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Distributed online load sensitivity identification by smart transformer and industrial metering

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Distributed On-Line Load sensitivity Identification by Smart Transformer and Industrial Metering

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Abstract – Load power sensitivity to voltage changes continuously in the distribution grid due to the increased variability of the load demand (e.g., electric vehicles charging) and generation production (e.g., photovoltaic). Classical sensitivity identification methods do not respect the fast dynamics of such changes: they require long data history and/or high computational power to update the load sensitivity. The proposed On-Line Load sensitivity Identification (OLLI) approach is able to identify the load sensitivity in real time (e.g., every minute). This paper demonstrates that the OLLI can be achieved not only with the advanced Smart Transformer metering system, but also with commercial industrial metering products. It is shown that OLLI is able to identify correctly the load sensitivity also in presence of noise or fast stochastic variation of power consumption. The industrial metering-based OLLI application has been proven by means of a power-hardware-in-loop evaluation applied on an experimental microgrid.

Index Terms—Smart Transformer, Solid State Transformer, Load Identification, Smart Metering, Conservation Voltage Reduction.

I. INTRODUCTION

Under high penetration of converted-based renewable DG, the power grid is challenged to maintain safe operations in terms of voltage and current operative limits. For this reason, Distribution System Operators (DSO) need a continuous upgrade of the grid infrastructure, i.e. cable and transformer replacement with larger size ones, that is costly and caused disruption to customers. The Smart Transformer (ST)[1-2], a power electronics-based transformer, aims to replace the conventional iron transformer in the grid where the need for controllability of the grid is high. The ST does not simply adapt the voltage from medium to low voltage grids, but at the same time, can offer ancillary services to the distribution grid. As shown in the OFGEM-funded project “LV-ENGINE” [3], the ST integration in the grid can bring up to £60m in savings by 2030. In Fig. 1, the 3-stage ST architecture is shown. The MV converter controls the AC current absorption, in order to maintain the nominal voltage in the MV DC link. The DC/DC converter regulates the power flow between the two DC links. In the LV side, the ST converter controls the voltage waveform in the grid. This means that the ST is able to vary amplitude, frequency and phase of the ST-fed LV grid upon request of services. In particular, the ST is able to apply controlled voltage and frequency disturbances in the LV grid in order to evaluate the load power sensitivity to voltage and frequency

[4]. This possibility allows to know how much the load consumption will vary, before applying any changes in the voltage amplitude or frequency. It gives the possibility to make the ST-fed grid a controllable resource, as demonstrated in [5], offering services like the Soft Load Reduction, that overcomes the classical concept of load shedding, or the ST-based Overload Control [6], that support the ST hardware during peak load periods. The ST, exploiting the load controllability, is able also to provide services to the transmission grid, such as supporting the primary frequency support of synchronous generators [7]. Controlling downwards or upwards the power consumption, the ST can increase the system damping, avoiding large frequency nadir during power imbalances.

However, the On-Line Load sensitivity Identification (OLLI) as described in [4] is performed at the ST busbar and it represents the sensitivity of the overall grid. In this paper, we will investigate the possibility to implement the proposed parameter identification methodology in real-time at customer level, adopting typical metering instrumentation that could be already available at any industrial or commercial facility, or in a small microgrid. The methodology is tested using measurements obtained on the field through affordable metering devices characterized by a small timestamp resolution and making use of common industrial automation protocols (i.e Modbus TCP/IP and RTU). The work’s outcomes depict how to characterize the sensitivities of a specific load (e.g., household, commercial activity) at the point of common coupling with the distribution system operator’s grid.

The validation of such methodology is performed implementing the OLLI approach in the power-hardware-in-the-loop facility and microgrid at LabZERO (Politecnico di Bari) [8]. The power output of a ST, simulated in a real-time digital simulator, is amplified through a 15 kW three-phase power module and used to supply energy to the local microgrid [9]. Measurements from field components are obtained using basic multifunction metering instrumentation characterized by good accuracy but high time resolution (1 second), and collected from the local gateway using Modbus TCP/IP. Both LAN/WAN communication architecture or HTTP-based solutions (RESTful API or MQTT) are viable for gathering data locally or in a centralized fashion.

