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Algorithms and Methods on Development of PMU Tester Installed in Smart Substation

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Abstract. The protocol and data transmitting of smart substation is different from ordinary substation. Based on the requirements of PMU in smart substation, the PMU tester in smart substation is researched according to the algorithms and methods under the condition of smart substation. Considering the characteristics of PMU installation in smart substation, different methods are presented. Moreover, various formats of signal in smart substation would be involved in PMU tester design. On account of massive jobs on the accuracy of currents and voltages test and composition of reports for engineers, the software designed in the PMU tester would guarantee the facility procedure, efficiency and validity test of PMU in smart substation.

Introduction

The focus of tests PMU is continually fulfilled by the academic community [1]. The researches of test systems are presented based on dynamic algorithms given by in [2]. The standards of evaluation are proposed in [3]. The progresses and comparisons of PMU testers and operation standards are elaborated by literature [4]. The studies of PMU tester on smart substation are demonstrated based on protocol of IEC61850 [5]. However, it is lacked that the integrated and completed tests on PMU of smart substation, which requires satisfying the static and dynamic accurate on every condition of power systems [6-7]. It also needs to solve the problems on miscellaneous and tremendous work of data disposal and composition of test reports [8].

This paper presents a new method and develops a device on verification of PMU function to solve the problems on PMU tests and to satisfy the literature [8] aiming at smart substation. The tester based on protocol of IEC61850-9-2, sends the digital direct sampling of currents and voltages to data acquisition units of PMU, while receive the data from phasor data concentrators of PMU. Adapted by the configuration and of PMU characteristics in smart substation, the PMU tester is flexible and available on tests items option and accurate and close-looped calculation on dynamic and static response of PMU. Finally, the tests reports generated by the results of test progress automatic without the manual disposal.

Research of PMU Tester

Analysis on Function of PMU and PMU Tester in Smart Substation

PMU in smart substation consists of data acquisition units and phasor data concentrators, which transmits the signals of currents and voltages by optical fibers. The interfaces of data acquisition units are fiber equipped allowed the protocol of IEC61850 as well as inputs interfaces of phasor data concentrators, while the outputs interfaces of phasor data concentrators are Ethernet protocol adaptive.

According to the characteristics of PMU in smart substation, the tester underdeveloped would play the role of 3 aspects by simulating the progress of function of PMU, which is:

(1) Sending the data to data acquisition units of PMU;
(2) Receiving the data from phasor data concentrators of PMU;

(3) Comparing the data from data acquisition units of PMU and phasor data concentrators of PMU and generating the detailed reports based on the test progress.

Thus, the tester requires containing block of data sending, which simulates the function of merge units by sending data of IEC61850-9-2, while the block of data receiving would be equipped in PMU tester adapted to Ethernet protocol. For purpose of accurate phasor relationships, the synchronous clock integrated in PMU tester would be vital element to design for data acquisition units and phasor data concentrators. The software, which is designed in PMU tester in order to acquire the comparison and calculation on test progress automatically, would shorten the massive jobs on composition of test reports.

The Structure of Hardware on PMU Tester

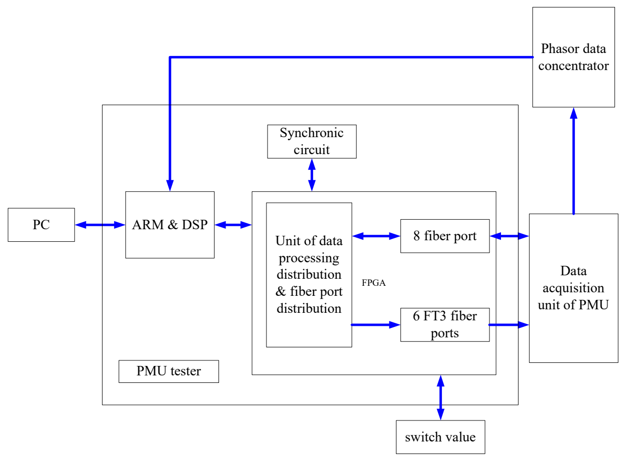

Figure 1. Hardware structure of PMU tester for smart substation.

