Testing of PMU Based Wide Area Monitoring and Recording Systems

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***Abstract*— Phasor Measurement Units (PMUs) are getting increasingly popular. Major incidents in the near past, such as the big blackouts in 2003 in the northeast of the USA and in Italy, have raised the interest in all means that support the observation of the condition of the electrical power network, assessing system stability, and predicting problems. PMUs are perceived to be valuable tools for this. The paper gives a brief introduction to the principle of operation of PMUs and the metrics for assessing their performance. Some exemplary test cases are explained and possible test configurations to perform the test cases are discussed. The shown methods are not only suited for laboratory applications. The usage of a classical protection test set with versatile time synchronization interfaces (GPS, IRIG-B, PPS) brings PMU testing into the reach of protection engineers for applications in the field.**

***Index Terms*— Phasor Measurement Units, PMU, Testing, Wide Area Monitoring**

I. INTRODUCTION

The industry is already working for quite a while on the issue of measuring the phasors of the quantities in the electrical power system. A first standard on this issue, IEEE 1344 [6] was available since 1995.

Phasor Measurement Units (PMUs) were already available in 2003, when the big blackouts in the north-east of the USA and in Italy gave this technology a big boost. The PMUs became recognized as an effective tool for observing the status of the power network and ensuring its stability. Shortly after the dramatic events, the Eastern Interconnect Phasor Project (EIPP) [4] was founded with the focus to apply wide area measurement, monitoring and control for improving the reliability of the power system. The activities of the EIPP will be continued by the North American Synchrophasor Initiative (NASPI) [8]. In Europe, the UCTE is also using wide area monitoring with PMUs for observing the status of the network [10].

II. CHANGES IN THE POWER SYSTEMS

For several years the generation, transmission and distribution of electrical energy is going through some drastic changes resulting in challenges for the electric power system operators and potential problems for the corresponding assets. The consumption of electrical energy is growing world-wide, but due to economic or environmental restrictions, the transmission networks do not grow in the same way. New large generation centers, such as hydro power plants in Brazil or China, or wind-parks in northern Germany are often built far away from the consumers. Through the liberalization of the energy markets, the power flows in the always growing power networks are becoming more difficult to control, leading to failures in the network. Measuring the synchrophasors offers possibilities to analyze such problems and eventually to react on them.

III. THE CONCEPT OF PHASOR MEASUREMENT

PMUs are installed at all important locations of the network to be observed. These PMUs are accurately time synchronized, typically through the Global Positioning System (GPS). Based on this time reference, the magnitudes and phases of voltages and currents at the PMU locations are measured, at exactly the same times in all locations.

The measured quantities are transferred over fast communication links to a monitoring center. In the monitoring center, the data from the connected PMUs are collected, aligned, archived, and provided to the SCADA applications.

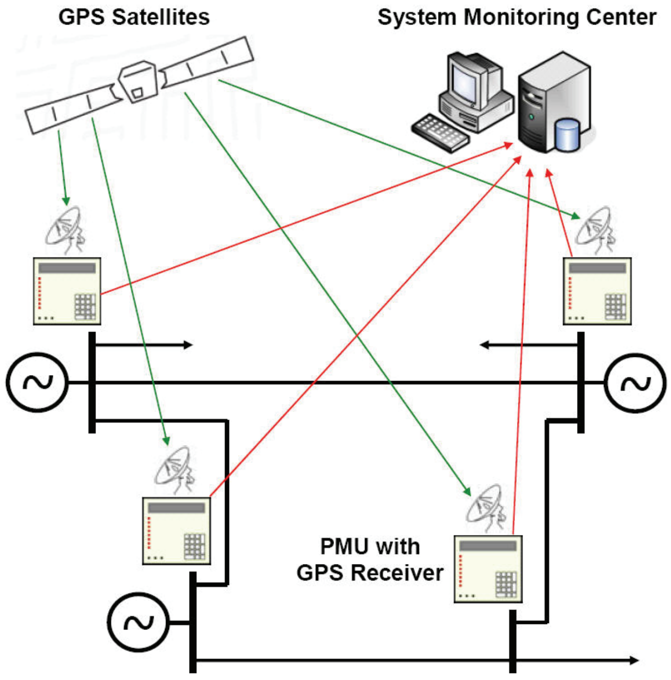

Fig. 1 - Principle of synchronized phasor measurements

A new quality of data is obtained by measuring precisely

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time synchronized at different locations in the power network and through the time stamping of the data.

