 13 and Fig. 14 generate data frames using the pulse width of PWM function according

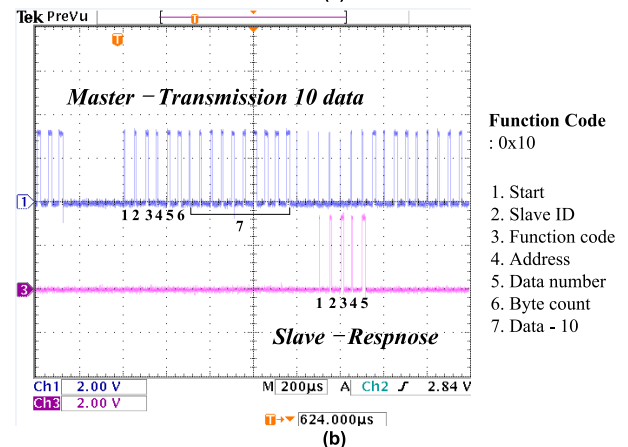
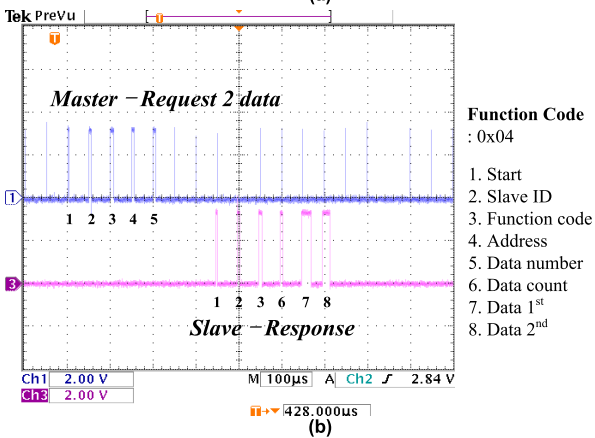
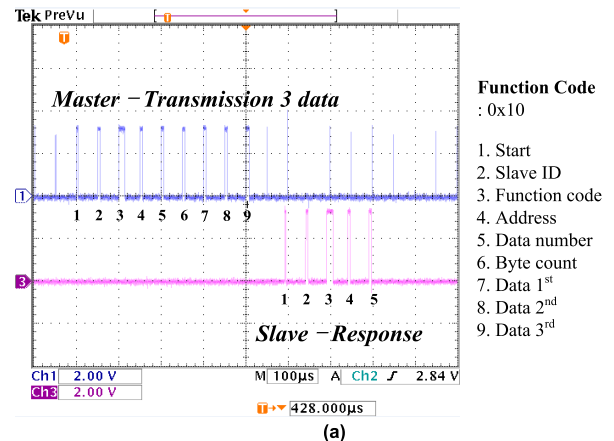
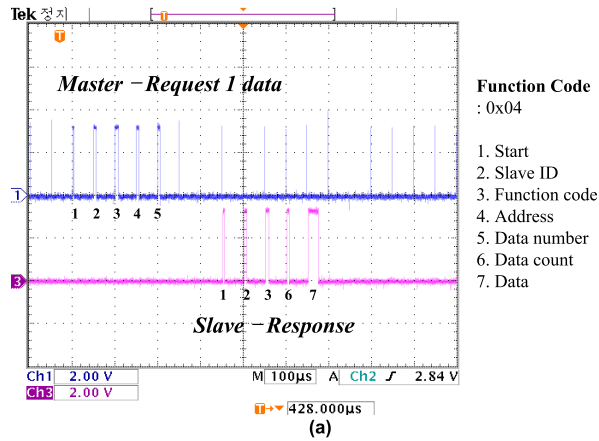


FIGURE 13. Communication experiment using data frame of MODBUS 0 × 04 function code, (a) request 1 data and response, (b) request 2 data and response.

FIGURE 14. Communication experiment using data frame of MODBUS 0 × 10 function code, (a) transmission 3 data and response, (b) transmission 10 data and response.

to the general MODBUS function code rule to verify data transmission/reception using the proposed PWM-Capture function. When this PWM-Capture communication method is applied, it can be confirmed that communication data transmission/reception between Master and slave is performed without any problem.

B. PROPOSED COMMUNICATION PROTOCOL EXPERIMENT

The experiment verified the validity of the proposed communication data frame for parallel control of the power conversion system.