Shown in fig.1, ARM chip plays a role in touch with PC clients in order to receive the commands from the PMU tester and to send the data of currents and voltages. The instructions received from ARM chip is transmitted to DSP chip, which creates the typical static and dynamic currents and voltages of power systems. The FPGA chip accepts digital signals of currents and voltages and instructions from DSP chips through the interfaces of PMU tester. The digital signals satisfying the protocol of IEC61850-9-2 with accurate time labeling, would be paved a way to PMU in smart substation through the optical fiber by PMU tester.

As well as fig.1, the signals acquired from PMU tester would be converted into the Ethernet protocol of PMU2.0 rather than IEC61850-9-2 at the end of signal flow. The comparison and calculation analysis between the different formats of signals would be obtained by the software designed in DSP chip.

Algorithms of Signal Analysis

The all-cycle DFT algorithm with all-cycle sliding window is applied in currents and voltages test of PMU tester, the general formula is drawn by

$$\begin{aligned} Ac_1(k)+jAs_1(k) &= Ac_1(k-1)+\frac{2}{N}\left[x(k)-x(k-N)\right]\cos\left(\frac{2k\pi}{N}\right) \\ &+j\times\left\{As_1(k-1)+\frac{2}{N}\left[x(k)-x(k-N)\right]\sin\left(\frac{2k\pi}{N}\right)\right\} \end{aligned} \tag{1}$$

Phase angle is

$$\varphi(k)=\arctan\left\{\frac{As_1(k-1)+\frac{2}{N}\left[x(k)-x(k-N)\right]\sin\left(\frac{2k\pi}{N}\right)}{Ac_1(k-1)+\frac{2}{N}\left[x(k)-x(k-N)\right]\cos\left(\frac{2k\pi}{N}\right)}\right\} \tag{2}$$

The results is complex data, where, Ac_1 is real calculation of currents or voltages, As_1 is imaginary calculation of currents or voltages, N is number of sampling.

The complex power is expressed as

$$S=\left[\left(U_{ar}I_{ar}+U_{ax}I_{ax}\right)+\left(U_{br}I_{br}+U_{bx}I_{bx}\right)+\left(U_{cr}I_{cr}+U_{cx}I_{cx}\right)\right]+ \\ j\left[\left(U_{ax}I_{ar}-U_{ar}I_{ax}\right)+\left(U_{bx}I_{br}-U_{br}I_{bx}\right)+\left(U_{cx}I_{cr}-U_{cr}I_{cx}\right)\right] \quad (3)$$

Where , U_{ar}、U_{br}、U_{cr}、I_{ar}、I_{br}、I_{cr} is real value of currents and voltages of 3 phases, while U_{ax}、U_{bx}、U_{cx}、I_{ax}、I_{bx}、I_{cx} is imaginary value of currents and voltages of 3 phases。

Frequency expression would be shown as

$$f = f_0 + \frac{\Delta\theta}{2\pi t} \quad (4)$$

Where, f_0 is fundamental frequency，$\triangle\theta$ is variation of phase angle during the time t.

The rate of variation on frequency is simplified as the frequency variation during the half cycle of fundamental period span.

$$\left.\frac{df}{dt}\right|_t = \frac{f_t - f_{(t-100ms)}}{100} \quad (5)$$

Where, f_t is frequency on time t,，$f_{(t\text{-100ms})}$ is value of frequency ahead the point of f_t by 100ms.

Define the errors on currents and voltages as pattern of

$$E_{xm} = \frac{\sum_{i=1}^{N}\left|\frac{X_{mi}-X_{si}}{X_d}\right|\times 100\%}{N} \quad (6)$$

Where, E_{xm} is general error, X_{mi} is ith value of measurement, X_{si} is ith actual value. X_d is basic value, that is, basic value of phase voltage is constant of 70V, basic value of current is 1.2A when the rated value of currents is 1A while basic value of current is 6A when the rated value of currents is 5A. the basic value of power is 3 times of multiplication of basic phase voltage and basic current.

