**Designing of PMU Tester in Smart Substation Based on Test Method**

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**Keywords:** PMU; Smart substation; Distribution characteristics; Test method; PMU tester.

**Abstract.** It lacks the effective ways to test the PMU in smart substation at present. The testing method based on distribution characteristics of acquisition unit and concentration unit of PMU in smart substations, is proposed to solve the situation of PMU of smart substation. Therefore, the PMU tester belonging to smart substation is designed based on the fundamental requirements of tester according to the methods proposed, and the vital points of designing are introduced and emphasized to tackle the reliability of PMU. The method and technology raised and the PMU tester designed in smart substation, in practical, could complete the test of accuracy of PMU, abbreviate the procedure of complicated data disposal and test report composing. It ensures to ameliorate the testing efficiency and validity on PMU of smart substation.

**Introduction**

PMU, based on the same time scale among the substations, could be used to measure the amplitude and phase angle of voltages and currents, active powers and reactive powers. It is widely applied in the area of WAMS application, state estimation, relay protection, area stability control, system analysis and estimation, etc. [1-2]. Thus, it is an essential device for security and stability of power systems [3-4].

PMU uses highly precise clock synchronization to monitor, protect and control the power systems based on the platform of dispatching and controlling by methods of transferring data to dispatching and controlling center [5-6]. However, traditional ways have already failed to meet the needs of PMU testing in smart substation as the rapid evolution of smart substation is putting forward [7-10]. Therefore, it is necessary to raise modifications, and to develop new devices to test the relative function of PMU [11]. The precision testing of PMU, among these testing items, is the most important [12-13]. In practice, lots of verbose and unmanageable tests concern about precisions of static and dynamic responses, which demand laborious work without guarantees of minimized errors and maximum correctness [14].

According to reference [14] proposed recently, focusing on the installation characteristics of PMU in smart substation, a new approach has been raised to test PMU. A new PMU tester in smart substation according to this new approach has also been developed. The tester, which integrates optional items of testing, could play a key role of close testing loop. The close loop could implement the testing of static and dynamic response precision of PMU quickly. Eventually, the tester automatically generates the testing report according the testing process.

**Test Method of PMU**

While acquisition unit of PMU is distant from concentration unit of the device, it is not achievable to exert a PC client receiving the data from concentration unit of PMU by using only one network cable. Thus, two PC clients should be applied to test the PMU, among one of which sends data to acquisition unit of PMU, the other receives data from concentration unit of PMU. From there, each PC clients could generate the data documents labeled time. Finally, the data documents are imported to tester software for processing and testing reports would be generated automatically. Figure 1 shows the detail principle of connections on PMU testing.
Derived from figure 1, the close loop testing method is suitable for special condition of installation of PMU. The testing method could be implemented by 2 PC clients, one sends PMU data to acquisition unit and the other receives data from concentration unit of PMU.

Design of PMU tester

Analysis of Function on PMU Tester

As mentioned above, the effects of PMU tester are functioned with three aspects: to send data to acquisition unit of PMU, to receive data from concentration unit of PMU, and to deal with data and automatically generates report. In this section we shall elaborate analysis of function needs about PMU tester incorporate with the test methods.

The PMU tester should be set up with data sending module, which simulates merge unit to send time labeled data to acquisition unit of PMU by optical port.

Data receiving module, which accepts the time labeled data from concentration unit of PMU by cable, should be set up within the PMU tester. The tester software should simultaneously analyze the data and implement the job of comparison.

GPS module should receive the accurate time label correctly, as well as synchronize between the PMU acquisition unit and concentration unit.

The software of PMU tester should work on comparison between sending data and receiving data then generates the report. The sending data and receiving data are generated by PC client respectively, so they should be imported in software to be processed. The test report is further generated based on the results of calculation.

Hardware Structure of PMU Tester

Major components of the PMU tester: ARM, DSP, DSP and synchronic circuits. The hardware structure is shown by figure 2.
which obeys IEC61850-9-2 protocol with accurate time labeling, is sent to acquisition unit of
pending PMU through the optical fiber.

The data received from PMU tester is transformed into the format of PMU2.0 \[15\] and return back
to PMU tester after the packing and gathering processes in concentration unit of PMU. The
comparison and analysis of loopback data between sending data marked with time label are drawn
by software calculation.

**Software Structure of PMU Tester**

The Windows XP platform is embedded as interface of the PMU tester. The interface of PMU tester,
which administrates the whole function of tester, has advantages of facility and user friendliness.
The user of PMU tester could integrate the items of PMU testing in the software of PMU tester and
setup the standard of testing tolerances.

The PMU tester is designed and developed by the idea presented in figure 3 according to actual
condition of smart substation and close loop of testing principle on PMU in previous sections.

Starting test with initializing \(t_1\), the PMU tester is due to send data with IEC61850-9-2 style to
acquisition unit of PMU after one cycle of \(\Delta t_n\) \((n=1,2,...)\). Then data sent will be transformed into
the format of Ethernet protocol by PMU. It would be added with \(\Delta t_n\) to continue the test unless the
test is stopped manually. The data results file would be generated if the test ends. Due to differences
between data sent and data received for PMU tester, it is crucial to analyze the data with different
styles. The charts of process on PMU data with different style analyses is demonstrated by figure 4.