Fig. 15 shows the proposed communication data frame. ① is the start signal of the data frame, ② is the function code, ③ is the status, ④ is the control reference 1, and ⑤ is the control reference 2. Here, ③ status indicates the classification and status of the command value and has an 8-bit data signal. The upper 4 bits indicate the operation status, and the lower 4 have data values for classifying the types of operation command values (I, R, P, and V). After receiving the command data sent from the Master, the slave changes the data enable signal from Low to High and sends the response data to the function code back to the Master.

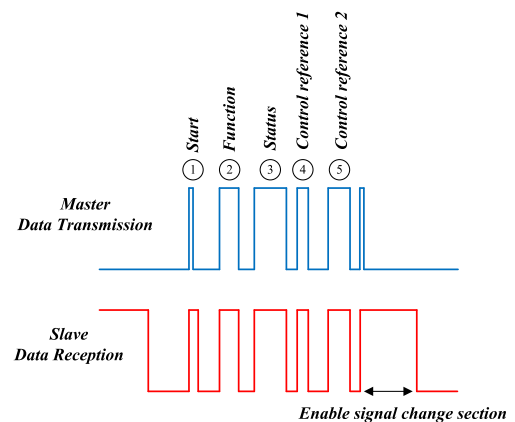


FIGURE 15. The data frame structure of the proposed method.

Fig. 16 shows the experimental data transmission/reception results between Master and slave using the proposed data frame. Fig. 16(a) is the experimental waveform when the Master’s retransmission period due to timeout is applied as 5ms during communication between the Master and the slave. One cycle of the power conversion system operating at 60 Hz is 16.67 ms. Therefore, when the data update period

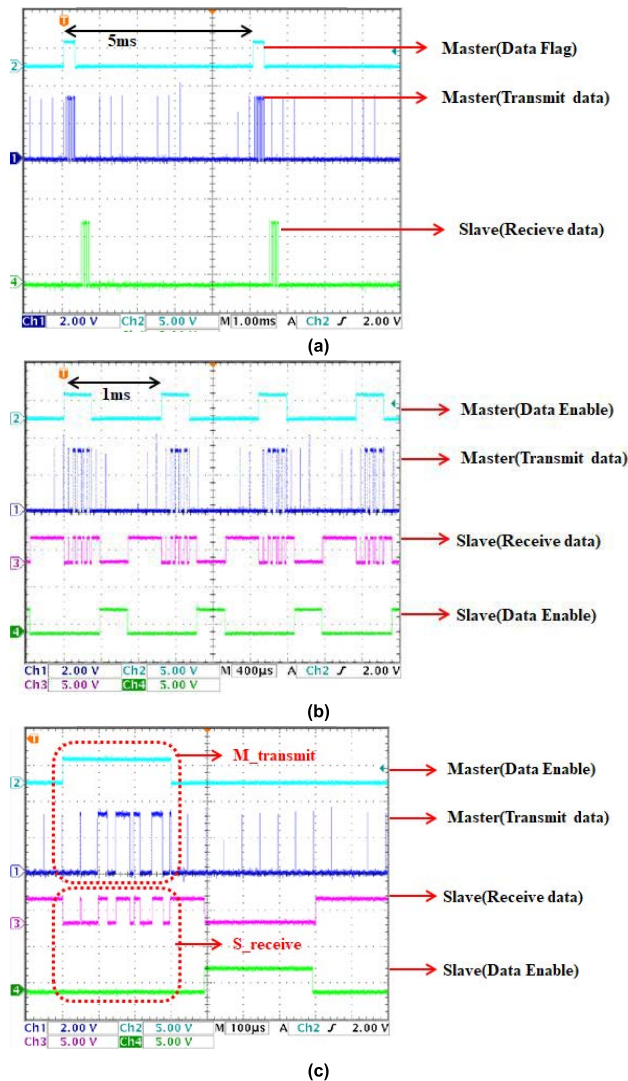


FIGURE 16. Data transmission/reception by the proposed communication protocol, (a) Master's retransmission cycle 5ms, (b) Master's retransmission cycle 1ms, (c) enlarged waveform of (b).

of the control reference is 5 ms, the control response speed is slow. Fig. 16(b) shows that the data retransmission period is set to 1ms to ensure control responsiveness and stable data transmission/reception between Master and slave due to timeout. It shows the Master's transmit data, the slave's receive data, and the master and slave data enable signals when the transmission period is 1ms. The data enable signal is a signal for distinguishing between the transmission and reception of data between the Master and the slave. The enable state is determined according to the high and low values of the enable signal. The high state is the data transmission area, and the low state is the data reception area. When the enable signal is high for the Master to transmit, the slave must wait in the low state to receive the data sent from the Master to the slave. Conversely, when the slave sends a response signal, the enable signal is created with the slave high and the master low. Fig. 16(c) is Fig. 16(b)'s enlarged waveform.