According to [8], define the error on the phase angle, frequency and rate of variation on frequency as pattern of

$$E_m = \frac{\sum_{i=1}^{N}\left|Y_{mi}-Y_{si}\right|}{N} \quad (7)$$

Where, E_{xm} is general error, Y_{mi} is ith value of measurement, Y_{si} is ith actual value. N is number of measurements. The standards of errors are presented by reference [8].

Test Procedure and Connection of PMU Tester

Connection with 1 PC

The connection pattern with 1 PC is suitable for the PMU installation with short distance between the data acquisition units of PMU and phasor data concentrator of PMU. The test procedure is implemented with 1 PC to send and receive the signals by cable connection. The progress of data disposal would be acted by software in PMU tester.

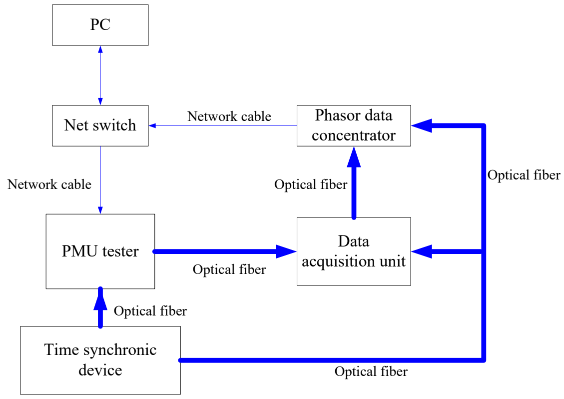

Figure 2. Test schematic of PMU considering short distance between acquisition unit of PMU and phasor data concentrator of PMU.

It would be shown in fig.2 that the net switch is used to send and receive the signal with 1 PC as well as data disposal by inserting the net switch between the PC and PMU tester. The advantage of the 1 PC connections is that it could simplify the devices and connection on test procedure.

Connection with 2 PCs

However, it is useless to apply the connection with 1 PC to complete the test due to the long distance between data acquisition unit of PMU and phasor data concentrator of PMU. Thus, on this condition, 2 PCs in all is used to complete the test, which 1 PC would be exert to send data, while another 1 PC would be exert to receive data with files in format of sending and receiving data respectively.

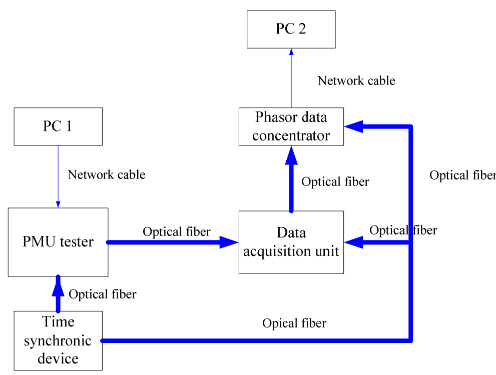

Figure 3. Test schematic of PMU considering long distance between data acquisition unit and phasor data concentrator.

It is an obvious close loop connection in fig.3 with strict progress as the relationship built by time scale. After the test, the files would be imported in software of PMU tester, which could analyze the time, header, tail and valid data to work out the errors.

