21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

C6-110

CIGRE 2012

# Smart meters enable synchrophasor applications in distribution grids

**S.SANTOS*, A.LLANO, A.ARZUAGA, T. ARZUAGA, L.MARRÓN, M.ZAMALLOA**
**ZIV Group**
**Spain**

## SUMMARY

Synchrophasors are being used widely in HV/MV substation applications. In these facilities we have synchronizing GPS receivers which are able to provide time stamping information to IEDs or other devices [1]. However, at the moment they are not being used in LV applications due to the cost restrictions found in the last segment of the distribution grid.

Smart meters that integrate PLC communication technology can be used to synchronize current and voltage measurements in the same network circuit. This will provide advanced power network status information with no additional costs.

Power line communication systems are a critical part of an AMI (Advanced Metering Infrastructure) system. It is possible to synchronize smart meters on a network thanks to a PLC pattern. In this way we can obtain simultaneous current and voltage measurements, which allow a wide range of new applications, such as overloaded neutral wires detection, voltage unbalances in different points, network instability due to unpredictable loads (EV), distributed generation (DER), or calibration errors and tampering schemes.

This new technology introduces an innovative methodology by which the metrological modules of smart meters can take advantage of the PLC technology to obtain additional useful information from the Low Voltage grid.

Usually, electricity meters measure input signals at an autonomous sample rate, based on their internal oscillator, and they also detect voltage zero crossings instants. In this traditional scenario, there is no interaction at all between two different meters. Their sample instants are calculated based on their own independent oscillators. In order to achieve collaborative measurements, the sample rates of both meters (and every meter involved in a specific algorithm), must be synchronized with a maximum defined time drift. This can be made by means of a PLC system. If we choose a widely deployed PLC technology such as PRIME, we

s.santos@ziv.es

can get a synchronization error drift close to 5us, applying statistical and expert control systems, and 12us thanks to the standard preamble pattern.
In three phase systems, with only single phase meters, the power phase unbalance could be measured along the derivation points using this method, i.e., reading samples of every meter and applying the standard formulae for direct, reverse and zero sequence calculation. Also neutral wire impedance and neutral current shape can be retrieved applying basic Kirchhoff rules.

In summary, PLC infrastructure, besides acting as a communication system for billing, event recording and other purposes, can also be used to add new capabilities to the system, by operating in a synchronized manner all the meters that are installed in different locations of the power network. This paper will further analyze this technology and the way it can be implemented for enhanced LV network monitoring applications, such as in DER scenarios.

**KEYWORDS**

Smart Meter - Smart Grid - Synchrophasor - Low Voltage - Power Line Communications - Voltage unbalance- Neutral Current- Power Quality- Clock Synchronization -System Losses

## SYNCHROPHASORS AND THEIR APPLICATIONS IN LOW VOLTAGE GRIDS

The electricity industry has been working on several grid improvements regarding communications, grid automation etc. during the last years. It is because of these improvements, initially introduced in High Voltage grids, why “smart grids” became a hot topic in the industry. This additional intelligence, which to a certain extent was driven by the integration of renewable energy sources, allowed a better control and a much more accurate knowledge of HV grids. As energy generation became more distributed, it was necessary to extend the smart grid to the MV. At the moment we are coming to the end of this top-down road of deploying an intelligent grid down to the end-consumers. In parallel, in many countries LV smart grid deployments have been driven by regulatory changes, which made the adoption of smart meters mandatory at LV levels supporting bidirectional communications with the end user. Active demand management was then a feasible option. This new intelligent LV infrastructure can also be used to comply with the future requirements that the distributed energy sources may impose to the existing LV grid (Combined Heat and Power (CHP), small domestic RES installations, etc).

The grid connection of any kind of LV energy production system (independently of its technology) should be carefully planned by the distribution system operators. Typically these systems include any sort of small renewable energy installation (rooftop photovoltaic panels, minieolic or minihidraulic installations, CHP etc, but also other storage-based energy sources such as V2G (vehicle to grid) technologies. Synchrophasors can become a key element to ensure that these new LV energy generators are introduced in the LV grid in such a way that enhances network performance and resilience, improving the efficiency of the system. Nowadays, Phasor Measurement Units (PMUs) are mostly GPS based due to the long distance and time accuracy requirements for automation applications.

