Evaluation of PMU Performance During Transients

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Abstract-- **The paper presents different test methods for PMU (Phasor Measurement Unit) during transients in detail and shows practical results from tests of PMU from various vendors. The authors emphasize transients, because the measurement of stationary signals and their accuracy is already defined in IEEE C37.118. However, with the exception of step functions no dynamic signals are considered. The results are compared and advice is given for testing and evaluation of PMU measurement with dynamic signals.**

Index Terms— **Phasor Measurement Unit (PMU), steady state, transients, Wide Area Measurement System (WAMS)**

I. INTRODUCTION

SYNCHRONIZED phasor measurements are an important precondition for wide area monitoring and control applications. The phase angle of voltage and current signals from different remote sites in power systems can be determined and compared directly because of the time synchronized measurement and time tagging of results. Calibration and testing procedures have been designed to maintain high accuracy in accordance to the requirements and current standards concurrently to the development of time synchronized PMU.

In 1995 the first standard for PMU [1] defined data protocols and basic aspects of the measurement. Phasor Measurement results of commercial PMU could be compared to each other [2]. Since the introduction of the current standard IEEE C37.118 [3] in 2005 the deviation of the parameters of the input signal has been limited by the classification of uncertainties and the corresponding allowable error. This error is called Total Vector Error (TVE) and describes the vectorial difference of the calculated phasor by the PMU to the real phasor in percentages. However, this comparison is only valid in steady-state conditions, because only for steady-state the concept of the phasor is defined.

In steady-state conditions when no transient events like faults, line trippings or power swings occur in a power system, the synchronous measurements by PMU can deliver reliable results according to the standard. Examinations about the blackout in the U.S. and Canada on August 14, 2003 [4] reported that because of the deployment of PMU and the extraction of the data the events previous and during the blackout could be analyzed. Changes of the powerflow could be tracked and the state of the power system could be evaluated. Only low frequency changes of the powerflow could be considered because the measurements of the PMU still relied on steady-state conditions. Concerning this issue it has been reported in [4] that “some PMU types are not well protected against such anomalous inputs, and … parasitic oscillations”. During full-scale experiments with synchronized measurements in Russia [5], [6] inadequate frequency changes in the system at the time of connecting 500 kV lines were recorded. It was assumed that the frequency burst recorded by PMU, happened due to wrong PMU filter algorithm. Conduct research to test the hypotheses through natural experiments is extremely difficult, because it requires considerable time and financial costs, and often impossible, because of the risk of development of non-controllable accidents. As a result, there was the need of the stand for functional diagnostic of devices such as PMU. In world practice, the use of hardware in the loop tests for similar purposes is widely known [7] – [9].

Since the introduction of the current standard [3] in 2005 standardized test procedures [5] of PMU have been developed. Test routines for steady-state signals according to the current standard have been developed and practical experience in testing PMU [2],[10] – [13] has been achieved. Besides tests basing on input signals in steady-state, where all parameters remain constant, step tests have been executed according to [3]. In step tests only one parameter, that means only frequency, angle or magnitude respectively, is changed by a step function. Additionally to [3], in [10] also dynamic changes have been considered by the introduction of structured signals using amplitude modulation. To describe dynamic signals for testing and calibrating PMU an “analysis model” which bases on a Taylor expansion has been presented in [11]. In the concept of testing PMU, the “analysis model” is intended to provide theoretical dynamic test signals including their parameters frequency, angle and magnitude which can be compared with the results from the PMU.

But testing and calibration of PMU should be an integrated part of the expansion and upgrade of current Wide Area Measurement Systems (WAMS). A reason for the need for dedicated testing of PMUs is planned widespread adoption of WAMS/WACS (Wide Area Measurement System / Wide Area Control Systems) technology [12], [14]. Validation tests of PMU devices from various manufacturers are necessary. For these purposes PMUs have to be tested against all signals

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which can occur depending on the topology and the application and their performance classified. It has to be expected that considered signals contain transients.