- Measured values of voltages and currents are available as complex phasors
- Synchronously measured values can be directly compared and easily processed

IV. APPLICATIONS OF PHASOR MEASUREMENT UNITS

Classical protective relays perform the protection of single elements of a power system, as generators, transformers, lines or busbars. For the protection of such objects, locally measured values are sufficient in most cases. The response times of such devices are typically in the range of several milliseconds.

SCADA systems however, have system wide view on the power system, but due to limited data rates this view is relatively static.

The data from the PMUs enable the SCADA applications to obtain a dynamic view of the network [9].

The abbreviation WAMPC stands for the following main applications:

- Network monitoring and fault analysis (**W**ide **A**rea **M**onitoring)
- Network/System protection (**W**ide **A**rea **P**rotection)
- Network operation and control (**W**ide **A**rea **C**ontrol)

Furthermore, certain system protection functions like load shedding at under frequency, overload protection or power swing detection can be integrated into the PMUs.

A. Network Monitoring and Fault Analysis

PMUs measure system wide at exactly specified moments and tag their measured values with time stamps.

Thus, the data from far distant locations can be compared easily and safely, e.g. for a fast and reliable fault analysis [2]. A network monitoring in real-time is as well possible. The following figure shows the runs of the frequencies in three isolated areas during a disturbance in the UCTE network on November 4, 2006 [11]. Clearly visible are the failed attempts to synchronize between area 1 and 2 (labels 1 to 7), where the frequencies of the two areas shortly move towards each other.

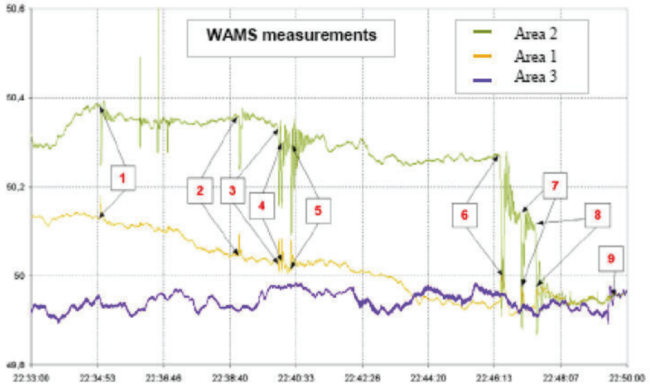

Fig. 2 Run of frequencies and synchronization attempts

B. State Estimator

The state estimator is a central function of each network control system. Its goal is to display the voltage phasors of the most important nodes of the network and the energy flows between them as accurately as possible.

Therefore, the network topology (status of CBs and disconnectors), the real and reactive powers at the feeders and the voltages at the busbars are monitored and measured.

The actual condition of the network is calculated from these measured data and other network parameters (line impedances, transformer data). Due to low data rates and unsynchronized measurements, convergence problems can occur during dynamic conditions. The state estimation can be enhanced by using PMUs with time synchronized measurement of the phasors of voltages and currents.

C. Further Applications

Besides the shown examples, there are numerous other applications for phasor measurements, such as:

- Determining network parameters (lines, generators,)
- Thermal load supervision
- Voltage stability supervision
- Detection and assessment of power swings
- Centralized control of tap-changers, phase-shifting transformers
- FACTS control (TCSC, HVDC, VSC)
- Selective backup protection

V. THE IEEE C37.118 STANDARD

The IEEE C37.118 standard [5] is currently the only standard world-wide for measuring Synchrophasors in electrical energy systems. Throughout the following text, it will be commonly referred as "the standard".

