

Fuzzy Logic-based Management of Hybrid Distribution Transformers Using LoRa Technology

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Abstract—Hybrid distribution transformers (HDTs) have better performance than traditional distribution transformers in improving power quality through reducing harmonics, unbalance, voltage fluctuations and low power factors in future smart power distribution systems. In order to increase the service life and reliability of hybrid distribution transformers, this paper proposes a remote management system using LoRa technology based on fuzzy logic. HDT based on a fuzzy logic judgment system (FLJS) replaces the Boolean logic with fuzzy logic and several power quality problems including power factors, load-side current harmonics and voltage unbalance are considered, as well as grid-side voltage deviation and unbalance. This management system can dynamically adjust the working states of HDT according to the output results of the FLJS to reduce the use time of power electronic devices. Due to the application of LoRa, this management system can remotely adjust the parameters of the FLJS in real time for different distribution network nodes to avoid frequent switching of HDT working states. In addition, it is able to remotely monitor the real-time working states and fault states of HDT to reduce recovery time and maintenance costs in case of HDT failure. Finally, simulation and experimental results are presented to verify the effectiveness of the proposed management system for HDT.

Index Terms—Fuzzy logic judgment system, hybrid distribution transformer, LoRa, Remote management.

I. INTRODUCTION

THE construction of the energy Internet, which can achieve wide area energy sharing and comprehensive regulation, has become an important issue in recent years [1]–[3]. As a part of the energy Internet, smart power distribution systems will integrate more and more distributed generators and further develop in the future in the direction of digitalization, decentralization, and lower carbon [4], [5]. However, as the penetration rate of various distributed power sources and DC loads in the distribution system continues to increase,

various power quality problems, such as harmonic distortion, unbalance, lower power factors and voltage fluctuations are becoming more and more serious [6].

Various solutions have been proposed to improve power quality including the static var compensator (SVC) [7], dynamic voltage restorer (DVR) [8], active power factor (APF) [9], solid-state transformer (SST) [10] and hybrid distribution transformer (HDT) [11]. Compared with SVC, SVG, APF, which can only solve part of the power quality problems, HDT can simultaneously achieve grid-side voltage compensation, load-side current compensation and a power factor (PF) of 1 [12]. Moreover, HDT has higher reliability and lower costs than SST because the main body of HDT is still a traditional distribution transformer (TDT) [13]. And when power electronic devices fail, HDT can still be used as a TDT by cutting off the power electronic devices [14]. So HDT is a promising device for constructing the future smart distribution system [15].

Some transformer management systems have been developed to optimize the distribution system [16], [17]. But these management systems are not suitable for HDT because the life of the power electronic devices are much shorter than transformers, for example if IGBTs are put into operation all the time, the life and reliability of HDT are worse than TDT. There might be dozens of HDTs at a distribution node, all the operation faults cannot be remotely monitored in real time, so there will be tremendous costs on regular inspections because HDTs are distant from each other.

LoRa (Long Range) is a long-range and low-power wireless telecommunications system that has great potential in remote management, and is promoted as an infrastructure solution for the Internet of Things by the LoRa Alliance [18]. To overcome the above mentioned problems concerning HDT, a remote management system for HDT based on fuzzy logic is proposed in this paper. Based on the application of LoRa technology, the use time of electronic devices are reduced by the management system output from FLJS, which can remotely control HDT changes into four different states in real time. The FLJS comprehensively considers multiple power quality indexes to avoid the singleness and absoluteness of power quality evaluation by replacing Boolean logic with fuzzy logic. Furthermore, the remote management system is able to remotely adjust the parameters of the FLJS for different distribution network nodes to avoid the concerns of frequent states switching in the HDT. The working states and fault states of HDTs can be monitored in real time through

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the wireless communication between HDTs and the remote management center, reducing the time of fault recovery and maintenance costs.

The main contributions of our study can be summarized as follows:

- For the first time, LoRa technology is applied in the remote management of HDT to increase the service life and reliability of HDT.
- The remote management, based on fuzzy logic, can comprehensively and reasonably consider multiple power quality indexes, while avoiding the singleness and absoluteness of power quality evaluation.
- The working states and fault states of all HDTs can be monitored in real time through wireless communication, reducing the time of fault recovery and maintenance costs.

The remainder of this paper is organized as follows: the operating principles and four working states of HDT are presented in Section II. The design of remote management system based on fuzzy logic for HDT is presented in Section III. The simulation of typical case analysis is presented in Section IV. Experimental studies are presented in Section VI. Finally, Section VI presents our conclusions.

II. TOPOLOGY AND MAIN FUNCTIONS OF HDT

A. Operating Principles and Main Functions of HDT

HDT consists of a three-phase three-winding main transformer T_1 , a three-phase two-winding isolation transformer T_2 and two voltage source inverters (VSIs) CV_1 and CV_2 . The three-phase equivalent topology of HDT is presented in Fig. 1. The presented HDT adds CV_1 as a current compensation device and CV_2 as a voltage compensation device to the TDT to realize the power quality management of the distribution system. A three-dimensional (3D) rendering of the HDT is shown in Fig. 2.

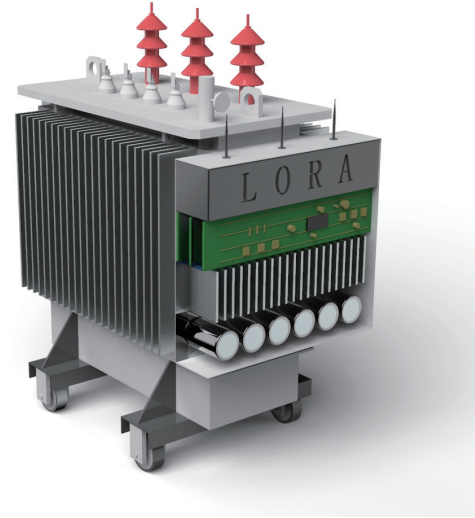


Fig. 2. 3D rendering of the HDT, including the LORA communication module, as described in Section III.