The protection and control of HV and MV networks required a detailed characterization of the network. Nowadays, the emerging technologies designed for LV distributed generation systems and the increasing use of smart meters that provide added value and advanced communications functionalities (AMI), enable a scenario where the automation and control of distribution systems and advanced measurement converge.

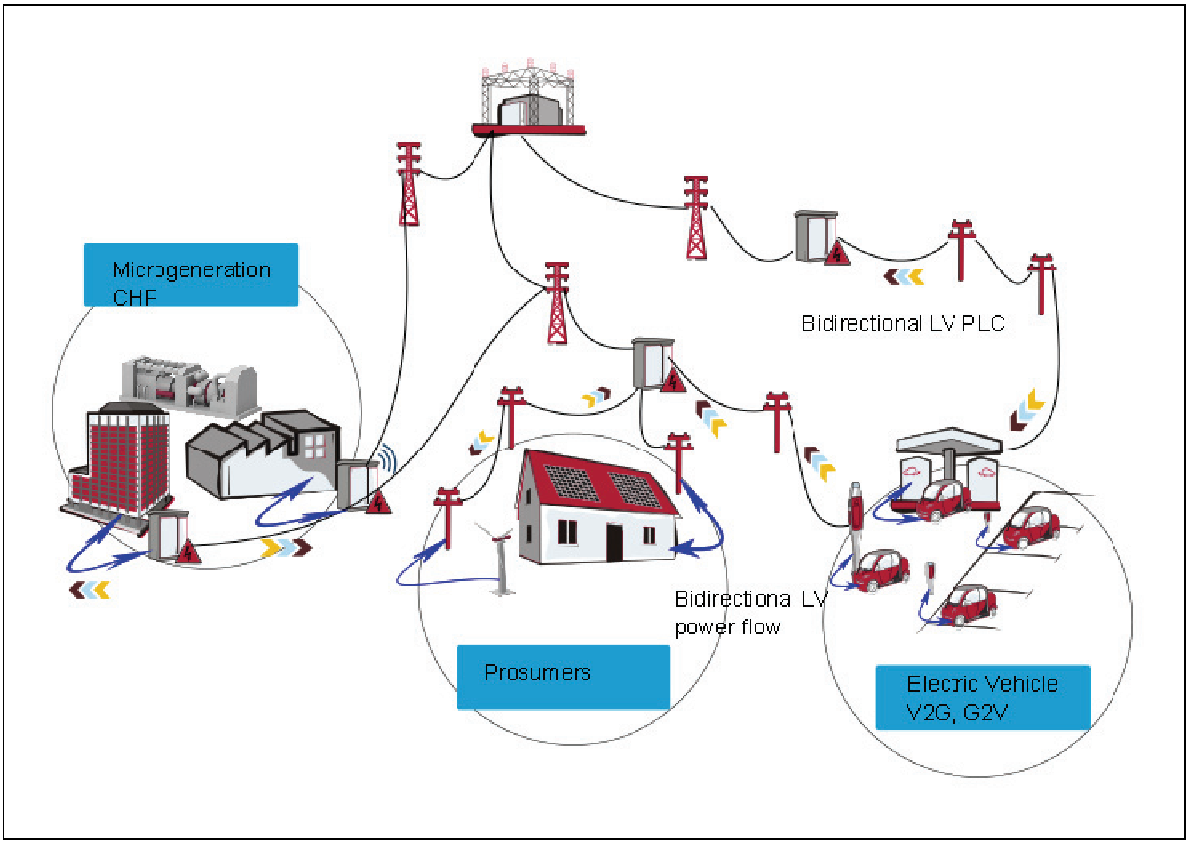

**Fig 1. Emerging systems of distributed generation in LV**

The utilization of synchrophasors in LV can help to make the LV grid a resilient smart grid allowing the following applications:

- **Advanced VAR/Volt compensation schemes for optimal voltage unbalance detection and correction in distribution grids.** Voltage unbalance in a LV grid can be compensated by elements (power electronics) which introduce reactive power that alters the voltage levels in the grid. Smart meters can provide distributed, synchronized voltage and power measurements, providing the required grid feedback for enhanced voltage unbalance compensation.
- **Base data samples for LV protection functions**. The introduction of distributed micro generation in the LV grid means that several generation sources may supply a fault, and as a result of this, dedicated protection functions are required. Synchronized meters can provide the required V and I values for the implementation of protection functions. However, these measurements will have to be computed and transmitted in a subcycle time (under 50 ms), which implies using the PLC communications system only for synchronization purposes (implementing out-of-band data communication for protection).

