Possibility of enhancing classical weighted least squares State Estimation with linear PMU measurements

C. Bruno, C. Candia, L. Franchi, G. Giannuzzi, M. Pozzi, R. Zaottini, M. Zaramella

***Abstract*--The introduction of Phasor Measurement Unit (PMU) technology is generally expected to significantly improve existing State Estimation (SE) algorithms regarding accuracy, observability, convergence. Since PMUs measure current and voltage phasors, in case of complete observability of all the network with PMUs, the PMU based SE will be linear, and consequently the SE algorithm faster and more accurate.**

Indeed, the complete observability of the network just with PMUs is, for many Transmission System Operators (TSOs), quite far to be reached; therefore, it becomes necessary to find suitable strategies in order to use all data by PMUs, in the best way in the classical SE.

This paper deals with the possibility of using PMUs information in the classical real time least squares SE, with particular attention to the Italian case. Simulations on the complete 380/220 kV Italian transmission system are reported, in order to show the obtained benefits.

***Index Terms*-- Power system state estimation, Wide area measurement system, Phase measurement, Interconnected power systems.**

I. Introduction

After the bulk outage experienced in 2003, TERNA, the Italian TSO, has undertaken a number of different actions to improve system security. The most innovative one was the implementation of a Wide Area Measurements System (WAMS), equipped with Phasor Measurement Unit (PMU) devices, for monitoring and control purposes ([1]).

The introduction of PMU technology is expected to significantly improve existing State Estimation (SE) algorithms regarding accuracy, observability, convergence, bad data detection and topology estimation properties ([2]). The SE application is considered a fundamental piece of modern EMS systems. It is designed to run periodically to provide a consistent and reliable state of the system based on a group of measurements and other information that the EMS maintains. The SE is expected to deal with very large models and with a higher frequency rate of execution, imposing hard performance requirements on the currently serial process of executing network security related applications. The WAMS technology gives both the possibility of enhancing SE algorithm performances, and the opportunity of adding new control functions at control centers ([3], [4], [5], [6]).

The Italian WAMS system currently features up to 30 PMU devices and exchanges real-time data with two European partners, Slovenia and Switzerland. Each PMU provides voltage and current phasors at a rate of 50 samples per second (i.e. one phasor update at each cycle at fundamental frequency). Sampled data are continuously sent to the National Control Center (NCC) through a private communication network. As shown in Fig. 1, at the NCC collected measures are stored in the shared memory of a server machine where they are available for on-line processing purposes. The server machine holds the data about phasors in its memory for 15 minutes. Older measures are moved to a relational database where they are stored for the following 10 days, available for off-line processing algorithms.

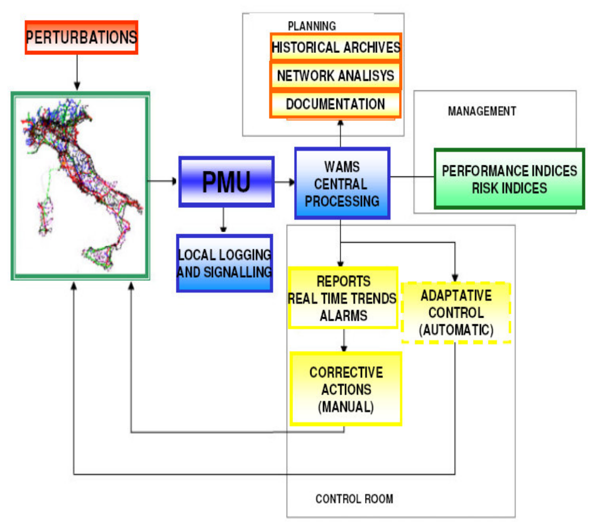

Fig. 1. Logical scheme for PMU data collection at the control center

II. PMU Positioning

Power station where PMU devices are installed have been carefully chosen during the first design stage. The choice of

C. Bruno, C. Candia, M. Pozzi and M. Zaramella are with CESI, Milan, Italy (e-mail: carlo.bruno@cesi.it).
L. Franchi, G. Giannuzzi, R. Zaottini are with TERNA, Rome, Italy (e-mail: giorgio.giannuzzi@terna.it).