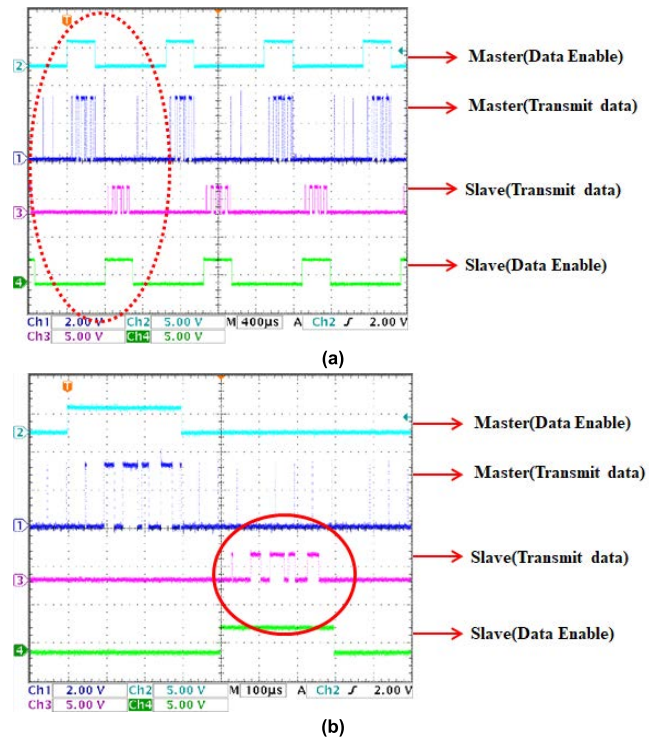


FIGURE 17. Response data sent by the slave to the Master, (a) When the data enable signal of the slave is high, (b) enlarged waveform of the red dotted line in (a).

Fig. 17(a) shows the response data sent by the slave to the Master. When the data enable signal of the slave is high, the slave transmits the function code requested by the master and response data to the received data. Fig. 17(b) is an enlarged waveform of the red dotted line in Fig. 17(a).

Fig. 18(a) is an experimental waveform in which the reference data sent from the Master is sent back from the slave to the Master. It can be confirmed that the data transmission/reception of the Master and the slave for the control reference is perfectly accomplished.

Fig. 19 is the data output waveform of the master side when the proposed communication method is applied to the parallel-controlled power conversion system. It can be confirmed that the Master's transmission and the slave's response data are transmitted and received correctly.

C. COMMUNICATION LINE DELAY TEST

In the proposed PWM-Capture function, the communication method can secure valid data by using dummy data to compensate for communication line delay. An arbitrary communication line is configured to verify the performance of the proposed method between the Master and the slave of the parallel-controlled power conversion system, and a stability test for data transmission/reception is performed.

Fig. 20 shows the experimental environment for analyzing line impedance's effect according to the communication line's length on the communication state. Connect an arbitrary communication line from 100 m to 300 m between the

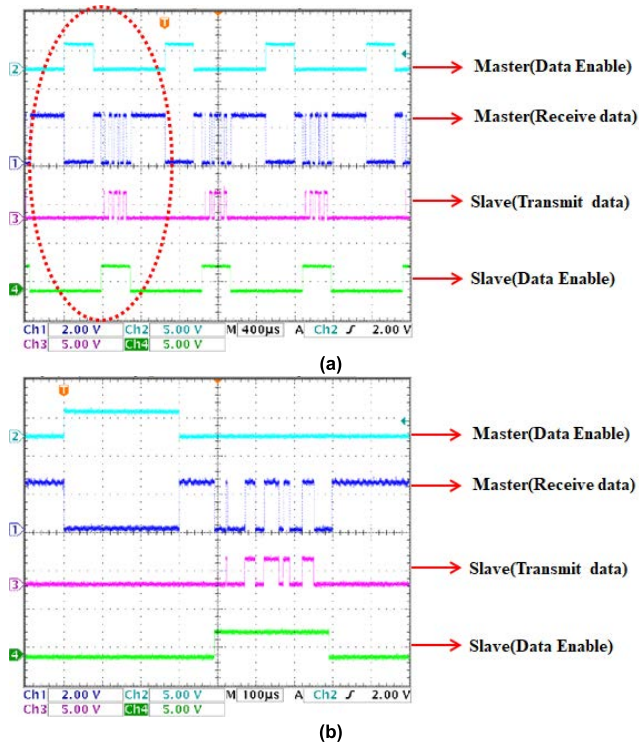


FIGURE 18. Verification of data transmission/reception status between Master and slave, (a) When the reference data sent from the Master is sent back from the slave to the Master, (b) enlarged waveform of the red dotted line in (a).

