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Efficient cloud-based digital-physical testing method for feeder automation system in electrical power distribution network

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Abstract: A feeder automation (FA) system is usually used by electricity utilities to improve power supply reliability. The FA system was realized by the coordinated control of feeder terminal units (FTUs) in the electrical power distribution network. Existing FA testing technologies can only test basic functions of FTUs, while the coordinated control function among several FTUs during the self-healing process cannot be tested and evaluated. In this paper, a novel cloud-based digital-physical testing method is proposed and discussed for coordinated control capacity test of the FTUs in the distribution network. The coordinated control principle of the FTUs in the local-reclosing FA system is introduced firstly and then, the scheme of the proposed cloud-based digital-physical FA testing method is proposed and discussed. The theoretical action sequences of the FTUs consisting of the FTU under test and the FTUs installed in the same feeder are analyzed and illustrated. The theoretical action sequences are compared with the test results obtained by the realized cloud-based simulation platform and the digital-physical hybrid communication interaction. The coordinated control capacity of the FTUs can be evaluated by the comparative result. Experimental verification shows that the FA function can be tested efficiently and accurately based on our proposed method in the power distribution system inspection.

Key words: cloud simulation, digital-physical testing method, feeder automation, feeder terminal unit, power distribution system

1. Introduction

In recent years, a feeder automation (FA) system has been widely used by electricity utilities to improve power supply reliability. The FA system is an indispensable technique to monitor the operating status of the power distribution system [1]. The monitoring terminals, also known as the feeder terminal units (FTUs) [2], data transfer units (DTUs) or remote terminal units (RTUs) [3], have been widely installed in the rural power distribution network. The FTU is designed to be used with the corresponding pole-mounted switch. The FTU functions mainly include remote and local control, signal measurement, and over-current protection.

The existing FA modes can be categorized as the centralized intelligent control mode, intelligent distributed control mode, and local reclosing control mode [4]. In the centralized intelligent control mode, each FTU detects the faults based on the local measured voltage and current signals, and then transmits the detection results to the distribution automation master station for advanced self-healing application [5]. The fault position will be located by the master station and then the FTUs installed at the left and right sides of the fault position would be controlled to emit the trip signal. In the intelligent distributed control mode, any adjacent FTUs communicate with each other to locate the fault and then send the trip signal to the corresponding switches to isolate the fault [6]. In the local reclosing control mode, once the recloser is reclosed for the second time, the FTU located before the fault position would automatically keep the corresponding pole-mounted switch in the open status without data communication [7, 8]. In the local reclosing control mode, the fault section can be isolated by the coordinated control of FTUs with different local setting parameters. The local reclosing FA mode has been widely applied in the field because it does not need any additional communication channel or the distribution automation master station.

In the local-reclosing FA system, the fault can be located and isolated only under the accurate coordinated control of all FTUs. If any FTU does not act with the proper setting parameters, the isolation area would be expanded and the FA system would lose efficiency. The FA testing technologies are usually used to test the fault isolation function of FA in the routine maintenance to prevent the FA system failure. Existing FA testing methods mainly include the host injection (HI) testing method and the secondary synchronous injection (SSI) testing method. In the HI testing method, one dedicated test platform is used to inject a testing signal to the distribution automation master station. Thus, the FA system with centralized control mode could be tested by observing whether the fault area could be isolated or not by the embedded self-healing subroutine [9]. In the SSI testing method, fault simulator devices (FSDs) are applied to inject a simulated fault signal into the corresponding FTUs [10]. All pre-built fault signals are reproduced by the FSD and the FTU functions could be tested for these fault signals. However, each FTU is tested for independent simulated fault signals generated by the FSD by the SSI testing method. Therefore, the coordinated control of the FTUs in the FA with local reclosing mode cannot be tested by existing testing methods.

In order to test the coordinated control capability of the FTUs in the FA system with local reclosing mode, a novel FA testing method is presented in this paper and realized by an efficient cloud-based power distribution system simulation platform and digital-physical hybrid communication interaction. Firstly, the principle of the local-reclosing FA system is analyzed. Secondly, the novel efficient cloud-based digital-physical FA testing method is proposed and analyzed. Thirdly, the proposed FA testing method is realized based on the cloud-based simulation platform and an interactive script in the FTU installed in the field. Finally, the proposed method is verified in the FA system testing experiments.

2. Coordinated control of FTUs in the local-reclosing FA system

In the local-reclosing FA system, voltage-time FTUs along with a source-side recloser are usually used to locate and isolate the fault section. Once a fault occurred, it would be detected and interrupted by the upline recloser. The voltage-time FTU detects loss and restoration of voltage and utilizes the voltage-time action logic to isolate the fault section with the actions of the recloser. In the voltage-time action logic, two parameter settings in the FTUs are related to the coordinated control of the FTUs in the self-healing process. One is the close time and the other is the reset time. The close time begins when the distribution line section before the installation position of the FTU is energized. After the close time, the FTU sends the close signal to the corresponding switches. The reset time is the length of time setting to reset. It begins when the FTU emits the close signal and the input voltage must be sustained at the acceptable voltage level during the reset time. The switch controlled by the FTU would unlock if the FTU re-emits the trip signal before the reset time elapses.