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

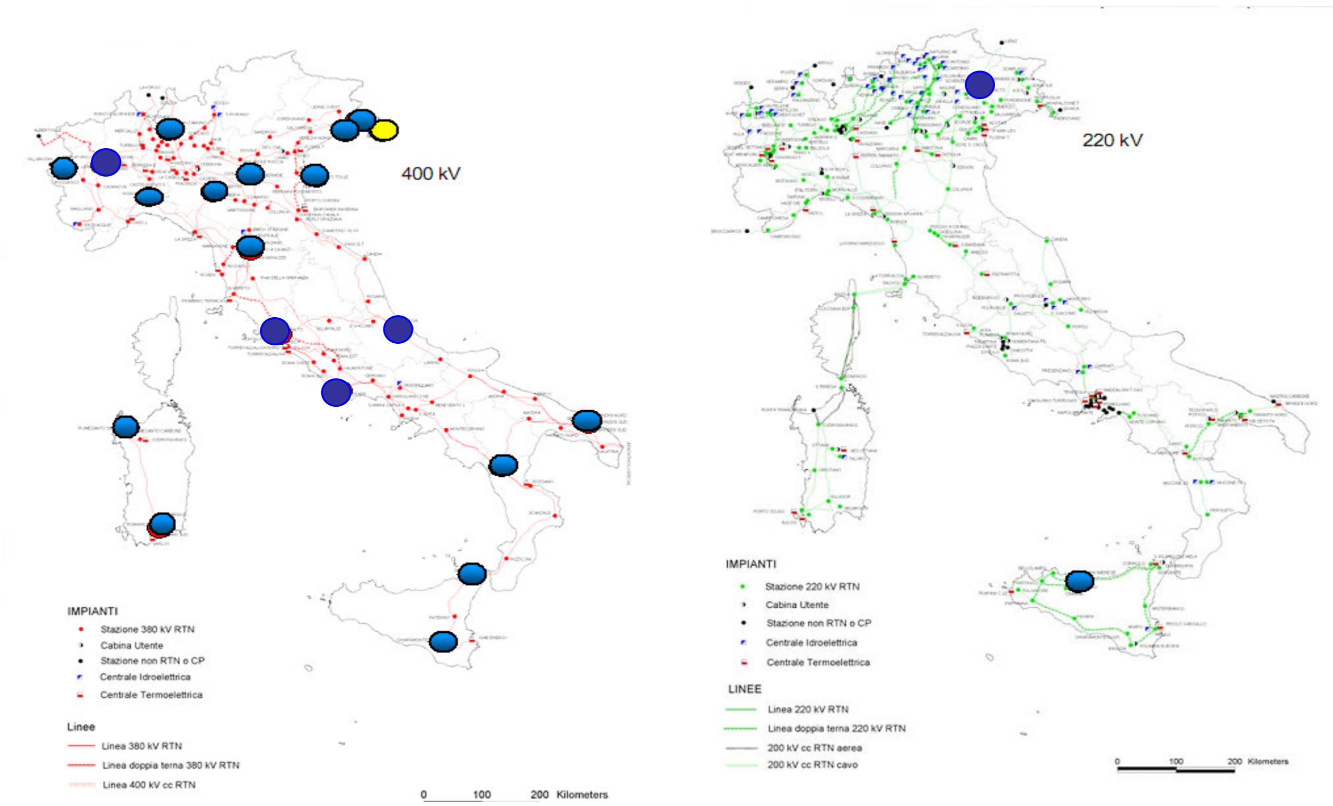

Fig. 2. PMUs currently in service in the Italian transmission network

the most suitable power station may depend on many factors: several studies ([7], [8], [9], [10]) have been carried out providing different criteria to select PMU locations. Each criterion was devoted to maximise a specific monitoring need, such as electromechanical oscillations identification, voltage instability prediction, event identification. Although SE purposes have not been considered during the PMU positioning, also an algorithm to find locations suitable for linear SE was developed ([9]). That algorithm advised which was the minimum PMU set necessary to solve the linear estimation problem, also under a certain degree of redundancy. Unfortunately, a complete linear SE algorithm, even without any PMU redundancy, would have required a number of measurement devices up to 25-30% of network buses (i.e. around 100 PMU devices for the Italian HV grid).

Power stations addressed by each positioning technique were finally merged together identifying the first 20 power stations were PMUs have been installed. Fig. 2 depicts the locations of the PMUs currently in service within the 380/220 kV Italian network.