- **Support for semi-islanding operation (or connected self-sufficient systems).** Completely isolated systems do not guarantee supply, and are not permitted by regulators in some countries. The semi-islanding system is connected to the grid, but no energy flows in unless the system generation is unable to keep it stable and synchronized. Load shedding mechanisms are implemented to further avoid external energy utilization. These systems require extensive synchrophasor information exchange between distributed generators (or devices monitoring them), and also control at the connection point.

Recent investigations enable new ways to perform these calculations [2] based in THD and neutral current. Additionally, by getting simultaneous synchronized measurements that a secondary substation data concentrator can post-process later, three-phase domain measurements can be estimated by using only single-phase meters arranged in a network. One application is the estimation of neutral currents or feeders where there is no specific meter. It is also possible to measure the voltage unbalance by single-phase meters connected between neutral and each phase. Knowing the feeding phase assigned to each user, virtual polyphase meters can be established.

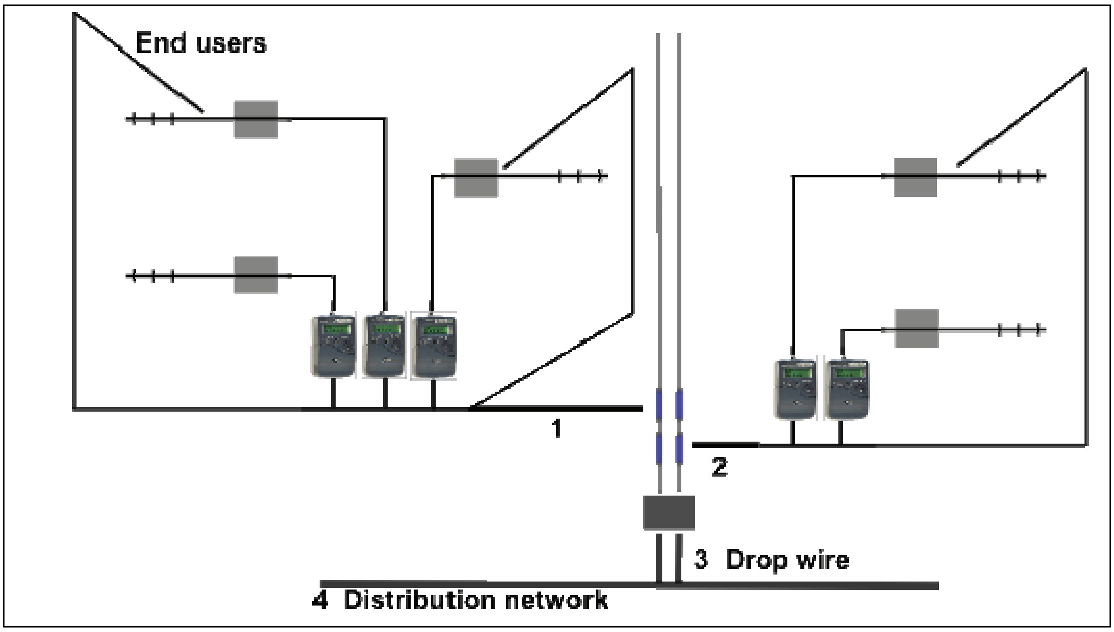

**Fig 2. Typical distributed measurement deployment**

Along a distribution system there are many unknown lines whose shape and current magnitudes cannot be measured, because there are no sensors installed in them. Meters for billing purposes are placed directly before the customer input. Obviously, customer loads are random in magnitude and time and, are always dependent on the consumption that exists in each home. Neutral currents are important since they are responsible of compensating the three phase voltage levels. In a building the different neutral current flows cannot be measured (Fig 2). While the amplitude of the voltage for a certain electrical point remains basically stable (we can neglect the impedance of the conductor), the current value in it is totally dependent on its time variant consumption. Once a virtual polyphase meter is created, Kirchhoff's Current Law can be applied to this circuit. Other calculations can be used with the information retrieved from the meters for a more accurate current estimation. This could also help calculating the non-symmetry that results in unequal self and mutual impedances, that creates differentiated neutral and “dirt” currents [3].

