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State estimation in MV distribution networks: experience in the Spanish smart grid project PRICE-GDI

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SUMMARY

This paper shows a practical implementation of a state estimator for distribution systems in the context of the Spanish pilot project PRICE-GDI. The objective of this pilot project has been to develop a set of key technologies enabling the massive integration of renewable generation in distribution systems. Undoubtedly, dispatch centres involving advanced algorithm such as distribution state estimators and volt/var controllers are necessary for this challenge. This paper has analysed the implementation of a state estimator taken into account all the specific characteristics of the distribution systems: large proportion of injections in the measurement set, long and short lines coming to the same bus, presence of current flow measurements to the detriment of power flows, high R/X ratios and, mainly, reduced number of on-line measurements. As a matter of fact, this last issue is the responsible of the lack of observability of the system being necessary to incorporate to the classical estimation algorithm a load allocation procedure providing a number of pseudomeasurements. This paper proposes to use a methodology using Daily Load Curves (DLCs) to allocate the load of the Distribution Transformers (DTs) which obtain better results that the ones obtained using a classical procedure resorting on the contracted power of DTs.

The paper is structured as follows. First, the introduction gives some information of the Spanish pilot project PRICE-GDI and the motivation of the paper. Then, a brief explanation of the state estimation algorithm specially intended for MV distribution networks follows. After that,the DMS architecture and how the algorithm has been integrated are described followed by a description of the feeder that has been used to test the algorithm and the main obtained results. Finally, the paper closes with the main conclusions.

KEYWORDS

Distribution state estimation, load allocation, smart grids

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1. Introduction

Traditionally, MV distribution networks are characterized to be passive systems, where the power flows from the primary substations to the final users, with a low number of available on-line measurements mainly located at the head of MV feeders. In spite of this lack of on-line information, the operation of the MV distribution system is possible mainly because of the radial topology of the feeders and their passive nature. This traditional approach, however, is steadily changing to the near future smart grid. This is because the deployment of some key technologies such as the advanced metering infrastructure (AMI), the distributed generation (DG) and the electric vehicle (EV) among others. As a result, the operation of the MV distribution system may not rely on the same traditional principles. Any new technological solution, however, has to be developed and tested in pilot projects as a previous step to their deployment in the field.

Taking this in mind, PRICE-GDI is a Spanish pilot project, financed by the Ministry of Economy and Competitiveness under the INNPACTO Program with the aim of analysing different technologies enabling the massive integration of DG in MV distribution system. This project has been, with the aim of analysing different technologies enabling the massive integration of DG. The PRICE-GDI project has been developed under a consortium formed by a comprehensive set of stakeholders covering utilities (Iberdrola DistribuciónEléctrica and Unión FenosaDistribución), information technology (IT) companies (Indra), manufacturers (Ingeteam and ZIV) and research centers (Tecnalia, Comillas Pontifical University and University of Sevilla). Basically, the objective of the project is to gather different technologies for exploring the benefits that the coordinated operation of distributed generation (DGs) may bring to the distribution system as can be seen in Figure 1. The key technologies that have been explored in this project are DGs, MV and LV STATCOMs, bidirectional Remote Units (RUs) associated to DG or STATCOMS and an energy dispatch center with advanced functionalities.

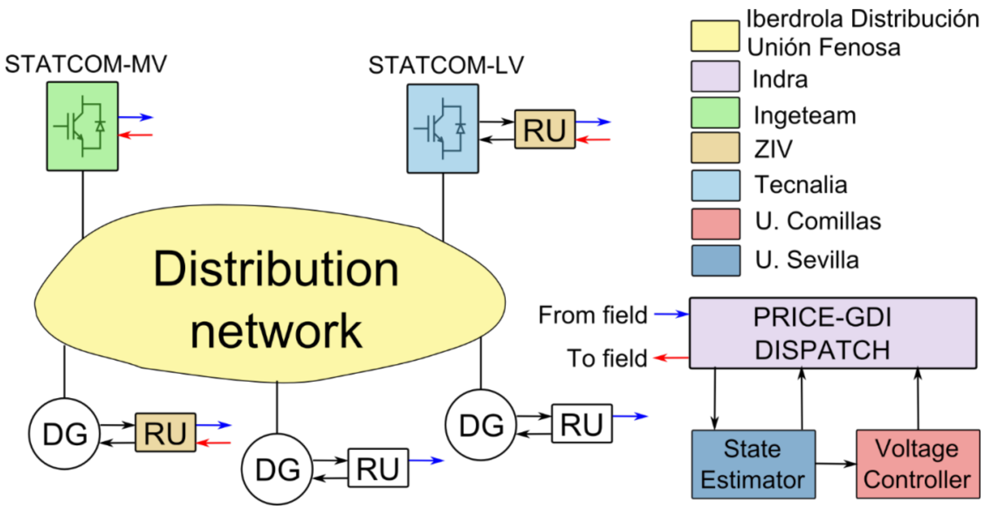

Figure 1. Main technologies deployed in the pilot project PRICE-GDI.