As shown in Fig. 1, the primary winding W_1 and the secondary winding W_2 of T_1 are respectively connected to the medium-voltage (MV) grid and the low-voltage (LV) grid, which transforms electric power from the MV to LV side. CV_1 , as the current compensation device, is connected to the tertiary winding W_3 of HDT through the inductor L_1 . CV_2 , as the voltage compensation device, is connected to the fourth winding W_4 of HDT through the inductor L_2 . Through the isolation transformer T_2 , CV_2 is connected to the MV grid together with W_1 after voltage level conversion. The power ratings of CV_1 and CV_2 primarily depend on the maximum fluctuation of the grid voltage and the power factor of the load in the extreme condition. In addition, the three sets of switches, S_1 , S_2 , and S_3 , in Fig. 1 are all bidirectional thyristors used to control the putting into use and removal of power electronic

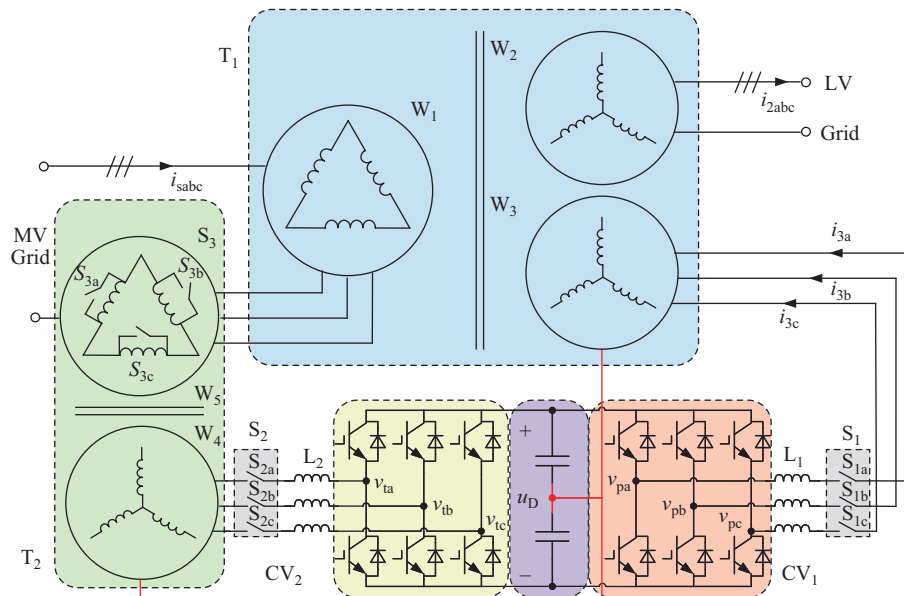


Fig. 1. Three-phase equivalent topology of HDT.

devices.

According to HDT's electric potential balance equation and magnetic potential balance (1), CV₁ is equivalent to a controllable current source. By controlling the output voltage v_{pk} of CV₁, the current i_{3k} of W₃ is able to compensate the harmonic, reactive, negative and zero sequence components of the load current i_{2k} . So when the load side has current distortion, unbalance, and low power factor problems, CV₁ can always keep the grid side current i_{sk} at the three-phase symmetrical sine and in phase with the grid voltage u_{sk} to ensure that the PF is 1 (k can be a, b or c).

$$\begin{cases} v_{pabc} - u_{3abc} = L_1 \frac{di_{3abc}}{dt} \\ N_1 i_{sabc} + N_3 i_{3abc} = N_2 i_{2abc} \end{cases} \quad (1)$$

where N_1, N_2, N_3 are the turns of the primary, secondary and tertiary winding respectively, L_1 is the connection inductance between W₃ and CV₁ and all the vectors are three-dimensional, e.g., $i_{sabc} = [i_{sa} \ i_{sb} \ i_{sc}]^T$.

$$\begin{cases} v_{tabc} - u_{4abc} = L_2 \frac{di_{4abc}}{dt} \\ \frac{u_{4abc}}{N_4} = \frac{u_{5abc}}{N_5} \\ \frac{u_{sabc}}{N_1} = \frac{u_{1abc} + u_{5abc}}{N_2} \end{cases} \quad (2)$$

where N_1, N_2, N_4, N_5 are the turns of W₁, W₂, W₄, W₅, u_{sabc} , u_{1abc} , u_{2abc} , u_{4abc} , u_{5abc} are the grid voltage and the voltage of W₁, W₂, W₄, W₅, respectively. L_2 is the connection inductance between W₄ and CV₂, and all the vectors are three-dimensional, e.g., $u_{sabc} = [u_{sa} \ u_{sb} \ u_{sc}]^T$.

According to (2), the output voltage v_{tk} of CV₂ is able to compensate the deviation, negative and zero sequence components of the grid voltage u_{sk} . So when the grid side has voltage fluctuation and asymmetric problems, CV₂ can always keep the load voltage u_{2k} stable, sinusoidal and symmetric (k can be a, b or c).

B. Four Working States of HDT

By controlling the switch group S₁, S₂, S₃, CV₁ and CV₂ can be operated so as to be connected or disconnected to/from the main transformer. HDT has the following four working states:

- Working state 1:
S₁, S₂ are open and S₃ is closed. HDT works as a TDT and only realizes the voltage level conversion from the primary side to the secondary side.
- Working state 2:
S₁, S₃ are closed and S₂ is open. Through the putting into use of CV₁, HDT realizes the compensation of the load side current i_{2k} . And HDT always keeps the grid side current i_{sk} at the three-phase symmetrical sinusoidal rated current value and in phase with the grid-side voltage to ensure that the PF is 1.
- Working state 3:
S₁, S₂ are closed and S₃ is open. HDT works in the voltage compensation state and maintains the load-side

voltage u_{2k} at the rated voltage of the three-phase symmetrical sine.

- Working state 4:
S₁, S₃ are open and S₂ is closed. HDT realizes the load side current compensation and the grid side voltage compensation at the same time.

III. REMOTE MANAGEMENT OF HDT USING LORA

A. Power Quality Indexes Calculation

Aiming at the problems of the load side current distortion, unbalance, low power factor, the three power quality indexes TDD_{i2} , ΔPF_2 , and UF_{i2} are proposed correspondingly in (3), (4) and (8):

$$TDD_{i2} = \frac{\sqrt{\sum_{n=2}^{\infty} I_{2an}^2} + \sqrt{\sum_{n=2}^{\infty} I_{2bn}^2} + \sqrt{\sum_{n=2}^{\infty} I_{2cn}^2}}{3I_{2N}} \quad (3)$$

$$\begin{cases} P_2 = P_{2a} + P_{2b} + P_{2c} \\ S_2 = S_{2a} + S_{2b} + S_{2c} \\ \Delta PF_2 = 1 - \frac{P_2}{S_2} \end{cases} \quad (4)$$

