A Security Oriented Approach to PMU Positioning for Advanced Monitoring of a Transmission Grid

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Abstract -- **This paper presents four deterministic methods for positioning Phasor Measurement Units (PMU's) with the aim of linear static state estimation of power networks. First method searches multiple solutions with a minimum set of PMU's, by means of direct and indirect voltage and current measurements, whereas the second approach is a fast, "single shot" solution of the problem. Additional strategies are proposed for PMU positioning with a N-1 contingency criterion, for both line and measurement device losses. These methods lead to an optimised allocation for changing topology networks, such as post-fault transmission line configurations. The algorithms are applied on some IEEE test networks and HV Italian transmission grids. Results are compared with those obtained by heuristic methods proposed in the literature.**

Index Terms – **Linear static state estimation, phasor measurement units, minimum spanning tree, observability, security criteria, N-1 security criterion.**

I. INTRODUCTION

STATIC state estimation has been a prime issue of system management and has been deeply investigated and systematically developed since seventies [1]. The original approach was a non-linear one, since power injection and power flow measurements were involved. Nevertheless, the linear static estimation was well discussed well before direct (and fast) phasor measurements were available [2, 3, 4]. The results of these studies can be directly applied to the linear static estimation which is now possible by means of phasor measurement of voltages and currents in terms of both magnitude and phase [5]. With regard to past approaches, the use of PMU's leads to two major advantages, i.e. faster static state estimation, since the system to be solved is linear, and faster measurements.

On the other hand, the fast nature of PMU's makes them hardly compatible with other traditional measurement devices, and it is generally needed a PMU allocation as much as possible redundant (both for measurements reliability and network observability needs) and minimal (for economics constraints).

These issues were well addressed and approached by means of the simulated annealing algorithm, which is an efficient heuristic search technique [6]. Anyway, the simulated annealing approach is an expensive combinatorial method and slows down with a factorial law as the network node number increases. In our idea, some alternative and somewhat "faster" techniques can be useful for solving the positioning problem.

Furthermore, the simulated annealing provides only one solution per run, which may limit practical considerations on PMU positioning. As a matter of fact, some network nodes, even though topologically relevant for state estimation, may be insignificant with regard to system security and control, whereas other buses, crucial for the security assessment, can be neglected. To overcome this problem, the proposed techniques try to find more than one solution per time.

The first method is a spanning tree search of multiple solutions for the minimal PMU positioning issue. It is a sort of modified depth first approach, repeated many times, with a different starting PMU location. At this aim, it is assumed a general network configuration, where pure transit nodes can be present. A faster, "single shot" technique is also presented. It works better for networks including few or no transit buses, which appears a realistic hypothesis when HV transmission networks are examined, since each node has very likely a power absorption or injection at lower voltage levels. This method starts from radial or inter-tie lines and moves towards more interconnected areas, using both topological rules and circuit theory laws. Both the procedures can be split into three main steps: a first generation of minimum spanning tree sets, a search of alternative solutions within the sets previously determined and a final "filtering" for reducing the PMU number using the properties of possible pure transit nodes.

These methods lead to a minimal or almost minimal set of PMU locations, but assume a fixed grid and ideal PMU reliability. A loss of one transmission line or of one PMU may lead to a loss of the complete system observability. Thus, the minimal positioning does not appear the most promising procedure for using PMU measures in a real time monitoring and emergency control of the networks. At this aim, two additional positioning methods are proposed, which lead to minimal sets of PMU allocations which undergo to an N-1 contingency criterion. In this way, whichever loss of transmission line does not affect system observability. As a by-product of these positioning techniques, generally also the loss of one measurement device does not affect the observability of the whole network.

The paper is organized as follows. In Section II, the theory of linear static state estimation and the rules for PMU positioning are quickly presented. Sections III, IV and V describe the algorithms for minimal and N-1 contingency positioning criteria. In Section VI, the techniques are applied to some IEEE test cases, i.e. the 14-, 39-, 118-bus networks, to the 173-bus WSCC grid and to some 400 kV Italian grids, up to 129 buses. Results are compared with the ones obtained by means of the simulated annealing technique. Finally Section VII draws conclusions and briefly discusses prospective applications for future works.

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II. RULES FOR POSITIONING PMU'S

A complete treatise of state estimation is reported in [1], whereas [2] presents an exhaustive summary of topological properties of the Jacobian matrix of the system equations. For sake of clarity, in this section, some of the topics covered in these works will be briefly summarized.

With regard to the estimation of voltages and currents flows in a steady-state electric power system, it is common practice referring to the set of voltage phasors at network buses as the state vector of the system. Generally, available measurements relay on power flows or power injections, and voltage magnitudes. Without the use of PMU, it was quite uncommon to have some direct phase measurement. Thus, the nature of the static state estimation problem, was non-linear. Typical solution methods involved a Newton Raphson technique [1, 3, 4] for solving the algebraic problem:

$$z = h(x) + \varepsilon \qquad (1)$$

where:

- z : measurement vector of order m;
- x : state vector of order n;
- h : vector of the relationships between states and measurements;
- ε : measurement errors vector.