Basically, it defines the following:

- Time reference: UTC
- Rate of measurement
- Phase reference: co-sine
- Accuracy metrics: TVE (Total Vector Error)
- Communication model (format of telegrams)

The standard does not specify:

- Speed of measurement
- Accuracy under transient conditions
- Hardware / Software of the devices
- Measurement algorithms

The specifications allow a simple processing of the Synchrophasor from different measuring systems, in real-time as well as off-line.

A. Definition of the Synchrophasor

The Synchrophasor $\underline{X}$ of a time signal $x(t)$ is defined as a complex value:

$$\begin{aligned}\underline{X} &= X_r + jX_i \\ &= \frac{X_m}{\sqrt{2}} e^{j\varphi} \\ &= \frac{X_m}{\sqrt{2}}\left(\cos\varphi + j\sin\varphi\right)\end{aligned}$$

x(t) is assumed to be sinusoidal, hence X_m is the amplitude and $X_m/\sqrt{2}$ is the effective value. φ is the phase angle with respect to a reference signal as shown in Figure 3.

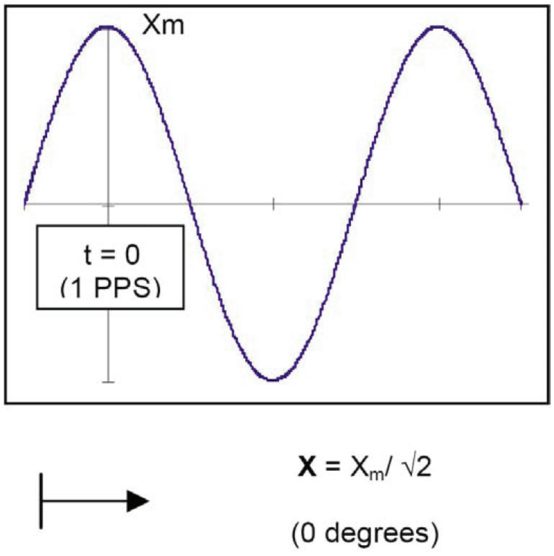

Fig. 3 - The reference time signal and its Synchrophasor representation [5]

The frequency of the reference signal is the nominal frequency of the power network. It is a cosine function with zero phase offset, thus it has its positive maximum at $t = 0$ (beginning of UTC second) [1]. A sine function (positive zero crossing at $t = 0$) would have $\varphi = -90°$ for its Synchrophasor representation.

B. *Accuracy*

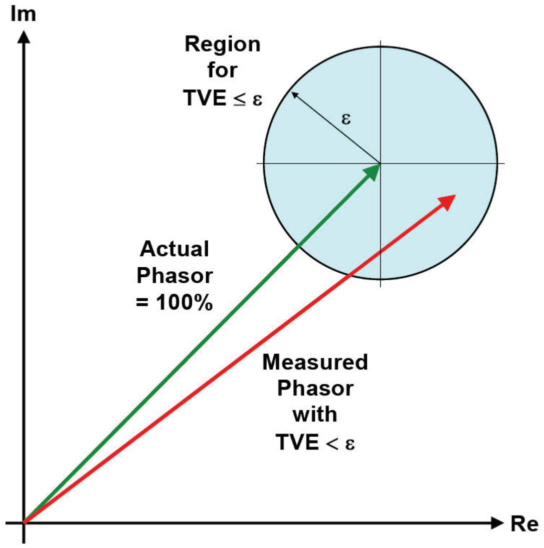

Fig. 4 - Phasors and Total Vector Error

The standard defines the Total Vector Error (TVE) as a measure to assess the accuracy of the measurements of a PMU (as the standard deals with phasors, it should have been named Total Phasor Error (TPE) instead). Figure 4 shows the relationship between the actual phasor, the measured phasor and the TVE for an arbitrary limit ε for the TVE.