![Figure 3. Flow chart of PMU tester on smart substation.](image)

![Figure 4. Comparison of message analysis on PMU of substation.](image)

In the circumstance of distant connection between acquisition unit of PMU and concentration
unit of PMU, 2 PC clients should be applied to send data and receive data respectively with files in
format of data sent and data received. After the test, the files should be imported in software of
PMU tester, which analyzes the time, header, tail and valid data to work out the errors.

According to reference \[14\], the errors of voltages and currents is defined by

\[
E_{\text{sum}} = \frac{\sum_{i=1}^{N} \left| \frac{X_{mi} - X_{di}}{X_{di}} \right| \times 100\%}{N}
\]

Among equation (1), \(E_{\text{sum}}\) is total error measurement; \(X_{mi}\) is the value of \(i\)th measurement; \(X_{di}\) is the
actual value of \(i\)th measurement; \(X_{di}\) is basic value. The basic value of voltage is fixed to 70V. The

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basic value of currents is 1.2A while the rated value of secondary side of current transformer is 1A. Similarly, the basic value of currents is 6A while the rated value of secondary side of current transformer is 5A. The basic value of power is defined as 3 times of multiplication of basic value of voltage and basic value of current.

The definition of angle, frequency and change rate of frequency is demonstrated by

$$E_m = \frac{\sum_{i=1}^{N}|Y_{mi} - Y_{si}|}{N}$$

(2)

$E_{um}$ is error of measurement; $Y_{mi}$ is $i$th value of measurement; $Y_{si}$ is $i$th actual value of measurement; $N$ means times of measurement.

The test report is obtained by test and calculation with Word 2007, which includes basic information of PMU, environment of test and results of test.

In conclusion, based on the method and PMU tester developed, the test steps of PMU in smart substation are listed below:

Step 1: implement the close loop connection according to the test principle of chart.
Step 2: import the SCD file of smart substation to the PMU tester.
Step 3: set up the input/output configuration and component message based on SCD file of smart substation.
Step 4: connect the PMU and PMU tester, complete the items of PMU tester.
Step 5: click the start button to test the PMU automatically and finish the process, then generate the test report automatically.

### Analysis of Test Case

### Background of Test

The PMU tester has been applied to a 500kV smart substation of 2/3 style. There are 2 transformers and 4 line outlets in the smart substation.

### Test on Part 500kV of Smart Substation

Take an example of a 500kV line to elaborate the static and dynamic response error of voltage and current. According to section 1.2, 2 PC clients are used in data sending and receiving.

Set up the standard of measurements on static and dynamic test as $U_n$ is rated voltage, $I_n$ is rated current. The test results as sub values demonstrated here below are only listed in the form of typical currents and voltage (static test) and amplitude modulation (dynamic test).

<table>
<thead>
<tr>
<th>Items</th>
<th>sub-items</th>
<th>standards</th>
<th>results</th>
<th>errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_a$ (V)</td>
<td>10%$U_n$ 10%$I_n$</td>
<td>5.7735</td>
<td>5.7723</td>
<td>0.0017</td>
</tr>
<tr>
<td></td>
<td>50%$U_n$ 50%$I_n$</td>
<td>28.8675</td>
<td>28.8667</td>
<td>0.0011</td>
</tr>
<tr>
<td></td>
<td>100%$U_n$ 100%$I_n$</td>
<td>57.7350</td>
<td>57.7334</td>
<td>0.0023</td>
</tr>
<tr>
<td>Angle of $U_a$ (°)</td>
<td>10%$U_n$ 10%$I_n$</td>
<td>0.0000</td>
<td>-0.0286</td>
<td>0.0286</td>
</tr>
<tr>
<td></td>
<td>50%$U_n$ 50%$I_n$</td>
<td>0.0000</td>
<td>-0.0286</td>
<td>0.0286</td>
</tr>
<tr>
<td></td>
<td>100%$U_n$ 100%$I_n$</td>
<td>0.0000</td>
<td>-0.0286</td>
<td>0.0286</td>
</tr>
<tr>
<td>$I_a$ (A)</td>
<td>10%$U_n$ 10%$I_n$</td>
<td>0.1000</td>
<td>0.0999</td>
<td>0.0056</td>
</tr>
<tr>
<td></td>
<td>50%$U_n$ 50%$I_n$</td>
<td>0.5000</td>
<td>0.4998</td>
<td>0.0168</td>
</tr>
<tr>
<td></td>
<td>100%$U_n$ 100%$I_n$</td>
<td>1.0000</td>
<td>0.9996</td>
<td>0.0297</td>
</tr>
<tr>
<td>Angle of $I_a$ (°)</td>
<td>10%$U_n$ 10%$I_n$</td>
<td>0.0000</td>
<td>-0.0286</td>
<td>0.0286</td>
</tr>
<tr>
<td></td>
<td>50%$U_n$ 50%$I_n$</td>
<td>0.0000</td>
<td>-0.0286</td>
<td>0.0286</td>
</tr>
<tr>
<td></td>
<td>100%$U_n$ 100%$I_n$</td>
<td>0.0000</td>
<td>-0.0286</td>
<td>0.0286</td>
</tr>
</tbody>
</table>
Table 2. Test results of 0.1 amplitudes modulation on 500kV line of smart substation.