The paper is structure as follows: Section II recalls the OLLI

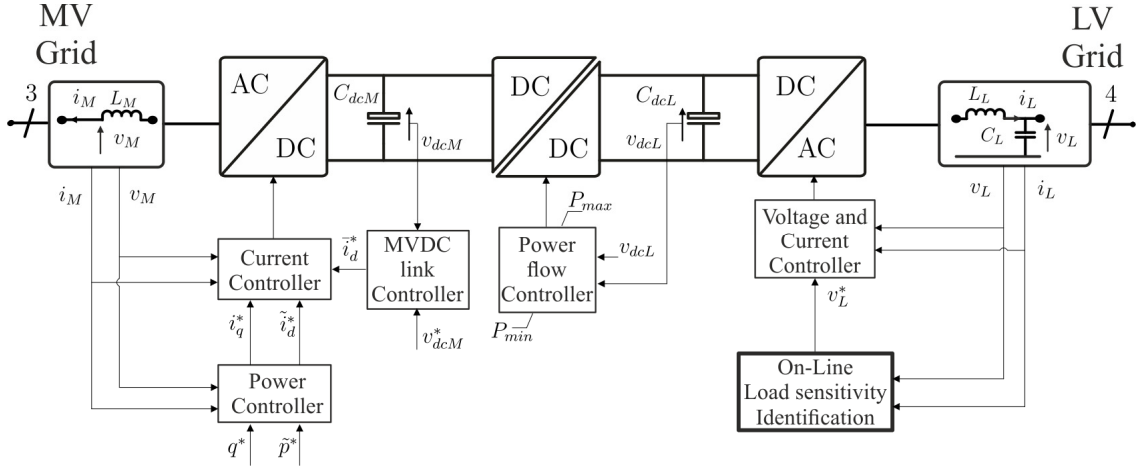


Fig. 1. Smart Transformer hardware and control scheme.

concept; Section III depicts possible OLLI applications in distribution grids, while Section IV describes the experimental facility used in this work and the experimental results carried out with different load composition. Finally, Section V is dedicated to the conclusions.

II. ON-LINE LOAD SENSITIVITY IDENTIFICATION CONCEPT

A. On-line load sensitivity identification (OLLI)

In literature, the load models are classified mainly in exponential model and ZIP model (constant impedance, constant current, constant power). Because of its simplicity, the load sensitivity are evaluated in this work with the exponential load described in (1), that allows to estimate only one parameter (i.e. K_p):

$$P = P_0 \cdot \left(\frac{V}{V_0} \right)^{K_p} \quad (1)$$

$$Q = Q_0 \cdot \left(\frac{V}{V_0} \right)^{K_q}$$

where P , Q , V , P_0 , Q_0 , V_0 are respectively the measured and the nominal active and reactive power, and voltage; K_p is the load active power sensitivity to voltage. Rearranging the equations and estimating the sensitivity at the operating point $V = V_0$, the load sensitivity to voltage in the i -th operating point can be expressed as:

$$\frac{dP/P_i}{dV/V_i} = K_p \quad (2)$$

$$\frac{dQ/Q_i}{dV/V_i} = K_q$$

The equations (2) can be thus discretized in a certain instant t_k obtaining:

$$\frac{P(t_k) - P(t_{k-1})}{P(t_{k-1})} = K_p \cdot \frac{Q(t_k) - Q(t_{k-1})}{Q(t_{k-1})} = K_q \quad (3)$$

where $P(t_{k-1})$, $P(t_k)$, $Q(t_{k-1})$, $Q(t_k)$, $V(t_{k-1})$ and $V(t_k)$ are the load active power and voltage at a certain instant t_{k-1} and the following one t_k . It must be noted, that the sensitivity is estimated independently from the load model adopted, but it is based only on the power and voltage measurement.

To evaluate the load sensitivity, the ST applies a controlled voltage disturbance, as shown in Fig. 2, and measuring the active and reactive power variation is able to compute the load sensitivity applying Eq. (3).

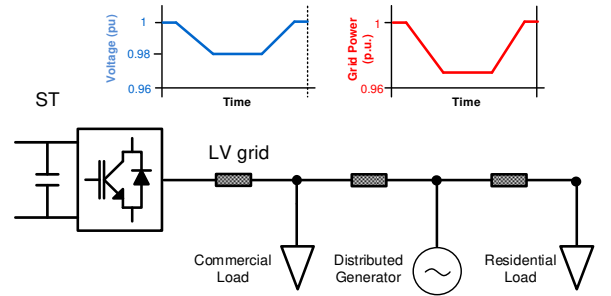


Fig. 2. Smart Transformer On-Line Load sensitivity Identification.

At a certain instant t_k , the ST applies a voltage variation, samples the voltage, active and reactive power measurement and compare them with the measurement of the previous instant t_{k-1} . With the current and previous measurements, the ST computes the active and reactive power sensitivity to voltage at the instant t_k using Eq. (3). During each instant t_k , the OLLI computes the new sensitivity, averaging the sensitivities in the first k instants for the number of the ramp time-steps:

$$K_p(t_k) = \frac{\sum_{i=1}^k K_p(t_i)}{k}, K_q(t_k) = \frac{\sum_{i=1}^k K_q(t_i)}{k} \quad (4)$$

The average over the k instants allows to filter any estimation errors due to measurement noise.

