A Smart Substation Training Platform based on Primary Equipment Simulator

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Abstract: A training scheme based on combination of virtual substation primary equipment real secondary devices is proposed for smart substation accident management. The primary equipment simulator is implemented through communication between 3D cartoon server and simulated switch controller. Electronic current and voltage transformer is simulated by EMTDC transient model and FPGA+DSP terminal controller. A smart substation on-site training environment is established for the substation O&M personnel.

1. Introduction

In the recent years, a growing number of smart substations has been built. The pre-sampling synchronization technique and fibre communication and has replaced the long-dance cable communication. Then the work pattern for the substation operation & maintenance (O&M) personnel has changed a lot. There are several traditional training methods for substation workers [1-4]. One is to teach the learners the treatment sequences and steps in oral lessons in a real substation with live equipment. However, the real harsh fault states are forbidden to be generated. It is difficult to grasp the points since the lack of atmosphere of real power failures. In another mode, the whole training system are pure software [5-9]. The work simulation is conducted through 2D cartoon modelling scene technique. The scheme is flexible with low cost, free of establishing a real substation, but still not enough for on-site training. In this paper, a smart substation simulation system is proposed. It is featured on virtual primary equipment and real secondary devices. The combined method is appropriate for training of relay protection and operation workers in power systems.

The equipment and devices in a smart substation are usually characterized as follows:

- The primary device is intelligent. Intelligent components are added to the primary equipment, which can automatically complete digital acquisition, health status monitoring, equipment alarm and operation.

- The secondary devices are networked, with the standardized interfaces and normalized data sharing through switches.

- The host becomes an integrated information platform, which integrates SCADA(supervisory control and data acquisition)system, the substation-layer interlock logic control for operation, online monitoring for primary devices, the sub-station of protection with fault information, etc.

- The substation mass alarm information realized hierarchical classification display, according to the alarm level, importance and alarm types. The key warning information is extracted and displayed, and the auxiliary decision-making function is added.
- During switching operations, the automatic system can conduct the programmed operation, greatly reducing the operation time and power failure time.

Compared with traditional substations, the smart substations have lower communication cost and more efficient data sharing in the power grid. Meantime it is designed and built according to the international standard of IEC61850.

2. System structure
The proposed structure of smart substation training system is given in Figure 1.

In the training strategy, the secondary devices are absolutely real. The substation supervisory monitoring monitor machine, relay protection devices, measuring and control devices, synchronizing clock, fault recorder, energy metering devices, merging units and smart terminals are real instruments of a smart substation. Inside real electronic transformers, the voltage and current are converted to digital data and transmitted. Data synchronization is completed in the merging unit before entering the relay protection and measuring & control devices. Considering the primary equipment virtualization, the data generator is used to simulate the electronic transformer. Each interval in the process layer is equipped with merging unit and smart terminal. Electromagnetic transient computing unit sends data to simulated electronic transformer in real time. The simulated transformers output FT3 signal to the merging units simulated on DSP+ FPGA control board. Inside the simulator, data packages are received, unpacked, reframed and distributed to data channels. The bay layer IEDs (Intelligent Electronic Device) and Ethernet switches are connected to the data channels, acquiring the communication frames in the format of IEC61850 9-2 standard. The clock of the combined unit is timed by the real synchronous clock device of the training station. The planed primary equipment includes main transformers, circuit breakers and disconnect switches. They are simulated by low voltage IEDs with red/green (closed/open) lights and states change indicator in response to remote control commands. In the process layer, the SMV (Sample Measured Value) data frames and GOOSE (Generic Object-Oriented Substation Events) messages share the same switches. The relay protection devices receive the voltages and currents from the network and the trip messages can be transmitted to smart terminals via the network.

![Figure 1. Proposed training structure for smart substation](image)

The power data source is an electromagnetic transient simulation server based on EMTDC. In use of real time digital simulator (RTDS), the server builds the dynamic models of transformer, transmission lines, capacitor and other components. The grid calculation model is designed in accordance with the typical 220kV smart substation. Inside the server, a pre-designed 220kV substation model is configured. There are totally two main transformers, with 220kV/110kV/10kV voltage sides. Double bus bar connection and two lines are adopted in 220kV and 110kV zone. The 10kV part is in use of single bus section, configured with one transmission line for each section.