A single ring main feeder with several laterals is shown in Figure 1. There are eight voltage-time FTUs and the corresponding switches. Different setting parameters should be set in different FTUs to ensure the coordinated control function of the FTUs during the fault isolation. The typical setting parameters are shown in Table 1. The most important principle of setting the parameters is that there should be only one or no switch in the closing process at the same time in the self-healing, once a fault occurred on the distribution line.

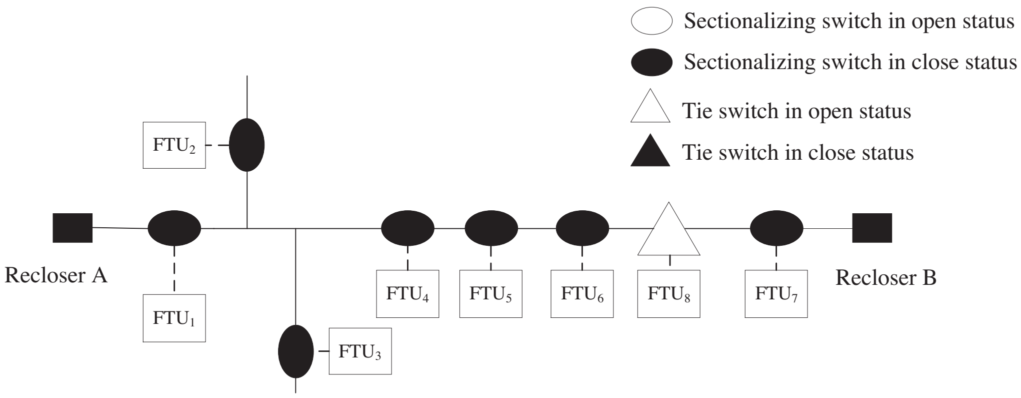


Fig. 1. A single-line diagram of typical ring main feeder with local-reclosing FA system

Table 1. The setting parameters for the FTUs shown in Figure 1

The device	**Recloser A**	**FTU$_1$**	**FTU$_2$**	**FTU$_3$**	**FTU$_4$**	**FTU$_5$**	**FTU$_6$**	**FTU$_8$**
The close time/s	15	7	14	21	7	21	7	75
The reset time/s	5	5	5	5	5	5	5	5

In Figure 2, one permanent fault occurred in the section between the FTU$_6$ and the FTU$_8$ at the time t_0. The recloser A would detect the fault and trip the distribution line immediately. Since the ring feeder is deenergized, all the switches on the left of the tie switch would be tripped by the corresponding FTUs, respectively. After 15 s, the recloser would reclose for the first time, and then the FTUs would send the close signal at the following time based on the setting time parameters given in Table 1.

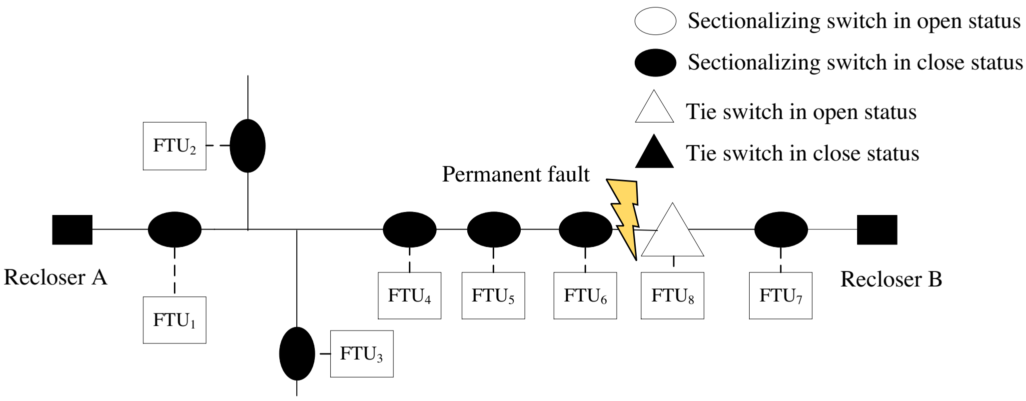


Fig. 2. Single, permanent fault that occurred on the feeder shown in Figure 1

1. The FTU_1 would emit the close signal at t_0 + 22 s.
2. The FTU_4 would emit the close signal at t_0 + 29 s.
3. The FTU_2 would emit the close signal at t_0 + 36 s.
4. The FTU_3 would emit the close signal at t_0 + 43 s.
5. The FTU_5 would emit the close signal at t_0 + 50 s.
6. The FTU_6 would emit the close signal t_0 + 57 s.
7. Due to the close of the corresponding switch controlled by the FTU_6, the recloser A would detect the fault and then trip the distribution line again. According to the action logic, the corresponding switch would be kept in the open status by the FTU_6.
8. The recloser would reclose for the second time at t_0 + 72 s.
9. The FTU_1 would emit the close signal at t_0 + 79 s.
10. The FTU_4 would emit the close signal at t_0 + 86 s.
11. The FTU_2 would emit the close signal at t_0 + 93 s.
12. The FTU_3 would emit the close signal at t_0 + 100 s.
13. The FTU_5 would emit the close signal at t_0 + 107 s.
14. The fault section between the FTU_6 and the FTU_8 is isolated and other area would be powered on.