III. REAL-TIME STATE ESTIMATION

Generally, the measurements that are transmitted in a traditional way to a NCC can not be all correct. For this reason, measurements may not be directly used to assess the state of the electrical system, but they must be processed by SE in order to detect, identify and eliminate bad data and determinate the correct state of the system.

Moreover, the traditional measurements are not all synchronous, and so, even if they are correct, they may be referred to different time frames, so introducing some uncertainties that must be corrected by SE. On the contrary, the PMUs are very accurate and reliable, and they can take measurements synchronously. Since PMUs measure current and voltage phasors, if all the network is observable by PMUs, the PMU based SE will be linear.

Notwithstanding the careful choice in the their positioning, in Italy PMU devices are still too few to make a linear real-time SE possible. The SE problem is solved on-line every 15 minutes with a Newton-Rhapson iterative Weighted Least Square (WLS) algorithm, where the inputs are the voltage magnitudes, the values of active and reactive power of the branches; no possibility to use current phasor measures as a direct input.

IV. OFF-LINE STATE ESTIMATION

A replica of the on-line SE algorithm is present in the CRESO tool ([11]) for off-line analyses: this tool is used and developed by TERNA in co-operation with CESI for a numerous set of off-line simulations.

The same input data used by the on-line SE are also available for off-line simulations: the off-line SE has been used to assess the possibility of enhancing the classical weighted least squares SE with PMU measurements. Recently the off-line SE algorithm has been enhanced with the possibility of using voltage phase as an input, and it is undergoing the test of the same enhancement also in the on-line SE.

Since the current phase measurement is not an input for neither the on-line nor the off-line SE, it would be necessary to change the WLS algorithm with the analytical description of the dependency of the current phases from the state variables, i.e. the nodal voltages. In any case, such a change in the WLS algorithm would lead to a new SE still not linear, so without the advantages of a SE entirely based on PMU measurements.

In order to use all the PMU measurements without changing the WLS algorithm, the procedure adopted consists in transferring the measure of the phase of the current to the second extreme voltage value (magnitude and angle) of the involved branch. In this way, the PMU information is not lost, with no need to change the classical SE algorithm.

For instance, if in Fig. 3 a PMU device measures the current phase at bus *i*, the input data to be used in the classical SE in substitution of the current phase is the voltage magnitude and phase at bus *k*. In this case, the relation used to convert the current phasor at bus *i* to a voltage phasor at bus *k* is the following:

$$\begin{aligned} V_{kd} &= V_{id} - R_{ik} I_{id} - R_{ik} Y_i V_{iq} + X_{ik} I_{iq} - X_{ik} Y_i V_{id} \\ V_{kq} &= V_{iq} - R_{ik} I_{iq} + R_{ik} Y_i V_{id} - X_{ik} I_{id} - X_{ik} Y_i V_{iq} \end{aligned} \qquad (1)$$

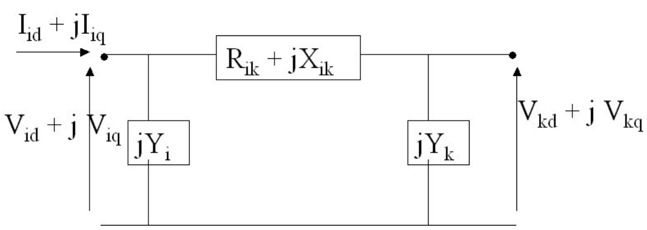

Fig. 3. Transfer of the current phase of bus *i* to the voltage value of bus *k* of a transmission line

Where:

$I_{id} + jI_{iq}$ [A] is the current phasor (measured by PMU) at bus *i* expressed in Cartesian coordinates;

$V_{id} + jV_{iq}$ [V] is the voltage phasor (measured by PMU) at bus *i* expressed in Cartesian coordinates;

$R_{ik} + jX_{ik}$ [Ω] is the value of the line impedance;

Y_i and Y_k [S] are the values of the line susceptances;

$V_{kd} + jV_{kq}$ is the searched voltage phasor at bus *k* expressed in Cartesian coordinates [V].