The TVE combines errors from the magnitude and phase measurements. The maximum error for the magnitude measurement (with no phase error) can be easily obtained from Figure 4, it would be ± ε. The maximum phase error occurs when the measured phasor is a tangent to the circular TVE region. The standard specifies a limit of ε = 1% for most cases, this corresponds to a maximum phase error of 0.57°.

The standard defines the accuracy for stationary conditions, i.e. at constant magnitude and frequency of the measured signal.

C. *Communication and Data Formats*

The standard defines the formats for frames sent out from the PMU (data, configuration, and header) and for command frames sent to the PMU.

Mappings to serial communication and to TCP/UDP are specified.

The data frames contain:

- Synchrophasors of the voltages and/or currents (1-phase, 3-phase, sequence components)
- Frequency & frequency change
- Further analog & digital values

The configuration and header frames transmit identifiers, format specifications, and conversion factors for the values transmitted in the data frames.

The operation of the PMU can be controlled by sending command frames to it, e.g. to request the sending of configuration and header frames or to disable/enable the sending of data frames.

VI. TESTING PMUS

A. *Requirements*

The standard makes one brief, but essential) statement on the requirements for test equipment ("calibration devices") [3] . It demands to "*have a 'test accuracy ratio' of at least four (4) compared with these test requirements (for example, provide a Total Vector Error less than 0.25% where TVE is 1%).*". This TVE of 0.25% for the signal source is quite challenging. The combined worst case error of a test source with a magnitude error of 0.1% and a phase error of 0.1° already equals to a TVE of 0.2%.

A test set also needs to provide versatile time synchronization features. Depending on the test case, the test set must itself synchronize to an external time source or provide a time reference for the devices under test (PMUs) to synchronize with.

B. *Tests Cases*

There are several ways to categorize the test cases. A basic classification can be into "static" and "dynamic" tests.

1) Static Tests

In **Static Tests**, the stimuli are applied in such a way that a static response can be expected from the device under test. Most readings can be easily obtained either from a display at the PMU, from a legacy monitoring software, or from a client SW that obtains the PMU measurements through the standardized protocol. These cases are well covered with the currently available testing tools.

The tests specified in IEEE C37.118 can be considered such static tests. Tests for magnitude errors and phase errors and TVE for voltages and currents depending on relative magnitude, symmetry of voltage or current systems, frequency, and harmonics can be performed this way.

2) Dynamic Tests

In **Dynamic Tests**, the response consists of a series of values that change too fast to be observed by a person. Therefore, the data from the PMU have to be recorded and processed for an assessment. Dynamic test are mostly related to the transient response of PMUs. Regarding this, IEEE C37.118 just states that different PMUs will behave different and that "*Behavior under transient conditions is not mandated*". Actually, PMUs might even go into a blocked mode if abrupt changes of the measured signals cause the algorithms to fail temporarily, thus flagging the data as invalid until the algorithm has caught up or the conditions have stabilized again. The extension of test cases to cover the responses on step and ramp changes of magnitude, phase, and frequency is a task for the future.

PMUs operate globally time synchronized, so it might appear mandatory that test sets always have to operate globally synchronized as well. There are indeed some test cases where this is required.

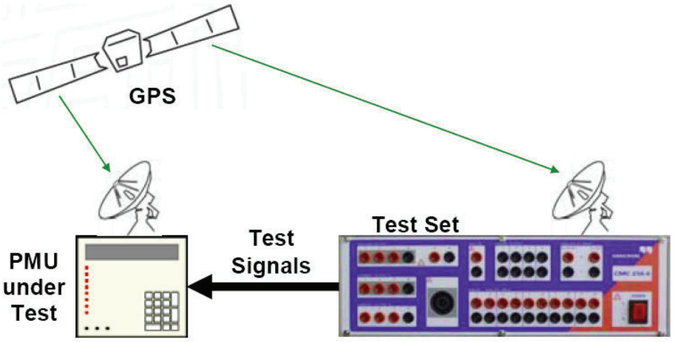

Fig. 5 - Globally synchronized test setup

But there are many other test cases, where the test set and a PMU can be operated in an isolated configuration without a reference to a global time source. Time synchronization is just established locally between the test set and the PMU.

