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An interface protection system based on an embedded metrology system platform

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ABSTRACT

The aim of this work is to present an interface protection system (IPS) for Distributed Generators (DG) and Energy Storage Systems (ESS). The new prototype of IPS guarantees standard protection requirements, in terms of both voltage and frequency measurement accuracies and trip times. Moreover, it has the additional functionalities of implementing a communication link between the Distribution System Operator (DSO) and the DG and ESS Inverter. The new IPS is based on a smart meter platform with an integrated power line communication modem. Moreover, it has also an integrated metrology section. Experimental tests will show how this last feature allows a significant reduction of the measurement data access time allowing an improvement of trip time accuracy.

1. Introduction

The spread of Distributed Generation (DG) connected at low voltage (LV) level has required in recent years a need for new management functionality for Distribution System Operators (DSO), in order to avoid critical situations due to renewable energy randomness [1–4]. The distribution network transition into smart grids requires an improvement of distribution network observability, increasing the number of new distributed measurement points [5,6]. Moreover, new remote control functionalities have to be introduced for both DG and ESS, based on a communication link with DSOs through different suggested technologies (PLC, Wireless, GSM/GPRS) [7,8]. In this direction, different international standards have been issued, which define the DG and ESS connection requirements to distribution network and the characteristics of the related Interface Protection Systems (IPS) [9,10]. As an example, the Italian standard for LV network connection is named CEI 0–21 [11]. It states some fixed voltage and frequency thresholds to be monitored to avoid islanding. Thus standard IPS operation are based on local measurements and thresholds comparison. On the other hand, an important evolution of these devices is to add besides those local measurements new additional functionalities based on the interaction with the DSO, exchanging information related to a global view of the whole network operation. To introduce these features, the IPS cannot be only a relay but it should embed measurement, control, communication and calculation capabilities of an intelligent node of a smart network.

The authors approached this problem by proposing a new monitoring and communication architecture for distributed generators [12]. The proposed solution takes as a reference the current architectures for automatic energy meter reading (AMR): a data concentrator is installed in each secondary substation to collect meter readings via PLC. The concentrator is then queried by the central system usually via wireless network (such as GSM). Similarly, the architecture proposed for the remote control of distributed generation remote control involves a concentrator in the MV/LV substation and an intelligent IPS for each distributed generator. In Ref. [13] a first version of IPS was proposed, which integrates communication capabilities through a narrowband PLC modem in CENELEC A band. The proposed device was based on a STM32 microprocessor with an operative system (OS), to which a PLC modem and some external measurement boards were connected. On the other hand, the addition of external measurement or communication hardware entailed the use of communication peripherals (SPI, USART, I2C), whose data flow has a certain latency, even in the order of tens of milliseconds. The management of peripheral communication can interrupt the sequence of operations being carried out by the microcontroller. In order to deal with this problem, an operating system was used that effectively scheduled the various operations to be carried out. However, this required accurate estimation of the priorities and scheduling times because the operations may have different computational loads. In conclusion, the un-correctness of execution delays estimation in IPS microcontroller firmware operations may affect the intervention times. Thus in this paper a new approach is proposed to face this problem.

More in detail, a new IPS prototype has been developed that has better capabilities from both measurement and communication point of view. A new method for measurement acquisition is proposed and implemented in a new smart meter chipset (STCOMET), which embeds a metrology section directly integrated on the microcontroller. The paper will show how this construction feature will significantly improve the IPS capabilities, in term of measurement acquisition, with respect to the previous prototype, based on an external metrology section. Moreover, it will be shown how the proposed IPS not only complies with the anti-islanding reference standards requirements (specifically the local voltage, current and frequency thresholds required by the CEI 0–21), but it is also able to interact with both the distributor (DSO) and the distributed generation and storage systems inverters, in order to remotely adjust the generated or stored power.

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Table 1
IPS protection settings according to CEI 0-21.

Protection type		Thresholds	Trip time *[s]*
Max Voltage	59.S1	1.10 Vn[a]	Max 603
Max Voltage	59.S2	1.15 Vn	0.2
Min Voltage	27.S1	0.85 Vn	1.5
Min Voltage	27.S2	0.15 Vn	0.2
Max Frequency (restrictive thresholds)	81>.S1	50.2 Hz	0.1
Min Frequency (restrictive thresholds)	81<.S1	49.8 Hz	0.1
Max Frequency (permissive thresholds)	81>.S2	51.5 Hz	0.1 or 1[b]
Min Frequency (permissive thresholds)	81<.S2	47.5 Hz	0.1 or 4[b]

[a] Vn is the RMS Voltage value of a single phase.
[b] Based on temporary or definitive mode setting.