3. System components
3.1. Primary Equipment Simulator
Due to the cost of training, the configuration of high-voltage equipment is unrealistic. Virtual model in form of IED is used to simulate circuit breaker, disconnecting switch, transformer three-side switch and related switch. The virtual device is about the same size as the actual secondary IED device. The device is equipped with a programmable logic controller, which can control the signal circuit and the contactor of the operating circuit. The LED lights on the display screen indicate the actual states of circuit breakers or disconnecting switches in the simulated substation interval. When the PLC detects the circuit change signal of the smart terminal, it will send commands to the 3D model server of the equipment simulator to renew the equipment states. The state control module calls the new equipment state model to display the 3D animation of the appearance of the equipment. The operating time of the circuit breaker is set in advance in the timing register to simulate the operating characteristics of the circuit breaker. The remote control mode and local control mode can be switched to each other freely. Through the configuration of the server, the circuit breaker faults can be set in the tripping circuit.

In order to provide the trainees with teaching substation environment, virtual reality technology is used to display 3D animation scene of high-voltage equipment on monitoring screen. The principle of communication interaction of the primary device simulator is shown in Figure 2(a).

![Communication scheme of primary equipment](image1)

(a) Communication scheme of primary equipment

![Simulated ECT/EVT](image2)

(b) Simulated ECT/EVT

The simulated primary equipment displays its states on the panel, and the control message is sent to the primary simulator server through the network router. The database of main equipment server configuration integrates the 3D parameters of substation high-voltage equipment. The software shows that the model is triggered and invoked by sudden changes in messages from the emulated primary equipment. Communication between the training server and the simulated primary equipment follows the publisher/subscriber model. During the whole training procedure, the work process of circuit breaker and disconnecting switch is vividly displayed on the screen.

A smart terminal is an intelligent operation box which has the function of “on-off” input and output. In the running state, the on/off states are real-timely sampled by smart terminals from the primary equipment simulator and sent to the bay layer devices. When a command from measuring and control device arrives, the smart terminals will control the “primary device” to act at once.

3.2. Simulated ECT/EVT
The data from the electronic transformer to the combined unit is Manchester coded in FT3 format. Before an IED at a smart substation receives data, the data should be firstly converted to the iec61850-9-2 standard. Inside the electronic transformer, the data conversion and synchronizations of different phases are ignored, with the output data of merging units strictly required to match IED interfaces. The structure of the simulated electronic transformer is shown in Figure 2(b).

The power data source server calculates the voltage and current values of each sampling period in real time, packages them and sends evenly spaced packets to the merging units through fibre serial
communication. Inside the ECT/EVT simulator, photoelectric conversion is first performed and then the data packets are transferred to FIFO module of FPGA. The data is extracted by DSP processor and then reframed as ECT/EVT data conforming to FT3 protocol. FT3 messages are sent to different FPGA I/O ports that were previously defined as specific merging unit data channels. The merging units receive digital currents or voltages data and converts it into SV messages in IEC61850-9-2 format. A typical Ethernet controller RTL8910AS is used to engender the FT3 messages and implement the external network communication. After electric-optical conversion, the optical communication messages are transmitted continuously to the bay layer IEDs. Power data source server is equipped with multi-core processors and based on QNX system. It is based on electromagnetic transient models of power system. The electro-magnetic transient model for the substation is established and real-timely calculated in the step of 78.125us. The transmission lines use the element lumped parameters based on Bergeron model[10] while the transformers adopt the unified magnetic equivalent circuit model. In every work step, the states of breakers and switches are firstly sampled to determine the net topology of substation. Then admittance matrix parameters are figured out according to the predesigned model. The calculated transient voltages and currents are continuously sent to the simulated merging units. In the accident mode, the faults can be set in the fixed positions of the power elements. The calculated current and voltage values will change dramatically. For example, short circuit faults in transmission lines will cause voltage drops and current surges. Therefore, relay protection device will immediately feel the high current and low voltage and trip the circuit breakers in primary equipment simulator. Meanwhile, the fault recorder will capture and record abnormal waveform data for accident analysis.