The supply voltage unbalance can be evaluated using the method of symmetrical components [4]. In addition to the positive sequence component, under unbalance conditions at least one of the complementary components could appear: negative sequence component and/or zero sequence component. Real power losses increase due to unbalanced power [5], so this technology could also be very useful for future researches focused on this problem, because it will make the measurement of these parameters easier at different points closer to end-users.

Due to the fast smart networks deployments and in response to the existing demand coming from utilities, a wide range of communication technologies have been developed mainly based on wireless systems or PLC. These are designed for retrieving energy measurements from the end user sensors. Data is normally stored and later processed for billing purposes. It is even possible to program different tariff calendars, power contract modifications or switching. Those technologies have been developed for noisy and highly unstable networks or with unpredictable behavior, and at a very low cost, due the large amount of devices to be deployed. This technology, if used as a synchronization provider, is suitable for applications for which GPS signals are not available.

## USING PLC AS A SOURCE OF SYNCHRONIZATION

Clock synchronization and event triggering using power line networks have been previously studied in other projects [6] [7], and also the issues and problems that have arisen have been addressed and improved [8], since the grid behaves like a particularly noisy medium [9]. The systems are based on standards such as IEEE 1588 or similar approaches to achieve synchronized events. These systems rely on the time for exchange of messages. This should happen over a period of time so small that may be safely considered constant. Another assumption is that the transit time of a message going from the master to a slave is equal to the transit time of a message going from the slave to the master.

PRIME PLC [10] technology, that has been used as synchronization mechanism for this research work, is divided into functional layers. The most important layers from the time domain point of view are the physical and the media access control (MAC) layers. **PRIME MAC layer is intrinsically synchronous, and this feature can be easily used to provide synchronization services to upper layers.**

The PRIME PHY PDU (protocol datagram unit) reception and transmission time has a precision that is generally below 12 µs. PRIME can achieve this thanks to the use of a linear chirp signal as a preamble at the beginning of every Phy PDU.

From the MAC layer point of view, there are two types of devices, the Base Node and the Service Nodes. The base node is usually located in the Transformation Center and is the core of the PRIME sub-network. It is in charge of maintaining it. The Service Node functionality is usually integrated in the meters in the meter rooms. They try to register in the Base Node directly. Some of them may automatically promote to behave as repeaters (Switches in PRIME jargon) in order to extend the network coverage, so that more Service Nodes are able to register through them. This procedure is repeated continuously to build up a hierarchy in order to provide full coverage.

The medium transmission time is divided in frames with a duration of 618.24 ms, one MAC super-frame contains 32 frames. This super-frame structure and timing information is propagated through the network by the beacon PDUs transmitted by the Base Node and by every Switch of the sub network. Every Node in a sub-network knows the timing of a super-frame with very accurate precision and predictability. It is required to be able to meet the CSMA/CA requirements and to maintain the Beacon transmission structure.

Actually, the MAC frame structure already provides an accurate time scale, so if the timing of an event is referenced to the beginning of a MAC frame and communicated over the sub-network, another Node will be able to know the exact time of that specific event.

With current implementations this precision is usually between 12 μs and 200 μs depending on the vendor. This precision is usually related to PHY signal processing and delay, and/or PHY-MAC intercommunication system. There is a growing interest on this research topic. For example, a recent study analyses how synchronization algorithms of SFN-aided systems improve the performance [11]. Surely, the required accuracy for the synchronous event is greater than these values, but it is easy to achieve a synchronization error drift close to 5 μs applying statistical and expert control systems. Taking into account the time constraints required for this application, a vendor should comply with special requirements as a figure of merit. If time accuracy is not guaranteed to be under limits, most of the applications will consider the resulting PMU as unacceptable. Although the proposed technology is unable to provide a sample timing accuracy with the same reliability as a GPS clock, the frequency obtained with a PRIME PLC based PMU in the first and second level network can meet the 31μs requirements for networks of 50 Hz proposed in section 4.4 of the IEEE Standard for Synchrophasors [12]. The indication of loss of synchronization requirement could also be provided.