After the coordinated control of the FTUs, the topological structure of the ring main feeder shown in Figure 1 has been changed and shown in Figure 3. That is, the fault area has been isolated by nearly fourteen actions controlled by the FTUs with different setting parameters, and the fault handling time equals about 107 s.

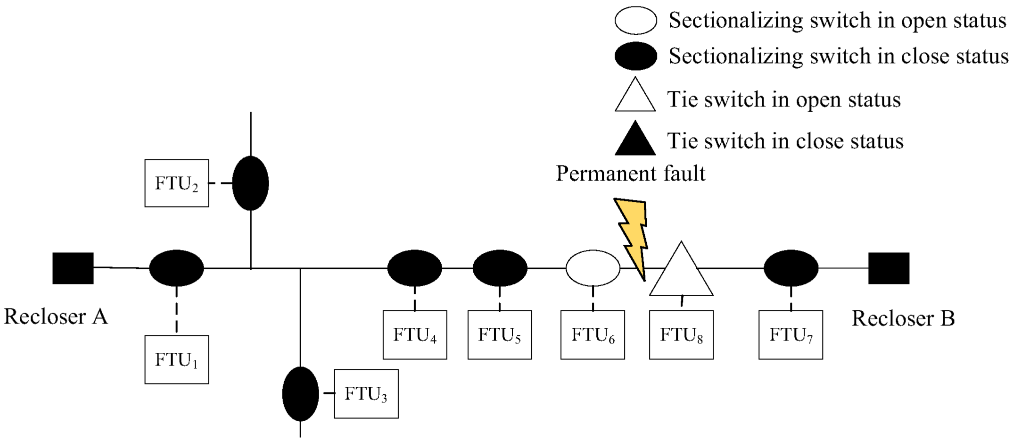


Fig. 3. The topological structure of the feeder shown in Figure 1 after the fault isolation

3. The principle of the proposed cloud-based digital-physical feeder automation testing method

3.1. Requirements for the feeder automation testing method

The following reasons may lead to the coordinated control failure of several FTUs in the FA system. One reason is that the hardware circuit or the software module of the FTU lost efficacy after a long running time. Another is that the setting parameters of some FTUs are set to incorrect values. In the fault isolation process of the local-reclosing FA system, the coordinated control of several FTUs relies on the accurate setting time parameters and the corresponding hardware and subroutine, especially the setting close time. The FA testing method should be used to detect the coordinated control capacity of FTUs under the setting parameters.

The series of switch actions taken by the FTUs would generate voltage and current waveforms. Theses waveforms are the input signals for the FTU under test. The transient and steady-state signals in the waveforms are influenced by all FTUs. Hence a digital simulation platform should be realized for the power distribution system. The simulation platform should contain an FTU digital model and produce the fault-generated waveforms considering the state of the switch.

Distributed FTUs are usually installed with the corresponding pole-mounted switch along the overhead distribution line in the outdoor environment. Therefore, the simulation-generated waveforms should be injected to the FTU under test conveniently. Meanwhile, due to the long distance between two adjacent FTUs and complicated field environmental condition, the FTUs in the filed except for the FTU under test should be replaced by the digital FTU models to simulate the coordinated control process of all FTUs.

3.2. The scheme of the proposed cloud-based digital-physical FA testing method

The proposed cloud-based digital-physical hybrid FA testing method can be divided into two parts. It includes an interactive script layer and a cloud-based simulation layer. The overall diagram of the testing method is shown in Figure 4.