If the considered line is a tie-line with a foreign country, with a PMU device at the Italian side, the phase current is not transformed into a voltage measurement at the foreign side, but it is transformed into an active *P* and reactive *Q* power injection, according to:

$$P + jQ = V \cdot I^* = (V_d + jV_q) \cdot (I_d + jI_q)^* \qquad (2)$$

Fig. 4 represents a transformer of ratio *t*, where a PMU device measures the current phase at bus *i*. In this case, the

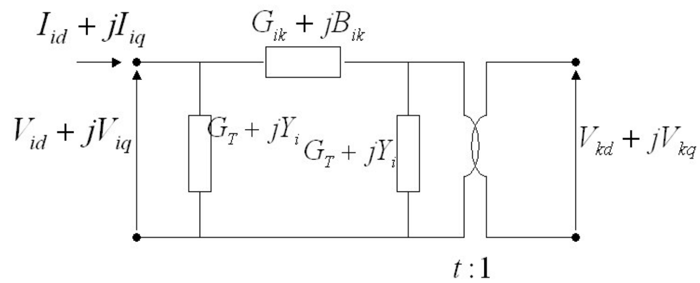

Fig. 4. Transfer of the current phase of bus *i* to the voltage value of bus *k* of a transformer of ratio *t*

equivalent voltage expression at bus *k* to be used in the classical SE instead of the current phase is the following:

$$\begin{aligned} V_{kd} &= \frac{V_{id} - R_{ik} I_{id} - R_{ik} Y_i V_{iq} + X_{ik} I_{iq} - X_{ik} Y_i V_{id}}{t} + \\ &+ \frac{R_{ik} G_T V_{id} - X_{ik} G_T V_{iq}}{t} \\ V_{kq} &= \frac{V_{iq} - R_{ik} I_{iq} + R_{ik} Y_i V_{id} - X_{ik} I_{id} - X_{ik} Y_i V_{iq}}{t} + \\ &+ \frac{R_{ik} G_T V_{iq} + X_{ik} G_T V_{id}}{t} \end{aligned} \qquad (3)$$

V. Simulations

The performance of the SE based on WLS algorithm with the addition of PMU samples has been tested on a representation of the Italian 380/220 kV transmission network in the off-line CRESO tool. The Italian 380-220 kV transmission system is roughly constituted by 1200 buses, and 1500 measurements.

The behavior of the classic SE algorithm in presence of PMU input data has been tested starting from snapshots of the electrical system given by the SCADA tele-measurements, and from the closest PMU samples stored in the WAMS database. The analysed snapshots represent the Italian system in some days of September 2008 and they have been chosen in order to represent different operating conditions (rush hours, night hours, …) of the transmission network.

For each snapshot, three different SE calculation have been performed, in order to compare the results:

- SE using only the SCADA tele-measurements as input;
- SE using as input the SCADA tele-measurements and the voltage phases directly given by PMUs;
- SE using as input the SCADA tele-measurements, the voltage phases directly given by PMUs and the voltage phases calculated through (1), (2) and (3) starting from the current phases given by PMUs.

The different snapshots have proved to have very similar behaviors, and for this reason the following results are shown for just one typical snapshot (referred to a rush hour of September 26th, 2008).

A. Comparison between SCADA and PMU data

SCADA snapshots have a rate of one sample per 15 minutes, while PMU data a rate of 50 samples per second. Starting from a given SCADA snapshot, the PMU data to be used for the comparison have been built with the average of all the PMU samples referred to the minute of the SCADA sample. The standard deviation for traditional SCADA voltage instruments is assumed to be equal to 5% of the rated voltage [kV], while for PMU devices is set to 1 kV. The standard deviation for the voltages calculated with (1), (2) and (3) is set to 2 kV. For each snapshot, data from SCADA and PMU have been compared, in order to highlight whether and where PMU and TM data are significantly different.

Fig. 5 is referred to a typical snapshot and it shows, for all high voltage buses with PMU devices, the percentage of them with difference among PMU and TM voltage measures smaller to a fixed value: over 85% of the PMU data are far less than 3kV to the corresponding tele-measurements.

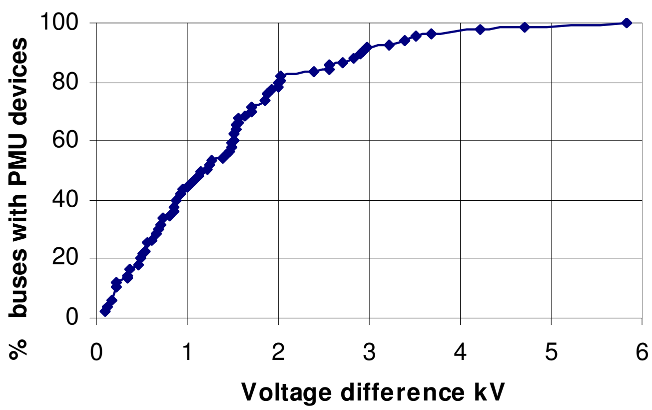

Fig. 5. Differences between PMU and TM measures

B. Comparison metrics

In general, SE metrics ([12]) may be referred to the accuracy (how close estimated value is to "true" value), performance (measure convergence properties and timing), robustness (ability to perform in the presence of bad measurement data), completeness (ability to provide information in parts of the network with little redundancy).