B. Rejection of power noise

The estimation of the load sensitivity is dependent on the instantaneous voltage and power measurements. Particularly the latter can be affected by the propagation of the errors in the product of the measured current and voltage. Furthermore, the load shows power stochastic noise, that belongs to fast switching of small loads or fast generation changes. This power noise does not cause a noticeable change in the overall load sensitivity, but it may affect the sensitivity estimation, influencing the instantaneous sensitivity calculation. In case of sensitivity estimation at the ST busbar, this problem can be solved exploiting the fast measurement system (sampling time $>5\text{kHz}$) and high computational capability of the ST control board to remove the noise from the sensitivity calculation. However, this is not possible in case of industrial metering due to standard measurement dynamics (about 1s sampling time) and limited computation capability of the measurement control board. For these reasons, in this work the following rules have been applied to remove the noise in the industrial metering-based OLLI approach.

Considering the power variation in per-unit at each k -th time step:

$$\Delta P(t_k) = \frac{P(t_k) - P(t_{k-1})}{P(t_{k-1})} \quad (5)$$

the power variation can be calculated considering the voltage variation measurement and the current load sensitivity coefficient calculated as shown in Eq. (4). For example for the active power sensitivity to voltage, the expected power is calculated as:

$$\Delta P_{exp}(t_k) = K_p(t_k) \cdot \Delta V(t_k) \quad (6)$$

A wrong power variation measurement can be discharged if the variation does not match the expected power variation within a certain tolerance ε . For this reason the following rule is applied:

$$\begin{aligned} & \text{if } |\Delta P(t_k) - \Delta P_{exp}(t_k)| > \varepsilon \\ & \text{then} \\ & \Delta P(t_k) = K_p(t_k) \cdot \Delta V_{avg} \end{aligned} \quad (7)$$

the value of the tolerance ε varies depending on the voltage variation slope. Here the tolerance $\varepsilon = 0.01\text{pu}$ is adopted. The updated power variation is, thus, evaluated taking into account the current sensitivity coefficient $K_p(t_k)$ and the average power variation along the ramp ΔV_{avg} , calculated as:

$$\Delta V_{avg} = \frac{\sum_{i=1}^k \Delta V(t_i)}{k} \quad (8)$$

As will be shown in Section IV.B, the relation in (7) allows to reject power disturbances that do not belong to the base load, but they are caused by measurement errors or fast power variations that are not of interest.

III. APPLICATIONS OF OLLI IN DISTRIBUTION GRID

Through the proposed OLLI approach, an on-line sensitivity index of voltage dependency can be associated to any electrical system or subsystem behind a power meter, provided that the meter has access to a communication network (directly or through a gateway). The availability of such index can allow several possible application with regard to (centralized) utility-based or (local) end users-based energy management routines.

A. Utility-based applications

Smart distribution grids require advanced modeling capabilities for system analysis and control. Typically, end-use loads are represented with time-invariant statistical ZIP models, whereas in smart grids, time-series simulations should be characterized by step-sizes down to the order of few minutes [10]. The most straightforward application of the proposed method relies in providing advanced updated models of physical nodes or portions of the network. Refined and updated models can be used in any kind of SCADA/DMS application such as distribution unbalanced load flow, distribution optimal power flow and assessment of power grid control actions and reconfiguration [11].

In particular, the knowledge of load-voltage dependence permits to overcome the crucial technical barriers for an effective implementation of Conservation Voltage Reduction (CVR) [12], including the assessment and verification of CVR effects, and the possible effects of distributed generation. It has been recently demonstrated that the distribution grid load is still sensitive to voltage variation, as shown in the ‘‘CLASS’’ project [13]. The load response to voltage variation has been found being often superlinear, with several MV feeders close to a quadratic response (constant impedance load) [14]. The proposed OLLI approach allows to generate time-varying equivalent load models of portions of the network, overcoming usual representations that use same models for entire subsystems. This more detailed representation allows to implement CVR in Adaptive Voltage Control routines, or more in general, in secondary distribution Volt-Var Optimization tools [15]. Knowing voltage (or even frequency) system dependence of subsystems can help minimizing controlling effort during congestions since the most sensitive loads can be curtailed though voltage reduction, whereas less sensitive ones could be just entirely switched off.