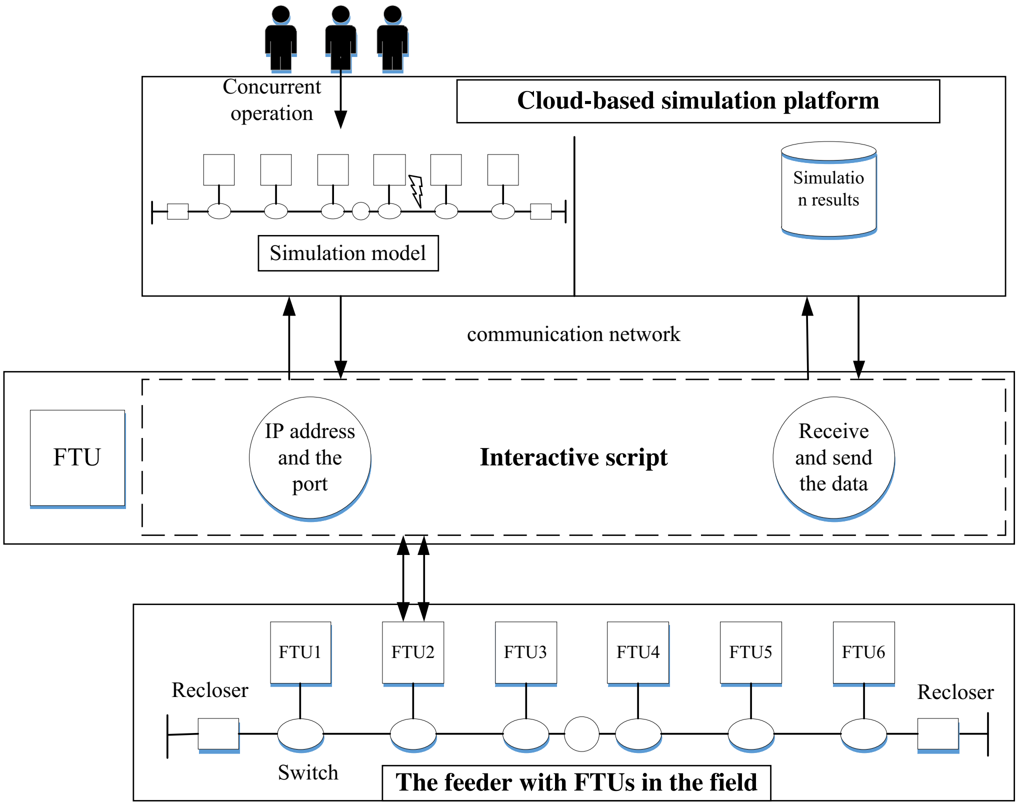


Fig. 4. The scheme of the proposed cloud-based feeder automation testing method

In the proposed FA testing method, the interactive script should be realized and added to the FTUs installed in the field firstly. Once the interactive script is activated, the FTU would change to the test mode automatically. In this mode, the voltage and current waveforms received by the microprogrammed control unit (MCU) in the FTU would come from the simulation results obtained from the cloud-based simulation platform. In the meantime, the trip or close signal generated by the FTU in the field would be sent to the simulation platform as the effect of the interactive script. The interactive script can be written in Python or C program languages.

In the cloud-based simulation layer, a corresponding power distribution system model would be constructed to demonstrate the transient and steady-state characteristics of the voltage and current in the feeder under test. The FTU digital model was also implemented by the signal monitoring and processing module, logic processing module and signal transmitting module. The setting parameters of each FTU model are directly obtained from the parameters of the FTUs installed in the field. The FTU model has two work modes, includes disable and enable modes. In the disable mode, the simulation FTU model does not work and the corresponding digital switch is controlled by the received signal sent by the interactive script embedded in the FTU installed in the field. In the enable mode, the simulation FTU model would work based on the realized functions and setting parameters to control the corresponding digital switch.

The flow chart of the proposed testing method is shown in Figure 5. There are six steps to test the FTUs installed in the feeder.

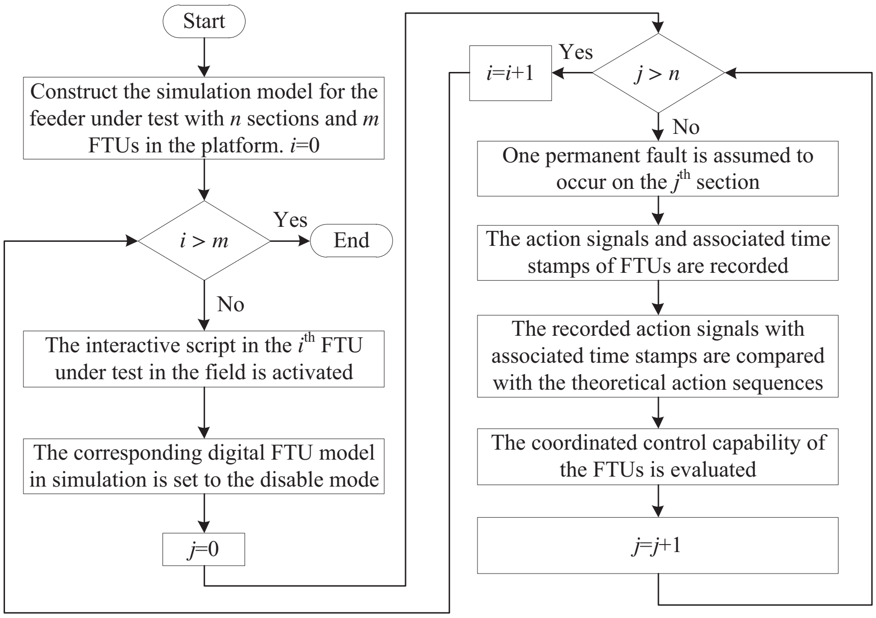


Fig. 5. The flow chart of the proposed cloud-based feeder automation testing method

Step 1: The corresponding simulation model for the feeder under test is constructed on the cloud-based simulation platform.

Step 2: One FTU in the field is selected as the object being tested. And then the interactive script is activated in the selected FTU. Simultaneously, the corresponding FTU model on the simulation platform is set to the disable mode.

Step 3: One permanent fault is assumed to occur in the first section of the feeder in the simulation, then the voltage and current waveforms at the corresponding disabled FTU model position are sent to the FTU under test in the field in real time. The trip or close signals generated by the FTU under test in the field would be sent back to the simulation mode and the corresponding switch in the simulation model is controlled by these signals.

Step 4: The action signals generated by the FTU models in the enable status and the FTU under test in the field are recorded, as well as the associated time stamps.

Step 5: The recorded action signals with the associated time stamps are compared with the theoretical action sequences obtained by the setting time parameters. The coordinated control capability of the FTUs can be evaluated based on the comparative analysis result.