The structure of the paper is as follows. In section II a discussion about testing procedures for PMU under consideration of transients will be presented. This section describes how test signals may be obtained. In section III the structure of a testing procedure is presented. Also two test environments for PMU, one in at Siberian Electrical Power Research Institute in Russia and one at the TU Dortmund in Germany are described. Section IV contains experimental data of testing PMU against transient signals followed by the conclusion in section V.

II. TRANSIENTS IN POWER SYSTEMS

Transients in power systems can be classified in four groups:

1) Thermal processes in steam generators and their controllers,
2) Electromechanical processes involving generator rotor speed/angle swings,
3) Electromagnetic transients involving various switching events,
4) Fast electromagnetic transients (lightning effects, arc blowout process, etc.).

Group 1 processes can last for minutes, and they are currently no problem to PMUs. Signals generated by this group of transients are steady-state from the viewpoint of PMU. Group 4 processes last for less than one cycle and cannot even be represented by vector measurements in any sensible way. These processes are too fast for PMU and they introduce very high-frequency components that are just filtered out by PMU.

Electromechanical processes are kind of processes that PMUs are supposed to measure. They are well represented as vector resp. phasor measurements, although strictly speaking, the concept of phasors is unambiguously defined only for steady-state. Electromagnetic transients last typically from several to 30-50 power system cycles and include substantially non-sinusoidal regimes. They can include both high-frequency (up to 5 kHz) and low-frequency (such as decaying DC components) components. Assuming the precondition for proper measurement of synchrophasors electromagnetic transients can't be adequately represented by phasors and typically PMUs have to filter them out.

Thereby test signals for evaluation of PMU performance may be roughly split into two groups. Signals of the first group represent electromechanical transients and should be used to evaluate *accuracy* of measurements. These test signals may be considered as “normal” inputs for PMU. PMU measurements should have reasonably small errors and no artifacts.

Signals of the second group represent electromagnetic transients and should be used to evaluate *correctness* of measurements. Test signals of the second group can be used to find out how well electromagnetic transients are filtered by PMU and to check if they produce any artifacts in measurements. In many cases digital signal processing algorithms do produce some artifacts and it's useful to measure how fast PMU recovers normal measurement process after some disturbance occurs in power grid.

The key issue of the evaluation of PMU is to determine the accuracy based on test signals. Test signals might be obtained by:

1) defining mathematical functions,
2) software simulations or
3) recorded oscillograms of real-world transients.

Mathematically-defined signals are easy to work with (clean and easy to understand representation, may have analytical solutions for spectral analysis purposes, require virtually no space to store them), but an appropriate set of test signals that represents transients of power systems adequately has to be chosen. Such signals might be composed using software for signal generators. Popular signals from this group are step signals (amplitude or phase of input signal changes stepwise), frequency ramp signals, signals with sinusoidally modulated amplitude, phase or frequency.

While recorded oscillograms represent real transient phenomena well by definition, they are hard to obtain, hard to interpret, may be noisy because of measurement issues. Software simulated signals look most promising. They represent transients well and can be produced in any quantities. Also, simulation software for electromechanical processes (such as Eurostag or PowerFactory) typically produces results as phasors since it calculates angular speeds of rotors, effective values and absolute values of currents and voltages. So PMU measurement quality might be analyzed by comparing phasors measured by PMU with original signal, because both are vector values.

Authors propose to create a library of transients and an automated test suite for evaluation of PMU performance using transients contained in a library. The biggest difficulty is creation of comprehensive library of transients containing broad range of transients. Also, the number of transients in a such library may become quite large and testing procedure employing all transients may become lengthy, so it is important that this procedure could be conducted as a batch job without human intervention. After performing all tests, the test suit should calculate necessary performance indices (such as measurement errors and response times). This information will be useful for both PMU developers and protection algorithms' authors. PMU developers will know what transients are the hardest to measure for PMU, so they can tune PMU algorithms for such transients. Protection algorithms' authors will know what accuracy PMU can provide in different situations.