Undoubtedly, the proposed PRICE-GDI Dispatch with advanced functionalities, including state estimation of MV feeders and volt/var control, is a necessary technology for the operation of this future MV distribution system. In this sense, the aim of this paper is to describe the practical implementation of a state estimator (SE) applied to a MV distribution system operated by Iberdrola.

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State estimators for distribution systems must tackle with issues specifically related to this type of networks such as the large proportion of injections in the measurement set, long and short lines coming to the same bus, presence of current flow measurements to the detriment of power flows and high R/X ratios. But undoubtedly the main hindrance specifically associated to MV systems is the lack of appropriate and well-distributed measurements. As a matter of fact, MV systems are usually operated radially by feeders that extend from substations to secondary distribution transformers, on line measurements being limited in most cases to the main HV/MV substations. Although there is a growing tendency to improve the observability of the system by installing new measurement points [1-3], for many distribution companies the still only on-line information available is that acquired at the feeder heads: current and/or active/reactive powers as well as the voltage magnitude on the MV busbars. This lack of on-line information causes a problem of non-observability of the system, so pseudomeasurements at MV/LV transformers have to be added previously to perform the state estimation of the whole MV system. To solve this problem, the distribution system state estimator (DSSE) is usually preceded by a tool for load allocation (LA) that tries to estimate the load of the customers connected to the secondary substations. Based on this limited information, the LA problem for each single feeder has been traditionally performed by resorting to the rated power of the existing DTs. This way of modelling the load demand from DTs has proved to be inefficient [4].

Previous works within this area can be classified according to how the LA and DSSE algorithms interact. On the one hand, [5] proposes to perform the estimation as a conjunction of two separate problems LA and DSSE which are solve sequentially. On the other hand, [6-8] have chosen to solve the LA and DSSE by feeding each other. The algorithm proposed in [9], whose practical implementation is described in this paper, belongs to this second group.

The paper will be organized as follows. First, a brief explanation of the state estimation algorithm specially intended for MV distribution networks follows. Second, the DMS architecture and how the algorithm has been integrated are described. Third, a description of the feeder that has been used to test the algorithm and the main obtained results are included. Finally, the paper closes with the main conclusions and future lines of research.

2. Distribution Load and State Estimation methodology

The implemented solution, namely Distribution Load and State Estimation (DLSE) Methodology, is based on two submodules (LA and DSSE) that interacts each other as can be seen in Figure 2.

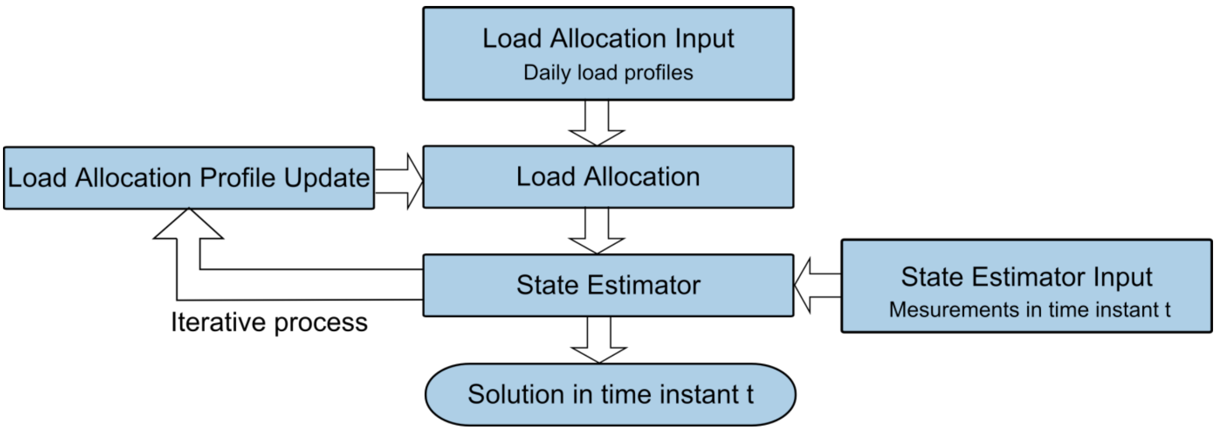

Figure 2. Distribution Load and State Estimation (DLSE) methodology.