Theoretically, the proposed approach can be implemented on an AMI-based platform [16], detecting response of loads at end-user level, instead of just substation or street control panel level. The OLLI approach does not require significant computation effort and sensitivities calculations could be made

locally. The main concern would rather rely on the coordination of the large amount of incoming data [10].

B. End-users applications

CVR techniques can be used at end-user level for peak shaving or other demand side management functions. This kind of practice is already employed for load control in large commercial buildings like malls or supermarkets. Clearly, the knowledge of voltage sensitivities can allow a better coordination of voltage control and load curtailment.

A very interesting application of the proposed OLLI technique could be found in the operation of critical power systems such the ones that supply large industrial plants, as for example refineries and petrochemical plants. In such systems, load shedding techniques are employed in normal operation in a 15-30 minutes control frame in order to control tie-lines or avoid critical operating points, where for example not enough spinning reserve is guaranteed in case of major faults [17]. Emergency load shedding is also a frequently employed control action whenever a system separation is caused by external perturbations, usually a fault or very strong voltage dips on the main grid. In such case, automatic islanding procedure can be triggered in a very short time (less than 500ms), since these kind of plants have often a relevant inner generation power capacity.

Depending on the plant configuration, system adequacy cannot be always ensured and load might have to be shed. At SCADA/EMS level, the amount of load to be shed in case of system separation is calculated continuously, based on active production processes, generation reserve and system operating state. Being able to serve as much load as possible is of utter importance since any interruption to critical loads can cause the stop of a process and the activation of emergency shutdown. As an example, in the case of a petrochemical plant, the shutdown of the cracking process implies, not only the loss of material, but also the activation of safety flaring procedures, with great impacts on the environment and social acceptability.

In both cases, the right amount of load to be shed could be calculated considering also the possibility to curtail some of it through a voltage reduction on a specific feeder (both ST-based or ULTC-based operation could be possible of course). Moreover, in [18], it was showed how the assessment of transient stability during emergency islanding is strongly affected by the load model used for simulation. Furthermore, it has been shown in [19-20], that modeling of induction motors and frequency dependent loads play an important role for preserving voltage stability in stressed systems. The OLLI updated indexes can clearly provide the SCADA/EMS with more appropriate dynamic models for transient simulations.

C. Requirements for on-line implementation

As previously remarked, for any of the possible approaches, being centralized utility or local end-user based, power measurements from meters must be made available to a central computation unit. The easiest implementation, since most of

the commercially available power meters for industrial application are intelligent electronic devices (IEDs), is to exploit the network capabilities of the meters. These meters could directly interfaced to a Local Area Network (LAN) or to a wider network (WAN), depending on the scale of the application. In such cases connection-less communication via IP-based protocols can allow an easy share of data. This is the actual case of the experimental results presented in this paper that have been based on studying the OLLI feasibility on a Modbus TCP/IP architecture, with a communication through a LAN. However, whenever a physical network interconnecting meters with a central SCADA or controller is not available, possible implementations could be based on HyperText Transfer Protocol (HTTP)-based communication, developing a web server applications or collecting data in a cloud platform through an Application Programming Interface (API). These approaches are possible if data must be collected or processed by an external entity such as a virtual power plant or an aggregator.

Two parameters that could affect the performance of the proposed approach are the time resolution of power meters and the latency of the adopted communication network. The dynamic profile of the voltage perturbation applied by the ST must be suitably chosen with respect to the time resolution of the meters. For example a voltage ramp faster than the time resolution could not be read by the meters. It was found that most of the ordinary industrial power meters have a time resolution stamp of about one second. This means that the voltage perturbation must be much slower than the one used in [4] where measurements were taken directly at ST-level by the ST control board.

Latency can also affect the methodology since the master request for a measurement could theoretically reach the slave meter in an untimely manner (and vice versa). However, as remarked in the next paragraph, communication latency can be assessed in few hundreds of milliseconds for both WAN-based and HTTP-based applications. Given the assumed order magnitude for measurement time resolution (no more than one measure per second), these values are small enough to introduce a negligible effect.

IV. EXPERIMENTAL VALIDATION IN A SMART GRID LAB

The tests were carried out exploiting the power-hardware-in-the-loop (PHIL) facility at LabZERO (Politecnico di Bari) [9]. The PHIL system is composed by a real time digital simulator (RTDS) OPAL RT OP5600 connected to the 16kW 4-quadrants programmable power source Triphase PM15A30F60, with 6-channel output to be used in various AC and DC configurations [21]. In its normal configuration at LabZERO, a 4-wire AC power output is used. The power source exchanges power with the local microgrid switchboard.