III. TESTING PROCEDURE

The general procedure of PMU testing is depicted in Fig. 1. Using this procedure test signals can be compared with the results from the PMU. For development of a great variety of applications based on PMU the user should be able to generate all possible signals which the PMU could receive. By the comparison of the signal and the phasors provided by the PMU it is possible to evaluate the measurement of the PMU. Transient signals which may corrupt the measurement can be identified. The following subsections contain the description of the steps of the testing procedure.

Following authors describe Engineering test bed MAES-RT created in SibEPRI, Novosibirsk in Russia and PMU Test Environment at the TU Dortmund in Germany.

A. Development of Test Signals

For the development of PMU-based applications this operation represents the interface between the simulation of the whole application and the measurement in reality. Test signals can be constructed in various ways as described in chapter II. Then obtained test signals should be converted to standardized data format recognized by signal generator.

B. Synchronism Check

The measurement of the angle is synchronized by the Pulse Per Second (PPS) provided by GPS. In addition PMU require time information for time stamping of the results. For this requirement GPS receivers transmit modulated signals like IRIG-B which contain time codes. So the synchronism of the PPS but also the correct time stamping over the entire testing procedure has to be checked previously and simultaneously to the test operations because the accuracy of PPS and the time code are essentially necessary for measurement and evaluation. Even if it can be expected that the accuracy of the edge of the PPS is within 1 μs also GPS receiver are not free of malfunctions. Therefore synchronism is checked by the comparison of the edge of the PPS from different GPS receiver containing different hardware. The authors suggest that at least one High Accuracy GPS receiver who provides PPS and IRIG-B and two other GPS receivers should be used for comparison of the PPS. Finally the High Accuracy GPS receiver represents the time reference for the testing.

C. Output and Measurement of Signals

In this step signals from simulations or other calculations are reproduced by a signal generator. To reproduce not only simple waveforms it is necessary that the signal generator provides user interfaces for exchanging signal data which were worked out in Step *A* and the composition of dynamic signals. Therefore signals can be produced which contain not only steady-state but also a wide variety of transient components.

The signal generator has to amplify the amplitude of voltage and current signals on a sufficient level in order to meet the nominal requirements for PMU measurement. Using amplifiers it has to be considered that noise has to be reduced because otherwise examination of the test signals could be interfered. If the signal generator is GPS synchronized the vector based reference values need to be stored and GPS time tagged. Concurrent to the output and measurement by the examined PMU the signals have to be measured and saved for the comparison. For the simultaneous measurement a digital oscilloscope has to be used. Measurement of signals means always a kind of signal processing, e.g. filtering and analog-to-digital conversion.

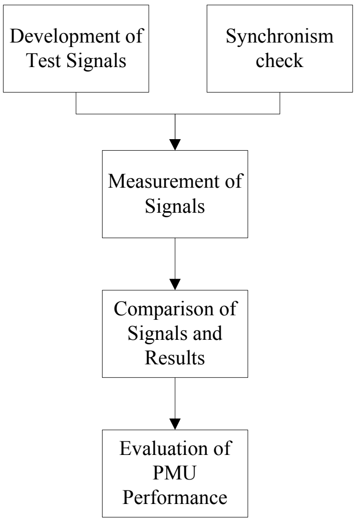

Fig. 1. Workflow for PMU-Testing

These processes cause parasitic influences on the samples. Therefore the impact of filtering on the phase shift has to be considered before the testing. If at least 16 bit analog-to-digital converters are used for measurement the quantization error can be neglected. In the case of a lack of GPS synchronized signal generator the digital scope has to store the PPS and IRIG-B code simultaneously for tracking of synchronization and time tagging. Depending on the duration of the test it is useful to use the PPS for external triggering of the signal generator respectively digital scope in order to avoid loss of the synchronization of the samples of the stored signals.