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LA and DSSE blocks are solved by means of the reciprocal feeding of information in an optimal and efficient way until convergence is reached. The LA methodology solves the initial problem of non-observability by estimating loads demanded from DTs or consumption buses from on-line measurements at the feeder head and other additional information that will be described later. These header measurements include total load demand plus power losses, so the LA methodology also allocates losses among consumers. DSSE uses these load estimations at DTs, and employs other available measurements along the analysed feeder if there were, in order to compute the best state that matches all these real and estimated measurements. After solving the DSSE problem, active and reactive power losses can be computed. These quantities are of interest for improvement of the LA, since power at the feeder head can be decreased by losses, thereby resulting in new total active and reactive powers better fitted to the total load demand. A second LA execution would result in further improved load estimations and the subsequent SE solution would estimate a new improved state. This feedback between the two applications would continue until convergence was reached (the difference in power losses between two iterations must be lower than a specified threshold).

Some relevant features of the two main LA and DSSE applications follow. Starting with LA, Daily load curves (DLC) are taken into account in order to improve the load allocation solution [4], being this action one of the most significant features of the new proposed methodology [9]. The main idea after the use of DLCs is to incorporate to the LA problem the new information available at the concentrators allocated at the secondary side of DTs. Additionally, the previous measurements to the current time instant collected at feeder head are also incorporated to the LA problem. On one hand, the information of data concentrators, coming from smart meters downstream of DTs, allows deducing the most common daily load patterns associated to the clients connected to the system (clustering techniques are considered to perform this task), so the resulting LA solution is better fitted to the real behaviour of connected loads. On the other hand, the other new information coming from the previous measurements registered at feeder head allows talking about a dynamic LA solution, with all the advantages coming from solutions that considerer not only the current studied time but also information associated to the previous one.

Regarding the DSSE, Hachtel's Augmented Matrix Method is the adopted solution because its efficient treatment of virtual measurements (zero active and reactive power injections) which are very common in distribution systems.
The complete closed-loop DLSE methodology, which has been validated in [9] by performing numerous rigorous tests on typical distribution systems under different conditions, has been doubly optimized from a computational point of view by adopting the following new improvements:

- Since the output of each application (LA and DSSE) depends on the other, an exact solution from each application makes no sense. Instead, a single iteration for the LA and SE applications independently should be sufficient, and the convergence of the whole procedure is guaranteed by the feedback between both applications. This simplification speeds up the whole procedure without losing accuracy [9].
- The LA problem that is formulated as an optimization problem, see [9] for details, is simplified by an approximated linear solution in an effort to speed up the final whole solution. Once again the accuracy of the final solution is not reduced by this simplification [9].

3. Description of the application architecture

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The architecture of the application can be explained with the help of the scheme depicted in Figure 3. All the measurements from the field have been collected using the current SCADA that Iberdrola uses to operate the distribution system. For this purpose, an ICCP (Inter-Control Center Communications Protocol)link between the current Iberdrola SCADA and the PRICE-GDI Dispatch has been developed. All the measurements are published to the bus SPEED (Smart Platform for Efficient Energy Distribution) which is a DDS Message Oriented Middleware based on subscriber/publisher protocols. The DLSE is launched in a periodic base by the Dynamic Service which is also in charge of the interaction with the SPEED bus through the corresponding subscriber/publisher proxies.

In order to integrate the DLSE within this architecture, the following modules have been implemented:

- *Subscriber Proxy*. It is the module in charge of gathering the measurement data from the messages sent via SPEED and translating it to a common data model. The subscribed measurements are: injected active and reactive powers, active and reactive power flows and voltage values and phases.
- *Publisher Proxy*. It is the module in charge of gathering the algorithm results and sending it via SPEED. The published data are: estimated injected active and reactive powers, estimated active and reactive power flows as well as estimated voltage values and phases.
- *Dynamic Service*. It is the module responsible for running the workflow, thus, it stores the measurements received from the Subscriber Proxy, executes the DLSE algorithm and sends the results through the Publisher Proxy.
- *Static Collector*. It is the module that collects the topology and inventory information necessary for understanding the messages received from the DDS.
- *Static Service*. It is the module responsible for filtering, transforming and loading the topology and inventory information (static data) to be used by the DLSE algorithm.