2. DG and ESS protection and control

As mentioned in the introduction, recent standard for DG and ESS connection to LV networks, such as CEI 0–21 [11] in Italy, have introduced new functionalities for IPSs. More in detail, IPS must be able to perform local measurements for islanding detection, moreover they should have a digital input for remote disconnection, even if the communication link with DSO is still under definition. Furthermore, the possibility is introduced for DGs to participate in voltage and frequency regulation, through the implementation of appropriate control strategies, based on curves pre-set on the inverter. Concerning the communication system, the use of PLC technology for the transmission of DSO messages is mentioned and suggested. However, the standard does not define the different signals to be transmitted and their transfer time requirements. As regards the islanding detection method, it is based on voltage and frequency measurement and comparison with some thresholds, summarized in Table 1 along with the correspondent trip times. As can be seen in the table, two type of frequency thresholds are defined (restrictive and permissive) which can be selected based on DSO request.

In [12], the authors proposed a new architecture with measurement, protection and communication all integrated in one device. Thanks to this architecture, new functionalities were proposed, such as the possibility of remotely selecting the inverter control curves, changing the active and reactive injected power, sending an active or reactive power command to the storage system, selecting the thresholds and sending a remote disconnection command, if needed. To this aim, a new IPS was developed based on the STEVAL-IPP001V2 hardware platform. This platform embeds a STM32F103 microprocessor, which is connected to a ST 7580 PLC modem, with PSK modulation in CENELEC band. Moreover, an external section has to be connected for metrological purposes, which consists of the energy calculator STEVAL-IPE010V1 and the daughter boards STEVAL-IPE014V1, with the embedded voltage and current transducers [12,13]. A complex firmware has been developed to interact with external peripherals. Specifically, communication between the IPS microcontroller and the external hardware is managed through SPI peripherals. An operating system was implemented, which effectively schedules the different operations to be carried out. Careful estimation of priorities and scheduling times was performed to manage operations that could have different computational loads. Moreover, a careful assessment of delays was made to avoid increasing the overall latency time, which could affect the intervention times required in the reference standards. To overcome these problems and improve the capabilities, a new IPS prototype is presented in this paper, which is based on a platform that integrates calculation, communication and measurement in a single chip.

3. New platform: STCOMET10-1

3.1. Hardware description

The case study device is the EVLKSTCOMET10-1. This is a development kit for the STCOMET platform, exploiting the performance capability of the full-feature STCOMET10 device. It embeds in a single device a flexible PLC modem with a fully embedded analog front end (AFE) and a line driver, a high performance 3-channel metrology function and a Cortex ™ - M4 application core (96 MHz maximum frequency). The kit is made of three modules (Fig. 1): the STCOMET main board, the LCD module and the power supply board based on the VIPER26H. This kit is usually employed to develop smart meter with PLC connectivity. PLC signal are injected and received on LV mains.

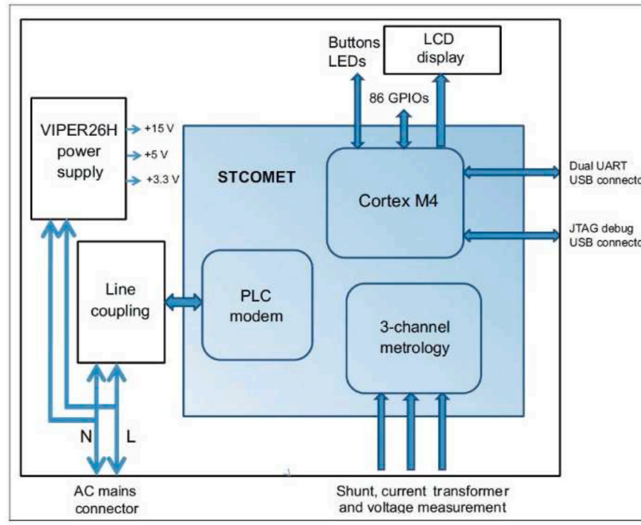

Fig. 1. EVLKSTCOMET 10-1 functional block diagram.