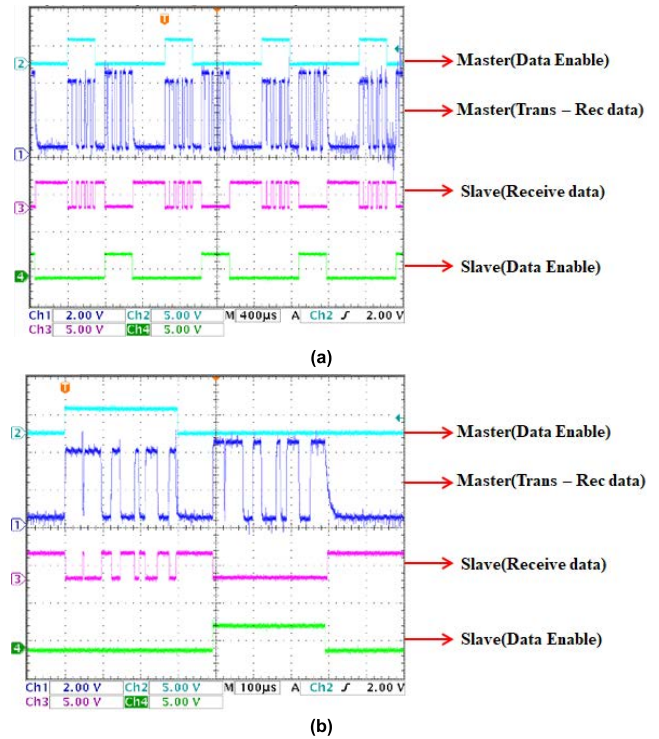


FIGURE 19. Data output of the master side when the proposed communication method is applied to the parallel-controlled power conversion system, (a) Data output waveform of the master side, (b) enlarged waveform of the red dotted line in (a).

Master and the slave and test the line impedance effect. Also, the effect of impedance change is analyzed using R and C.

Fig. 21(a) and Fig. 21(b) show the transmission data sent from the Master to the slave and the data signal received from the slave when the length of the communication line is 100 m and 300 m, respectively. Although the two lines have a difference in length of 200 m, the data signal waveform does not show a significant difference. The status of data transmission between Master and slave is verified by checking the transmit/receive response data value for each line using CCS software for DSP driving. The experiment confirmed that the data was transmitted stably on the communication line up to 300 m.

Fig. 22(a) shows the transmission/reception data waveform according to the impedance change by fixing the line between the Master and the slave at 300 m and adding R and C further to check the effect of the communication line impedance. Fig. 22(a) shows the distortion of the slave received data due to the length of the communication line and the added impedance. Through the experiment, when a value of 20 Ω and 20 nF, or more, is added to the communication line, the start bit overflow occurs between the Master and the slave due to data distortion, making data transmission/reception difficult. Therefore, an automatic initialization setting sequence of the start bit according to the line impedance is required.

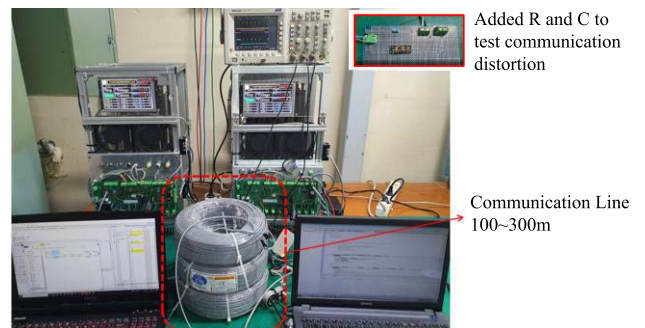


FIGURE 20. Experimental environment to analyze the effect of line impedance according to the length of the communication line on communication status.

Fig. 22(b) shows the transmission/reception data waveform when the length of the communication line is less than 10 m under the same conditions. Through the experiment, it can be confirmed that the longer the communication line or, the higher the resistance, the greater the data error. However, the error of the control reference, such as voltage, current, and power of the power conversion system, is deficient, so there is no problem in system control. The communication method using the proposed PWM-Capture function can operate up to 300 m in length, so it is suitable for operating Master and slave equipment of a parallel-controlled power conversion system in the actual field.