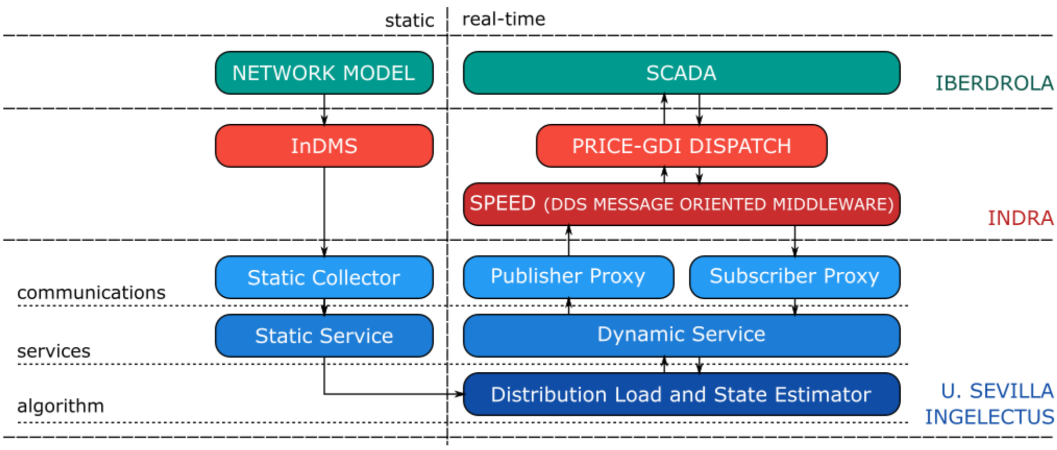

Figure 3. Architecture of the application.

4. Test case

4.1. Distribution network

The application considers the whole distribution network within the regional area known as *Corredordel Henares* comprising 9 HV/MV substations, 131 MV lines, 2.228 secondary MV/LV substations, 170.729 clients and a total installed power of 1.126 MW. However, this paper includes

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results of only one MV distribution feeder, shown in Figure 4, which has been intensively analysed to assess the benefits of the proposed DLSE methodology. This MV distribution feeder (20 kV of nominal voltage) is composed of a 46 secondary MV/LV substations, an installed power of 40.7 MW, contracted power of 26.09 MW and total length of 12.57 km.

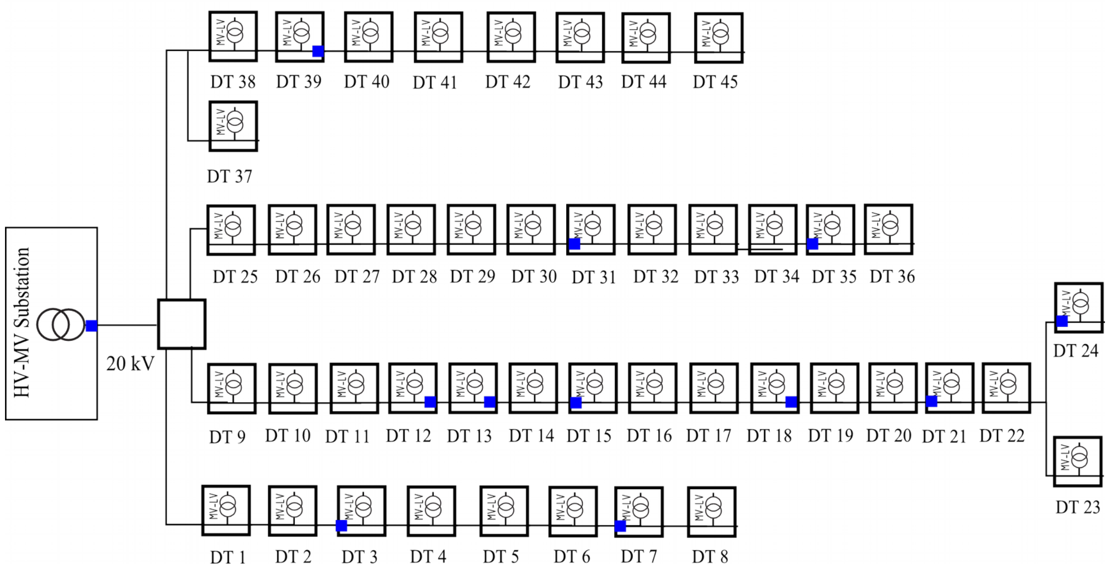

Figure 4. One-line diagram of the distribution feeder used in the test cases.

Within this feeder the following measurements are available:

- Voltage, current, active and reactive powers at the MV feeder head.
- Voltage, current, active and reactive powers in 12 MV/LV secondary substations. These measurement points have been marked up with a blue square in Figure 4.

4.2. Computation of the DLCs

The DLCs used in the algorithm have been computed by applying the clustering algorithm proposed in [11]. For this purpose, the hourly energy consumption of the all the clients which are connected to the analysed feeder during six months have been used as input data of the algorithm. Figura 5 represents the DLCs related to domestic and service loads that have been used in this work. Note that only two DLCs are required to represent residential clients while in the case of industrial customers four DLCs have been used. This issue is basically due to the fact that residential and service clients are more homogenous between them being possible to represent them with a lower number of DLCs.

