REAL-TIME MONITORING OF DISTRIBUTION NETWORKS: EXPERIMENTAL APPLICATION OF ITALIAN RES. 646/2015/R/EEL

Maurizio DELFANTI
Politecnico di Milano – Italy
maurizio.delfanti@polimi.it

Davide FALABRETTI
Politecnico di Milano – Italy
davide.falabretti@polimi.it

Marco MERLO
Politecnico di Milano – Italy
marco.merlo@polimi.it

ABSTRACT

Italian Resolution 646/2015/R/eel recently promoted the implementation of innovative services devoted to the effective management of distribution networks with great penetration of Dispersed Generation. The OSS-2 service provides the delivery to the TSO of real-time (20 s sample time) estimations of the overall load and DG production (classified as production from PV source and from other sources). The work presents the approach adopted within the project of DEVAL (Aosta Valley DSO) for the implementation of the OSS-2 service and the results obtained.

INTRODUCTION

Fostering Renewable Energy Sources (RES) is a need in the perspective of a new sustainable energy paradigm. In presence of non-programmable energy sources, however, the adoption of novel strategies becomes essential in order to allow a reliable and effective power system operation.

To this purpose, in Italy, the Energy Authority (Autorità per l'Energia Elettrica il Gas ed il Sistema Idrico, AEEGSI) recently promoted the implementation of innovative services aimed to the management of distribution networks with great penetration of Dispersed Generation (DG). Resolution 646/2015/R/eel [1] defined a set of output-based incentive mechanisms, intended to stimulate the development of appropriate investments on distribution networks and directing the DSOs' choices towards investments able to maximize the benefits for the whole system. In particular, in a first phase of experimentation, the Italian Authority decided to focus on two main services: the observability of power flows and state of DG, and the voltage regulation on MV distribution networks.

Concerning the observability service (OSS service), it is addressed to provide a new management tool to the TSO: by more effectively quantifying the DG production in each node of the transmission system, it supports the TSO in better identifying the strategies needed to manage RES intermittency (e.g. amount of sources to collect on the Dispatching Service Market). Italian Authority identified two different degrees of implementation of the service: OSS-1 and OSS-2 levels. Actually, OSS-2 level requires a more complex architecture; on the other hand, it provides better information about the condition of the distribution grid. OSS-2 level, in fact, provides the delivery by the DSO to the TSO of real-time (20 s sample time) estimations of the overall load and DG production (classified as production from PV source and from other sources) downstream each MV busbar of Primary Substation (PS). To this purpose, a main challenge for the DSO is to compute accurate and reliable estimations based on a very limited set of measurements on the network (e.g. at MV users' premises): in fact, the entity of the incentive set by the Italian Energy Authority is not devoted to cover the costs of a pervasive monitoring system distributed on the MV grid. Therefore, DG power injections not directly monitored have to be estimated through suitable algorithms. Weather forecasts, refined with historical data about generation and load, measures already available to the DSO, and data from meteorological stations can also be used to improve the performance of the estimation. The accuracy of the procedure is evaluated ex-post, by comparing the data delivered to the TSO with the measurements collected for commercial purposes by users' energy meters.

In order to quantify the actual benefits of the service, AEEGSI encouraged preliminary tests on the networks involved in the Smart Grid projects activated by Res. ARG/elt 39/2010 (a former incentive scheme of the Italian Authority devoted to promote the deployment of Smart Grid pilots in Italy [2]). Actually, these grids represent the ideal scenario for the implementation of this innovative function, because they are already equipped with computing and monitoring systems aimed to perform a real-time control of the distribution grid. The final goal of the experimental application is to provide realistic evaluations of the approach performances, useful to the AEEGSI in order to define an economic remuneration of OSS-2 service.

In the following, the work will present the approach adopted by DEVAL SpA (DSO of the Italian mountainous region of Aosta Valley, north-west of Italy) within its Smart Grid project for the implementation of the OSS-2 service and the results obtained in the first period of tests.