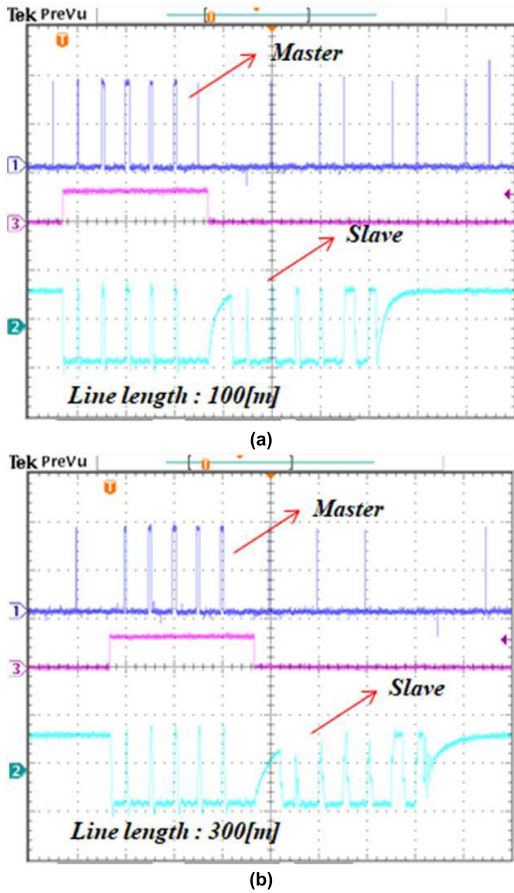


FIGURE 21. Communication data on the communication line, (a) 100m communication line, (b) 300m communication line.

TABLE 2. Communication method comparison.

Type	MODBUS	Proposed
Protocol	Cannot changeable	Can changeable
data transfer rate (8bit)	Pure data: 62 μ s with start bit: 92 μ s	Pure data: 13.6 μ s with start bit: 14.3 μ s
CRC	Applied	Not applied
speed adjustment	Boud rate	free
transmission method	half-duplex	Half- & Full-duplex
versatility	High	High

Table 2 shows the differences between the existing MODBUS method and the proposed PWM-Capture method.

The existing MODBUS method cannot change the protocol, but the protocol can be freely changed between transmitting and receiving devices in the proposed method. Based on 8-bit data transmission, when the start bit is included, the difference in transmission speed is up to 6 times. In addition, the communication speed can be freely changed according to the number of parallel control devices and the amount of data according to the broadcast or slave designation method. Since various protocol types can be applied to parallel-controlled power conversion devices, it can be used as a new universal communication method.

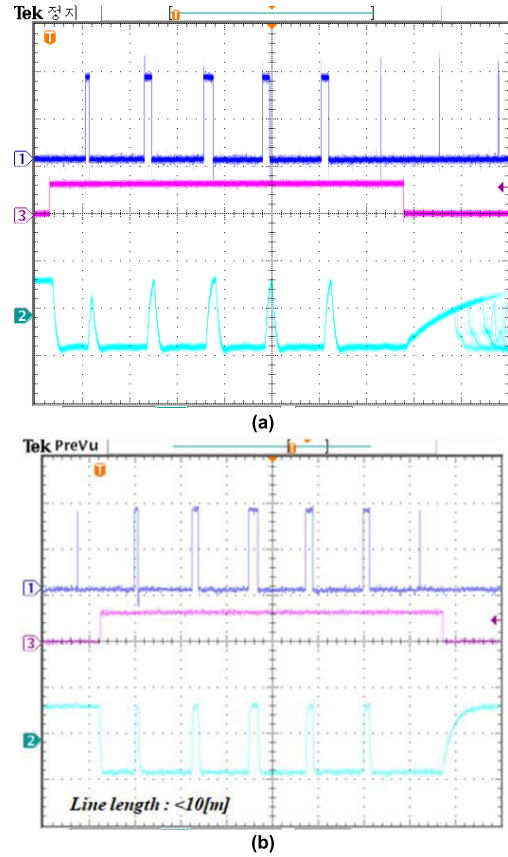


FIGURE 22. Transmission/reception data waveform according to the impedance change, (a) by fixing the line between the Master and the slave at 300m and adding R and C further to check the effect of the communication line impedance, (b) when the length of the communication line is less than 10m under the same conditions.

D. PARALLEL OPERATION TEST OF ELECTRONIC LOAD APPLYING THE PROPOSED COMMUNICATION METHOD

Fig. 23 shows three single-phase electronic loads used to verify the proposed communication method. Connect three single-phase electronic loads to R, S, and T phases and use them as three-phase electronic loads for testing. Each 10 kW single-phase load is connected to the R, S, T, and N phases. Among them, the electronic load connected to the R-N phase plays the role of a master, and the two electronic loads connected to S-N and T-N are slaves, respectively. The three-phase power system can be controlled for each phase through the parallel operation of three single-phase electronic loads.