Step 6: The fault position is changed to the next section, and steps 3, 4 and 5 are repeated. Once the fault position is located in the last section, this loop is broken.

Step 7: Another FTU in the field is selected as the object being tested, and then steps 1, 2, 3, 4, 5 and 6 are repeated. Once all the FTUs installed in the field have been tested, this loop breaks and the whole test ends.

3.3. The theoretical action sequences of FTUs in the FA testing method

According to the setting time parameters and the voltage-time action logic, the theoretical action sequences can be obtained and used to evaluate the coordinated control capability of the FTUs.

Take one power distribution system with N FTUs as an example. The variable N represents the number of FTUs. When the m^{th} FTU in the field is under test, and one permanent fault occurs in the section between the k^{th} and $(k+1)^{\text{th}}$ FTU at the time t_0, the following action sequences can be derived from the setting time parameters in two situations. One situation is that the FTU under test is located before the position of the k^{th} FTU. The other situation is that the FTU under test is located after the position of the $(k+1)^{\text{th}}$ FTU.

1. The first situation, the FTU under test located before the position of the k-th FTU

In this situation, the number k is greater than number m. The digital recloser would trip the distribution line and reclose at the time $t_0 + t_{c1}$. The symbol t_{c1} represents the setting reclosing time of the recloser.

The i^{th} digital FTU built on the simulation platform would emit the close signal after the first reclosure at the time given by,

$$\begin{cases} t_{icf} = t_0 + \sum\limits_{p=1}^{i} t_{p\,\mathrm{d}x}, & i < m \\ t_{icf} = t_0 + \sum\limits_{p=1}^{m-1} t_{p\,\mathrm{d}x} + t_{mx} + \sum\limits_{p=m+1}^{i} t_{p\,\mathrm{d}x}, & m < l \le k \end{cases}, \tag{1}$$

where t_{icf} represents the close signal sent out by the i^{th} FTU after the first recloser, $t_{p\,\mathrm{d}x}$ represents the setting time length X in the p^{th} digital FTU model built on the platform, t_{mx} represents the setting time length X in the FTU under test in the field numbered m.

Once the k^{th} FTU sent out the close signal, the recloser would detect the fault and trip the distribution line again. Hence the k^{th} FTU would emit the block signal and keep the corresponding switch in the open status.

The recloser would reclose at the time

$$t_0 + 2t_{c1} + \sum_{p=1}^{i} t_{p\,\mathrm{d}x} + t_{mx} \sum_{p=m+1}^{k} t_{p\,\mathrm{d}x}\,,$$

according to Equation (1). The i^{th} digital FTU built on the simulation platform would emit the close signal after the second reclosure at the time given by

$$\begin{cases} t_{icf} = t_0 + 2t_{c1} \sum\limits_{p=1}^{m-1} t_{p\,\mathrm{d}x} + t_{mx} + \sum\limits_{p=1}^{i} t_{p\,\mathrm{d}x}, & i < m \\ t_{icf} = t_0 + 2t_{c1} \sum\limits_{p=1}^{m-1} t_{p\,\mathrm{d}x} + 2t_{mx} + \sum\limits_{p=m+1}^{k} t_{p\,\mathrm{d}x} + \sum\limits_{p=m+1}^{i} t_{p\,\mathrm{d}x}, & m < l \le k \end{cases}. \tag{2}$$

Since the setting time parameters t_{c1} and $t_{p\,\mathrm{d}x}$ were embedded in the digital models constructed on the simulation platform, the action sequences are determined by the setting time parameter t_{mx} embedded in the FTU under test in the field.

2. The second situation, the FTU under test located after the position of the $(k+1)^{\text{th}}$ FTU

In this situation, the number $k+1$ is smaller than the number m.

Since the FTU under test is located after the position of the permanent fault, the FTU under test would send out the close signal after the action of the tie switch to restore electricity of the healthy area. The FTU used to control the tie switch is numbered h in the following analysis.

The i^{th} digital FTU built on the simulation platform would emit the close signal after the first reclosure at the time given by,

$$t_{icf} = t_0 + t_{c1} + \sum_{p=1}^{i} t_{p\,\mathrm{d}x}, \qquad i \le k. \tag{3}$$

Due to the existence of the permanent fault, the recloser would trip the distribution line again and reclose at the time,

$$t_0 + 2t_{c1} + \sum_{p=1}^{k} t_{p\,\mathrm{d}x},$$

according to Equation (3). The i^{th} digital FTU located before the k^{th} FTU built on the simulation platform would emit the close signal after the second reclosure at the time given by

$$t_{icf} = t_0 + 2t_{c1} + \sum_{p=1}^{k} t_{p\,\mathrm{d}x} + \sum_{p=1}^{i} t_{p\,\mathrm{d}x}, \qquad i < k. \tag{4}$$

The i^{th} digital FTU located after $(k+1)^{\text{th}}$ built on the simulation platform would emit the close signal after the section of the tie switch.

$$\begin{cases} t_{icf} = t_0 + t_{hs1} \displaystyle\sum_{p=m+1}^{h-1} t_{p\,\mathrm{d}x} + t_{mx} + \sum_{p=1}^{m-1} t_{p\,\mathrm{d}x}, & k+1 < i < m \\ t_{icf} = t_0 + t_{hs1} \displaystyle\sum_{p=i}^{h-1} t_{p\,\mathrm{d}x}, & m < i < h \end{cases}, \tag{5}$$

where t_{hs1} represents the setting time parameter in the h^{th} FTU used to control the tie switch.