CASE STUDY

The tests on the OSS-2 innovative function have been performed on the Primary Substation (PS) Villeneuve, managed by DEVAL SpA. PS Villeneuve is equipped with two HV/MV transformers (rated power 16 and 25 MVA), each one supplying a MV busbar (rated voltage 15 kV).

In the Villeneuve area there is a great availability of hydraulic power source, while Photovoltaic (PV) generation has only a marginal spread: 13 hydro MV power plants (overall rated power of 17.876 MW) and 270 small PV power plants (2.142 MW). About PV generation, in particular, all the power plants are connected to the LV grid, with contractual powers ranging from 1.07 to 100 kW.

As already mentioned, since 2010 the Villeneuve distribution grid is involved in one of the Smart Grid experiments promoted by AEEGSI through Res. ARG/elt 39/10. In order to satisfy the requirements set in the selection procedure by AEEGSI, the MV network and some MV users has been equipped with monitoring systems able to collect in real-time all the data needed for the project evaluation. The communication between the monitoring devices is performed by fiber-optic and mobile (3G) technologies, using non-proprietary protocols (IEC 61850). More in detail, 8 hydro plants (11.44 MW) are involved in the Smart Grid architecture. Figure 1 details the geographic area involved in the experiment. The blue dot on the map identifies the Primary Substation. Power plants reported in Figure 1 as yellow dots are already monitored in real-time from the DEVAL control center, while generators shown as orange dots are just equipped with all the required devices for the communication, but will be monitored in the next future. Generators that are not monitored but whose exchange power profiles have to be estimated by the OSS-2 architecture are coloured in red.

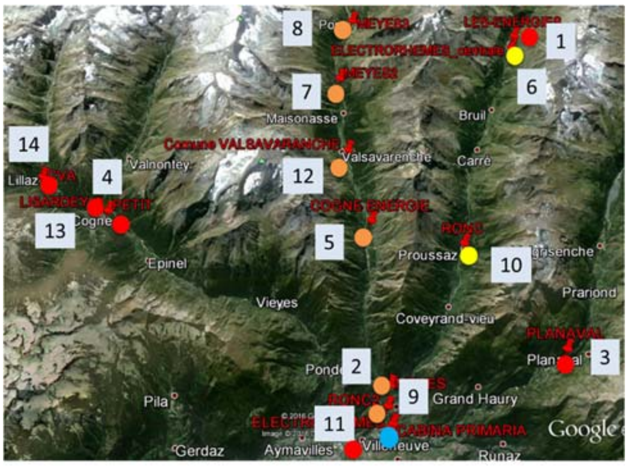

Figure 1. Area involved in the DEVAL OSS-2 and Smart Grid projects (blue: PS Villeneuve; red: non-monitored power plant; yellow: monitored power plant; orange: monitorable power plant).

ANALYSIS ON THE TIME SERIES CORRELATION

Statistical analyses have been carried out in order to evaluate on a purely mathematical basis the numerical correlation between the historical production profiles of the generators connected to the distribution network under analysis. The purpose is to identify the best proxy for the power exchange profiles of non-monitored DG, so as to exploit it in the estimation phase providing the best results. A database with the measurements collected by tariff meters on each power plant every 15 minutes from March 2015 to December 2015 has been exploited.

Figure 2 shows the profile of one of the generators under study as "energy map": it represents the production profile in three dimensions, as quarter-hour energy measurements as a function of the day of the year and the quarter-hour of the day. Through this approach the periodicity of the energetic behaviour of a given renewable energy source is evident. For example, Figure 2 clearly highlights that, in compliance with RES availability in the area of the experiment (water flow originated by the melting of Alpine glaciers), the electricity production basically has a seasonal trend, without energy generation during the coldest seasons and maximum production during spring and summer (during these periods, however, generators can be subject to temporary stops for maintenance).