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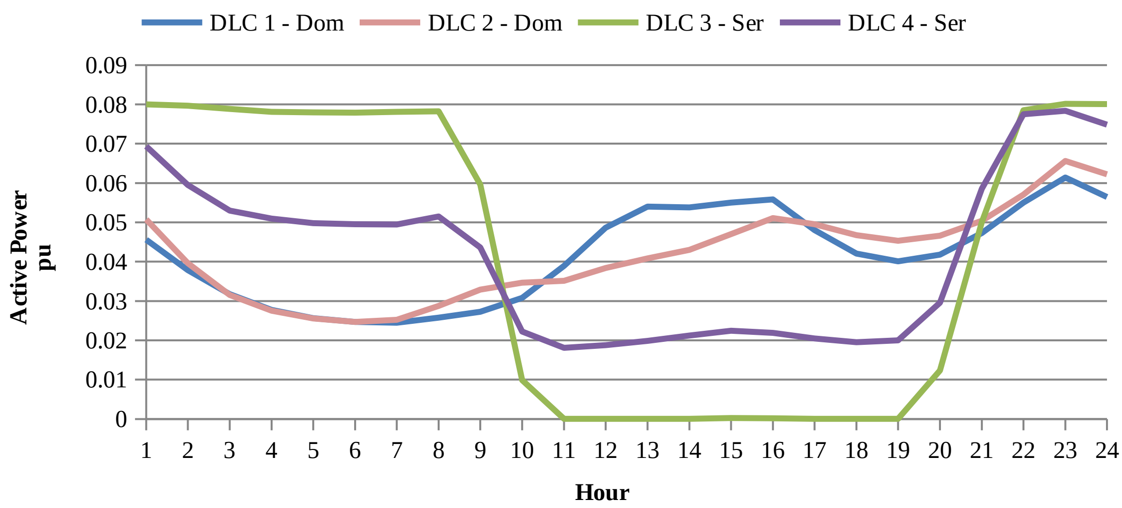

Figura 5. Residential and service DLCs.

4.3. Main results

This section presents some of the results obtained by the application during the 18th of April 2015. Figure 6 shows the measurements of active and reactive power flows at MV feeder head during this day. Note that the demand scenario is quite low during this 24 hours period. As a result, the reactive power is negative due to the capacitive behavior of the underground cables and the bus voltages are high as can be seen in Figure 7. The voltage profiles corresponding to the feeder head and the farthest node from the substation have been highlighted to stress that the remaining voltages measurements are within this range. In addition,Figure 8 shows the active power flows measurements which have been acquired in the different measurement points along the distribution system.

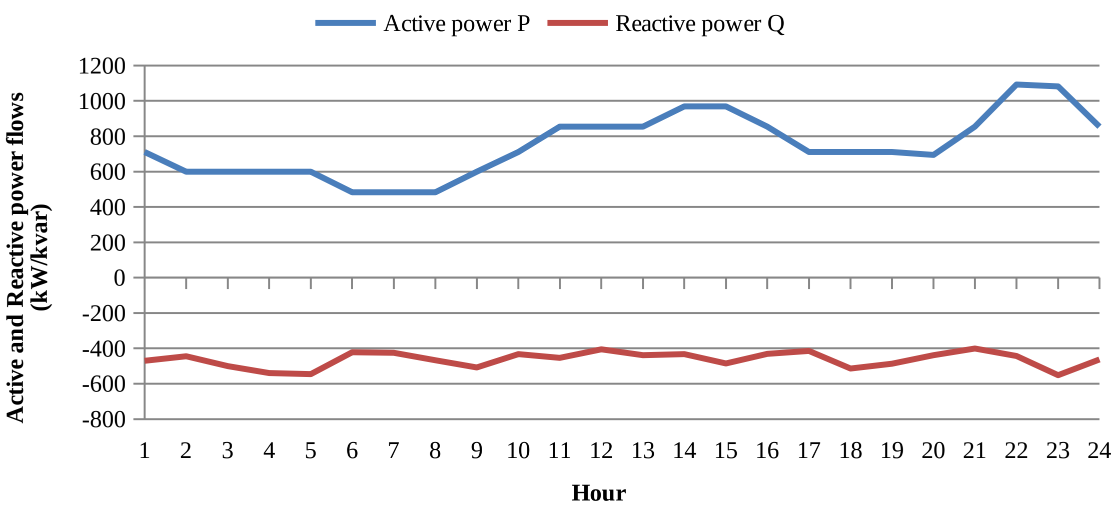

Figure 6. Active and reactive power flows at MV feeder head.