D. Comparison of Signals and Results

Because of the simultaneous measurement of the test signals as well as the time information each sample can be referred to the Coordinated Universal Time (UTC). This enables a direct comparison of the results from the examined PMU and the test signals. In the case that signal generator is not GPS synchronized and does not deliver time tagged refence values in vector format the parameters, magnitude, angle and frequency of the test signal have to be calculated.

For steady-state this calculation is a common practice but for transients it is not possible to implement a uniform algorithm since the phasor concept is only defined for steady-state. So for the comparison it depends on the user who examines the PMU-based application. Therefore the user has to define how much the measurement shall be corrupted by transients or what kind of events have to be tracked. For this purpose it is necessary that the user sets up an algorithm which defines how the angle and magnitude has to be considered until these transients occur. An example of such user defined algorithm is given in [15].

E. Evaluation of PMU Performance

The comparison of the data from the PMU with the results of the user defined algorithm can be regarded as a benchmark. The purpose of the benchmark is not to compete with the algorithm from the vendors but to give them a reference. Firstly the *correctness* of PMU measurement during transients may be proven. But also it is possible to measure the performance during transients depending on the requirements defined by the user who has developed a PMU based application. Then the accuracy as well as the performance of the PMU during transients can be determined by the difference of each parameter magnitude and angle but also by calculating the TVE again.

F. Engineering test bed MAES-RT for Protection Devices and PMU

The structure of the test bed MAES-RT is displayed in Fig.2. The research stand consists of three main components: 1) Virtual Laboratory, 2) Simulator and 3) Management System. Virtual Laboratory software tool is designed to measure voltage, current and frequency in a wide range. Virtual Laboratory can be used as: 1) oscilloscope for observation and measurement of continuous and discrete variables, 2) high-speed recorder of continuous and discrete signals, 3) analysis of vector diagrams, 4) spectrum analyzer, 5) generator of continuous and discrete signals, 5) multimeter. Management computer is designed to control the research stand during testing RP and EA devices. Multiprocessor system is designed to simulate the transient processes, including the microsecond range. The algorithm of work and the structure of the stand software are discussed in detail in [16] – [18].

The Coordination Device provides a link between the digital model of the power network and the actual testing device. Server, Industrial Computer and Digital Recorder of Accident Events provide information exchange between the staff and the test stand. The Simulator is able to reproduce realistic processes occurred during the commutations in high-voltage AC power lines and allows use of stand for comparative testing of different devices such as PMU. Also different rates of frequency change can be programmed. Thus, the research stand can be used as a laboratory for comparative testing of different PMU, forming WAMS/WACS structures. Moreover, the research stand can be used to verify the conformity of the PMU to IEEE C37.118-2005 standard.

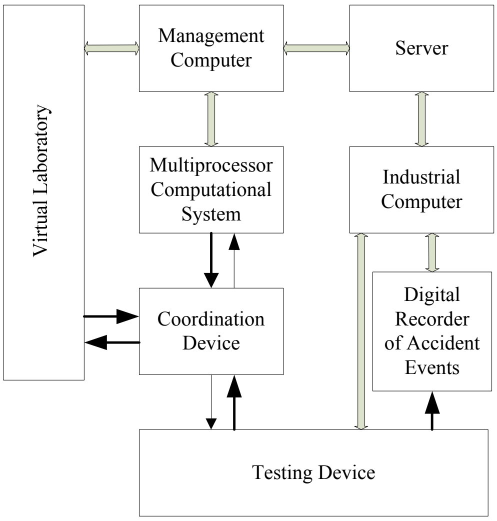

Fig. 2. Structure of MAES-RT test bed

G. Test Environment for PMU

The test equipment for PMU in Dortmund (see Fig.3) is managed by a computer. Simulations can be executed or theoretical signal composed. These signals will be downloaded to a signal generator. The PMU measures the signal output while the digital scope stores the samples and the time information from GPS receiver. So for this configuration signal generator does not need GPS-synchronization.