The operational performance of the proposed communication method is verified through three-phase balanced control and unbalanced control with different control setpoints for each phase. The electronic load connected to the R phase was designated as Master, the S phase as Slave1, and the T phase as the electronic load of Slave2, and the experiment was conducted.

Fig. 24(a) is an experimental waveform when the R-phase current command value is increased from 5% to 25% among three electronic loads composed of three phases. It can be confirmed that the current command value is transmitted by

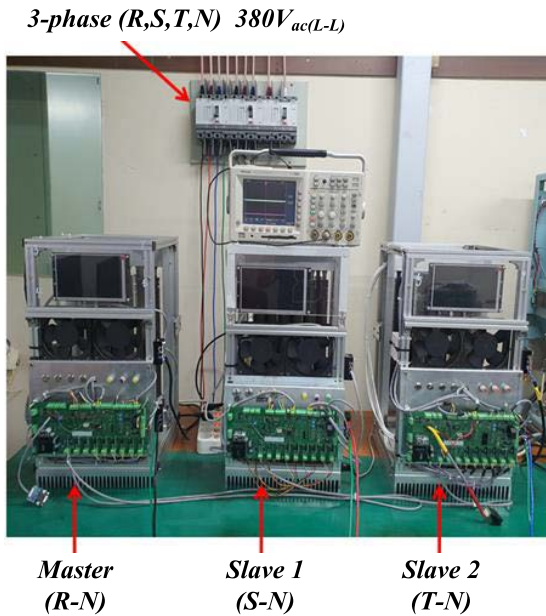


FIGURE 23. 10 kW single-phase electronic load for verification of the parallel operation of power converters.

the proposed communication method, and the current in the R phase is accurately controlled. Fig. 24(b) is an enlarged waveform of Fig. 24(a).

Fig. 25 shows the current change at the point where the Master transmits and receives the control command through the proposed communication method to check the control response of the S and T phases designated as slaves. As a result of the experiment, a little communication delay time of about us appears according to the communication time interval between master-slave, but it can be confirmed that accurate data transmission and reception are performed.

E. RELIABILITY VERIFICATION OF THE PROPOSED COMMUNICATION METHOD

Fig. 26 shows the confusion matrix used to verify the reliability of the proposed communication method. Signal data was verified using 200 test signals, respectively, when the impedance of the communication line was 1 Ω or less, 5 Ω, or 20 Ω. Here, True Positives (TP) correspond to a case where a 1 (High) signal is correctly recognized as a 1 (High). False Negatives (FN) are cases in which a 1 (High) signal is incorrectly recognized as a 0 (Low) signal. False Positives (FP) are cases in which a 0 (Low) signal is incorrectly recognized as a 1 (High). True Negatives (TN) are cases in which a 0 (Low) signal is correctly recognized as a 0 (Low) [29]–[34].

Fig. 27(a) results from accuracy analysis using the confusion matrix and (6). It is the result of the number of times that the 1 (High) signal of the test signal is correctly classified as 1 and the 0 (Low) signal as 0. When the impedance of the communication line is less than 5ohm, the Accuracy is 0.985 or higher, but at 20 Ω, it drops to 0.94. Therefore, in a communication line with a longer distance, it is necessary to