The microgrid is composed by several microsources such a PV generator, a wind turbine and a small scale biomass combined cycle plant. Moreover, a LiFePO₄ Battery Energy

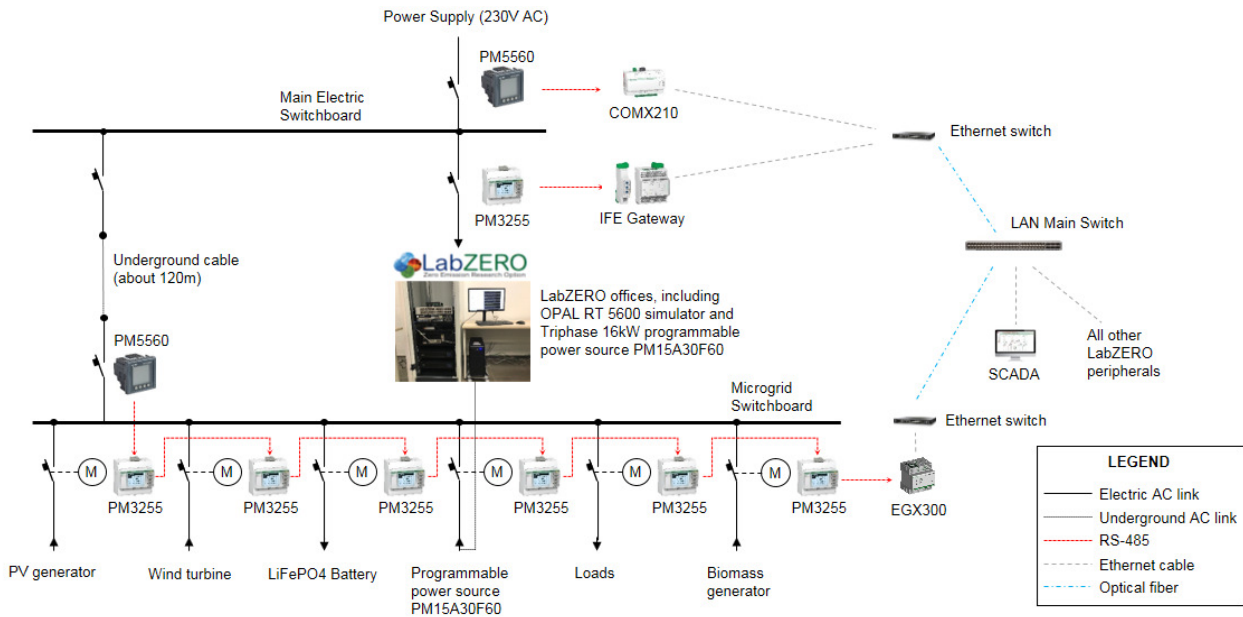


Fig. 3. Power and communication scheme of the LabZERO power-hardware-in-the-loop test facility at the Politecnico di Bari

Storage System is installed, together with several loads.

In Fig. 3, a simplified scheme of the power and communication system of LabZERO is given. Please note that most of the devices represented in the figure are commercial available automation products. The main switchboard, represented in the upper part of the figure, supplies directly energy to the laboratory offices, where also the PHIL system is installed. The main switchboard is then linked to the microgrid through a cable of about 120m, covering the distance between two non-adjacent separate buildings. An analogous link allows to transfer the power output of the programmable power source to the microgrid.

In the microgrid, energy resources are connected to the switchboard through a remote-controlled switch. Each feeder is monitored through a power meter PM3255, whereas a PM5560 is used at the main microgrid switch, which represents the point of common coupling of the microgrid. All these meters are on the same Modbus RS-485 bus and are then connected to the laboratory LAN through an Ethernet gateway (EGX300). An optical fiber link is used to connect the microgrid local Ethernet switch to the main switch located at the LabZERO offices. A similar structure (RS-485 serial bus, Ethernet gateway and switch) is used to connect all power meters at the LAN.

An Energy Server Com'X210 collects the data from all Modbus TCP/Modbus serial line gateways and enables data logging and reporting functions such as a web server. A PLC is also used to provide a HMI interface and further monitoring and control functions such as alarms, switch operation and remote control, network topology, BESS control. For the sake of simplicity, the communication infrastructure related to all these other signals is not represented in the simplified scheme

(Fig. 3).

The tests, that implied the study of the response of loads to voltage perturbations, were carried out separating the microgrid from the main switchboard (i.e. the main switch beside the PM5560 on the left of Fig. 3 is switched off), and supplying the microgrid through the power amplifier operating in voltage source control mode. Thus, the time varying voltage output of a Smart Transformer is simulated and applied through the programmable power source to the microgrid.