Procedure of PMU Tester in Software Design

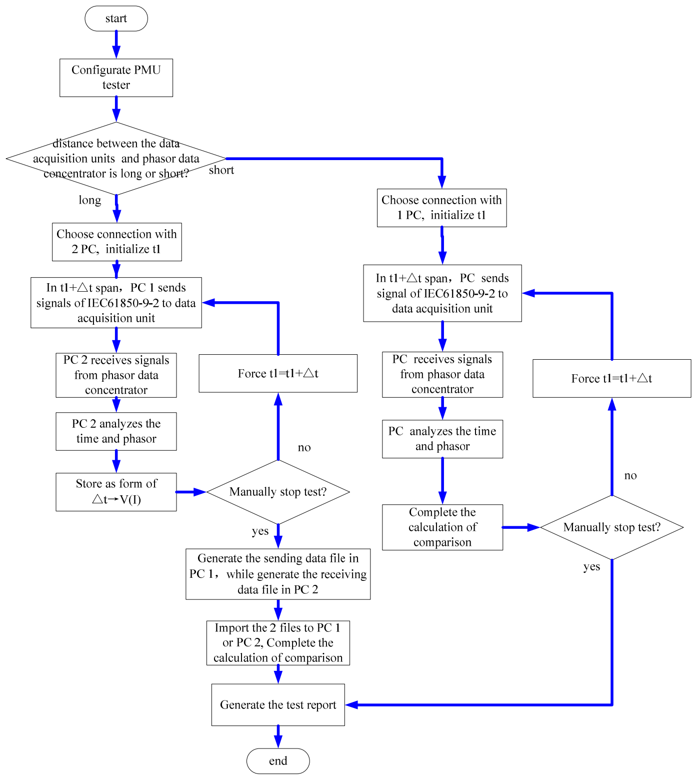

Figure 4. Flow chart of PMU tester on smart substation.

The installation and location of PMU in smart substation would be hinges for users to choose the different test patterns. The flow chart of PMU tester is designed as fig.4.

The ramification of test model is available for the flexible test according to the actual condition of smart substation, including the error calculation and test report generation.

Testing and Validation of the Method

Test Background

The static and dynamic response error of voltage and current test results are shown by an example of 500kV smart substation. In block of 220kV, the data acquisition unit of PMU and phasor data concentrator of PMU share one box, that is, the distance between them is short. Whereas, In block of 500kV, the data acquisition unit of PMU and phasor data concentrator of PMU are set up in two rooms respectively, that is, the distance between them is long.

The Test on Block of 220kV in Smart Substation

Due to the short distance between data acquisition unit of PMU and phasor data concentrator of PMU, according to the principle above, the connection pattern with 1 PC is exerted to complete the static and dynamic test of accurate. According to the standard of [8], the test evaluations are demonstrated. The tab.1, where U_n represents rated voltage, I_n represents rated current, shows the secondary value of stable value (static test) and amplitude modulation (dynamic test).

Table 1. Test results of static current and voltage on 220kV line of smart substation.

Items	Test details	Standards	Measurements	Errors（%/°）
Amplitude of U_a (V)	10%U_n 10%I_n	5.7735	5.7723	0.0017
	50%U_n 50%I_n	28.8675	28.8667	0.0011
	100%U_n 100%I_n	57.7350	57.7334	0.0023
Amplitude of I_a (A)	10%U_n 10%I_n	0.1000	0.0999	0.0056
	50%U_n 50%I_n	0.5000	0.4998	0.0168
	100%U_n 100%I_n	1.0000	0.9996	0.0297
Phase angle of I_a(°)	10%U_n 10%I_n	0.0000	-0.0286	0.0286
	50%U_n 50%I_n	0.0000	-0.0286	0.0286
	100%U_n 100%I_n	0.0000	-0.0286	0.0286

Table 2. Test results of 0.1 Hz amplitudes modulation on 220kV line of smart substation.

Items	Test details	Standards	Errors（%, °, Hz, Hz/s）
Amplitude of U_a (V)	57.7400	57.7300	0.0144
Phase angle of U_a (°)	0.0000	-0.1662	0.1662
frequency (Hz)	50.0000	50.0000	0.0000
Rate of Variation on frequency (Hz/s)	0.0000	-0.0010	0.0010

The test results of the connection pattern with 1 PC above give the conclusion that the accurate of line is qualified. Based on check in PMU and dispatch & control center, the displays of currents and voltages on static test and dynamic test are eligible for security production in power systems.