3.2. Measurement acquisition method

The STCOMET device embeds a metrology sub-system designed for high accuracy measurement of active, reactive and apparent power and energy. The metrology sub-system consists of an analog and a digital section. The analog section is based on two programmable gain amplifiers (PGA) with low-noise and low offset and three 24-bit 2nd order ΣΔ ADCs. The sampling frequency is $Fs = 7.8125$ kHz. The digital section consists of a hardwired DSP and a DFE to the input modulators and an interconnection bus with the Cortex™-M4 core. DSP block on STCOMET calculates RMS values of current and voltage continuously, every 128 μs, as soon as a new sample is available from the ADC. The integration time is 10 cycles. The STCOMET DSP calculates the period using the zero-crossing signal (ZRC) of the fundamental harmonic voltage, which is measured through a low-pass filter connected at the voltage channel. The resolution of the zero-crossing signal is 8 μs (given by the internal clock at 125 MHz). Thanks to the interconnection bus, it is possible to quickly access the registers (32-bit words) of the DSP that contain the digitized values of the measurements.

Metrics for Power Factor, period, RMS and instantaneous values are already implemented in the STCOMET firmware. The current channel inputs are connected, through external anti-aliasing RC filter, to a Rogowski coil current transducer (CT) or a Shunt. The device also monitors SAG or SWELL events on voltage and SWELL events on current. In Ref. [14], the metrology section was characterized for the above mentioned measurement parameter and additional Power Quality parameters. A new firmware with correction algorithms was implemented to obtain full compliance with class S requirements of IEC 61000-4-30. Moreover, a new algorithm was developed for harmonic analysis compliant with class II requirements of IEC 61000-4-7. Harmonic analysis was performed by FFT algorithm on 2048 samples. The 2048 samples were obtained by linear interpolation of the samples acquired in an observation window of 10 cycles. The number of samples can vary based on the measured period. For example, in the case of a perfectly 50

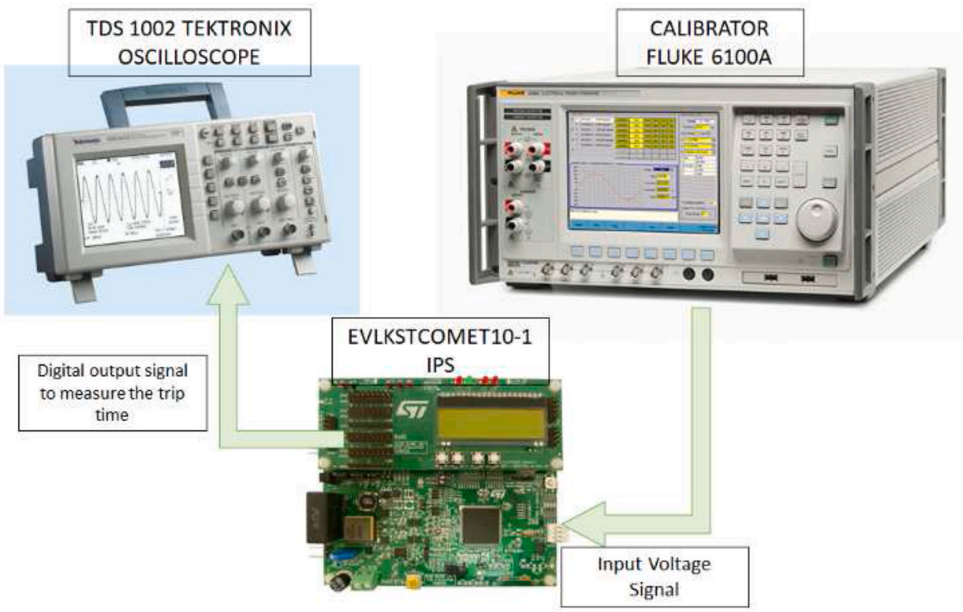

Fig. 2. IPS test bench.

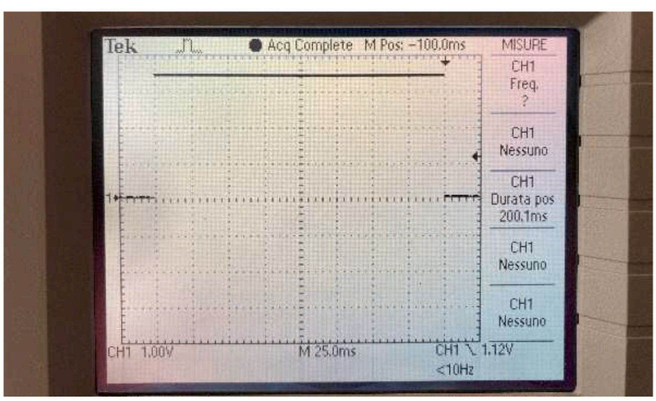

Fig. 3. IPS Trip time measurement for the voltage protection 27. S2.

