

Synchrophasors Application For Protection – Can We Use Them?

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1 INTRODUCTION

The developments of multifunctional intelligent electronic devices for protection and other applications that perform synchrophasor calculations and the improvements in inter and intra-substation communications bring the industry to a time when many specialists are thinking about the use of synchrophasors for protection applications.

The paper describes first the introduction of two synchrophasor performance classes defined in IEEE PC37.118.1. The p class is intended for applications such as protection that requiring fast response, while the m class is intended for applications which could be adversely affected by aliased signals but do not require the fastest reporting speed.

Synchrophasors based applications to substation protection are later discussed. Examples considered in the paper include line and bus differential protection.

Transmission line protection using synchrophasors for the calculation of the differential current is later described. Requirements for the communications interface between the substations are analyzed. The impact of loss of time synchronization in one of the substations is also discussed.

The testing of synchrophasors based protection systems is described at the end of the paper.

2 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.

A new quality of data is obtained by measuring precisely time synchronized signals 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

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 one cycle.

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.

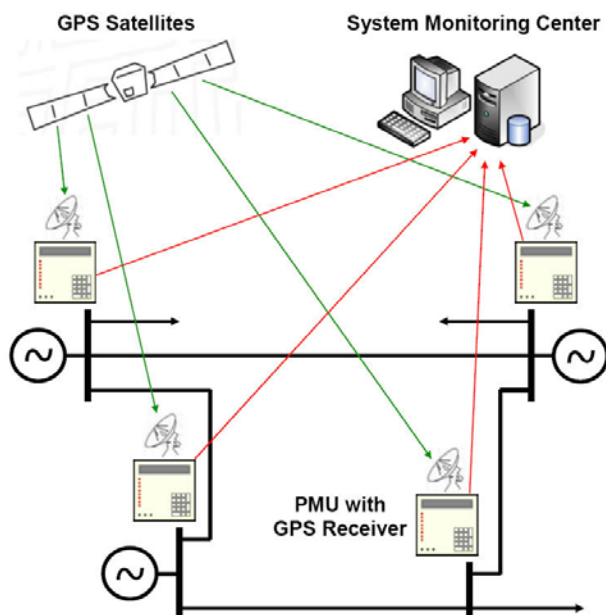


Figure 1: Principle of synchronized phasor measurements

The dynamic observation of the state of the electric power system can be achieved using synchrophasor measurements in what is known as wampcs. This abbreviation 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.

3 THE IEEE C37.118 STANDARD

The ieee c37.118 standard 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 synchrophasors from different measuring systems, in real-time as well as off-line.

In 2011, as a result of decisions to harmonize ieee and iec standards development, the original standard was split in two standards: c37.118.1-2011 - ieee standard for synchrophasor measurements for power systems and c37.118.2-2011 - ieee standard for synchrophasor data transfer for power systems.

3.1 Definition of the synchrophasor

According to ieeec37.118.1 the sinusoidal waveform defined by

$$x(t) = X_m \cos(\omega t + \phi) \quad (1)$$

Is commonly represented as the phasor

$$\begin{aligned} \mathbf{X} &= (X_m / \sqrt{2}) e^{j\phi} \\ &= (X_m / \sqrt{2}) (\cos \phi + j \sin \phi) \\ &= X_r + jX_i \end{aligned} \quad (2)$$

The value of ϕ depends on the time scale, particularly where $t = 0$. It is important to note this phasor is defined for the angular frequency ω ; evaluations with other phasors must be done with the same time scale and frequency.

The *synchrophasor* representation of the signal $x(t)$ in (1) is the value $\mathbf{x}$ in (2) where ϕ is the instantaneous phase angle relative to a cosine function at the nominal system frequency synchronized to utc. Under this definition, ϕ is the offset from a cosine function at the nominal system frequency synchronized to utc. A cosine has a maximum at $t = 0$, so the synchrophasor angle is 0 degrees when the maximum of $x(t)$ occurs at the utc second rollover (1 pps time signal), and -90 degrees when the positive zero crossing occurs at the utc second rollover (sin waveform). Figure 2 illustrates the phase angle/utc time relationship.