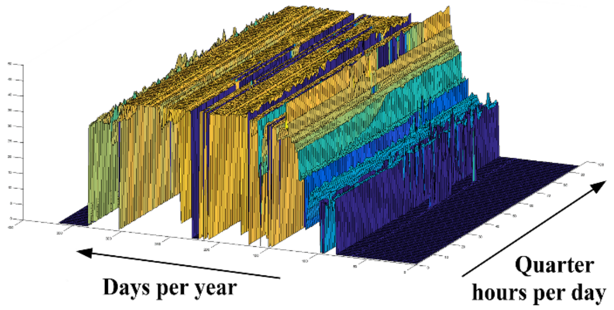

Figure 2. Example of power exchange profile with the electrical network of a power plant under study.

On the database of measurements, we evaluated the Pairwise linear correlation index: this index (ranging between 0 and 1) is typically adopted in statistics in order to assess, at an overall level, if two time series are interrelated. In particular, in Table 1 the index is computed between each pair of power plants: so the table has as many rows and columns as the total number of power plants involved (14 generators: 14 rows and 14 columns). Columns and rows are numbered according to the ID numbers reported in the previous Figure 1.

Table 1. Pairwise linear correlation evaluated between the DG production profiles.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1,00	0,71	0,43	0,67	0,57	0,58	0,66	0,63	0,04	0,70	0,12	0,72	0,57	0,73
2	0,71	1,00	0,43	0,64	0,66	0,68	0,85	0,82	-0,01	0,73	0,06	0,77	0,56	0,75
3	0,43	0,43	1,00	0,36	0,45	0,43	0,38	0,38	0,04	0,42	0,07	0,39	0,44	0,52
4	0,67	0,64	0,36	1,00	0,66	0,59	0,66	0,66	0,05	0,70	0,12	0,71	0,55	0,59
5	0,57	0,66	0,45	0,66	1,00	0,80	0,83	0,84	-0,08	0,79	0,14	0,85	0,68	0,68
6	0,58	0,68	0,43	0,59	0,80	1,00	0,84	0,85	0,05	0,86	0,10	0,83	0,65	0,64
7	0,66	0,85	0,38	0,66	0,83	0,84	1,00	1,00	-0,09	0,83	0,12	0,89	0,67	0,74
8	0,63	0,82	0,38	0,66	0,84	0,85	1,00	1,00	-0,10	0,82	0,12	0,89	0,67	0,72
9	0,04	-0,01	0,04	0,05	-0,08	0,05	-0,09	-0,10	1,00	0,10	-0,05	-0,02	-0,01	-0,04
10	0,70	0,73	0,42	0,70	0,79	0,86	0,83	0,82	0,10	1,00	0,12	0,87	0,68	0,72
11	0,12	0,06	0,07	0,12	0,14	0,10	0,12	0,12	-0,05	0,12	1,00	0,14	0,13	0,14
12	0,72	0,77	0,39	0,71	0,85	0,83	0,89	0,89	-0,02	0,87	0,14	1,00	0,72	0,74
13	0,57	0,56	0,44	0,55	0,68	0,65	0,67	0,67	-0,01	0,68	0,13	0,72	1,00	0,73
14	0,73	0,75	0,52	0,59	0,68	0,64	0,74	0,72	-0,04	0,72	0,14	0,74	0,73	1,00

Each cell of the table reports the correlation estimated by the Pairwise linear correlation index adopted between two generators. Note that the elements on the diagonal are all equal to unity, obvious consequence of the fact that they are the autocorrelation coefficients of each production profile.

Moreover, a significant result is that off-diagonal elements are usually low: this fact denotes a weak correlation between time series of different generators. Therefore, these first results bring into question the possibility of identifying power plants (sentinel power plants) able to well represent the energy production of the entire set of generators connected to the distribution network.