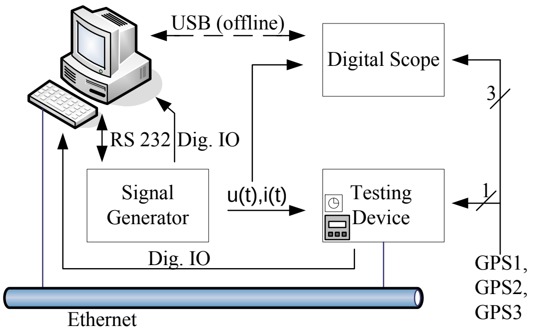

Fig.3. Structure of PMU-Test Environment

The PMU sends the measurement results to the computer. The computer receives the data by a client and stores in data file. After the test the stored samples are being downloaded from the digital scope to the computer. In order to evaluate the PMU measurement parameters angle and magnitude need to be obtained from the stored samples time stamped using the stored time information. Evaluation of PMU measurement is done offline by using a reference algorithm; the user is not obliged to use specific software. By using a reference algorithm different approaches for PMU evaluation are possible. One approach is to test a single PMU and to prove its accuracy compared to a benchmark algorithm as reference. But test environment allows also comparative testing of several PMUs.

IV. TEST RESULTS

Two kinds of events are very common and may occur under normal operating conditions on the grid. These events are faults which represent electromagnetic transients and line trippings and its induced oscillations which represent electromechanic transients. In these cases the main objective is that the measurement shall not be interrupted heavily by these events. In the following tests three commercial PMU have been tested and referred to an algorithm for a benchmark. Because of the comparison to the benchmark algorithm *correctness* of the PMU measurement can be determined during transients. In the examples the test signals contain mainly steady-state signals at nominal value of the voltage and current input until an event occurs. In order to avoid confusion by presenting several figures the depicted test signals and results refer to the measurement of one phase despite the fact that all three phases have been examined.

A. Step Signal Tests

In this series of tests performance of PMU devices is investigated using step signals. Step signals were applied to a balanced three-phase inputs as defined by following formula:

$$X_a(t) = X_m \cdot (1 + k_m h(t)) \cdot \cos(2\pi f_0 t + k_a h(t)) \quad (1)$$

Where X_a is an amplitude of test signal on phase A, f_0 is the nominal power system frequency, k_m and k_a are magnitude and angle step sizes and h(t) is a unit step function. For phases B and C formulas are the same with corresponding phase shifts. Step signal tests can be interpreted as simplified versions of switching transients. More realistic examples of switching transients are presented further in sections B and C.

Step signal changes usually cause artifacts in form of oscillations in phasors measured by PMU. Calculating TVE to assess PMU performance during step tests is not very helpful, because of big difference in signal levels before and after step. Formally calculating TVE leads to meaningless values of tens and hundreds of percents. As proposed in [19] a more appropriate measure of PMU performance is *step response* as a number of samples between the first sample that has TVE greater than 1% (allowed value for steady-state conditions) and the first sample which is again in 1% corridor along with all subsequent samples when *correctness* is given again. Results of testing of two PMUs are listed in tables I and II. Tests were performed with report rate set to 50 frames per second. PMU B recovers from abrupt amplitude changes faster than PMU A, PMU B has slowly decaying phase measurement error after angle step test.

Also the malfunction in measurement algorithm of PMU B was found: if magnitude of signal on voltage inputs of device drops to zero, measurement of phase angles of currents is halted. Manufacturers of the device confirmed that they are aware of the problem and are working on it. The reason for such incorrect behavior of the device is that current angles are calculated relative to voltage angles, and voltage angles are unavailable if there are no voltage signals available.