The FTU under test in the field numbered m would emit the close signal at the time given by

$$t_{icf} = t_0 + 2t_{hs1} + \sum_{p=m+1}^{h-1} t_{p\,\mathrm{d}x} + t_{mx}, \quad i = m. \tag{6}$$

The theoretical action sequences of FTUs in the FA testing method can be obtained based on Equations (1)–(6). The result of the action sequences in the test based on the proposed cloud-based FA testing method would be compared with the theoretical action sequences. Hence the coordinated control capability of the FTUs could be evaluated according to the abovementioned test procedures.

4. The implementation of the proposed cloud-based digital-physical feeder automation testing method

4.1. The realization of the cloud-based simulation platform

In the proposed FA testing method, the electromagnetic transient simulation (EMTS) should be realized first to describe the transient and steady-state process of the distribution power system. Traditional EMTS mainly relies on an EMTP-type program, including ATP-EMTP [11], PSCAD/EMTDC [12], etc. Due to the large-scale distribution system model and advanced control logics in the FTU models, existing tools cannot be used directly for the real-time physical/digital hybrid testing method because of the time-consuming simulation speed and lack of collaborative modeling feature [13].

Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources. Based on cloud computing, different physical and virtual resources can be dynamically assigned and reassigned according to the simulation demand. At the same time, the computing resources can be accessed and used by heterogeneous thin or thick client platforms.

By using the cloud computing theory, several parallel computing-based EMTP-type programs have been proposed based on PC clusters and other heterogeneous platforms [14, 15]. These cloud-based power system simulation programs would be used in the FA testing method. Additionally, The FTU model is constructed to realize the coordinated control function in the fault isolation by the basic simulation modules or object-oriented programming language. The work flow of the FTU model is shown in Figure 6.

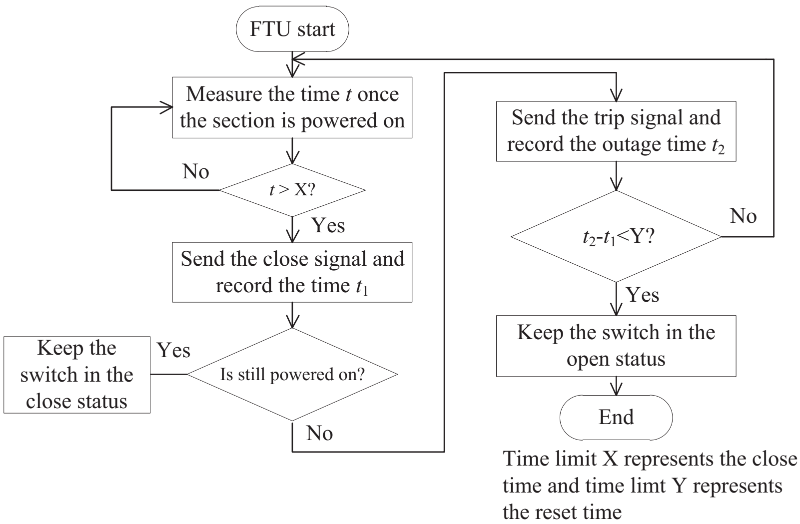


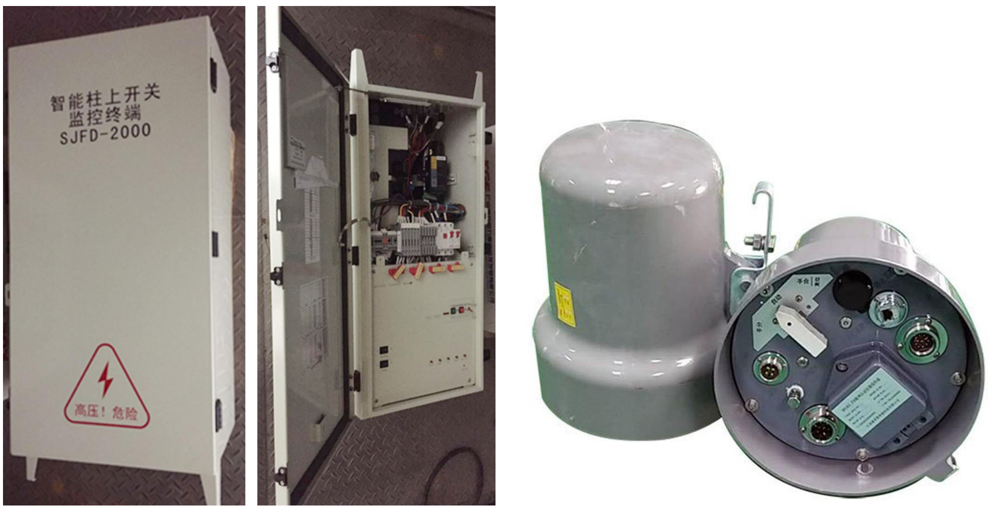
Fig. 6. The work flow of the FTU model constructed on the cloud-based simulation platform

Once the distribution line section located before the position of the FTU is powered on, the FTU starts timing and would send the close signal to the corresponding switch if the duration time is bigger than the setting close time X, which is represented by t_1. The corresponding switch would be kept in close status if the prior section is powered on. Once the mentioned distribution line section lost efficiency, the FTU would emit the trip signal as soon as possible which is represented by t_2. If the time difference between the time t_2 and the time t_1 is less than the reset time Y, the FTU would emit the block signal and control the corresponding switch in the open status until the fault is repaired. Otherwise, the FTU would return the initial state.