The response of a variable set of loads to voltage profiles were recorded and studied using a common PC connected to the LAN and the Modbus Master emulator of Matlab Instrument Control Toolbox. All adopted meters are able to make power measurements available on the LAN network, using a Modbus TCP/IP protocol (either directly if Modbus TCP/IP is supported by the equipment or via an Ethernet gateway). Data were read from the holding registers of slaves and logged, using the minimum time resolution possible with this set-up (about 100 ms). However, such resolution is not needed since the power meters update their reading only after one second.

If these data must be read or analyzed by a centralized operator, being either a DSO or an energy services aggregator, the holding registers of Modbus TCP/IP meters can be accessed from any master located in a wide area network (WAN). If this is not possible, or economically viable, data can be collected by a local gateway and published utilizing HTTP-based applications like RESTful API or MQTT API. The experimental results in the development of a cloud based energy management system [22], showed a latency associated with the transfer of real-time data using a WAN of about 100 ms [8]; whereas in the case of a MQTT API the overall

delay was about 100 ms comprehensive of the time necessary to build the message to be published. Both timings are compatible with the assumed 1 s resolution.

A. Experimental validation

The analysis of the sensitivity in the studied microgrid has been performed applying to the LabZERO microgrid continuous voltage variations of 0.02pu with a ramp of 5s and a steady-state time of 5s. The controlled voltage variation has a total time window of 15s.

The sensitivity analysis is carried out considering 4 test cases, characterized by the presence on the monitored feeder of some small loads. The rationale under this choice is to prove how the methodology can be applied also with minor load variations. The proposed cases are the following:

- Case A:* Electrical heater consuming 800W; this is the typical constant impedance load case, depending on the square of the voltage;
- Case B:* Electrical heater consuming 800W and household electrical appliance (i.e., desktop computer); the latter, being power electronics-interfaced with the grid, has the tendency to behave as constant power load;
- Case C:* Same as Case 2, but the electrical heater reduces the power consumption to 400W, decreasing the constant impedance contribution of the total load;
- Case D:* Same as Case 2 but with a small power tool (i.e. a heat gun) of about 400W also connected; it represents the case of small electrical appliances.

The overall experimental test voltage and power profiles are plotted in Fig. 4 and each of the aforementioned test cases are marked with a black box in the figure.

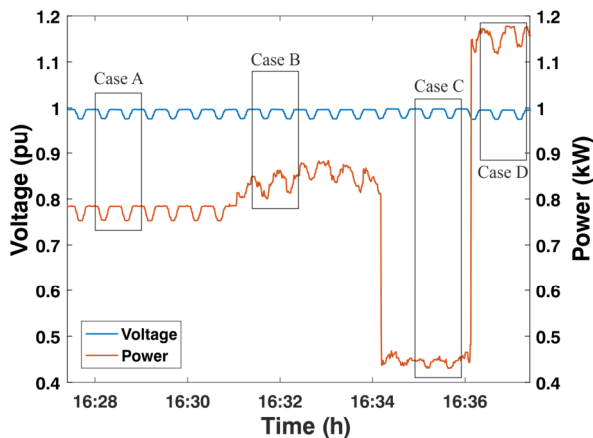


Fig. 4. Voltage (blue, pu) and power (red, kW) profile of the investigated load, in 12 minutes time window.

Case A: The ST applies a controlled voltage variation as shown in Fig. 5 and, being the load passive, the active responds accordingly to a squared relation with the voltage. The estimated load sensitivity $K_p=1.98$ in accordance with the constant impedance nature of the load. As can be noted from

Fig.5, the estimated power profile matches almost perfectly the measured power in both analyzed voltage variations.

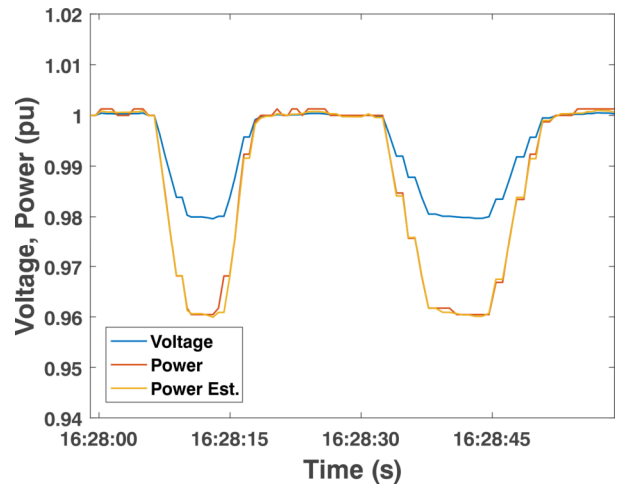


Fig. 5. Measured voltage (blue) and power (red) of the load in Case A, and estimated power consumption with the obtained load sensitivity to voltage.