For the purposes of this paper, the convergence of the different SE calculations (with and without PMU data) has been compared on the basis of the following metrics:

- Average error of measure *x* (current, voltage, active or reactive power)

$$ERR(x) = \sqrt{\sum \left(\frac{out(x) - inp(x)}{\sigma} \right)^2 / Ms} \qquad (4)$$

where
inp(x) measured value
out(x) estimated value
σ standard deviation of measurement device
Ms number of available measure of *x* type

The average errors are computed after the SE convergence and they are linked to the difference of the estimated values from the given measures.

- Number of dubious estimated values: an estimated value is considered dubious if its difference with the correspondent measurement is greater than three times the standard deviation of the measurement device

- Convergence parameter *CP*

$$CP = \frac{ERR}{Ms - N} \qquad (5)$$

where
N number of independent variables (i.e. observable voltages)

$$ERR = \sum_{x=V,\vartheta,P,Q,I} Err(x)^2 \qquad (6)$$

C. SE with PMU voltage phasors

Table I presents the comparison, for a typical snapshot, between SE results with only SCADA measurements and with the addition of PMU voltage phase measurements. The convergence parameter is improved in case of SE with the addition of PMU input data. The voltage magnitudes measured through PMU devices are about the 10% of the total: because of the more accurate precision of a small number of measurements, there is an increase of the average error on voltage magnitudes, even if the total average error is kept constant.

Although the used SE algorithm accepts current magnitudes as input, no current values are present in SCADA data.

TABLE I
COMPARISON BETWEEN CLASSICAL SE AND SE WITH PMU VOLTAGE MEASURES

	SE with only TM measures		SE with also PMU measures	
Convergence parameter	7.08		7.05	
Degrees of freedom	2166		2204	
Average errors on:	value	N° measur.	value	N° measur.
V magnitude	0.31	422	0.37	427
V phase	0.00	0	0.11	33
P power	1.49	2081	1.50	2081
Q power	2.27	2077	2.28	2077
Current	0.00	0	0.00	0
Total	1.83	4580	1.83	4618
N° dubious measures	194		191	

D. SE with PMU voltage and current phasors

Table II presents the comparison, for the same snapshot of Table I, between SE results with only SCADA measurements and with the addition of PMU voltage phase measurements and current phase measurements transformed according to (1),

(2) and (3). Moreover, also the current magnitudes measured by PMU devices are considered as input data. The PMU input data introduce 152 new measured elements: in particular 81 voltage phases, 10 voltage magnitudes and 61 current magnitudes are available in addition to the SCADA input, while other SCADA voltage magnitudes are replaced by the PMU data. Moreover, values of active and reactive injections at some border load buses (like in Rondissone and Redipuglia stations) are replaced by PMU values.

TABLE II
COMPARISON BETWEEN CLASSICAL SE AND SE WITH PMU VOLTAGE AND CURRENT MEASURES

	SE with only TM measures		SE with also PMU measures	
Convergence parameter	7.08		6.82	
Degrees of freedom	2166		2318	
Average errors on:	value	N° measur.	value	N° measur.
V magnitude	0.31	422	0.41	432
V phase	0.00	0	0.36	81
P power	1.49	2081	1.51	2081
Q power	2.27	2077	2.28	2077
Current	0.00	0	1.59	61
Total	1.83	4580	1.83	4732
N° dubious measures	194		191	

With PMU data, the SE gives results with a better *CP* and a total average error unchanged, even if calculated on a greater number of measures. The limitation of the expected benefits are due to the fact that PMU devices are still few with respect to the entire extension of the Italian transmission network. Even if PMU devices are installed around the whole network (see Fig. 2.), they cover just only the 20% of the SCADA voltage tele-measurements.