Here:

$$\begin{cases} P_{2k} = U_{2k1} I_{2k1} \cos \varphi_{2k} \\ S_{2k} = \sqrt{\sum_{n=1}^{\infty} U_{2kn}^2} \sqrt{\sum_{n=1}^{\infty} I_{2kn}^2} \end{cases} \quad (5)$$

where U_{2kn} and I_{2kn} are the effective value of the n^{th} harmonic component of u_{2k} and i_{2k} ; I_{2N} is the rated current value of the secondary side of HDT; k can be a, b or c.

$$I_{2a}^{120} = \mathbf{A} I_{2abc} \quad (6)$$

Here, $I_{2a}^{120} = [I_{2a1} \ I_{2b2} \ I_{2c0}]^T$, $I_{2abc} = [I_{2a} \ I_{2b} \ I_{2c}]^T$ and:

$$\mathbf{A} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \quad (7)$$

where $\alpha = e^{j2\pi/3}$; I_{2a} , I_{2b} , I_{2c} are the three-phase current phasor of the load; I_{2a1} , I_{2a2} , I_{2a0} are the positive sequence, negative sequence and zero sequence components of I_{2a} .

$$UF_{i2} = \frac{\sqrt{I_{2a0}^2 + I_{2a2}^2}}{I_{2N}} \quad (8)$$

Similarly, for the problem of the grid side voltage fluctuation and unbalance, two power quality indexes UF_{us} , and AD_{us} are proposed in (10) and (11):

$$U_{sa}^{120} = \mathbf{A} U_{sabc} \quad (9)$$

$$UF_{us} = \frac{\sqrt{U_{sa0}^2 + U_{sa2}^2}}{U_{1N}} \quad (10)$$

where $U_{sa}^{120} = [U_{sa1} \ U_{sa2} \ U_{sa0}]^T$, $U_{sabc} = [U_{sa} \ U_{sb} \ U_{sc}]^T$; U_{sa} , U_{sb} , U_{sc} are the three-phase voltage phasor of the grid; U_{sa1} , U_{sa2} , U_{sa0} are the positive sequence, negative sequence and zero sequence components of U_{sa} ; U_{1N} is the rated voltage value of the primary side of HDT.

$$AD_{us} = \left| \frac{U_{sa1} + U_{sb1} + U_{sc1}}{3U_{1N}} - 1 \right| \quad (11)$$

where U_{sk1} is the fundamental component of the grid side voltage u_{sk} ; k can be a, b or c.

All power quality indexes, except ΔPF_1 and ΔPF_2 , are normalized according to the rated parameters of HDT to ensure the effectiveness and rationality of the FLJS under no-load or light load situations.

Based on the same method, the FLJS also calculates the power quality indexes about the load side voltage and grid side current: TDD_{is} , ΔPF_1 , UF_{is} , UF_{u2} , and AD_{u2} . Through these indexes, the remote management system can judge the failure of HDT.

B. Design of Fuzzy Logic Judgement System

In order to avoid the singleness of power quality evaluation indexes, the FLJS uses the power quality index matrix U that uses TDD_{i2} , ΔPF_2 , UF_{i2} , UF_{us} and AD_{us} as input.

$$U = [UF_{i2} \quad TDD_{i2} \quad \Delta PF_2 \quad UF_{us} \quad AD_{us}] \quad (12)$$

The evaluation set matrix V of fuzzy logic is shown in (13):

$$V = [NB \quad NS \quad PS \quad PB] \quad (13)$$

With different requirements for each power quality problem, as shown in Table I, membership functions should be diversely designed for TDD_{i2} , ΔPF_2 , UF_{i2} , UF_{us} and AD_{us} respectively. In this paper, the upper limit standards of TDD_{i2} , ΔPF_2 , UF_{i2} , UF_{us} , and AD_{us} are respectively 15%, 20%, 10%, 5% and 10%.

TABLE I
POWER QUALITY STANDARDS FOR DISTRIBUTION SYSTEM

Related Standards	Power Quality Problems	Requirements
IEEE Std 519-2014 [19]	Harmonic	$TDD_i < 20\%$
IEEE Std 1159-2009 [20]	Unbalance	$UF_v < 2\%$
GB/T 15543-2008 [21]		$UF_i < 10\%$
GB755-87 [22]		
Regulation of power factor adjusting charge [9]	Reactive power	$PF > 0.8$

Considering the delay of wireless transmission, severe damage may occur on the load side before a voltage compensation device can be put into operation once the grid voltage indicates serious problem cases. Thus, high priority protection needs to be designed to avoid these potential risks. Once UF_{us} or AD_{us} exceeds the upper limit value, CV_2 is immediately put into operation through local management to protect the critical load.

The FLJS designs corresponding membership functions for these five power quality indexes and uses UF_{i2} as an example. Since the unbalanced requirement about the load-side current in the power distribution system cannot be greater than 10%, the triangular membership function of UF_{i2} is shown in Fig. 3.

The fuzzy relationship mapping $U \rightarrow V$ is completed by (14) to obtain the fuzzy matrix R .

$$R_{5 \times 4} = U^T \circ V \quad (14)$$

The output of the FLJS F_{i2} and F_{us} are shown in (15):

$$\begin{cases} F_{i2} = B_I R S^T \\ F_{us} = B_U R S^T \end{cases} \quad (15)$$

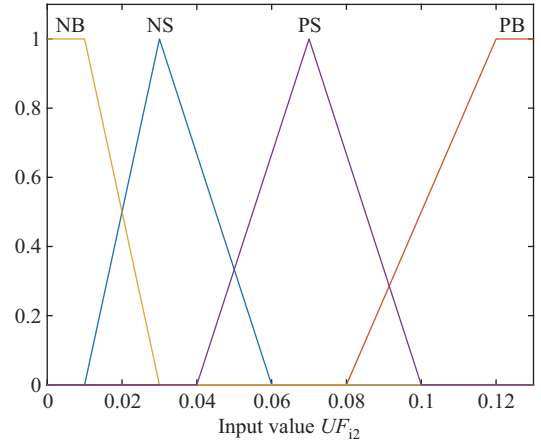


Fig. 3. Triangular membership function of UF_{i2} .

where $S = [s_1 \quad s_2 \quad s_3 \quad s_4]$ is the evaluation set weight matrix; $B_I = [b_1 \quad b_2 \quad b_3 \quad 0 \quad 0]$ is the load-side current index weight matrix; $B_U = [0 \quad 0 \quad 0 \quad b_4 \quad b_5]$ is the grid-side voltage index weight matrix.