Based on the just mentioned evidence, we investigated the opportunity to improve the accuracy of the estimation exploiting historical time series. The simplest estimation approach provides to assume the current energy production of each power plant equal to that measured in a given instant in the past (e.g., a year, a week, a day before). This approach, known as persistence model, well applies to RES changing with slow or periodic dynamics, so that it can be assumed that the power plant behaviour keeps unaltered on a given time interval, or it repeats with a particular timing (e.g. daily or yearly).

In Table 2 we used the metering data of yesterday to estimate the DG production of today, while Table 3 shows the results of the same analysis obtained adopting a time lag equal to a week. Therefore, through this approach the energy production of the 14 power plants involved in the experiment is determined on the basis on the 14 historical time series, resulting from the application of the persistence model to each generator. Each row of the table corresponds to a power plant, while each column refers to the time series (columns numbers indicate the generator on which energy measures are collected) of the persistence model.

Table 2. Pairwise linear correlation evaluated between the DG production profiles (columns) and the relevant time series (rows) on a 24 h time horizon.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0,84	0,69	0,42	0,65	0,54	0,55	0,65	0,62	-0,06	0,66	0,12	0,69	0,55	0,71
2	0,69	0,92	0,41	0,62	0,63	0,66	0,82	0,80	-0,11	0,69	0,05	0,75	0,51	0,72
3	0,42	0,42	0,86	0,35	0,45	0,43	0,38	0,38	0,00	0,41	0,08	0,38	0,41	0,50
4	0,67	0,63	0,36	0,93	0,64	0,58	0,65	0,64	-0,01	0,68	0,11	0,70	0,54	0,57
5	0,56	0,65	0,42	0,64	0,93	0,78	0,82	0,83	-0,15	0,78	0,15	0,84	0,65	0,65
6	0,57	0,66	0,41	0,58	0,79	0,86	0,83	0,84	-0,11	0,79	0,10	0,81	0,63	0,62
7	0,64	0,82	0,36	0,64	0,80	0,82	0,98	0,97	-0,17	0,80	0,11	0,87	0,63	0,72
8	0,62	0,80	0,36	0,64	0,81	0,83	0,97	0,98	-0,17	0,80	0,12	0,87	0,63	0,69
9	-0,02	-0,11	0,00	-0,01	-0,14	-0,11	-0,17	-0,17	0,12	-0,08	-0,05	-0,13	-0,12	-0,15
10	0,69	0,71	0,40	0,68	0,79	0,76	0,81	0,81	-0,11	0,82	0,12	0,84	0,65	0,69
11	0,12	0,06	0,06	0,12	0,14	0,10	0,11	0,12	-0,07	0,12	0,78	0,15	0,14	0,14
12	0,70	0,76	0,37	0,70	0,82	0,79	0,88	0,87	-0,16	0,84	0,14	0,94	0,66	0,72
13	0,54	0,53	0,44	0,52	0,64	0,63	0,65	0,65	-0,16	0,64	0,13	0,69	0,86	0,69
14	0,71	0,73	0,51	0,58	0,65	0,62	0,72	0,70	-0,15	0,70	0,13	0,72	0,69	0,92

Both tests showed a good correlation between DG real-time production and historical time series, with only a marginal worsening of the performance of the estimation with the increasing of the time lag between the time series (actual production vs. persistence).

In conclusion, the performed analyses were useful in order to validate the use, for the DG production real-time estimation, of the data acquired in the past by the standard metering system for tariff purposes.

These figures, in addition to the data collected at the same instant on other power plants of the same technology equipped with advanced meters (as better clarified in the following section, so called "sentinel power plants"), are supposed to drive an accurate estimation of the DG generation, i.e. the correlation indices resulted to be adequately high.