E. Consideration about the measurement precision

Generally, the estimated values greatly depend on the weight which is given to the measured value, i.e. on the standard deviation assumed for the measurement instrument. Since their great accuracy and reliability, PMU devices have a standard deviation lower with respect to traditional devices: for this reason, SE algorithm tends to compute voltage values very close to PMU values where available, with the consequence to have greater differences with the measurement from traditional devices.

Fig. 6 reports, for all the buses with PMU devices, the difference between the calculated values by SE with and without PMU data. The percentage of the high voltage buses with difference around 5 kV is about 80%; the aggregation that can be seen between 3 and 5 kV is due to the buses on the 220kV voltage level.

VI. CONCLUSIONS

This paper has investigated the possibility of using PMU information in a classical weighted least square SE, with the

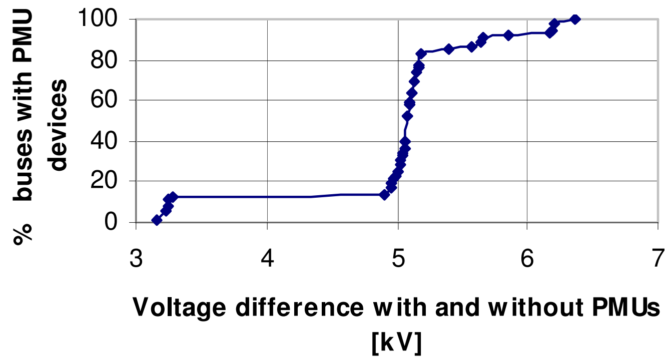

Fig. 6. Differences between estimated voltage magnitudes with and without PMU

purpose of enhancing the set of input data and of obtaining more accurate results. Simulations are reported for the entire Italian 380/220kV transmission network.

Even if the PMU devices are still few with respect to the Italian transmission network, the number of available phasorial measurements is increased by the described procedure, which consists in replacing the branch current phasors with voltage phasors at the second extreme.

The reported results show that the presence of PMU data gives benefits also to a classical WLS SE algorithm, in terms of convergence parameters and average errors. The tests have been made using directly the SCADA measures also used by the on-line SE algorithm; in this way, the off-line tool may be used as a validation environment for future upgrades of the on-line SE.

VII. REFERENCES

[1] G. Giannuzzi, M. Sforna, S. Cecere, D. Cirio, A. Danelli, and M. Pozzi, “Wide Area System Monitoring and Control: the Italian research and development”, presented at CIGRÉ 2006, Paris, paper C2-208

[2] R. Avila-Rosales, M. Rice, R. Lopez, L. Beard, T. Mathur, F. Galvan, V. Gupta, J. Lambert, J. Graffy, and M. Papic, “Impact of PMU technology in state estimation”, presented at CIGRÉ 2008, Paris, paper C2-111

[3] M. Shiroie and S.H. Hosseini, “Observability and estimation of transformer tap setting with minimal PMU placement”, presented at Power and Energy Society General Meeting, Pittsburgh, PA, 20-24 July 2008

[4] D.H. Wilson, K. Hay, R.F.B. Maclaren, D.J. Hawkins, A. Dunn, A.J. Middleton, A. Carter and W. Hung, “Control centre applications of integrated WAMS-based dynamics monitoring and energy management systems”, CIGRÉ 2008, Paris, paper C2-105

[5] G. Giannuzzi, C. Sabelli, R. Salvati, R. Zaottini, C. Candia, M. Cignatta, A. Danelli and M. Pozzi, “Voltage and angle stability monitoring: possible approaches in the framework of a wide area measurement system (WAMS)”, presented at CIGRÉ 2008, Paris, paper C2-114

[6] A. G. Phadke, “Synchronized phasor measurements–a historical overview”, Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES , vol. 1, 6-10 October 2002, pp. 476-479.

[7] R. F. Nuqui and A. G. Phadke, “Phasor measurement unit placement based on incomplete observability”, Power Engineering Society Summer Meeting, 2002 IEEE , vol. 2 , 21-25 July 2002, pp. 888-893.

[8] I. Kamwa and R. Grondin, “PMU configuration for system dynamic performance measurement in large multiarea power systems”, IEEE Transaction on Power Systems, Vol. 17, n. 2, May 2002, pp.385-394.