<table>
<thead>
<tr>
<th>items</th>
<th>standards</th>
<th>results</th>
<th>errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_a$ (V)</td>
<td>52.3152</td>
<td>52.3052</td>
<td>0.0145</td>
</tr>
<tr>
<td>$U_b$ (V)</td>
<td>63.4630</td>
<td>63.4722</td>
<td>0.0133</td>
</tr>
<tr>
<td>$U_c$ (V)</td>
<td>52.7471</td>
<td>52.7365</td>
<td>0.0153</td>
</tr>
<tr>
<td>Angle of $U_a$ ($^\circ$)</td>
<td>0.0000</td>
<td>-0.1776</td>
<td>0.1776</td>
</tr>
<tr>
<td>Angle of $U_b$ ($^\circ$)</td>
<td>-120.0000</td>
<td>-120.1722</td>
<td>0.1722</td>
</tr>
<tr>
<td>Angle of $U_c$ ($^\circ$)</td>
<td>120.0000</td>
<td>119.8341</td>
<td>0.1659</td>
</tr>
<tr>
<td>fundamental frequency (Hz)</td>
<td>50.0000</td>
<td>50.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Rate of change on frequency(Hz/s)</td>
<td>0.0000</td>
<td>-0.0010</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

The test items are passed according to the test results. In fact, the displays of acquisition unit of PMU about measurement are corresponding to dispatch and control center. In conclusion, the PMU tests results of smart substation based on the method and the PMU tester are valid and reliable.

Comparison of Test

With same tests items performed in section 3.2, the PMU tester is applied to PMU which is made by 2 manufactures with the same standards mentioned in section 3.2. The test results are given by Tab.3.

Table 3. The comparison of test results between two PMUs produced by different manufactures.

<table>
<thead>
<tr>
<th>items</th>
<th>standards</th>
<th>results of man.1</th>
<th>results of man.2</th>
<th>Errors of man.1 (%)</th>
<th>Errors of man.2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_a$ (V)</td>
<td>57.7350</td>
<td>57.7334</td>
<td>57.7321</td>
<td>0.0023</td>
<td>0.0041</td>
</tr>
<tr>
<td>Angle of $U_a$ ($^\circ$)</td>
<td>0.0000</td>
<td>-0.0286</td>
<td>0.0308</td>
<td>0.0286</td>
<td>0.0308</td>
</tr>
<tr>
<td>$I_a$ (A)</td>
<td>1.0000</td>
<td>0.9996</td>
<td>0.9994</td>
<td>0.0297</td>
<td>0.0500</td>
</tr>
<tr>
<td>Angle of $I_a$ ($^\circ$)</td>
<td>0.0000</td>
<td>-0.0286</td>
<td>0.0290</td>
<td>0.0286</td>
<td>0.0290</td>
</tr>
<tr>
<td>0.1Hz modulation ($U_a$) (V)</td>
<td>52.3152</td>
<td>52.3052</td>
<td>52.3192</td>
<td>0.0145</td>
<td>0.0057</td>
</tr>
<tr>
<td>0.1Hz modulation (angle of $U_a$) ($^\circ$)</td>
<td>0.0000</td>
<td>-0.1776</td>
<td>0.1344</td>
<td>0.1776</td>
<td>0.1344</td>
</tr>
</tbody>
</table>

From the table, the items tested of both manufactures are qualified. The static test accuracy of manufacture 1 is better than that of manufacture 2 while the dynamic test accuracy of manufacture 2 is better than that of manufacture 1.

By examining test span, data dealing time and report generation, prominent advantages of the tests based on the method and PMU tester on smart substation are seen. Authentic automation and intelligence of the test have been achieved from a principal level.

Summary

The essay raises the method that suits for PMU of smart substation according to the characteristics of PMU. Based on method and function needs, the PMU tester of smart substation is developed and researched. Introduction of crucial steps in the development have been emphasized. The tests of voltage and current accurate about the static and dynamic tests could be implemented fast and correctly. It surely decreases the amount of works on data processing and report writing, and improves the effectiveness and correctness on the tests of PMU in smart substation.

According to the field tests of PMU on a new 500kV smart substation, the PMU tester is a powerful, flexible, user-friendly device, which would guarantee reliable operations of smart substation. The application of PMU tester developed would greatly improve the quality of domestic wide area measurements, and ensure the security of smart power systems.
References


[12] IEC61850-7-4 Communication networks and systems for power utility automation: Part 7-4 basic communication structure—compatible logical node classes and data object classes [S]. 2010.