The Test on Block of 500kV in Smart Substation

Due to the long distance between data acquisition unit of PMU and phasor data concentrator of PMU, according to the principle, the connection pattern with 2 PC is exerted to complete the static and dynamic test of accurate. According to the standard of [8], every condition of test is the same as above.

Table 3. Test results of static current and voltage on 500kV line of smart substation.

Items	Test details	Standards	Measurements	Errors（%/°）
Amplitude of U_a (V)	10%Un 10%In	5.7735	5.7723	0.0017
	50%Un 50%In	28.8675	28.8667	0.0011
	100%Un 100%In	57.7350	57.7334	0.0023
Phase angle of U_a (°)	10%Un 10%In	0.0000	-0.0286	0.0286
	50%Un 50%In	0.0000	-0.0286	0.0286
	100%Un 100%In	0.0000	-0.0286	0.0286
Amplitude of I_a (A)	10%Un 10%In	0.1000	0.0999	0.0056
	50%Un 50%In	0.5000	0.4998	0.0168
	100%Un 100%In	1.0000	0.9996	0.0297
Phase angle of I_a (°)	10%Un 10%In	0.0000	-0.0286	0.0286
	50%Un 50%In	0.0000	-0.0286	0.0286
	100%Un 100%In	0.0000	-0.0286	0.0286

Table 4. Test results of 0.1 amplitudes modulation on 500kV line of smart substation.

Items	Test details	Standards	Errors（%, °, Hz, Hz/s）
Amplitude of Ua (V)	52.3152	52.3052	0.0145
Phase angle of Ua (°)	0.0000	-0.1776	0.1776
frequency (Hz)	50.0000	50.0000	0.0000
Rate of Variation on frequency (Hz/s)	0.0000	-0.0010	0.0010

The test results of the connection pattern with 2 PC above give the conclusion that the accurate of line is qualified. Based on check in PMU and dispatch & control center, the displays of currents and voltages on static test and dynamic test are eligible for security production in power systems.

Comparison of Test Patterns

Based on the test pattern with 1 PC connection, considering the static test and amplitude modulation test (50Hz fundamental sine signal, 0.1Hz modulation), the performances of 2 PMUs designed by dominated manufactures respectively are carried out under the condition above. The results are revealed in fig.6.

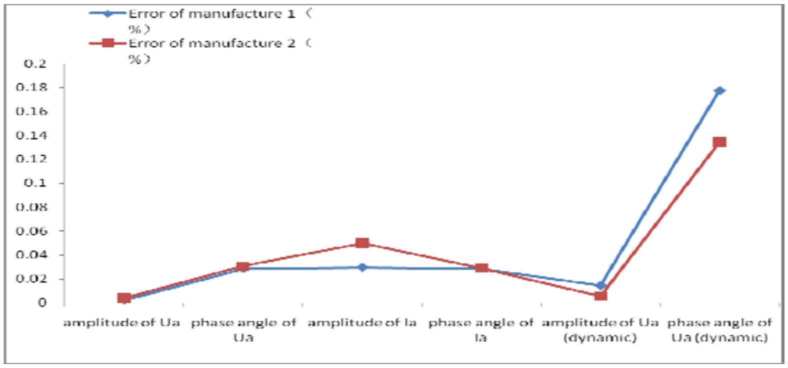

Figure 5. Test results comparison of PMUs on smart substation produced by two manufactures.

As shown as fig.5, the PMUs made by separate manufactures are qualified. However, the accurate of static belonging to manufacture 1 is better than manufacture 2, whereas, the accurate of dynamic belonging to manufacture 2 is better than manufacture 1.

Summary

Based on PMU test needs, the paper develops the device that is consistent for PMU of smart substation. According to the verification of PMU on a new 500kV smart substation, the PMU tester is a useful, flexible, user-friendly device，which would be worth to be popularized in territory of state on device of power systems. The application of PMU tester would greatly improve the quality of phasor measurements and certainly guarantee reliable operations of high voltage level smart substation.

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