[9] C. Candia, D. Cirio, G. Giannuzzi, M. Pozzi and M. Sforna; "PMU Location and Parameter Identification Techniques for the Italian Wide-Area Measurement System", presented at WESC, Torino 2006

[10] G.B. Denegri, M. Invernizzi and F. Milano, “A security oriented approach to PMU positioning for advanced monitoring of a transmission grid”, International Conference on Power System Technology, 2002. Proceedings. Volume 2, Issue , 2002 Page(s): 798 - 803 vol.2

[11] C. Bruno, L. Campisano, M. Ciccotelli, L. Franchi, G. Giannuzzi, M. Salvetti, R. Zacheo and R. Zaottini, “CRESO and SICRE: Modern Environments for Power System Static and Dynamic Analysis”, presented at PowerGrid Europe, May 26-28, 2009, Cologne, Germany

[12] R. Avila-Rosales, J. Giri and R. Lopez, “Recent Experiences and trends with state estimation in very large networks”, presented at RTE-VT Workshop, Paris, 29-30 may 2006

VIII. Biographies

Carlo Bruno received his Doctor degree in Electrical Engineering (Energy Systems) in 1999 from the Politecnico di Torino. In the same year he joined CESI S.p.A. in Milan (Italy), where his area of interest includes power system analysis and optimization. Nowadays, he his with CESI Energy Division, where he is particularly involved in the definition and implementation of models for the safety and optimization of the electrical system.

Cristiano Candia received his Doctor degree in Electrical Engineering (Energy Systems) in 2004 from Università degli Studi di Genova. In February 2005 he joined CESI S.p.A. in Milan (Italy), where his area of interest includes power system security. Nowadays, he his with CESI Energy Division, where he is particularly involved in the development of algorithms for Dynamic Security Assessment and Wide Area Measurement System data analysis.

Luigi Franchi received his Doctor degree in Physical Science from the University of Milano in 1978. Until September 1996 he worked for ENEL Automatic Research Centre taking part in different electrical network studies, signals and models identification, Optimal active and reactive power software development, planning and development of Network Configuration and State Estimation software, planning and development of offline software packages for network analysis and for optimal day ahead production forecasting. From 1996 to 1999 he joined the former ENEL National Control Centre in Rome and then he moved to Italian ISO GRTN till 2005. Nowadays he his with the Italian TSO TERNA as expert in online and offline network analysis, software development and data definition/collecting for network description.

Giorgio Giannuzzi received his Doctor of Electric Engineering degree from the University of Rome in 1996. Until December 2000 he worked for ABB, where he was in charge of network studies, protection and control applications, with special reference to RTU apparatus and data engineering issues. Since 2001 he works for TERNA as expert in defense plans/systems, dynamic studies, protection, remote control and substation automation. From 2005 he is a member of a UCTE Expert Group on Power System Stability. Currently is responsible of the System Protection, Control and Monitoring Unit in the Dispatching Engineering Department.

Massimo Pozzi received his Doctor degree in Electronics (Automatic Systems), from the Polytechnic of Milan (Italy) in 1987. In 1989 he joined to the Automatica Research Center of ENEL, where he worked as Researcher in the control system and voltage regulation group. From 1997 he worked at ENEL Ricerca, as Senior Researcher in the framework of grid voltage control and power electronics applications. From 2000 to 2004 he worked at CESI as Product Leader, in the framework of grid supervision and control. Since 2005 he is responsible of T&D Networks Unit of CESI, within the Energy Division, Systems Technical Area. He is author of about 40 papers concerning power system regulation, stability monitoring, emergency control and restoration.

Roberto Zaottini gained a degree in Electrical Engineering at the University of Rome 'La Sapienza', in 1999. Before this, in 1995 he worked in EDP-Consultant in collaboration with AUTOSTRADE. In 2000 he worked for the telecommunications company, INFOTEL, in association with ERICSSON. Since 2001 he has been working at Italian TSO (TERNA: System Protection, Control and Monitoring Unit in the Dispatching Engineering Department), involved in static and dynamic studies, defense plans and restoration strategies. From 2005 he is a member of a UCTE Expert Group on Power System Stability.

Milena Zaramella received her Doctor degree in Mathematics in 1992 from Università degli Studi di Milano. In 1995 she joined to the Automatica Research Center of ENEL, where she worked as researcher in the control system and voltage regulation department. In this period her main interest was in the framework of grid voltage control (secondary and tertiary voltage regulation). Since 2000 she has been working at CESI, nowadays with Energy Division, where she is particularly involved in the definition and implementation of models for the optimization of the electrical system.