4.2. The realization of the interactive script in the FTU installed in the field

In the proposed FA testing method, the FTU under test in the field would communicate with the realized cloud-based distribution power system simulation platform. In the interactive communication, the transient and steady-state voltage and current signals generated by the simulation platform would be sent to the FTU under test, and the trip or close signal generated by the FTU under test would be sent to the simulation platform. Therefore, an interactive script should be realized and embedded in the FTU under test to establish the communication channel and execute the test process.

The appearance and interior of the FTU in the field is shown in Figure 7. Although there are differences among the FTUs produced by different manufacturers, the functions of the FTU are implemented by the same several core units, including the signal processing unit, remote signal measurement unit, remote control unit, remote on-off state measurement unit, power supply unit, central processing unit, and the communication unit.



(a) (b)

Fig. 7. The appearance and interior of the typical FTUs in the field: (a) the first type; (b) the second type

The operating principle of the FTU in the field is shown in Figure 8. The voltage and current signals from the current transformer and voltage transformer are measured by the measurement unit and then sent to the central processing unit.

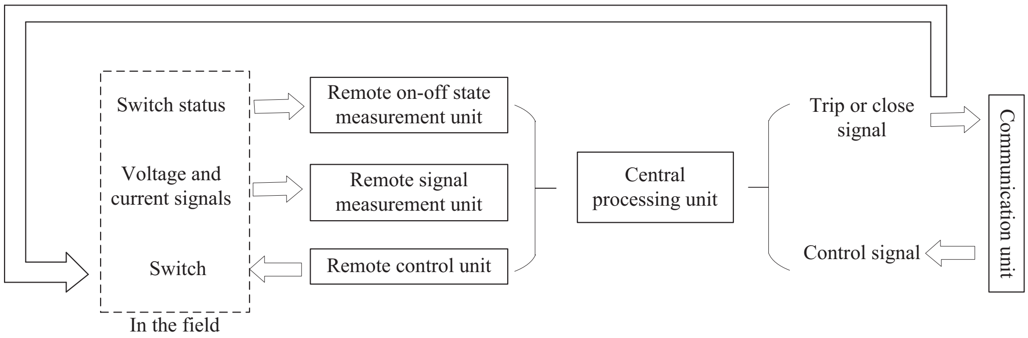


Fig. 8. The operating principle of the FTU in the field

The waveforms are analyzed in the central processing unit based on the work flow given in Figure 6 and then the trip or close signal are generated by the action logic and sent out to control the switch. In the meantime, the control signal received by the central processing unit would be analyzed, and then the switch could be also controlled through the remote-control unit.

In our proposed FA testing method, the interactive script is embedded in the central processing unit. It was designed as an independent module and only executed in the test mode. The operating principle of the interactive script is shown in Figure 9. Once the interactive script is executed, the status of the switch and the condition monitoring signals in the field would not be transferred to the central processing unit. The signals from the corresponding position in the cloud-based simulation platform are used as the input signals instead. In the meantime, the switch in the field is not controlled by the FTU under test. The trip or close signal sent by the FTU under test would be sent out to the simulation platform and was used to control the corresponding switch on the platform.

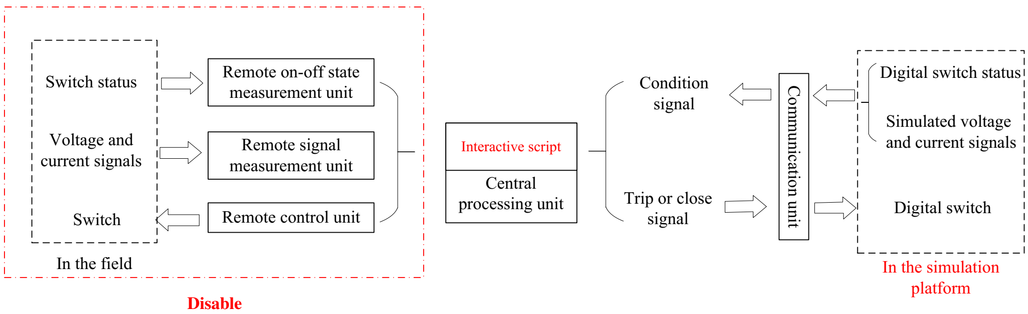


Fig. 9. The operating principle of the embedded interactive script in the FTU

In the interactive script, the main functions include the network interface function, the event handler function and the data caching function. In the network interface function, the communication channel between the FTU with the interactive script and the cloud-based simulation platform can be set up and maintain data communication. In the event handler function, the signal reception and signal transmission would lead to the corresponding subprogram being called. In the data caching function, the Redis-type database is used to storage the interactive data.