## PERFORMANCE ANALYSIS

The following simulation has been made to demonstrate the effects of synchronization while measuring the symmetric components of a three-phase system and its common neutral conductor. The system considers three single phase meters which are connected to the same neutral conductor, and different phases. Their sample rates are synchronized using PRIME technology, which is integrated in the meters. Using only the rms values to calculate unbalance causes unpredictable results under harmonic components. Using the inverse and positive sequences provides a more precise value because the angular displacement is taken into account. The effect of harmonics could be minimized by filtering.
The collaborative simulation has been performed under the conditions shown in table I:

Table I. Simulation parameters

| | |
|---|---|
| Frequency: 50Hz | Sample rate: 4800 Hz |
| Nominal voltage: 230V rms. | Current: 10 A rms. |
| Balanced system (120º) | Current phase R shifted to 45º |

A current of 7.654A appears through the neutral conductor and the symmetric components (indirect and zero) get close to 0% (and may be affected for the harmonic effects of the sampling process). The simulation of the sampling deviation is induced clockwise to one of

s.santos@ziv.es

the meters and anticlockwise to the other. Only one of the meters keeps on track with the master's trigger with no deviation jitter.

With an estimated sample rate for measurement around 4.8 kHz, and jitter errors under 12µs, the system will maintain the measurement under limits that will provide enough information.

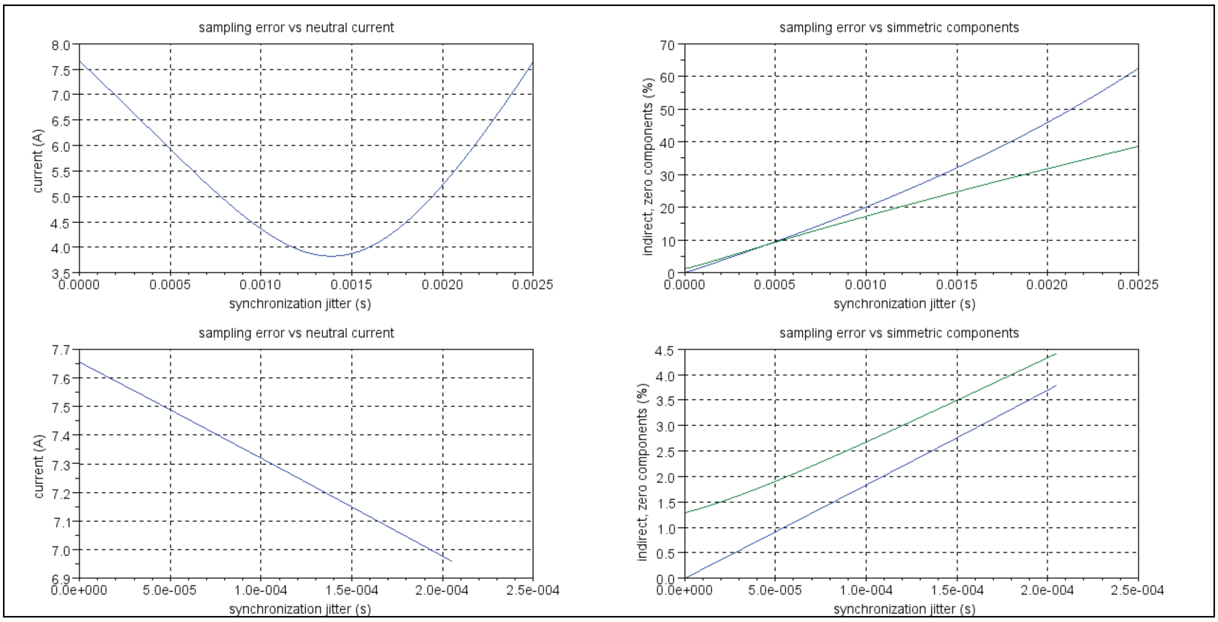

**Fig 3. Neutral current and symmetrical components error due to sampling jitter**

Note that maintaining the sampling error below the sampling rate will result on a neutral current estimation and symmetrical components measurement under reasonable boundaries. The average time jitter of 12µs will result on a current estimation error under 1%.

## CONCLUSIONS

The development of smart metering devices with communication capabilities for billing and demand response control purposes, enable the metering scheme improvements by using a PLC or wireless network to synchronize events. It is also possible to allow monitoring voltages and currents from various locations on the grid in a synchronized manner. Linking the location of each meter at the LV grid to the data received by concentrators opens the door to more advanced applications.