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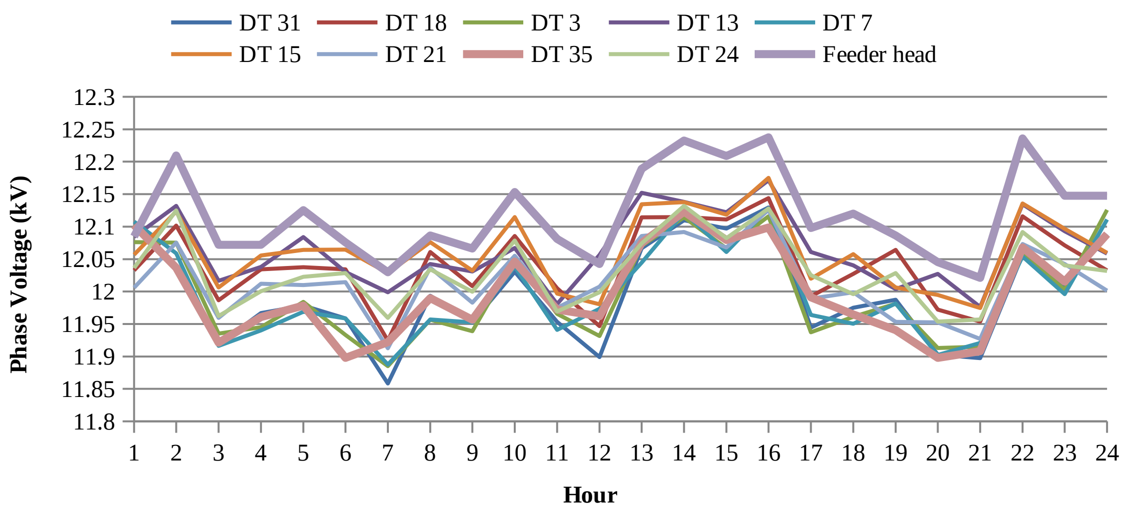

Figure 7. Voltage measurements at MV feeder.

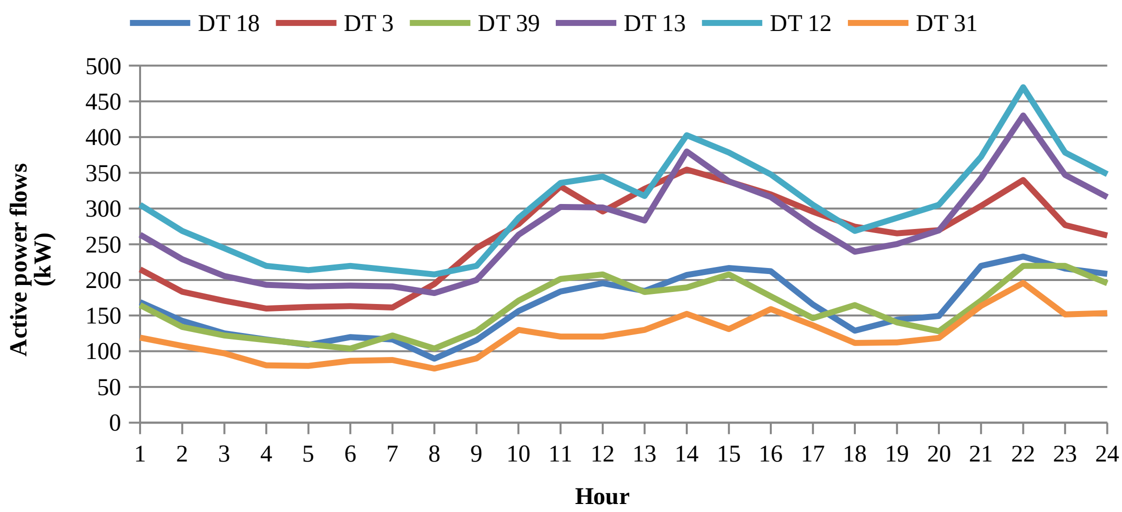

Figure 8. Measurements of active power flows.

All this information constitutes the on-line measurements to the DLSE algorithm which has to be completed by the pseudomeasurements of the LA algorithm in order to obtain an observable system. With this regard, as previously stated, it is possible to apply different strategies. On the one hand, it is possible to perform the LA procedure in a classical basis using the information of contracted power of each DT (LA-CP). On the other hand, it is possible to take advantage of the information provided by the previously computed DLCs (LA-DLC). In order to highlight the benefits of the proposed LA-DLC the estimation results of three different DTs depicted in Table 1 are analyzed. Note that the selected DTs are of different nature. DT43 and DT4 are mainly composed of residential and industrial loads respectively while DT34 has a mix of service and residential clients.

Tabla 1. Analyzed secondary distribution transformers.