As Figure 6 shows, this can lead to a simplified test setup. Consequently, such test cases are often easier to implement and can still cover a quite significant range of tests.

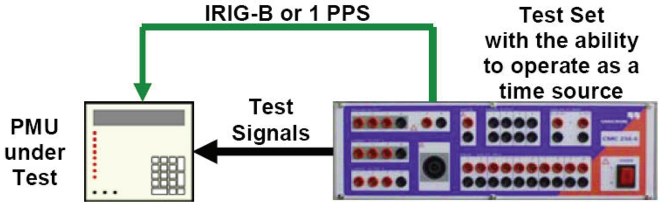

Fig. 6 - Locally synchronized test setup

Highly accurate protection test sets with GPS, IRIG-B, and PPS interfaces serve the requirements for PMU testing. For the PMU development at the vendors, custom test programs utilizing a programming interface support the automation of special tests. For testing in the field, test plans with standard test modules provide as well a high degree of test automation.

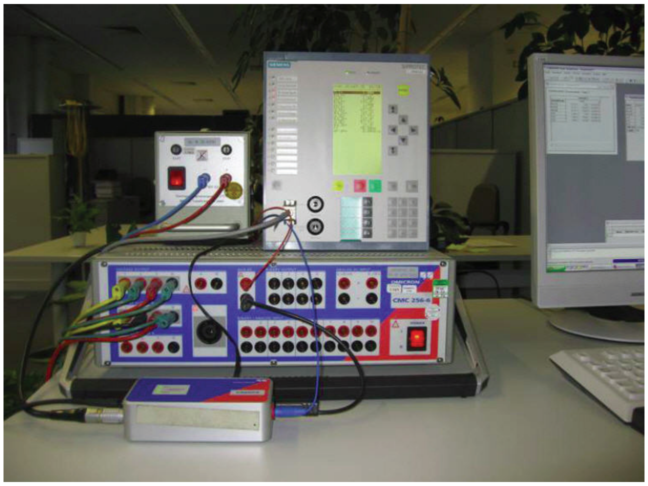

Fig. 7 - PMU test with protection test set and GPS receiver

C. Compatibility between different PMUs

PMUs according to IEEE C37.118 grant a TVE less than 1% under the conditions specified in the standard. Compatibility tests with PMUs from different vendors show, that all devices keep the static accuracy as required by the standard, but there are significant differences in the dynamic behavior [7].

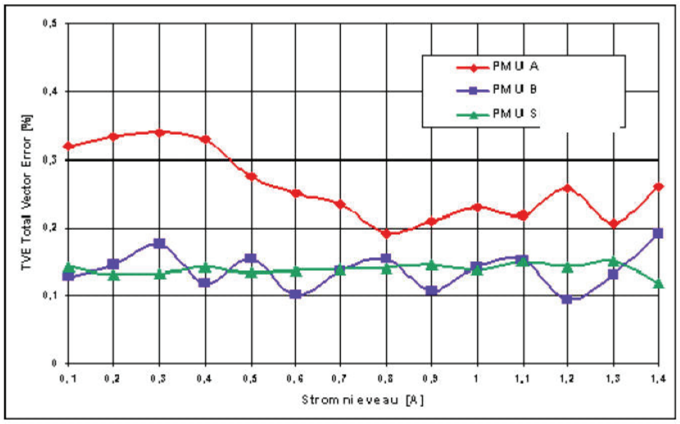

Fig. 8 - PMU comparison: TVE over current magnitude

VII. CONCLUSIONS

With the development and deployment of PMUs in significant numbers, there is an increasing need for testing of such devices. Highly precise protection test sets with versatile time synchronization features can cover a significant range of test cases. Protection test sets are different than other general purpose laboratory testing equipment for time, voltage and current. They are perfectly adapted to the domain of three phase electrical power systems and allow the specification of the test signals in familiar terms.