C. Application of LoRa for a Remote Management System

Because the distance between HDTs in the distribution system is very long, this paper proposes a remote management system to realize the real-time working status adjustment and fault detection of all HDTs in the power distribution system by applying LoRa.

The overall structure diagram of HDTs' remote management center is shown in Fig. 4. The LoRa data transceivers of all HDTs wirelessly send the grid-side voltage U_{sabc} and current I_{sabc} and the load-side voltage U_{2abc} and current I_{2abc} of the distribution node to the remote management center. Then it calculates the power quality indexes TDD_{i2} , ΔPF_2 , UF_{i2} , UF_{us} , and AD_{us} representing U_{sabc} and I_{2abc} and the power indexes TDD_{is} , ΔPF_1 , UF_{is} , UF_{u2} , and AD_{u2} representing U_{2abc} and I_{sabc} . And the FLJS calculates F_{i2} and F_{us} based on fuzzy logic and sends them to the management system. All HDTs of the distribution network node are performed using independent remote management.

Finally, the management system judges the correct working state of HDT according to whether the values of F_{i2} and F_{us} are positive or negative, and sends the working state command to HDT through the LoRa data transceiver. At the same time, the management system calculates the average value C of W in the previous period nT in real time as shown in (16). The management system knows the effect of the power quality management of the distribution node and whether the HDT has failed by comparing C with the corresponding power quality index in Table I.

$$C = \frac{\int_{t-nT}^t W dt}{nT} \quad (16)$$

where $W = [TDD_{is} \quad \Delta PF_1 \quad UF_{is} \quad UF_{u2} \quad AD_{u2}]^T$; $C = [c_1 \quad c_2 \quad c_3 \quad c_4 \quad c_5]^T$; $T = 1/f_0$, f_0 is the rated frequency of HDT.

The workflow and judgment logic of the management system is shown in Fig. 5.

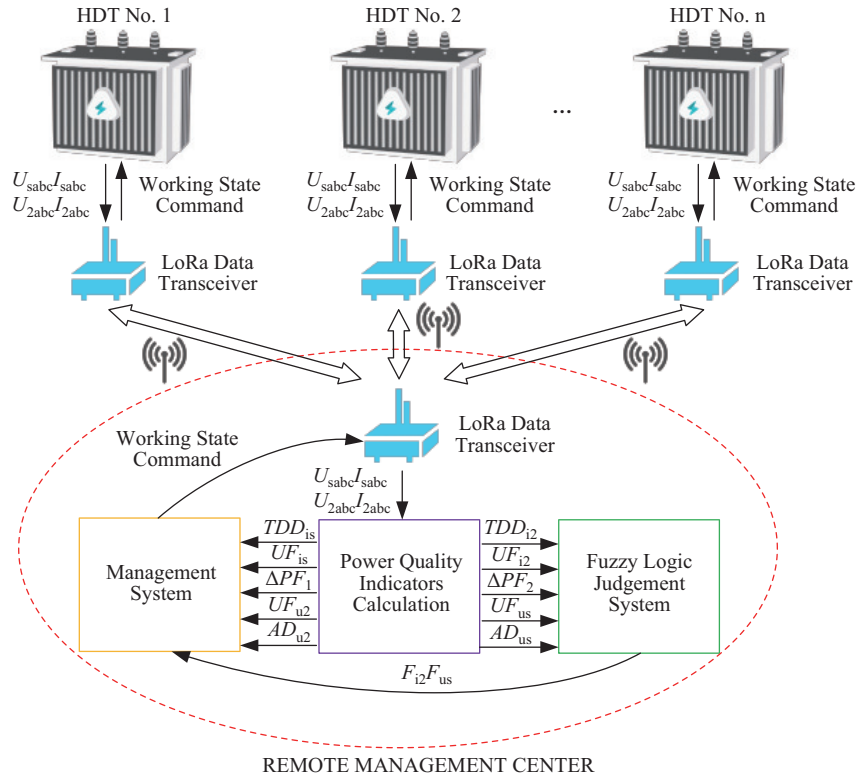


Fig. 4. Overall diagram of HDTs' remote management center.

Once a fault is found in a certain HDT, the remote management system will issue commands to remove the power electronic device and use it as a TDT to ensure that the power distribution system can still operate stably. At the same time, the management center will report the number of the faulty HDT and its location in the power distribution system so that the HDT can be repaired in time. Using LoRa to achieve remote real-time monitoring of HDT instead of regular inspection maintenance can reduce HDT failure recovery time and maintenance costs.

IV. SIMULATION ANALYSIS OF TYPICAL CASES

Since all HDTs are independently managed, the simulation results of one HDT can verify the effectiveness of the proposed remote management system. Simulation analyses are conducted for typical cases under different working states of HDT in this section. The HDT and management system parameters used in simulations are shown in Table II. The influence of the time delay of the wireless transmission of

TABLE II
HDT AND MANAGEMENT SYSTEM PARAMETERS USED IN SIMULATION

Parameter	Value	Parameter	Value
U_{1N}	10 kV	u_D	1000 V
U_{2N}	$400/\sqrt{3}$ V	f_0	50 Hz
U_{3N}	100 V	L_1	1.5 mH
U_{4N}	150 V	L_2	4 mH
U_{5N}	2000 V	B_I	[0.35 0.4 0.25 0 0]
I_{1N}	2 A	B_U	[0 0 0 0.35 0.65]
I_{2N}	$50\sqrt{3}$ A	—	—

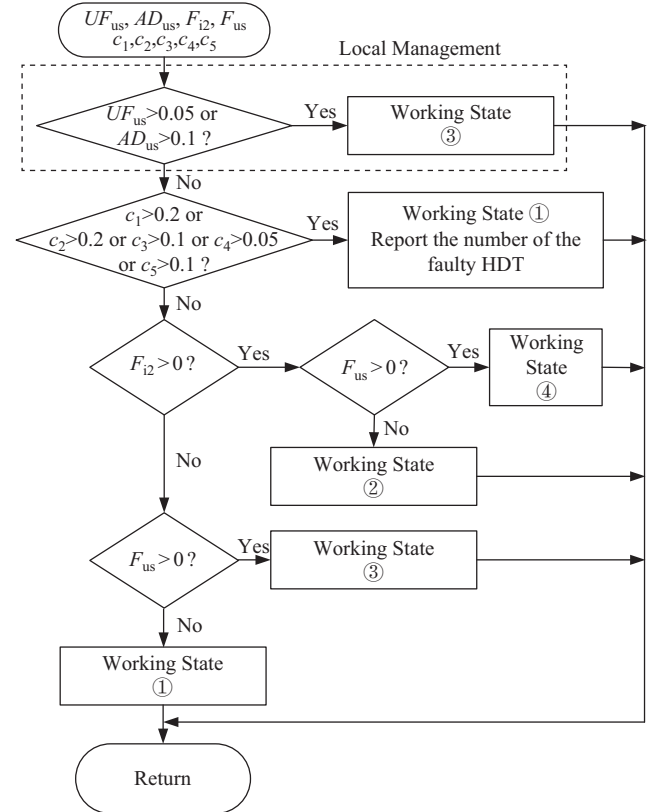


Fig. 5. Flowchart of the management system for HDT.

the LoRa communication module is not considered in the simulation but is studied in the experiment in Section V.