To understand the working of the OLLI algorithm, the voltage sensitivity for each instant t_k is plotted in Fig. 6. During the evaluation time window, the OLLI gives a sensitivity contribution that depends on the instantaneous active power and voltage measurements. As can be noted, the sensitivity in each instant is in the neighborhood of the estimated $K_p=1.98$.

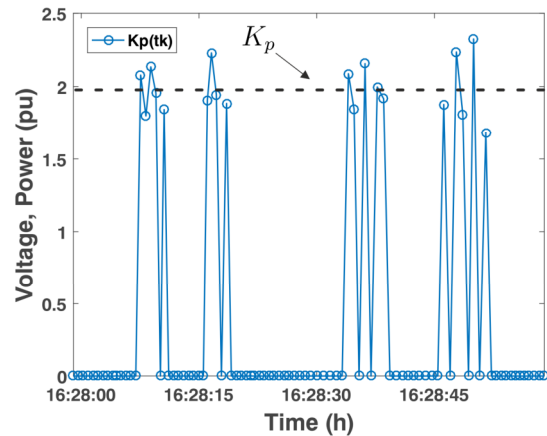


Fig. 6. Contribution in each instant t_k of the load active power sensitivity K_p , in Case A.

Case B: A typical constant power load (desktop computer) is connected in the grid, introducing more noise in the power profile, as can be seen from Fig. 7. The power has been normalized at the beginning of the time window, showing although, fast power variations. The OLLI algorithm has evaluated the load sensitivity to voltage equal to $K_p=2.02$. Despite the introduction of a constant power load, the sensitivity shows still a constant impedance behavior. This is due to the limited demand of constant power load and to the presence of some load fluctuations during the turning on of the

PC. However, the approximation given by the proposed approach can be considered still acceptable as in Fig. 7.

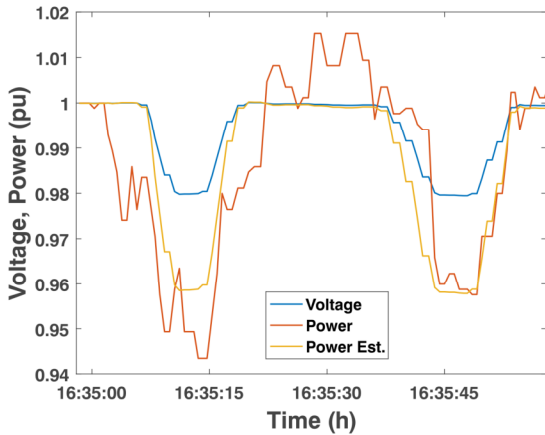


Fig. 7. Measured voltage (blue) and power (red) of the load in Case B, and estimated power consumption with the obtained load sensitivity to voltage.

Case C: To reduce the impact of the constant impedance contribution in the analyzed load, the electrical heater power consumption is then reduced to 50%, working at the operating point of 400W. As result, the total load is less sensitive to voltage variation than in the Case B, with an evaluated sensitivity equal to $K_p=1.74$ (Fig. 8). Compared to previous one, Case B is less sensitive to random load fluctuations. The introduction of a new load of different nature (constant power instead of constant impedance) is now evident.

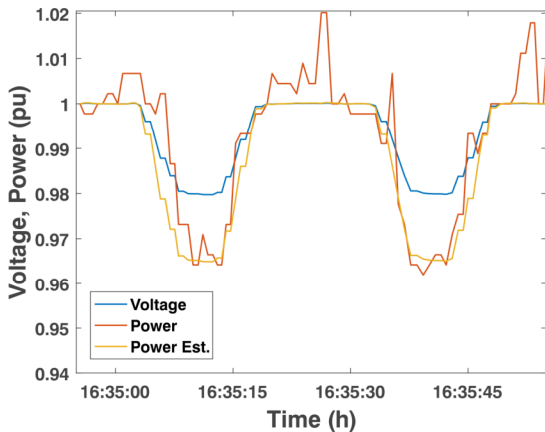


Fig. 8. Measure voltage (blue) and power (red) of the load in Case C, and estimated power consumption with the obtained load sensitivity to voltage.

Case D: As final case, a small power tool load is added to the loads depicted in Case B. Comparing Fig. 9 and Fig. 7 can be noted that the load is less sensitive to voltage variation, varying the power consumption in less than square way with respect to voltage. The estimate sensitivity is $K_p=1.81$. The index K_p decreased value can be explained by the power electronics

control of the small power tool, which is less sensitive to voltage variations.