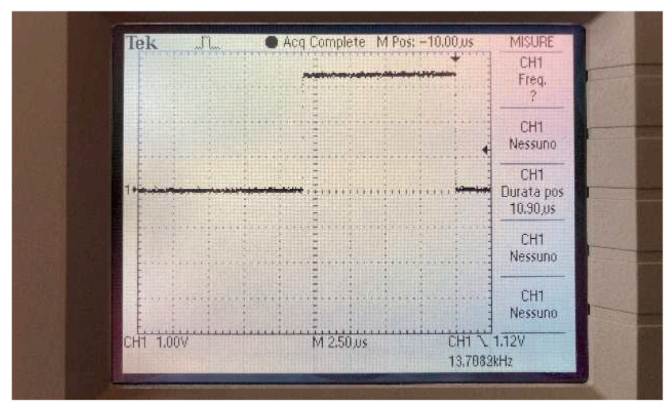

Fig. 4. Reading time measurement.

Hz signal, the STCOMET acquires 1562 samples in the $Tw = 200$ ms observation window ($N_{samples} = Fs*Tw = 7812.5 * 0.200 = 1562.5$). Performing a linear interpolation with 2048 samples results in a new virtual sampling at a frequency of 10.240 kHz ($f_{s\_virtual} = Ns/Tw = 2048/0.200$), which allows a better accuracy in harmonic amplitude and phase measurements [14]. In this paper, a new firmware was developed to implement measurement and protection functions according to standard requirements for IPS [11]. Although the RMS measurement already implemented on STCOMET is updated every 128 μs, it calculates RMS over a base time interval of 10 cycles. This caused problems to obtain compliance with the required trip times and thresholds. Thus the new developed firmware allows to calculate the RMS on 1 cycle, using less samples. In this way the acquired samples are 156 ($N_{samples} = 20/0.128 = 156{,}25$) and full compliance with trip times and thresholds requirements could be achieved.

4. Interface protection system prototype

4.1. Protection tests

The correct functionalities and performances of the IPS were verified in laboratory with the test bench of Fig. 2. According to the standard requirements [11], the following tolerances should be satisfied for three successive tests:

- $\leq 5\%$ for the voltage thresholds;
- $\leq 20mHz$ for the frequency thresholds;
- $\leq 3\% \pm 20ms$ for the trip times.

The results obtained in laboratory tests show a tolerance of less than 0.5% on the voltage and an error of no more than 10 mHz on the frequency measurement. The error in trip time measurements is less than 1 ms, which is well within the expected tolerance. As an example in Fig. 3, a trip time of 200.1 ms was measured for voltage protection 27. S2. It can be seen how the measured time is well within the error limits required by the standard. The comparison between trip times errors with those of the previous IPS prototype proposed in Ref. [13] shows a significant improvement.

4.2. Test of reading time of measure

To explain the best performances, a further test was performed to investigate the new way of measurement data accessing. In order to measure the reading times of voltage and period measurements, a digital pin of STCOMET was acquired. The logic level of the digital pin is controlled through a specific function in the implemented firmware,

Table 2
Reading time.

Average Time Value *[μs]*	Standard Deviation *[μs]*
10.94	0.10

respectively, before and after the execution of the function which allows measurement values reading. The execution time for digital pin status switching is in the nanosecond range because it involves the logical value changing of one bit of a microcontroller register. Thus, this delay time can be neglected. In this way, a measure of the measurement reading time was obtained. Fig. 4 shows the time required to read the period and the RMS measurement values of current and voltage, i.e. the access to two 32-bit registers of the DSP. The measured value is 10.90 μs.

The average value and standard deviation of a series of reading time measurements are reported in Table 2. The results show how the measurement reading times can be considered negligible with respect to trip times (hundreds of milliseconds), and even negligible with respect to the related tolerances [11]. The results show a clear improvement compared to the solution proposed in Ref. [13] where measurement access times were three orders of magnitude higher. Thus the features of the new hardware together with the firmware implemented in the new prototype allow to avoid any latency on anomalous condition detection (both for voltage and frequency) and on related command sending time, for remote disconnection of DG or ESS systems from electrical network.

5. Conclusions

In this paper, a new IPS prototype is presented which has improved measurement and communication capabilities by exploiting the use of a commercial smart meter through the development and implementation of a new firmware. The proposed IPS is able to interact with both DSO and distributed generation inverters. The IPS implements the protection algorithm based on local voltage, current and frequency measurements required by CEI 0–21 standard. In addition, thanks to its communication capability, it allows the remote disconnection of the plant, even regardless of the thresholds, thus facilitating better management of islanding situations.