The coincidence in the same environment of communication, metering and grid automation systems that are looking for specific solutions to various problems makes possible a new approach and the development of synergic solutions for the smart grids [13].

Additionally, the centralized point-multipoint topology of PRIME is an intrinsic feature that is especially suitable to maintain the devices arranged in the same network on time track. This approach eliminates most of the problems that could appear using other methodologies, such as IEEE 1588 that rely on the message symmetric delay time for adjustment. Anyway, further research is needed: first of all, it is important to describe how existing smart meters with a PLC modem could standardize the use of a built-in PLC based PMU. Another challenge is to

s.santos@ziv.es

describe an operational procedure for configuring the network to provide the required amount of data from each meter, because of the intrinsic PLC low bandwidth.

This technology makes possible to obtain reasonable results for a wide range of use cases, including sampling rate adjustment. Taking into account the different types of measurements that can be performed and the maximum permissible error rate, additional advantages are expected from this technology. The capital expenditures can be considered practically null if the hardware infrastructure already planned for AMI can be used.

## BIBLIOGRAPHY

[1] Lopez, S.; Gomez, J.; Cimadevilla, R.; Bolado, O.; "Synchrophasor Applications of the National Electric System Operator of Spain," (Protective Relay Engineers, 2008 61st Annual Conference for, vol., no., pp.436-456, 1-3 April 2008)

[2] Sung-Il Jang; Kwang-Ho Kim; "An islanding detection method for distributed generations using voltage unbalance and total harmonic distortion of current," (Power Delivery, IEEE Transactions on , vol.19, no.2, pp. 745- 752, April 2004)

[3] Kersting, W.H.;"The computation of neutral and dirt currents and power losses," (Power Systems Conference and Exposition, 2004. IEEE PES, vol., no., pp. 213- 218 vol.1, 10-13 Oct. 2004)

[4] IEC 61000-4-30 “Testing and measurement techniques - Power quality measurement”

[5] L. F. Ochoa, R. M. Ciric, A. Padilha-Feltrin and G. P. Harrison, "Evaluation of Distribution System Losses due to Load Unbalance", (Proceedings 15th Power Systems Computation Conference (PSCC'05), August 22-26 2005, Liège, Belgium)

[6] G. Gaderer, T. Sauter and G. Bumiller, "Clock synchronization in powerline networks," (Power Line Communications and its Applications, 2005, pp. 71-75)

[7] Jin Ho Kim, Suk Hyung Seo, Jung Hoon Chun, Jae Wook Jeon, Young Youl Ha and Tae Jin Park, "Distributed clock synchronization algorithm for industrial networks,"(Factory Communication Systems (WFCS), 2010 8th IEEE Workshop on, 2010, pp.211-214.)

[8] S. Schriegel, H. Trsek and J. Jasperneite, "Enhancement for a clock synchronization protocol in heterogeneous networks" (Precision Clock Synchronization for Measurement, Control and Communication, 2009. ISPCS 2009. International Symposium on, 2009, pp. 1-5.)

[9] G. Gaderer, P. Loschmidt, T. Sauter and G. Bumiller, "Investigations on fault tolerant clock synchronization within a powerline communication structure," (Power Line Communications and its Applications, 2006 IEEE Symposium on, 2006, pp. 178-183.)

[10] PRIME ALLIANCE, Draft Standard for PRIME, v1.3.6. URL:http://www.prime-alliance.org/Docs/Ref/PRIME-Spec_v1.3.6.pdf

[11] Shuo Yang; Shumin Chen; Yunfeng Liu; Libo Pan; Yuanxin Xu; "Synchronization of SFN-aided PRIME narrowband PLC system," (*Signal Processing, Communications and Computing (ICSPCC), 2011 IEEE International Conference on*, pp.1-4, 14-16 Sept. 2011)

[12] "IEEE Standard for Synchrophasors for Power Systems," (IEEE Std C37.118-2005 vol., no., pp.0_1-57, 2006)

[13] Löf N., Pikkarainen M., Repo S., Järventausta P., "Utilizing Smart Meters in LV Network Management". (Proceedings of the 21th International Conference on Electricity Distribution, June 2011, Frankfurt, Germany)