3.3. Synchronization of Merging Units

The simulated electronic current and voltage transformers are connected to different merging units. In a traditional way, the synchronous clock device dispatches synchronizing signals to different merging units. The sampling pulses from specific merging unit are sent to the ECT/EVT, in order to synchronize the currents/voltages via separate physical channels. For the simulated ECT/EVT equipment, a time-delay compensation method is adopted. The current/voltage data is sampled in ECT/EVT and then travels to the MU in the form of serial Manchester coding. This peer to peer pattern is free of data collision problem as in CSMA/CD pattern. Then the time delay between the ECT/EVT and MU is fixed and measurable.

Take a transmission line interval for example, the time delay from an output channel i of ECT/EVT to the MU is assumed to be \( T_d^i (i=1, 2, \ldots 12) \). According to the MU model, the 12 channels refer to three phase measurement currents, three phase relay currents, three phase relay voltages, zero-sequence current of neutral point, zero-sequence voltage of neutral point, bus bar voltage. If the current/voltage data arrives at the FIFO area in MU at time \( t_m \), then the real sampling time happens at the time \( t_m - T_d^i \). The MU will not synchronize the data until all the sampled voltages/currents from the other channels has arrived and entered into FIFO. When the MU detects the data group ready for all the channels in FIFO buffer, it resamples the voltage and current value in use of Lagrange interpolation according to its own synchronization pulses. The synchronizing pulses are frequency-splitting generated by the DSP board, which is timed by the synchronization clock device. Suppose that the MU sampling period is \( T_s \) (usually 250 s), the interpolation time plus coding communication time is \( T_f \) (usually \( T_f < 50 \) s), if it is in the worst situation, the data package at one time stamp will cause the time delay

\[
T_m = \max \left( T_d^i \right) + T_s + T_f, \quad (1)
\]

The first item in the right side equation is the biggest time delay of all the current and voltage channels. In the substations below 220kV, the potential transformers are usually commonly used by other line intervals, then the MU of EVT is usually in series with the MU of ECT. Inside the MU of EVT, the anti-aliasing filter, resampling, coding, sending modules can’t be omitted. The MU of ECT has to wait until the EVT MU data arrives. This will cause a bigger time lag. However, in the centralized way,
the simulated ECT/EVT data generation is ruled by the same clock, then the time delay problem of merging units in series is solved.

4. System Test

In order to test the function of the system, a B-C phase fault was set on a 220kV line. After the fault is set through the man-machine interface, the substation monitoring interface displays the circuit breaker tripping action, and the alarm window highlights the relay protection device action messages in red. The relay protection device for the transmission line gives out the message “the phase to phase impedance relay acts and export relay operates”. The display panel of simulated primary breakers for the corresponding transmission line shows that three phase lights turn off and the smart terminal gives out no reclosing action. The fault recorder is triggered and the currents and voltages are recorded the waveforms are shown in Figure 3.

![Figure 3. Wave data analysis for the fault recorder in a smart substation](image)

The listed data waveforms from top to bottom indicates the three phase line currents, zero sequence current, three phase voltages, zero sequence voltages, tripping signals for ABC three phases, breaker states for ABC three phases. It is obvious that the amplitudes of currents and voltages of the two phases of BC have changed suddenly, and the current magnitudes of the two phases are the same while the direction is opposite. At the same time, the zero sequence voltage and current are all zero. Through waveform analysis, the fault reasoning conclusion is: B to C phase short circuit fault happens, no reclosing action, three-phase tripping signals sent out from the line relay protection. The behaviour of the protection action is in accordance with the actual phase short circuit states. The training system can also be used to test the relay protection algorithms, Ethernet switch functions, fault recorder actions, and so on.

5. Conclusions

(1) Smart substation on-site training can be economically achieved through the combination of primary equipment simulator and the real secondary devices.

(2) The accident treatment training for substation O&M work is facilitated by 3D server interactive call based on switches communication and 3D cartoon models.

(3) The proposed platform exhibits the same electricity features and relay actions with the real fault situation. It can be extended to the application of the smart substation study.

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