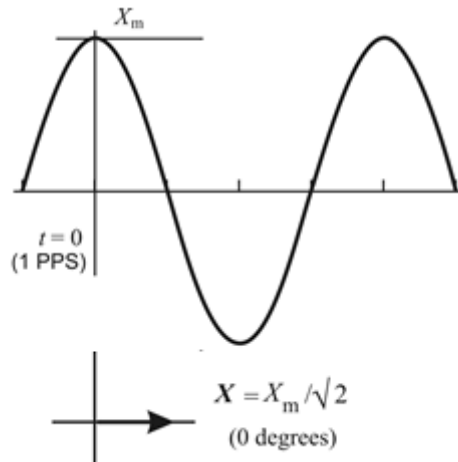


Figure 2: The reference time signal and its synchrophasor representation

C37.118.1-2011 defines synchrophasors, frequency, and rate of change of frequency (rocof) measurement under all operating conditions. It specifies methods for evaluating these measurements and requirements for compliance with the standard under both steady-state and dynamic conditions. Time tag and synchronization requirements are included. Performance requirements are confirmed with a reference model, provided in detail. This document defines a phasor measurement unit (pmu), which can be a stand-alone physical unit or a functional unit within another physical unit.

This standard for the first time introduces two performance classes. As the letter indicates, the p class is intended for protection types of applications requiring fast response and does not require explicit filtering. M class is intended for applications which could be adversely affected by aliased signals but do not require the fastest reporting speed, thus the m class requires anti-alias filtering. All standard compliance requirements are specified by performance class. The standard requires that if a supplier provides both p and m class performance in a device, these shall be user selectable.

Ieee c37.118.1 does not specify hardware, software, or a method for computing phasors, frequency, or rocof.

3.2 Communication and data formats

The second new standard c37.118.2-2011 specifies a method for real-time exchange of synchrophasor measurement data between power system equipment. It specifies messaging that can be used with any suitable communication protocol for real-time communication between phasor measurement units (pmu), phasor data concentrators (pdc), and other applications. It defines message types, contents, and use. Data types and formats are specified. A typical measurement system is described. Communication options and requirements are described in annexes. 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.

Another document that specifies synchrophasor communications is iec 61850 part 90-5: use of iec 61850 to transmit synchrophasor information according to ieee c37.118. It provides a way of exchanging synchrophasor data between pmus, pdc, wampac (wide area monitoring, protection, and control), and between control center applications. The data, to the extent covered in ieee c37.118-2005, is transported in a way that is compliant to the concepts of iec 61850 and supports the exchange within the substation or between substations (based on routable profiles) using in iec 61850-8-1 goose and iec 61850-9-2 sv packets.

4 PROTECTION APPLICATIONS OF SYNCHROPHASORS

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 one cycle.

Based on the introduction of p class synchrophasor measurements now it is possible to start considering their use for protection applications. One of the barriers for the wide spread implementation of synchrophasor based protection functions is the concern with the impact of the loss of gps signal. Now this should not be an issue anymore due to the availability of affordable and portable atomic clocks.

Below are two examples that can help answer the question in the title of the paper:

4.1 Line differential protection

Line differential protection is typically achieved based on the calculation of the differential current using the individual current measurements from all ends of the protected line.

The following steps are common:

- Calculation of current phasors
- Communications of current phasors
- Calculation of differential current
- Differential characteristic based operation

The primary protection element of a multifunctional transmission line protection relay should be a segregated phase current differential protection. This technique involves the comparison of the currents of each phase at each line terminal. A communications path is therefore an essential requirement of any such scheme.

Differential currents may also be generated during external fault conditions due to ct saturation. To provide stability for through fault conditions, the relay adopts a restraining technique. This method effectively raises the setting of the relay in proportion to the value of through fault current to prevent relay mal-operation. Figure 4 shows the operating characteristics of a phase differential element.