The tests under stationary conditions as mentioned in the IEEE Std C37.118-2005 are already well covered with the current means.

Tests under dynamic conditions can be designed by applying further tools that record and evaluate the data sent out from the PMUs through the communications interface.

VIII. ACKNOWLEDGEMENTS

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IX. REFERENCES

[1] Arbiter Systems Inc.: What is Absolute Phase Angle?; http://www.arbiter.com

[2] Bertsch, Carnal, Korba, Ingram, Broski, Sattinger: Experiences and Benefits of Systems for Wide Area Monitoring; WPDA, Spokane, April 2004

[3] Dickerson: Establishing Traceability of Synchronized Phasor Measurements at the National Laboratory Level; Securing Critical Infrastructures, Grenoble, October 2004

[4] http://phasors.pnl.gov/eipp_vision.html Eastern Interconnect Phasor Project (EIPP) at the Consortium for Electric Reliability Technology Solutions (CERTS) Website

[5] IEEE Std C37.118-2005, IEEE Standard for Synchrophasors for Power Systems

[6] IEEE Std 1344-1995, IEEE Standard for Synchrophasors for Power Systems

[7] M. R. Ingram, A. G. Phadke, J. Depablos, V. Centeno, “Comparative Testing of Synchronized Phasor Measurement Units"

[8] http://www.naspi.org North American Synchrophasor Initiative (NASPI)

[9] Elmo Price, “Practical Considerations for Implementing Wide Area Monitoring, Protection and Control”

[10] Reinhardt, Carnal, Sattinger: West- und Südosteuropa werden zusammengeschaltet; Bulletin SEV/AES 3/2005

[11] UCTE Final Report - System Disturbance on 4 November 2006

X. BIOGRAPHIES

Fred Steinhauser was born in Feldkirch, Austria, in 1960. He studied Electrical Engineering at the Technical University of Vienna, where he obtained his diploma in 1986 and received a Dr. of Technical Sciences in 1991.

In 1998 he joined OMICRON, where he worked on several aspects of testing power system protection. Since 2000 he works as a product manager with a focus on substation communication issues. Fred Steinhauser is a representative of OMICRON in the UCA International Users Group. He is member of WG10 and WG17 in the TC57 of the IEC working on the standard IEC 61850, and a member of CIGRÉ SC B5.

Benton Vandiver III received BSEE from the University of Houston in 1979. He began his career with the Substation Division of Houston Lighting & Power, in 1978 engineering relay protection systems for all T&D voltages. In 1991 he joined Multilin Corp. as a Project Manager on a team responsible for designing and developing a new family of utility grade digital relays. In 1995 he joined OMICRON electronics as Sales & Application Engineer responsible for sales, training, and promotion of the revolutionary CMC Universal Test Set to North & South America.

He is currently Technical Director for OMICRON Electronics Corp. USA in Houston, TX. He is a long time member of IEEE and is Chairman of Working Group H5-C Common Data Format for IED Sampled Data. He holds a US Patent and has authored or co-authored numerous technical papers for various conferences in North America.

Alexander Apostolov received a MS degree in Electrical Engineering, MS in Applied Mathematics and Ph.D. from the Technical University in Sofia, Bulgaria. He has more than thirty years experience in the field of electric power systems protection, control and communications..

He is presently Principal Engineer for OMICRON electronics in Los Angeles, CA. He is an IEEE Fellow and Member of the Power Systems Relaying Committee and Substations C0 Subcommittee. He is the past Chairman of the Relay Communications Subcommittee, serves on several IEEE PES Working Groups and is Chairman of Working Group D21: Investigate Supporting of IEC Standard for Distance Relay Characteristics.

He is member of IEC TC57 and Convenor of CIGRE WG B5.27 and member of several other CIGRE B5 working groups. .He is Chairman of the Technical Publications Subcommittee of the UCA International Users Group. He holds three patents and has authored and presented more than 280 technical papers. He is also Editor-in-Chief of the PAC World magazine.