Table 3. Pairwise linear correlation evaluated between the DG production profiles (columns) and the relevant time series (rows) on a week time horizon.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0,72	0,72	0,38	0,57	0,47	0,50	0,65	0,62	-0,10	0,60	0,08	0,65	0,47	0,68
2	0,67	0,81	0,34	0,58	0,57	0,61	0,81	0,79	-0,13	0,64	0,02	0,70	0,45	0,66
3	0,46	0,45	0,64	0,26	0,45	0,41	0,45	0,45	-0,01	0,42	0,07	0,39	0,41	0,47
4	0,69	0,64	0,38	0,74	0,52	0,52	0,65	0,64	-0,03	0,60	0,11	0,65	0,46	0,56
5	0,60	0,67	0,32	0,66	0,85	0,76	0,85	0,86	-0,11	0,77	0,14	0,82	0,57	0,63
6	0,56	0,68	0,30	0,52	0,74	0,79	0,86	0,86	-0,14	0,74	0,09	0,80	0,62	0,64
7	0,63	0,80	0,27	0,61	0,74	0,77	0,95	0,94	-0,17	0,76	0,09	0,83	0,57	0,68
8	0,61	0,78	0,27	0,61	0,75	0,78	0,95	0,95	-0,17	0,75	0,09	0,83	0,57	0,66
9	-0,02	-0,12	-0,05	-0,12	-0,14	-0,14	-0,16	-0,16	0,00	-0,15	-0,08	-0,12	-0,05	-0,13
10	0,66	0,74	0,33	0,63	0,73	0,73	0,84	0,83	-0,17	0,76	0,11	0,83	0,62	0,70
11	0,13	0,08	0,08	0,13	0,15	0,12	0,13	0,13	-0,07	0,13	0,72	0,15	0,16	0,18
12	0,70	0,78	0,29	0,70	0,75	0,76	0,90	0,89	-0,17	0,80	0,12	0,89	0,61	0,71
13	0,54	0,58	0,48	0,53	0,65	0,66	0,70	0,71	-0,16	0,66	0,11	0,68	0,68	0,66
14	0,72	0,77	0,49	0,57	0,65	0,63	0,75	0,72	-0,15	0,71	0,11	0,75	0,64	0,81

THE APPROACH

According to the instructions of the Italian Energy Authority regarding the OSS-2 service, the DSO has to provide to the TSO, every 20 s, real-time estimations of the overall DG production on the whole PS, classified in generation from PV source and generation from "other sources" (hydro, wind, thermal).

Considering the different measurements available on each power plant that can be used in the estimation process, the DG units connected to Villeneuve distribution network are classified as follows.

- Sentinel power plants: generators whose measures are available in real-time through the Smart Grid monitoring system.
- Satellite power plants: generators whose real-time production has to by estimated by the OSS-2 service; measurements of these plants are available with a delay depending on the procedure adopted by the DSO in order to collect data through the standard metering infrastructure and to process it (within the DEVAL use case, 24 h has been assumed a reasonable time lag to perform all these operations).

In the case study of PS Villeneuve, the two power plants monitored in real-time within the DEVAL Smart Grid project (power plants #6 and #10 in Figure 1) have been selected to be modelled as sentinel plants, while the other generators are all assumed as satellite plants.

It each instant t, the overall production for a given DG source (e.g. hydro) downstream the PS is evaluated by the OSS-2 architecture as sum of the power measured on the monitored plants and that estimated on non-monitored plants (satellite plants):

$$P_t = \sum_{n=1}^{N} P_{n,t}^{sen} + \sum_{i=1}^{I} P_{i,t}^{sat} \tag{1}$$

In eq. (1), $P_{n,t}^{sen}$ is the power measured on the n-th sentinel power plant at the instant t and $P_{i,t}^{sat}$ is the power estimated for the i-th satellite power plant at the same instant.

The algorithm estimates the production of each satellite plant as linear combination of the production acquired in real-time on sentinel plants and the power profiles obtained applying the persistence model with a predefined time lag to the historical time series collected on both sentinel and satellite plants.