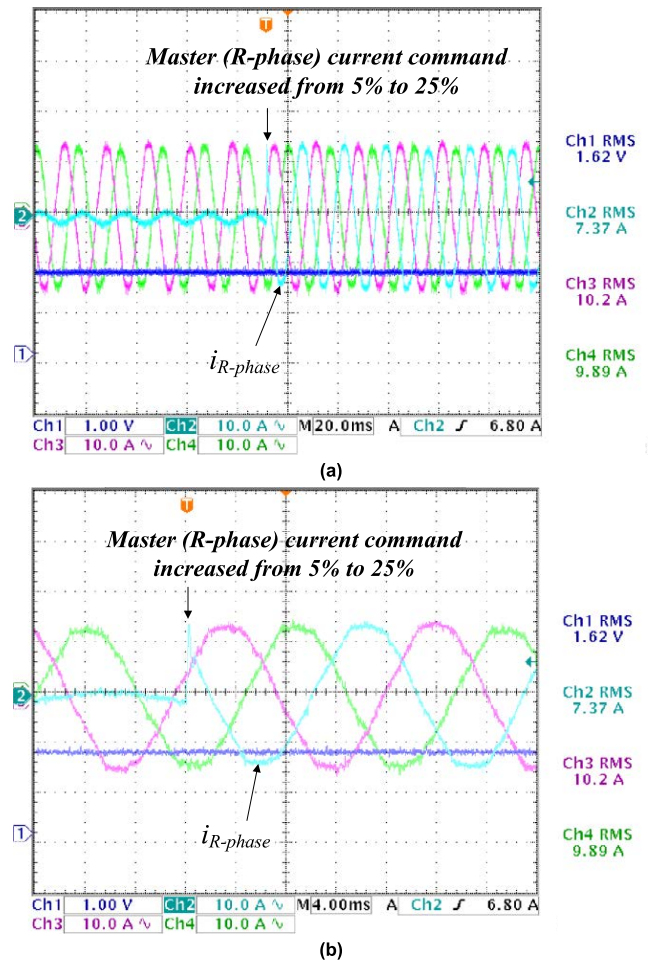


FIGURE 24. Current control of parallel-connected electronic load using the proposed communication method, (a) Experimental waveform when the Master (R-phase) current command of the electronic load increases from 5% to 25%, (b) Each phase current waveform at the moment when the current command is delivered.

correct the start bit according to the size of the impedance through the initialization process.

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN} \tag{6}$$

Fig. 27(b) is the precision analysis result calculated from the confusion matrix and (7). It is a criterion for evaluating how reliably an analytical model presents results. When the communication impedance is less than 5 Ω, it shows a high precision of 0.99, but at 20 Ω, it drops to 0.912.

$$\text{Precision} = \frac{TP}{TP + FP} \tag{7}$$

Fig. 27(c) is the confusion matrix and the recall analysis result calculated by (8). It is a measure related to communication practicality that can be compared with precision. It shows a high recall result of 0.98 or more at low impedance but drops to 0.97 at 20 Ω.

$$\text{Recall} = \frac{TP}{TP + FN} \tag{8}$$

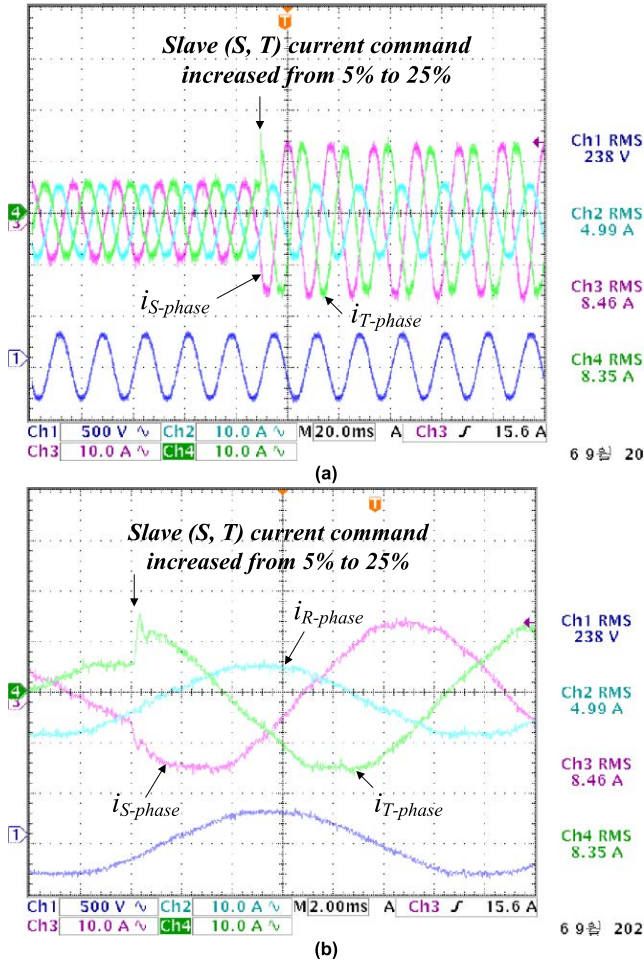


FIGURE 25. Current control of parallel-connected electronic load using the proposed communication method, (a) Experimental waveform when the slaves (S- and T-phase) current command of the electronic load increases from 5% to 25%, (b) Each phase current waveform at the moment when the current command is delivered.

		Predicted signal	
		P	N
Actual signal	P	True Positive (TP)	False Negative (FN)
	N	False Positive (FP)	True Negative (TN)

FIGURE 26. Confusion matrix for the reliability verification of the proposed new communication technique.