The differential current is calculated as the vector summation of the currents entering the protected zone. The restrain current is the average of the measured current at each line end. It is found by the scalar sum of the current at each terminal, divided by two.

each of these calculations is done on a phase by phase basis differential protection function with transient shift

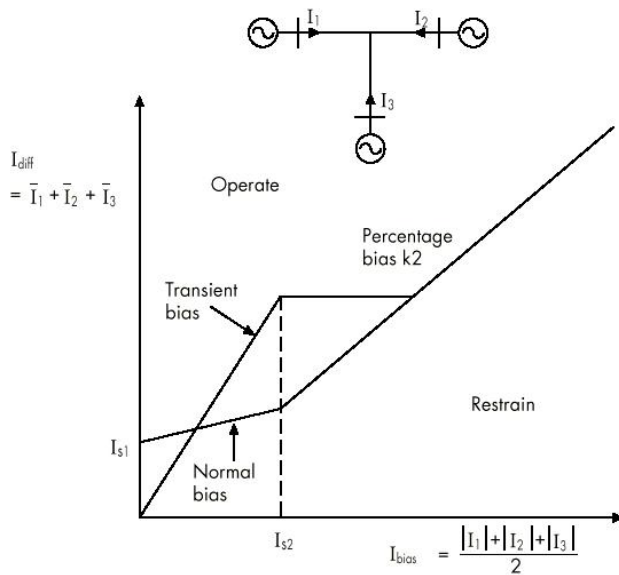


Figure 3: Restrained characteristic for a segregated phase differential protection

The level of restrain used for each element is the highest of the three calculated for optimum stability.

When a trip is issued by the differential element, in addition to tripping the local breaker, the relay will send a differential inter-trip signal to the remote terminals. This will ensure tripping of all ends of the protected line, even for marginal fault conditions.

An unrestrained differential high set element can provide high-speed operation in the event of ct saturation. Where transformer inrush restraint is used, the resultant second harmonic current produced from ct saturation may cause slow relay operation.

To calculate differential current between line ends it is necessary that the current samples from each end are taken at the same moment in time. This can be achieved by time synchronizing the sampling, or alternatively, by the continuous calculation of the propagation delay between line ends.

In the case of use of synchrophasors, by their definition they are calculated based on an accurate time synchronization of the pmus and using a fixed calculation and transmission rate.

Since many line differential relays have been using direct fiber for their communications interface for many years, we can assume that the same approach will be applied when using synchrophasors, i.e. The delay between the relays at all ends of the protected line will be the same with minimal latency.

To calculate the differential and restrain currents, the phasor samples at each line end must correspond to the same point in time. In this case each relay calculating the differential current will need to use the synchronized measured currents with the same time stamp.

Using 240 calculations of p class synchrophasor currents per second should provide sufficient performance for the line differential protection to ensure the stability of the electric power system.

The communications method in case of direct fiber between the substations at the ends of the line included in the zone of protection is defined as “tunneling” according to iec 61850 part 90-1 use of iec 61850 for the communication between substations. The message format and the communications are based on iec 61850-9-2 sv packets.

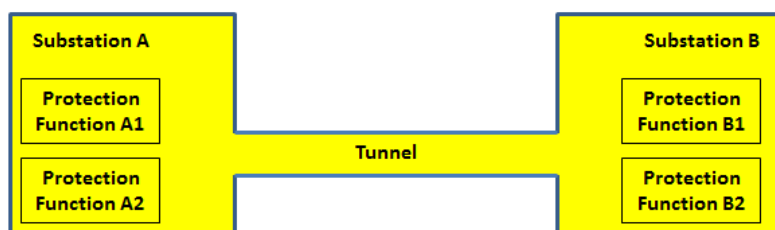


Figure 4: Communications tunnel between substation

4.2 Bus differential protection

Distributed bus differential protection systems based on proprietary communications of current phasor measurements between peripheral units and a central unit performing the differential protection function have been used for more than a decade. Iec 61850 allows the implementation of distributed bus differential protection systems using sampled analog values over the substation process bus have been discussed in several papers. Now it is possible to implement bus differential protection using synchrophasors. The architecture of such a system is shown in figure 5.