The proportionality coefficient of each couple satellite/sentinel plants ($k_{i,m}$) is assessed through analyses on the historical data collected (i.e. it is obtained through a least mean square algorithm, weighting more the contribution of generators that provided in the past more accurate estimations):

$$P_{i,t}^{sat} = \frac{\sum_{m=1}^{M} k_{i,m} \cdot P_{m,t}^{sen}}{M} \tag{2}$$

Figure 3 reports an example of power profile for one of the hydro power plants involved in the experiment (Power plant #2 in Figure 1) estimated with the proposed approach. As better clarified in the following, the graph is obtained by applying the hypotheses of the case study E in Table 4.

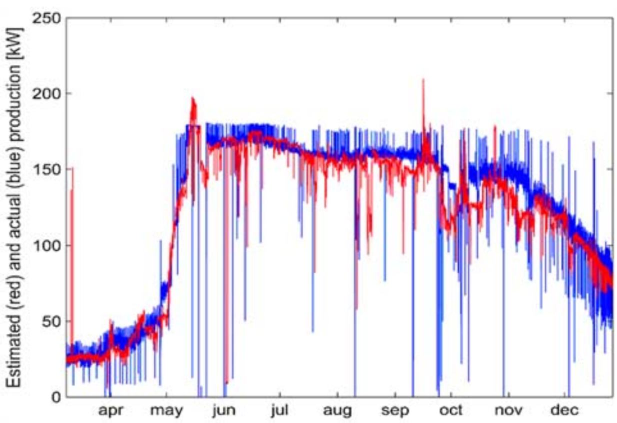

Figure 3. Example of power profile (estimated vs actual) for a hydro generator (power plant #2 – case study E of Table 4).

A proper evaluation of the accuracy of the estimations provided to the TSO in the OSS-2 experiment is a key aspect in order to define incentive schemes adequate to promote the deployment of the innovative service on national distribution networks.

In our study, we computed the error in terms of energy imbalances (i.e. the difference between the estimated production and the actual one) in a given quarter-hour, w.r.t. the rated power of the power plant involved in the analysis. For sake of simplicity, energy imbalances are evaluated just on the hydro source (as already mentioned, PV production is negligible).

Imbalances in a given quarter-hour are evaluated according to the following equation:

$$Err\% = \frac{100 \cdot \left| E - \sum_{j=1}^{J} P_j \cdot T \right|}{T \cdot J \cdot P_n} \tag{3}$$

Where:

- E is the quarter-hour energy measured by the tariff metering system on all the involved power plants;
- P_j is the total DG production estimated by the OSS-2 algorithm (P_t in eq. 1);
- T is the sampling time adopted (20 s);
- J is total number of samples in a quarter-hour (45);
- P_n is overall rated power of the power plants involved in the experiment.

Table 4 shows the error committed by the different strategies we investigated to estimate the DG power production. Strategies A and B provide to update the proportionality coefficients between the power exchanges of satellite and sentinel power plants ($k_{i,m}$ in eq. 2) on the basis on historical data collected once-a-month, while with strategies C, D and E a weekly update is carried out. As one can observe in Table 4, more frequent is the coefficient update more accurate is the estimation: the algorithm is in fact more effective in modelling the correlation between time series.

For the purposes of this analysis, it is useful to highlight how the overall power of sentinel plants is equal to about 11.5 MW: a significant amount compared to the total power of hydro generation downstream the PS Villeneuve (17.8 MW). This fact has obvious beneficial effects in limiting the estimation error committed by the estimation strategy.

We also tested different time gaps for the persistence model (time delay between the collection of the measurements by the metering system and their use in the estimation process). Considering, for example, to apply the strategy A, the power injections at the current instant are estimated using the data collected by tariff meters a week ago.

This approach is based on the assumption that the electricity generation from hydro source could be considered in the scenario under study (mountainous region, with river flows with seasonal trends) almost constant over a week. Reducing the time gap between the data acquisition and its use within the OSS-2 algorithm (e.g. 48 or 24 h) the performances of the model improve, reducing the estimation error (energy imbalances) up to 6.24% (obtained as mean of quarter-hour values on the whole period under analysis, March 2015 – December 2015).