TABLE I
STEP RESPONSE DURING AMPLITUDE STEP TEST

Magnitude step, %	Step response time, frames	
	PMU A	PMU B
50	5	4
10	4	3
-10	3	1
-50	8	4
-90	12	6

TABLE II
STEP RESPONSE DURING PHASE ANGLE STEP TEST

Phase angle step, degrees	Step response time, frames	
	PMU A	PMU B
45	7	13
15	4	13
-15	6	13
-45	7	13

B. Example Fault

In this example the signal represents a heavy loaded line which faces a remote symmetrical fault. The current for this case has been calculated only theoretically without any support of simulation software. The signal has been composed by the user interface of a signal generator. The produced test signal of the current in Fig. 4 contains a sine wave as a main component at a frequency of 50 Hz. The amplitude of signal rises from 2.75 s to 2.76 s. Then the signal contains a decaying DC-component for several periods. Because of the fault also the magnitude of the current is increased.

It is expected that measurement of the angle of PMU is not interfered too much. The DC component should be filtered out and the measured angle may remain constant.

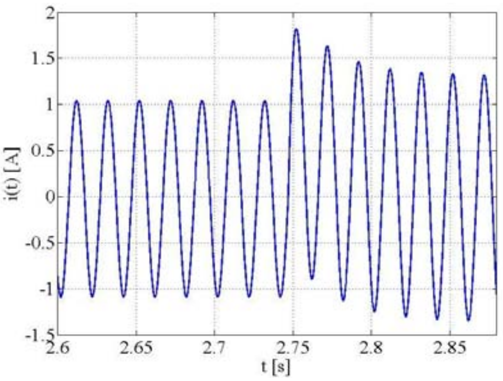

Fig. 4. Test signal of current during a fault

In Fig.5 the results from the three PMU and the benchmark algorithm is displayed. During the steady-state the phase angles of all PMUs remain constant as expected.

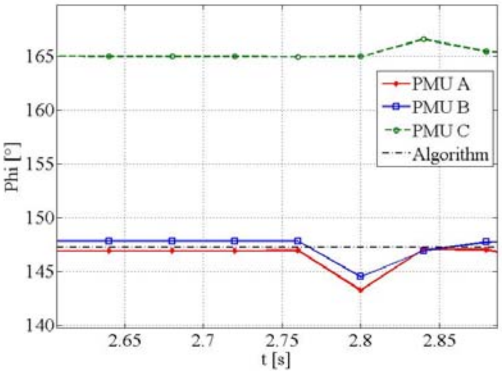

Fig. 5. Algorithm as Benchmark – Angle is supposed to remain constant during the fault

However at time t=2.8 s PMU A and B measure a deviation of angle. The angle of PMU C contains a constant offset of about 18 degrees. Such difference to the benchmark but also to the other PMU reveals a malfunction. Furthermore PMU C measures a rising of the angle with 40 ms delay compared to PMU A and B.

In Fig.6 the magnitude is displayed. In steady-state the amplitude remains constant for all PMU and the benchmark algorithm. With the rising of the amplitude of the test signal also the magnitude rises. It can be assumed that in contrast to the benchmark algorithm the results of the PMU refer to the end of the considered time stamp. However the results of the algorithm for the benchmark refer to the middle of the considered window. Additionally, PMU C detects the rising of the amplitude 40 ms after PMU A and B and 80 ms after the benchmark algorithm.

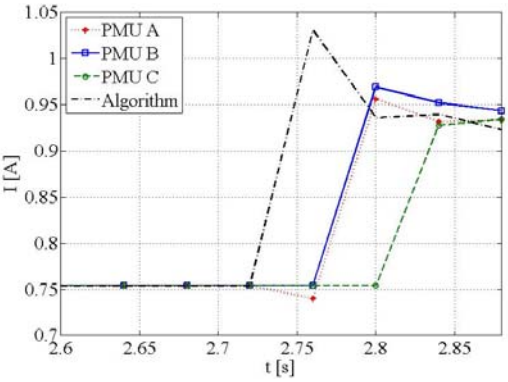

Fig.6. Magnitude of the test signal from PMU in comparison to the benchmark algorithm

In Fig. 7 the calculated TVE is displayed. The TVE is defined only for steady but it can be used also for evaluation during transients. So the offset of the phase angle of PMU C can be clearly derived of the entire test procedure. Also the time shift in measurement of the angle and the magnitude compared to the benchmark algorithm can be identified.