A. Working State 2

Assuming that the voltage on the grid side has always been stable, the simulation of working state 2 considers the process of connecting the distorted load, connecting the unbalanced load, removing the distorted load and removing the unbalanced load on the load side.

The response process of HDT and the management system under load distortion and unbalance is shown in Fig. 6. At $t = 0.06$ s, a distorted load is connected to the load side, causing TDD_{is} and TDD_{i2} to increase. The FLJS judges that the load-side current needs to be compensated and the management system sends the command of working state 2 to HDT at $t = 0.072$ s. TDD_{is} drops to 8.3% through the access and current compensation of CV_1 .

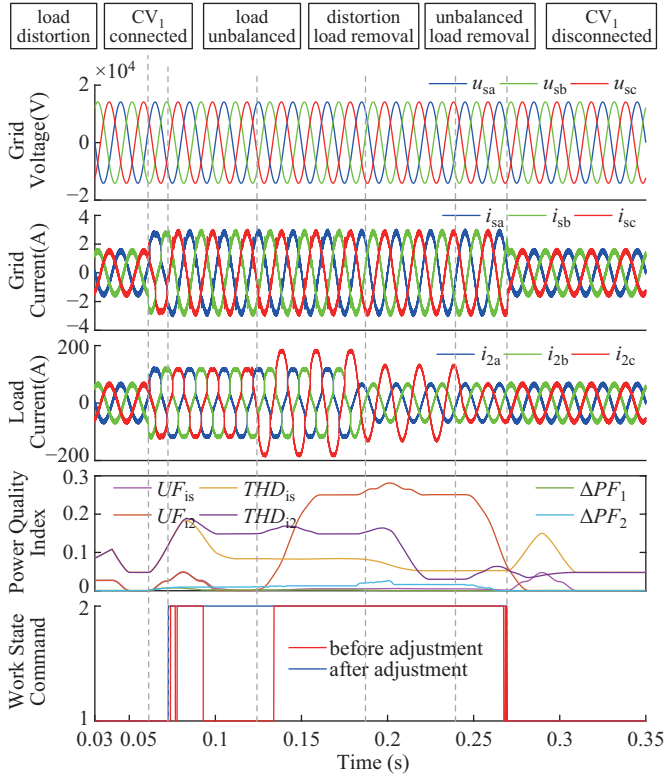


Fig. 6. Response process of HDT and the management system under load distortion and unbalance.

At $t = 0.12$ s, the unbalanced load access causes UFI_2 to rise to 25%. The load side removes the distorted load at $t = 0.18$ s and the unbalanced load at $t = 0.24$ s. During the period of 0.072 s ~ 0.24 s, the FLJS always judges that the current power quality needs compensation and HDT maintains the access of CV_1 .

As shown in the second and fourth graphs of Fig. 6, the grid-side current remains symmetrical and sinusoidal under the compensation of CV_1 . TDD_{is} decreases from 14.8% to 8.3% and UFI_s decreases from 25% to 0.5%. The current compensation effect of CV_1 is shown in Table III.

At $t = 0.27$ s, the FLJS judges the power quality recovery of the load-side current and the management system sends the command of working state 1 to HDT.

TABLE III
CURRENT COMPENSATION EFFECT OF CV_1 FOR DISTORTION AND UNBALANCE

Cases	Grid Side Current Index	Value	Load Side Current Index	Value	Standard Upper Limit
distortion load access	TDD_{is}	8.5%	TDD_{i2}	15.1%	15%
unbalanced load access	UFI_s	0.5%	UFI_2	25%	10%

The last graph in Fig. 6 shows a comparison of the command of the management system corresponding to the different evaluation set weight matrices of S . The blue line represents the case of $S = [-100 \ -50 \ 100 \ 300]$ and the red line represents the case of $S = [-150 \ -50 \ 100 \ 200]$. Through comparison, it can be seen that if S is inappropriate, it will cause frequent switching of the HDT working state and incorrect judgment of the FLJS. Therefore, the remote management system needs to adjust S according to different distribution nodes to avoid this situation.

B. Working State 3

Assuming that the current on the load side has always been symmetrical and sinusoidal, the simulation of working state 3 considers the process of voltage dip, voltage unbalance, voltage swell and voltage recovery on the grid side.

The response process of HDT and the management system under sudden change and unbalance of the grid voltage is shown in Fig. 7. At $t = 0.06$ s, a sudden drop in the grid voltage causes AD_{us} and AD_{u2} to increase. After half a

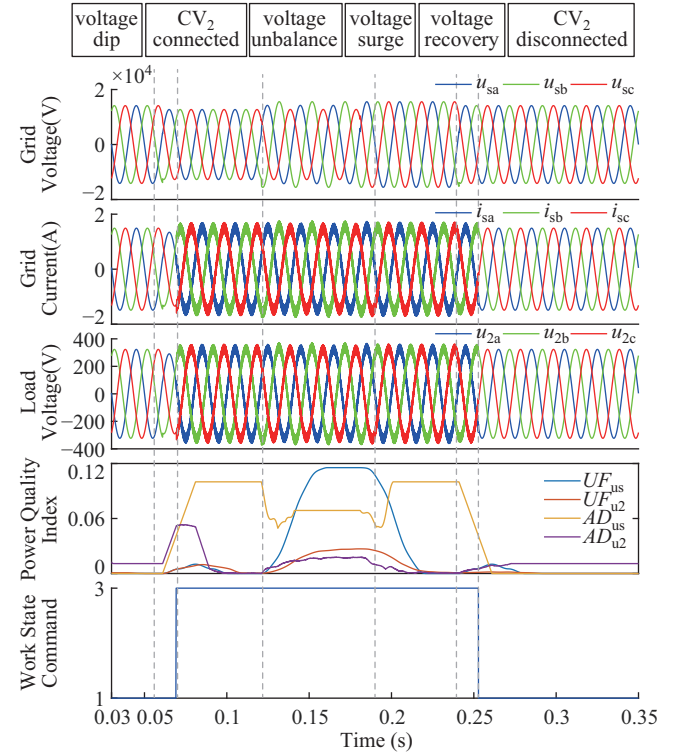


Fig. 7. Response process of HDT and management system under sudden change and unbalance of grid voltage.

power frequency period, the FLJS recognizes that the grid side voltage needs compensation. HDT is adjusted from working state 1 to 3 at $t = 0.07$ s. After that, the grid voltage is unbalanced and suddenly increases at the times of 0.12 s and 0.18 s.