Table 4. Performances of the strategies adopted for the OSS-2 service estimation.

Strategy	Update frequency of coeff. *k*	Persistence model time gap	Mean imbalances [%]
A	Monthly	Week	12.90
B	Monthly	48 h	17.67
C	Weekly	Week	8.51
D	Weekly	48 h	6.63
E	Weekly	24 h	6.24

Figure 4 shows an example of the energy imbalances obtained on the time interval considered by applying the algorithm proposed, using the estimation strategy E of Table 4.

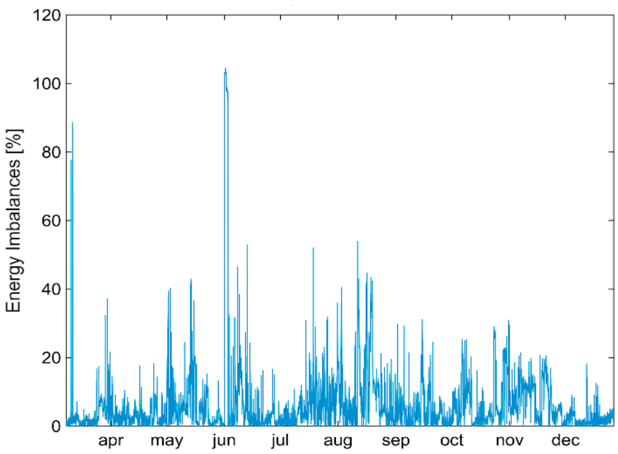

Figure 4. Energy imbalances trend obtained applying the estimation strategy E of Table 4.

Despite the low value of the main error confirms that the estimation method adopted well applies to the considered framework, the results in the graph highlights that it is very difficult to provide an accurate estimation of power profiles in any condition. This is an expected result: the limited number of points of measurement and the unpredictability of RES are the elements that most affect the prediction. However, we can conclude that, from the TSO point of view, in general it is more important the average performance of the prediction, instead of its instant-by-instant accuracy. This because estimation errors committed on the single PS tend usually to compensate on a wide geographical basis.

CONCLUSION

The paper presented the approach developed within the DEVAL Smart Grid project on the PS Villeneuve in order to satisfy the prescriptions of the Italian Energy Authority about the implementation of the OSS-2 service. The service aims to deliver to the TSO real-time data collected on distribution networks, more and more essential with the increasing of the share of generation from RES. The results obtained within the experiment will provide useful indications to AEEGSI in order to define a suitable incentive scheme to apply to DSOs and TSO. Moreover, they will support DEVAL in the deployment of the innovative function on the other Primary Substations of its distribution system.

ACKNOWLEDGMENTS

Authors gratefully acknowledge the support of DEVAL SpA.

REFERENCES

[1] Italian Energy Authority, Resolution 646/15/R/eel "Testo integrato della regolazione output-based dei servizi di distribuzione e misura dell'energia elettrica, per il periodo di regolazione 2016-2023", 22 December 2015.

[2] Italian Energy Authority, Resolution ARG/elt 39/10 "Procedura e criteri di selezione degli investimenti ammessi al trattamento incentivante di cui al comma 11.4 lettera d) dell'Allegato A alla deliberazione dell'Autorità per l'energia elettrica e il gas 29 dicembre 2007, n. 348/07", 25 March 2010.

[3] M. Delfanti, D. Falabretti, M. Fiori, M. Merlo, 2015, "Smart Grid on field application in the Italian framework: The A.S.SE.M. project", Electr. Power Syst. Res., vol. 120, 56-69.

[4] M. Delfanti, D. Falabretti, S. Mandelli, M. Merlo, M. Moncecchi, "Energy planning approach for an efficient distribution grid", CIRED Workshop 2016, Helsinki, 14-15 june 2016.