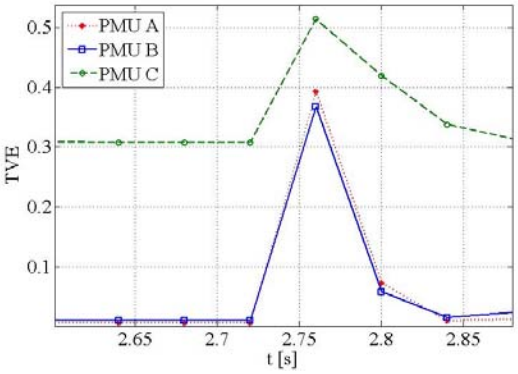

Fig. 7. Calculated TVE of PMU

C. Example Trip Line

In this scenario a grid is heavily loaded. Generation as well as the amount of the load is very high. In this example a tie line will be tripped at the time t=12.15 s (see Fig.8 and 9).

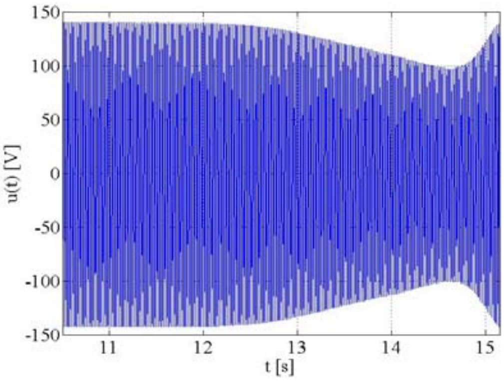

Fig. 8. Entire sequence of the voltage until line tripping and the caused fast change of the amplitude

The tripping causes an oscillation with slow change of amplitude of the voltage from t=12.15 s till t=14.75 s. From 14.75 s to 15 s the oscillation contains fast change of the magnitude. Because of the complexity this example has been simulated by software. Therefore, not only steady calculations are done, as well subsequent effects like oscillations are examined.

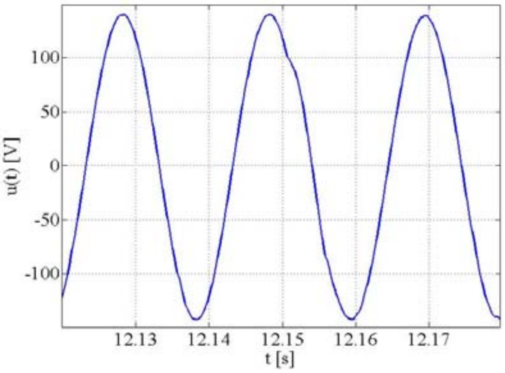

Fig. 9. Voltage during switching

The switching process of the line lasts only 3 ms and causes a subtransient shift of the angle of the voltage at time t=12,15 s.

The measurement of the angle along the entire sequence is displayed in Fig.10. It is expected that again the response time of the PMU is delayed compared to the benchmark algorithm. But because a long time period is considered the resolution of the result is not as high that time shift of 40 ms can be revealed.

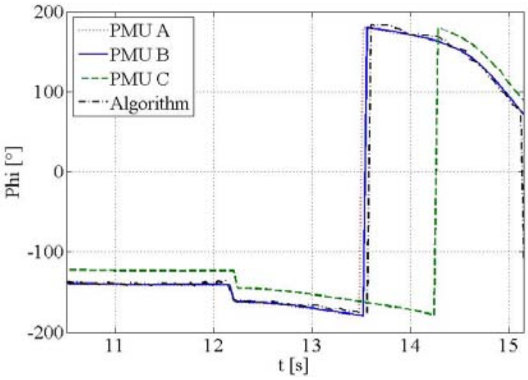

Fig. 10. Measured angle by PMU and benchmark algorithm during switching and oscillation

The offset of the angle of PMU C is as high as during the fault test in subsection *A*. During this test the angle of the test signal is calculated by the benchmark algorithm by detecting the maxima of the sine-wave. However noise disturbs the calculation, the value of the angle varies around five degrees.