5. Experimental verification

Take the electrical distribution network shown in Figure 1 as an example, the corresponding digital simulation model is constructed in the cloud server. One experimental result is shown in Figure 10. In the experiment, one permanent fault occurred in the section between the FTU_5 and the FTU_6 at a time of 0.5 s, and the FTU_5 in the field is under test.

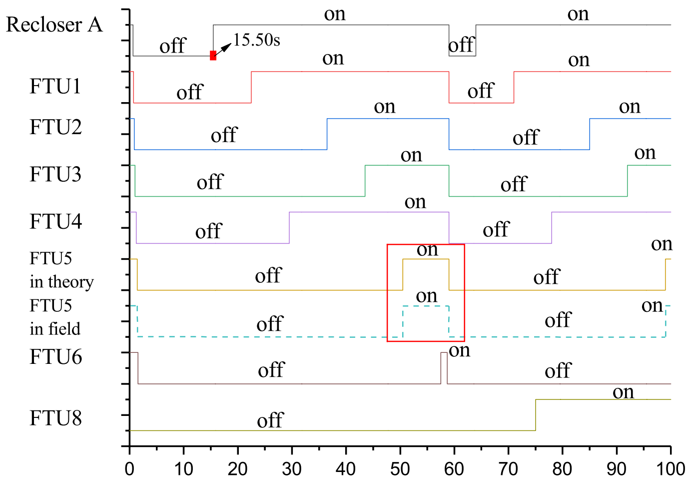


Fig. 10. The sequence diagram of the status of switches in the experiment (FTU5 is under test)

In the experiment, the status of the switches on the cloud-based platform and the action time were recorded. The switch associated with the FTU_5 was controlled by the FTU_5 in the field, and the other switches were controlled by the FTU models in the digital simulation. Since the distribution line was tripped by the recloser A followed by the fault appearance, all the sectionalizing switches were tripped by the corresponding FTUs. At a time of 15.5 s, the recloser A was reclosed. According to the different setting parameters in the FTUs, the close signals were sent out by the FTU_1, FTU_4, FTU_2, FTU_3, and FTU_5 (in the field) in sequence. And then the fault was detected and the recloser A tripped the line again. Therefore, the FTU_5 (in the field) would keep the corresponding switch (in the cloud-based platform) in the open status. After a series of closing switches, the fault was successfully isolated. The conclusion of this test was that the FTU_5 in the field could act accurately once the fault occurred in the section between the FTU_5 and the FTU_6.

Another experiment was conducted and the results were shown in Figure 11. In this experiment, the FTU_3 in the field was under test, and one permanent fault occurred in the section between the

FTU_6 and the FTU_8 at a time of 0.5 s. According to the results, the FTU_3 and FTU_4 are closed at the same time in 29.50 s. The action time of the FTU_4 is consistent with the setting parameters which is shown in Table 1. However, the actual operation time of the FTU_3 is inconsistent. The reasons may be the wrong setting time parameter in the FTU_3 or the failure of hardware/software built in the FTU_3.

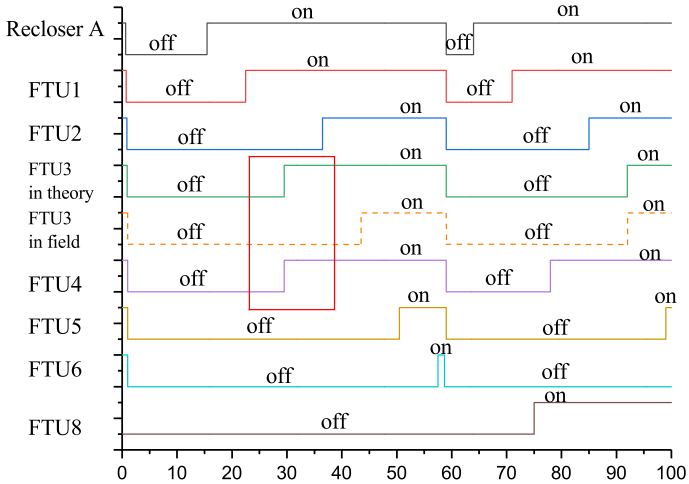


Fig. 11. The sequence diagram of the status of switches in the experiment (FTU3 is under test)

6. Conclusion

In this paper, a cloud-based digital-physical testing method for feeder automation (FA) in the power distribution system is proposed and discussed. It includes an interactive script layer and the cloud-based simulation layer. In the cloud-based simulation layer, a corresponding power distribution system model has been constructed to demonstrate the transient and steady-state voltage and current characteristics of the feeder under switch actions if any fault occurred on the feeder. The interactive script embedded in the FTU under test in the field can receive the digital voltage and current waveforms generated by the cloud server and send the trip or close signal to the corresponding digital FTU model on the simulation platform.

Based on the proposed cloud-based digital-physical FA testing method, the trip or close signal associated with the time stamps sent by the FTU under test can be observed according to the sequence diagram. It can be directly used to assess the correctness of the action of the FTU under test, and the coordinated control function among the FTUs to isolate the fault area.

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