DT	Clients	Contracted	Industrial	Services	Residential

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Name		power (kW)	(%)	(%)	(%)
DT 43	170	940.95	0	10.95	89.05
DT 34	181	1228.61	5.65	38.40	55.95
DT 4	1	180	100	0	0

Figura 9 to Figura 11 show the estimated active power demand by using the classical LA-CP and the proposed LA-DLC procedure. Note that all the estimated active power demands using the LA-CP methodology follow the active power curve of the nearest upstream measurement, which is not usually the case as different consumption patterns exist depending on the type of clients connected to the DT. With this regard, note that the estimated active power by the LA-DLC methodology during some periods does not follow this curve because uses the information provided by the DLCs.

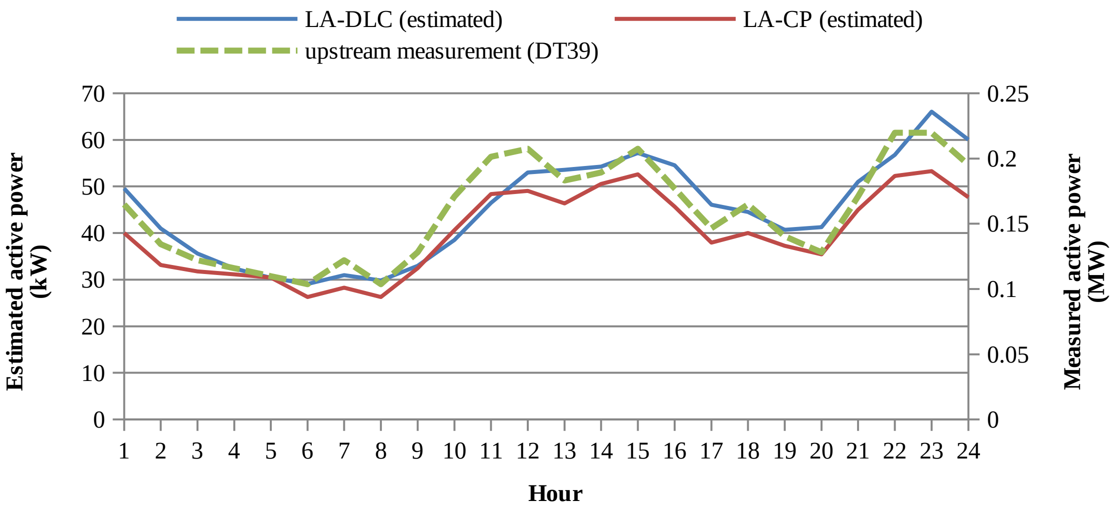

Figura 9. Estimation of the active power demand on DT43.

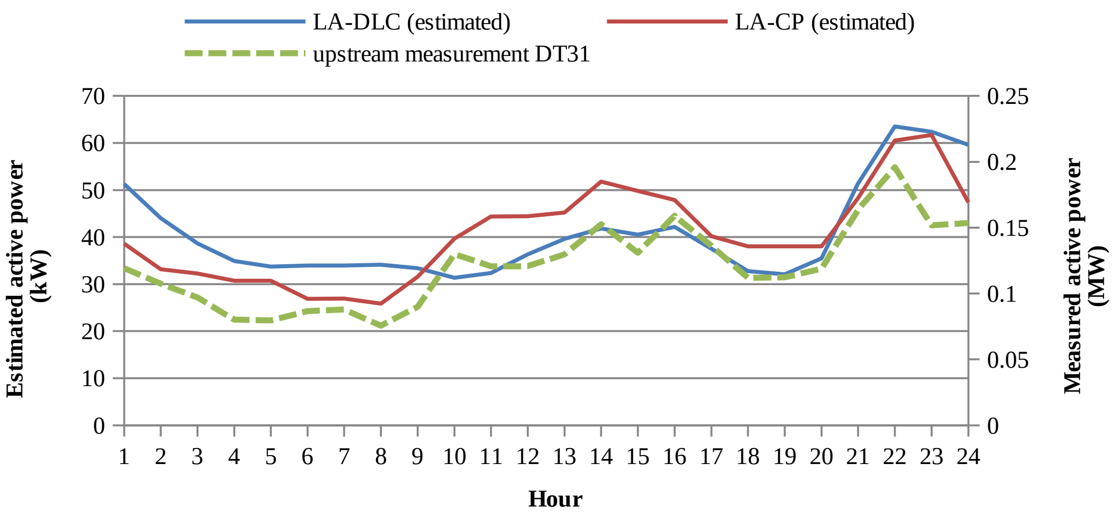

Figura 10. Estimation of the active power demand on DT34.