In Fig. 11 the magnitude is plotted. Beside the time shift no big differences occur. As expected the magnitude decreases after the switching and increases because of the oscillation.

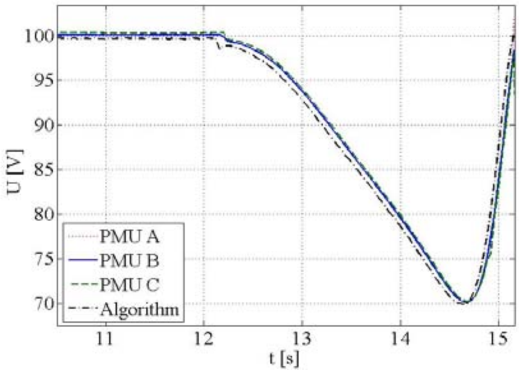

Fig. 11. Measured magnitude of the voltage by PMU and benchmark algorithm Eva-McIden during switching and subsequent oscillation

The calculated TVE is displayed in Fig.12. All PMU have a rising TVE compared to the benchmark algorithm at the switching of the line. But it can be expected that difference is because of the time shift of the results from the PMU compared to the benchmark algorithm. Also it has to be pointed out that the TVE is much higher than one percent during the whole test.

The reason is the varying result of the angle detected by the benchmark algorithm induced by noise. In consequence for this test a dedicated benchmark algorithm is necessary. Again a phase shift of the PMU C exists also in this test.

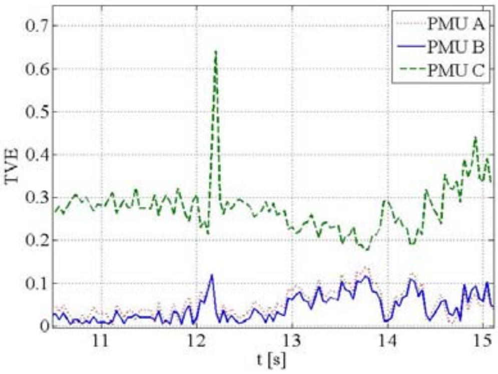

Fig. 12. Calculated TVE referred to benchmark algorithm

D. Overall Evaluation of the Performance

With the comparison of magnitude and angle of given test signals to the results of PMU the performance of PMU during transients is examined. In all dynamic tests PMU A and PMU B have proven a sufficient measurement performance. PMU C reveals always an offset of the phase angle independent from the input (current or voltage). Further investigations have revealed that the synchronism for this device was not given.

V. CONCLUSION

Performance of PMU during transients can be evaluated with the presented test procedure. Great variety of power system transients exist, so creation of comprehensive library of test signals is probably the biggest difficulty in evaluating PMU performance during transients. Additional benchmark algorithms which provide reference values for evaluation need to be developed and applied. Joint efforts or researchers working on problem of PMU testing and developers of WACS systems' algorithms will be required. An effort to create such a library can succeed only if it is a public work open to international contributions.

Besides measurement accuracy, another important characteristic of PMU is measurement latency. In general there will be some delay between a moment of time associated with a phasor data frame and moment when the phasor data is output by PMU, because digital signal processing algorithms implemented in PMU devices usually operate on blocks of data. In real-time applications using synchrophasor data measurement *latency* is as important as *accuracy*, so latency of PMU should be measured before deploying such application. A possible tool to evaluate measurement latency is Phasor Data Concentrator (PDC), which has an independent connection to a high-precision time source. Time-synchronized PDC is in development by authors of this paper at the present time and it will be discussed in detail in further publications.

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