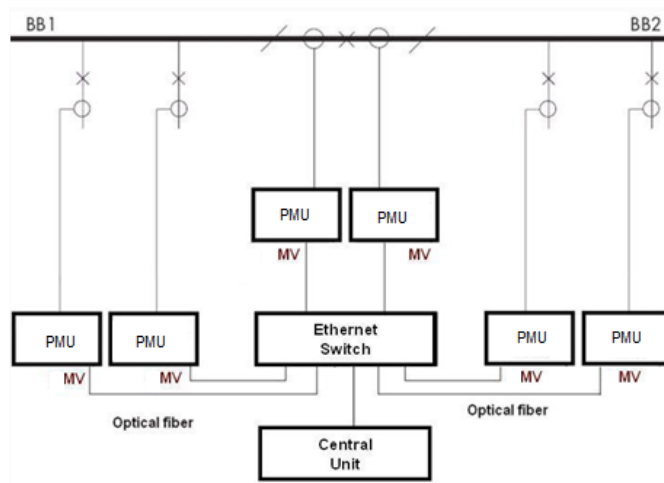


Figure 5: Bus differential based on synchrophasors

The peripheral unit in the proprietary differential protection systems is replaced by the pmu in the synchrophasors based solution. The pmu in this case has the task to convert the analog signals to p class measurements that are transmitted over the substation network to the central unit that performs the differential current calculation and makes a decision if there is a fault within the zone of protection.

Interoperability between pmus and protection, control, monitoring or recording devices is ensured based on the iec 61850 standard. A rate of 240 synchrophasor measurements per second should be acceptable to meet the typical requirements for bus protection.

The time stamp of the synchrophasor measurements is used by the central unit to select the measurements to be used for the calculation of the differential current.

in the case of proprietary distributed bus differential protection systems the data acquisition in the peripheral units is synchronized by the central unit. That is not the case with synchrophasors. In this case the time synchronization of the individual pmus has to be better than 1 microsecond, which can be achieved using iee c37.238.

5 TESTING SYNCHROPHASORS BASED PROTECTION SYSTEMS

Testing of synchrophasor based protection systems should follow the basic principles defined for the testing of any type of distributed protection scheme. The methods for testing of such types of systems are proposed based on the following order of system components tests:

- Functional testing of individual pmus and ieds used in the system
- Functional testing of distributed functions within a substation
- Functional testing of distributed functions between substations
- Functional testing of complete protection system
- End-to-end testing of the protection system

Ieee c37.118.1 defines the compliance requirements for the two classes of synchrophasor measurements defined in the standard. To be compliant with it, a pmu shall provide synchrophasor, frequency, and rate of change of frequency (rocof) measurements that meet the requirements in the standard. It details the requirements and conditions under which those requirements must be met and describes the test equipment needs and conditions for the tests.

There are two types of compliance – steady-state and dynamic. The steady-state compliance shall be confirmed by comparing the synchrophasor, frequency, and rocof estimates obtained under steady-state conditions to the corresponding theoretical values.

The dynamic compliance covers:

- Synchrophasor measurement bandwidth
- Performance during system frequency ramp
- Performance during step changes in magnitude and phase

5.1 Test equipment requirements

The standard makes one brief, but essential) statement on the requirements for test equipment ("calibration devices"). 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° 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.

5.2 Tests cases

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

5.2.1 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.

5.2.2 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. Dynamic tests are mostly related to

pmus providing p class measurements. The extension of test cases to cover the responses on step and ramp changes of magnitude, phase, and frequency is a task related to this class.

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.

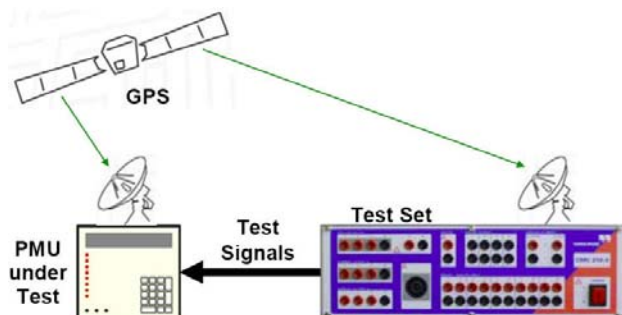


Figure 6: Globally synchronized test setup

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. 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.

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.

6 CONCLUSIONS

With the development and deployment of pmus in significant numbers, there is an increasing need for increase of their applications. The introduction of the p class of synchrophasor measurements makes it possible to consider the development and implementation of protection schemes based on such measurements.

The fact that the pmus are accurately time synchronized makes it possible to use synchrophasor measurements for transmission line differential, as well as bus differential protection.

Testing of such devices and protection schemes requires highly precise protection test sets with versatile time synchronization features that can cover a significant range of test cases.

To answer the question in the title of the paper – yes, we can use synchrophasors for protection. But we need to understand and test the performance of all components of protection schemes based on their use.

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