Fig. 27(d) is the result of the analysis of the F1 score calculated from the confusion matrix and (9). The F1 score is the harmonic average of precision and recall. Since the communication test signal is imbalanced, the F1 score is analyzed and presented in addition to Accuracy. It can be seen that it is almost similar to the accuracy result shown in

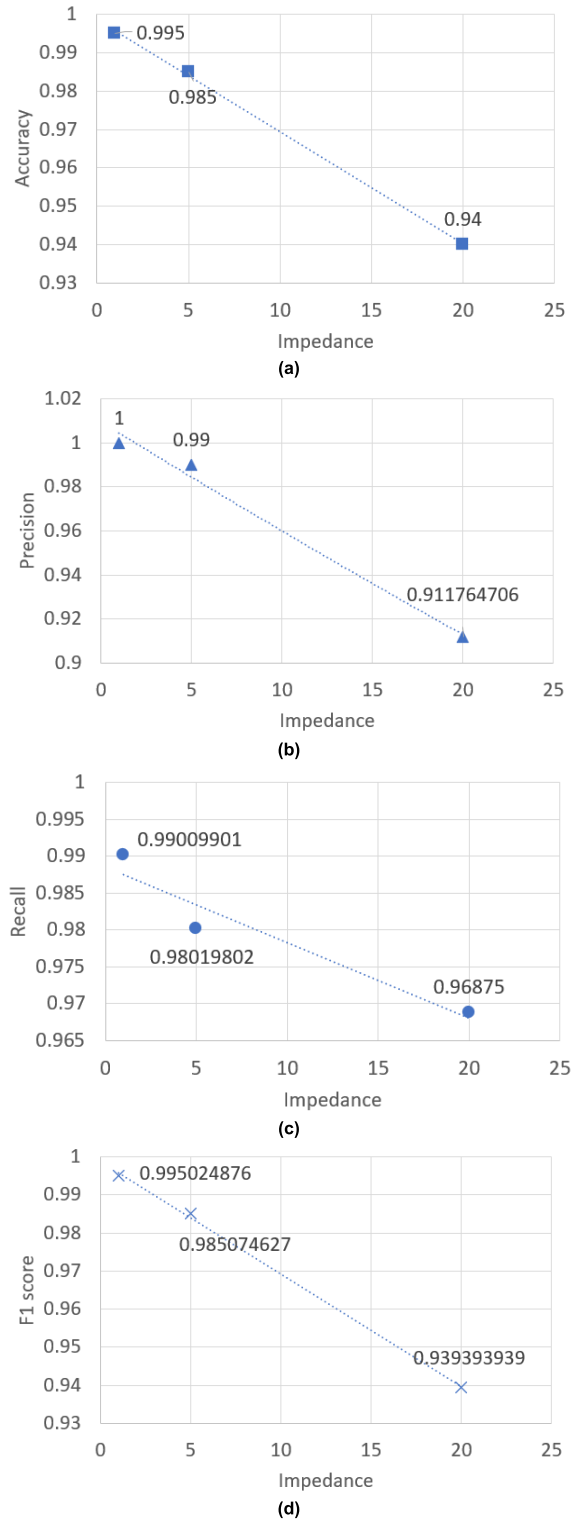


FIGURE 27. Reliability verification of the proposed communication method according to the impedance using the confusion matrix (a) accuracy, (b) precision, (c) recall, (d) F1 score.

Fig. 27(a).

$$F1_score = 2 \times \frac{Precision \times Recall}{Precision + Recall} \quad (9)$$

V. CONCLUSION

we propose a new communication method that enables fast and accurate communication between master and slave systems combined in parallel using the PWM and Capture functions of DSP. The proposed communication method uses the pulse width in the PWM function of DSP to express the size of the data and uses it together with the Capture function to enable bidirectional communication.

When using the 150 MHz CPU clock, the MODBUS protocol requires about 64 μs to transmit 8 data frames. The proposed communication method takes about 13.6 μs to transmit in the form of a pulse signal using the PWM function of DSP. It was confirmed that the data transmission speed could be improved by about 4.7 times. Also, thanks to the fast data transmission speed, it can have a data value of 10 bits, so noise canceling is possible by removing the lower 2 bits by using them as dummy data.

The experiment of the proposed method confirmed that the communication line operates accurately and stably up to a maximum length of 300 m and a line impedance of 20 Ω and 20 nF. It was confirmed that the proposed communication method works correctly from the current control response experiment according to the command value through the electronic load of the master-slave configuration operated in parallel. In conclusion, the proposed communication method has sufficient potential to replace the existing MODBUS method because it enables fast and accurate communication using the DSP's internal function used for power converter control.

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