In this article, a new methods of local measurement acquisition is shown. Specifically, the developed IPS uses a metrology section directly integrated on the board's microcontroller. The experimental results show how this solution brings considerable advantages in terms of reduced access time and use of the acquired measurements, thus guaranteeing high accuracy and full compliances with trip time constraints. Moreover, the integrated circuit guarantees a reduction in complexity and costs, because no additional acquisition hardware is required.

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References

[1] N. Shaukat, et al., A survey on consumers empowerment communication technologies and renewable generation penetration within Smart Grid, Ren. and Sust. En. Rev. 81 (2018) 1453–1475.
[2] A.J. Collin, A. Delle Femine, C. Landi, R. Langella, M. Luiso, A. Testa, The role of supply conditions on the measurement of high-frequency emissions, IEEE Transactions on Instrumentation and Measurement 69 (9) (Sept. 2020) 6667–6676.
[3] E. Kabalci, Y. Kabalci, From Smart Grid to Internet of Energy, Academic Press, London, UK, 2019.
[4] G. Crotti, G. D'Avanzo, D. Giordano, P.S. Letizia, M. Luiso, Extended SINDICOMP: characterizing MV voltage transformers with sine waves", Energies 14 (2021) 1715.
[5] G. Artale, A. Cataliotti, V. Cosentino, D. Di Cara, R. Fiorelli, S. Guaiana, et al., A new PLC-based smart metering architecture for medium/low voltage grids: feasibility and experimental characterization, Measurement 129 (2018) 479–488.
[6] A. Delle Femine, D. Gallo, D. Giordano, C. Landi, M. Luiso, D. Signorino, Power quality assessment in railway traction supply systems, IEEE Transactions on Instrumentation and Measurement 69 (5) (May 2020) 2355–2366.
[7] G. Artale, A. Cataliotti, V. Cosentino, D. Di Cara, R. Fiorelli, S. Guaiana, et al., A new low cost power line communication solution for smart grid monitoring and management, IEEE Instrum. Meas. Mag. 21 (2) (April 2018) 29–33.
[8] M. Pasetti, E. Sisinni, P. Ferrari, S. Rinaldi, A. Depari, P. Bellagente, D. Della Giustina, A. Flammini, Evaluation of the use of class B LoRaWAN for the coordination of distributed interface protection systems in smart grids, J. Sens. Actuator Netw. 9 (1) (Feb. 2020) 13.
[9] A. Cataliotti, V. Cosentino, D. Di Cara, S. Guaiana, N. Panzavecchia, G. Tinè, D. Gallo, C. Landi, M. Landi, M. Luiso, Experimental evaluation of an hybrid communication system architecture for smart grid applications, in: Proceedings of the 2015 IEEE International Workshop on Applied Measurements for Power Systems, AMPS 2015, Aachen, Germany, 2015, 23–25 September.
[10] O. Núñez-Mata, R. Palma-Behnke, F. Valencia, P. Mendoza-Araya, J. Cotos, Integrated protection and monitoring system for safe operation of photovoltaic-based isolated microgrids, in: 2017 IEEE Power and Energy Society General Meeting, PESGM 2017, 2018, pp. 1–5.
[11] CEI 0-21, "Regola tecnica di riferimento per la connessione di utenti attivi e passivi alle reti BT delle imprese distributrici di energia elettrica" (Reference technical rules for the connection of active and passive users to the LV electrical Utilities,), Apr. 2019 (In Italian).
[12] A. Cataliotti, V. Cosentino, D. Di Cara, S. Guaiana, N. Panzavecchia, G. Tine, A new solution for low-voltage distributed generation interface protection system, IEEE Transactions on Instrumentation and Measurement 64 (8) (Aug. 2015) 2086–2095.
[13] A. Cataliotti, V. Cosentino, S. Guaiana, D. Di Cara, N. Panzavecchia, G. Tine, An interface protection system with power line communication for distributed generators remote control, in: 2014 IEEE International Workshop on Applied Measurements for Power Systems, AMPS 2014, Aachen, Germany, 2014, pp. 103–108. Sept. 24-26.
[14] G. Artale, G. Caravello, A. Cataliotti, V. Cosentino, D. Di Cara, N. Dipaola, et al., PQ and harmonic assessment issues on low-cost smart metering platforms: a case study, Sensors 20 (2020) 6361.

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