As shown in the fourth graph of Fig. 7, UF_{us} increases to 11.5% during 0.12 s $\sim$ 0.18 s and AD_{us} increases to 10% during 0.06 s $\sim$ 0.12 s and 0.18 s $\sim$ 0.24 s.

But as the second graph of Fig. 7 indicates, the load side voltage maintains the rated working voltage after 0.07 s. Meanwhile, AD_{u2} and UF_{u2} are reduced to a maximum of 1.5% and 2.5% respectively under the compensation of CV_2 . The voltage compensation effect of CV_2 is shown in Table IV.

TABLE IV
VOLTAGE COMPENSATION EFFECT OF CV_2 FOR VOLTAGE DIP, SWELL AND UNBALANCE

Cases	Grid Side Current Index	Value	Load Side Current Index	Value	Standard Upper Limit
voltage dip	AD_{u2}	0.1%	AD_{us}	10%	10%
voltage unbalance	UF_{u2}	2.5%	UF_{us}	11.5%	5%
voltage unbalance	AD_{u2}	1.5%	AD_{us}	7%	10%
voltage swell	AD_{u2}	0.1%	AD_{us}	10%	10%

At $t = 0.253$ s, the FLJS determines that the grid voltage is restored to the rated voltage and HDT returns to working state 1 by cutting off CV_2 .

C. Working State 4 and Fault State

Assuming that both the grid voltage and load current have power quality problems, the simulation of working state 4 considers the process of $PF_2 = 0.865$, voltage dip, connecting the distorted load and voltage recovery. And the simulation of the fault state takes into account that the CV_1 of HDT has an IGBT open circuit fault.

The response process of HDT and the management system under grid voltage dip, load distortion and fault state are shown in Fig. 8.

As shown in the first and fourth graphs of Fig. 8, the grid voltage dropped suddenly at $t = 0.06$ s and the management system sends a command to adjust HDT from working state 1 to 3 after less than half a power frequency period. At $t = 0.12$ s, a distorted load is connected to the load side. Then HDT is connected to CV_1 and CV_2 at the same time and is adjusted to working state 4 at $t = 0.13$ s. After that, the grid voltage recovers at $t = 0.18$ s and HDT is adjusted from working state 4 to 2 at $t = 0.192$ s.

As shown in the second, third and fifth graphs of Fig. 8, the load voltage maintains the rated sinusoidal voltage and AD_{u2} is always less than 2% when the system is stable during 0.06 s $\sim$ 0.24 s. In addition, the grid current is always sinusoidal, symmetrical, and in phase with the grid voltage when the system is stable. ΔPF_1 and TDD_{is} are respectively less than 0.2% and 8.5% under the compensation of CV_1 . The compensation effect of CV_1 and CV_2 is shown in Table V.

The last graph in Fig. 8 shows a comparison of the command of the management system based on Boolean logic and fuzzy logic. Based on Boolean logic, the management system will

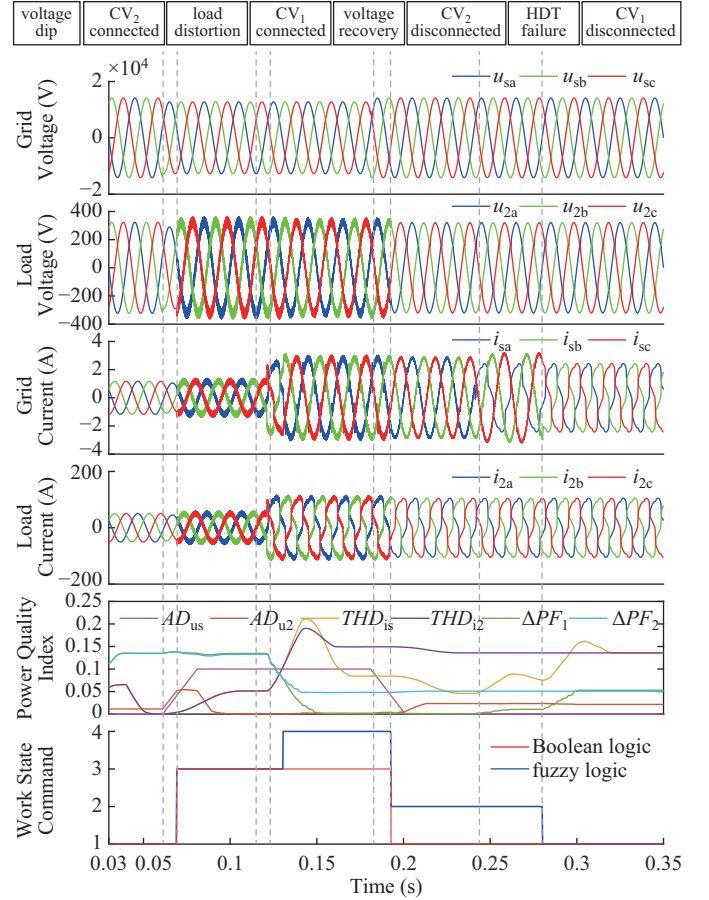


Fig. 8. Response process of HDT and management system under grid voltage dip, load distortion and fault state.

send the corresponding compensation command when one of the indexes in TDD_{i2} , ΔPF_2 , UF_{i2} , UF_{us} , and AD_{us} exceeds the upper limit standard. Because ΔPF_2 and TDD_{i2} have not exceeded the corresponding upper limit standards, the management system based on Boolean logic does not send the command of current compensation during 0.12 s $\sim$ 0.24 s. Fuzzy logic allows the management system to comprehensively consider various power quality indexes and overcomes the singleness and absoluteness of power quality evaluation.