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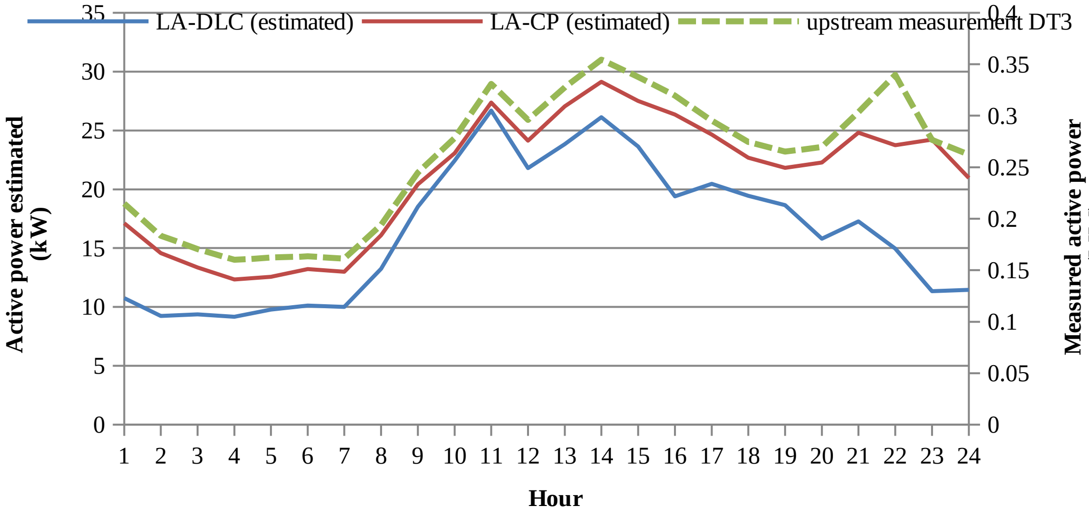

Figura 11. Estimation of the active power demand on DT4.

Finally, Figura 11 shows the relative error between the estimated and the actual active power demanded by DT43. The actual active power demand has been obtained afterwards using the measurement provided by the data concentrator installed in the distribution center. Again, this result reveals the effectiveness of using the methodology based on DLCs as its associated error is quite reduced.

5. Conclusions

This paper has shown a practical implementation of a state estimator for distribution systems in the context of the Spanish pilot project PRICE-GDI. The objective of this pilot project has been to develop a set of key technologies enabling the massive integration of renewable generation in distribution systems. Undoubtedly, dispatch centres involving advanced algorithm such as distribution state estimators and volt/var controllers are necessary for this challenge. This paper has analysed the implementation of a state estimator taken into account all the specific characteristics of the distribution systems and, mainly,their reduced number of on-line measurements. For this reason, a recent novel LA algorithm has been implemented to provide a number of pseudomeasurements to create an observable system. With this regard, it has been shown the advantages that the use of previously computed DLCs may bring compared to classical techniques based on contracted or rated power of DTs.

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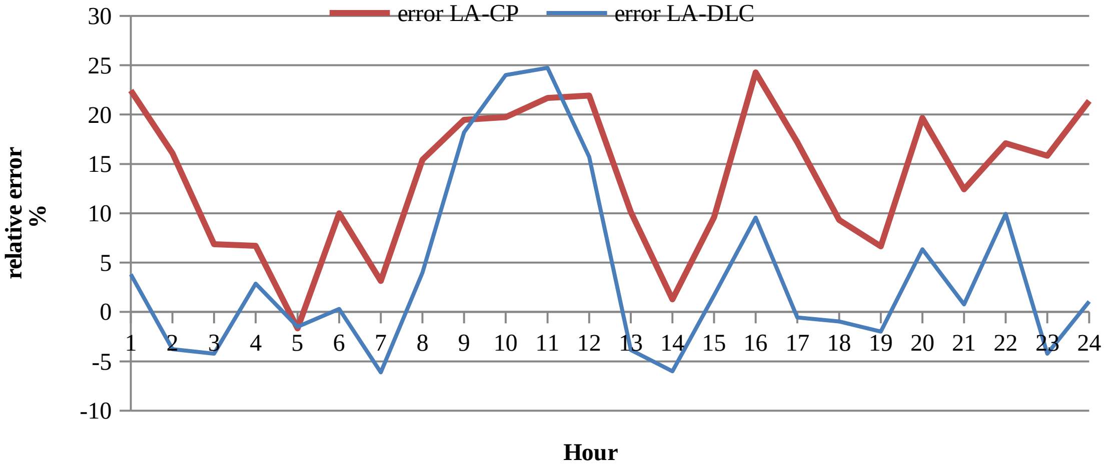

Figure12. Relative error in the estimation of active power for DT43.

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