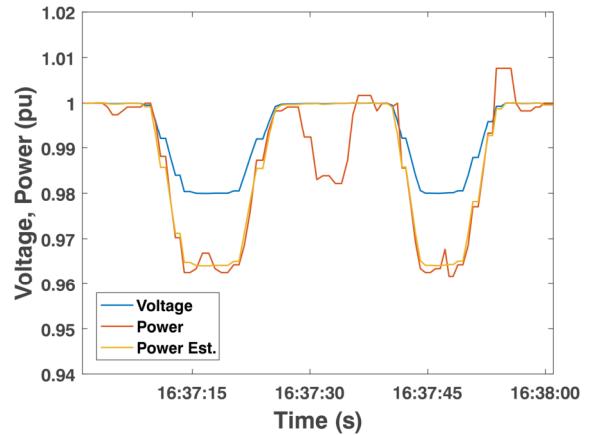


Fig. 9. Measured voltage (blue) and power (red) of the load in Case D, and estimated power consumption with the obtained load sensitivity to voltage.

B. Rejection of power noise

To validate the performance of the OLLI under high noise condition, a source of noise, i.e., an Uninterruptible Power Supply (UPS), has been connected to the grid in Case D, supplying an auxiliary circuit of about 150W. The UPS, despite processing low power, for synchronization purpose, injects a pulsating power in the grid, about every 15 seconds, as shown in Fig. 10. The OLLI algorithm recognizes that these spikes create power variations very different from the averaged voltage sensitivity of the load, and consequently filters out the spikes contributions.

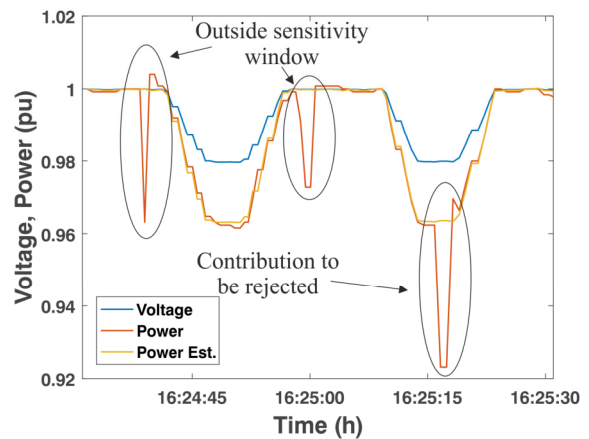


Fig. 10. Measure voltage (blue) and power (red) of the load in Case D with pulsating power noise, and estimated power consumption with the obtained load sensitivity to voltage.

In Fig. 11, it can be noticed that the OLLI algorithm recognizes the power spike during the sensitivity analysis and rejects this contribution, on the basis of the power noise rejection rule in Eq. (7).

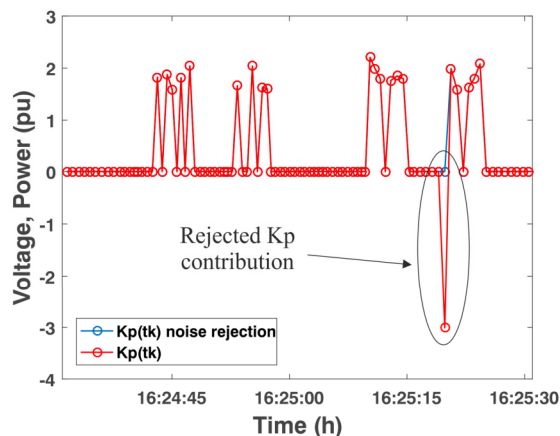


Fig. 11. Contribution in each instant tk of the load active power sensitivity K_p in Case D with (blue) and without (red) power noise rejection algorithm.

V. CONCLUSIONS

The On-Line Load sensitivity Identification allows a real time identification of the load power sensitivity to voltage and frequency. In this paper, the identification has been performed using commercially available industrial metering devices, characterized by a relatively high timestamp resolution.

To validate the industrial metering-based approach, experimental results were obtained in a small microgrid setup and having modeled the power output of the Smart Transformer with a programmable power source. Through the proposed tests, the load sensitivity was correctly identified at end-user level, using measurements with a 1-second time resolution at the point of common coupling with the grid. The measurements were collected in a LAN using common communication protocols, such as Modbus TCP/IP. Experimental data confirms the possibility to extend the same methodology to WAN or HTTP-based cloud applications.

Results showed that the OLLI method correctly identifies the load sensitivity, even when very small power deviations are measured. Furthermore, in this paper, a simple rule for rejecting bad data due to noise and power fluctuations has been proposed and tested with experimental results.

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