The IGBT in the CV_1 of HDT has an open circuit fault at $t = 0.24$ s. The FLJS recognizes that CV_1 had a failure and the management system removes all HDT's power electronic devices and reports the failure state of HDT at $t = 0.28$ s.

V. EXPERIMENTAL STUDIES

An experimental prototype of HDT based on DSP and LoRa communication is developed to further verify the proposed remote management system, as shown in Fig. 9. Due to the limitations of the laboratory conditions, both the voltage and capacity level of the experimental prototype are lower than that in the simulation, as shown in Table VI.

Three typical cases of current compensation, voltage compensation and HDT fault are studied separately in this section.

TABLE V
COMPENSATION EFFECT OF CV_1 AND CV_2 FOR LOW POWER FACTOR,
VOLTAGE DIP AND LOAD DISTORTION

Cases	Grid Side Current Index	Value	Load Side Current Index	Value	Standard Upper Limit
voltage dip	AD_{u2}	0.1%	AD_{us}	10%	10%
low PF load distortion	ΔPF_1	2.5%	ΔPF_2	13.5%	20%
low PF load distortion	TDD_{is}	8.3%	TDD_{i2}	14.8%	15%

TABLE VI
PARAMETERS OF EXPERIMENTAL PROTOTYPE

Parameter	Value	Parameter	Value
U_{1N}	50 V	I_{2N}	1.6 A
U_{2N}	22 V	u_D	50 V
U_{3N}	16 V	f_0	50 Hz
U_{4N}	20 V	L_1	1.5 mH
U_{5N}	20 V	L_2	5 mH
I_{1N}	$\sqrt{2}/2$ A	—	—

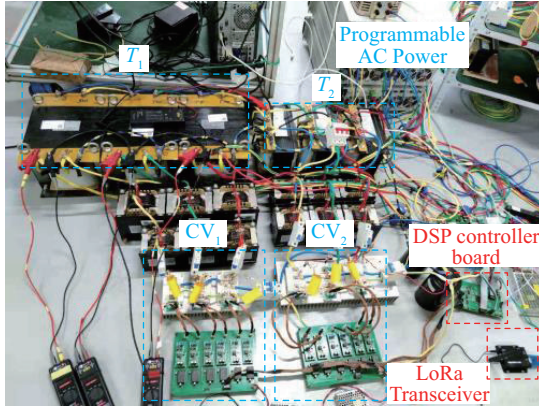


Fig. 9. Experimental prototype of HDT.

A. Experimental Waveforms of Current Compensation

1) Experiment of Load Distortion

Figure 10 shows the experimental waveforms of load distortion and CV_1 connected. Initially, the load side is connected to a symmetrical resistance load and the HDT works at state 1. After the distorted load is connected, both the grid current and the load current are distorted. Then the remote management system determines that the load current needs to be compensated and sends the command to HDT. After a delay of about 0.22 s, CV_1 is connected and the grid current is compensated to symmetrical sinusoidal waveforms.

2) Experiment of Load Distortion and Unbalance

Figure 11 shows the experimental waveforms of load distortion and unbalance. The distorted load is initially connected to the load side and the HDT works at state 2. After the unbalanced load is connected, CV_1 still performs current compensation. And there is no sudden change in the grid current and it has always been symmetrical and sinusoidal.

3) Experiment of Distortion Load Removal

Figure 12 shows the experimental waveforms of distortion load removal and CV_1 disconnected. Initially, the load side is connected to a distortion load and the HDT works at state 2.

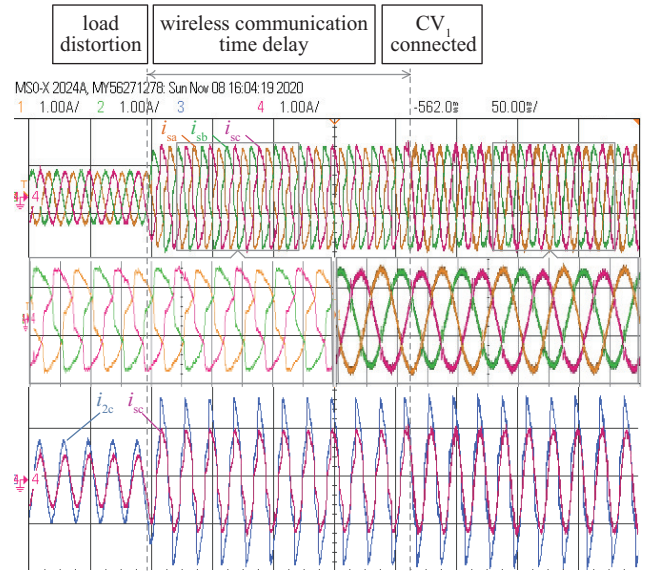


Fig. 10. Experimental waveforms of distortion load access and CV_1 connected.

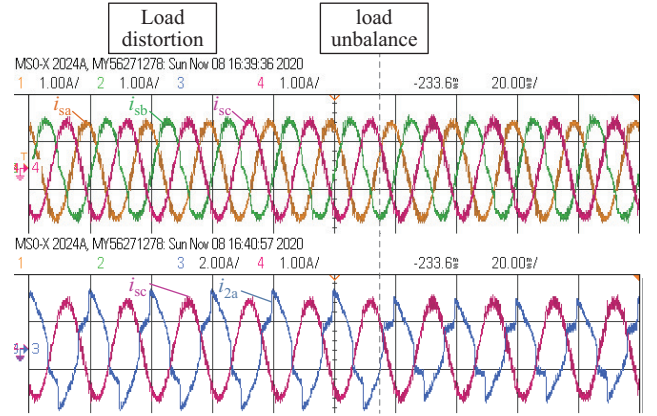


Fig. 11. Experimental waveforms of load distortion and unbalance.

After the distorted load is removed, the load current returns to symmetrical and sinusoidal. After a delay of about 0.2 s, CV_1 is disconnected and HDT returns to work as TDT.

B. Experimental Waveforms of Voltage Compensation

Figures 13 and 14 show the experimental waveforms of grid voltage that dips 20% and 6.5%, respectively. When the grid voltage dips 20%, the voltage compensation device CV_2 immediately is put into operation to avoid huge fluctuations on the load voltage. After a transient process of about 0.03 s, the load voltage is restored to the rated voltage through local management. And in the case that the grid voltage dips only 6.5%, the remote management system adjusts the working state of HDT from 1 to 3, and the load voltage returns to the rated voltage after a delay of about 0.2 s. Similarly, as shown in Fig. 15, CV_2 is cut off and HDT returns to working state 1 after a delay of about 0.2 s when the grid voltage is restored.

C. Experimental Waveforms of HDT Fault

Figure 16 shows the experimental waveforms of HDT fault

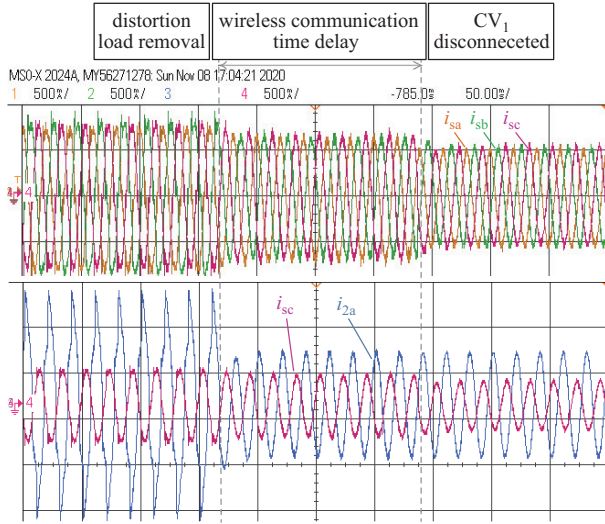


Fig. 12. Experimental waveforms of distortion load removal and CV₁ disconnected.

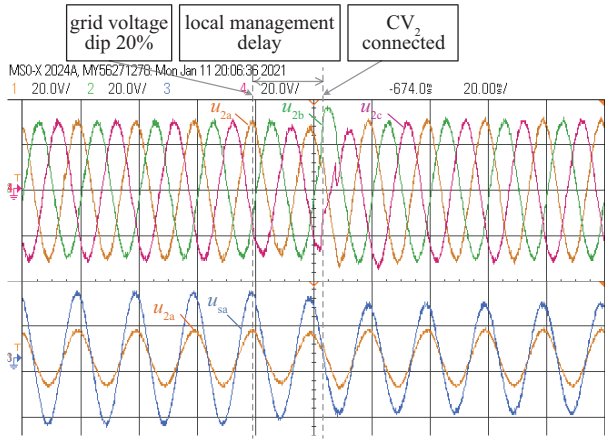


Fig. 13. Experimental waveforms of grid voltage dip 20%.

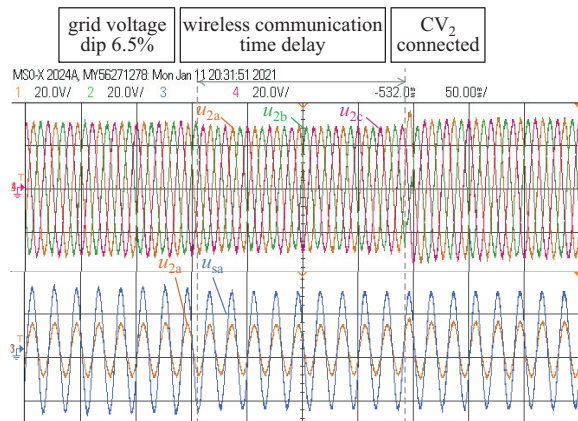


Fig. 14. Experimental waveforms of grid voltage dip 6.5%.

response process. Initially, HDT was working in the current compensation state. At a certain moment, the a-phase IGBT of CV₁ suddenly has an open circuit fault. The remote management system recognizes that the HDT is malfunctioning and sends a command to remove all power electronic devices.

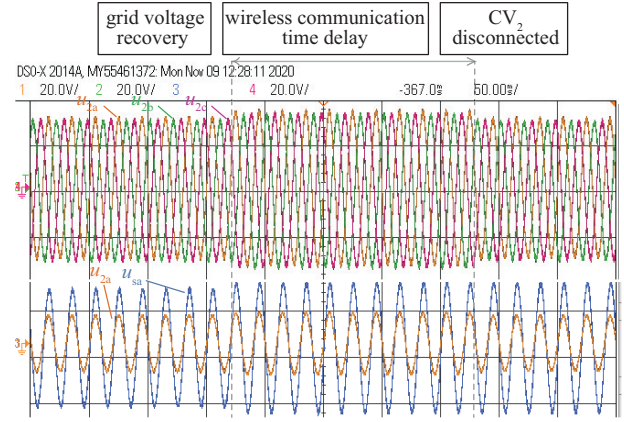


Fig. 15. Experimental waveforms of grid voltage recovery and CV₂ disconnected.

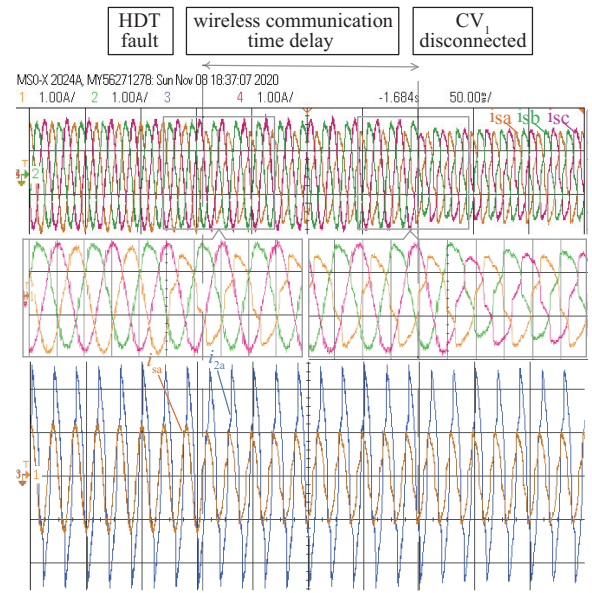


Fig. 16. Experimental waveforms of HDT fault response process.

After a delay of about 0.2 s, HDT returns to work as TDT and ensures that the distribution system can continue to operate stably.

VI. CONCLUSION

In this paper, a remote management system of HDT using LoRa technology is developed for power quality management of power distribution systems. The remote management center adjusts the working state of HDT in real time to ensure that the load voltage always maintains the rated value, the grid current maintains sinusoidal symmetry and the power factor is 1 according to the status of each distribution node. The fuzzy logic judgement system can comprehensively take harmonics, unbalance, and low power factor states into consideration, in order to increase the service life and reliability of HDT. The proposed system allows HDT to still work as TDT and maintain stable operations of the distribution network in the case of HDT failing. At the same time, it reduces the maintenance cost of HDT and the recovery time in case of failure.

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