It has to be noted that generally $m > n$, thus leading to an over-determined problem. The linearization of (1) allows to define a Jacobian matrix, named state matrix, of the system:

$$\Delta z = \left.\frac{\partial h}{\partial x}\right|_{x_0} \Delta x + \varepsilon \qquad (2)$$

and several topological and analytical properties of the matrix of the linear system has been found and discussed [2]. Algebraic and topological properties of the state matrix can be expressed in term of "observability", which has been inherited by the automatic control theory. In this case, observability can be defined as the ability of reconstructing all states of the system. Two different aspects can be considered:

- *Algebraic observability*: it is defined as the property of the measurement configuration set to be correlated to a state matrix of full rank and well-conditioned;
- *Topological observability*: it is defined as the property of a measurement configuration set of branch currents, related to a spanning tree in the network, to be correlated to a state matrix of full rank (including at least one voltage measurement as reference phasor).

Using devices able to provide voltage and current phasors, allows to rewrite system (1) such that the link between state variables and measurements variables is linear:

$$z = Hx + \varepsilon \qquad (3)$$

where H is the state $m \times n$ matrix. Even in this case, the measurement number is generally greater of the number of states to be calculated, thus the solution of equation (3) is obtained by a least mean square technique, such as Moore-Penrose pseudo-inversion. However, with respect to (1), the solution of (3) is simpler since the state matrix H is constant.

It has to be noted that there can be many sets of PMU placements that lead to a complete observability of the network. Thus, the related problem to the use of PMU's for state estimation is to determine their best placement. This aim could be met accounting both for device and channel number, relating to the previously introduced observability definitions. When economic constraints are relevant, the best configuration consists in the use of a minimum number of PMU's as proposed in [6], but there can be other issues, such as to reach observability with an N-1 criterion. This can be intended as applied to both grid component and measurement device outages, as it will be discussed in the next section.

In this investigation, we assume the following hypotheses:

- Complete knowledge of transmission grid parameters;
- Double circuit lines meant as single equivalent ones, such as usually adopted in European grid security guidelines;
- Node and bus-bar system representing a single element, i.e. neglecting separate operation at a multiple bus-bar station;
- Complete acquisition of node voltage and incident branch currents by any placed PMU;
- Possible availability of grid breaker status.

As for the PMU placement rules, we basically follow the ones proposed in [6]. For sake of clarity, these rules are listed below, producing the spanning technique for grid observability:

Rule 1: Assign one voltage measurement to a bus where a PMU has been placed, including one current measurement to each branch connected to the bus itself (Fig. 1.a).
Rule 2: Assign one voltage pseudo-measurement to each node reached by another equipped with a PMU.
Rule 3: Assign one current pseudo-measurement to each branch connecting two buses where voltages are known (Fig. 1.b). This allows interconnecting observed zones.
Rule 4: Assign one current pseudo-measurement to each branch where current can be indirectly calculated by the Kirchhoff current law (Fig. 1.c). This rule applies when the current balance at one node is known, i.e. if the node has no power injections (pure transit node). In fact, if N-1 currents incident to the node are known, the last current can be computed by difference.

III. RECURSIVE SECURITY N ALGORITHM

This method is a sort of modified depth first approach, repeated as many times as the number of nodes. The procedure can be subdivided into three main steps: a first generation of minimum spanning tree sets, a search of multiple solutions starting from the sets previously found, and a final reduction of the PMU number by means of Rule 4.

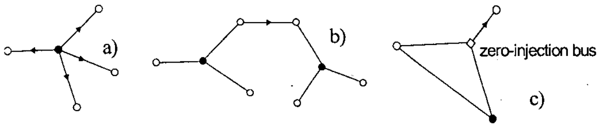

Fig. 1. Graphical explanation of PMU placement rules.

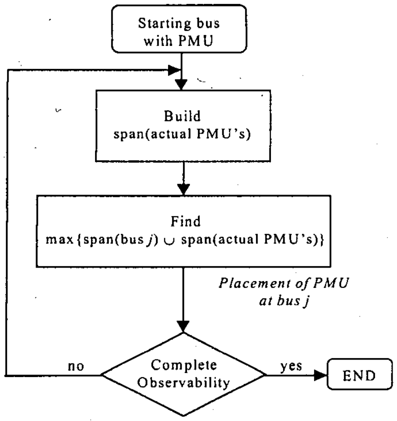

Fig. 2. Minimum spanning tree algorithm.

a) Generation of N minimum spanning trees

Fig. 2 depicts the flow chart of the minimum spanning tree generation algorithm. If *N* is the number of buses of the network, the algorithm is performed *N* times, thus using all the nodes as starting bus. After choosing the first PMU position, the remaining PMU's are recursively set in those nodes which are found both to be closer to the observability region, and to provide the higher number of observed buses. PMU's location ends when the entire network is observable, and thus a minimum spanning tree is built.

This modified depth first search does not guarantee an efficient positioning of PMU's, because the growing of the spanning tree is strongly conditioned by the first PMU choice. It has been found that a pre-ordering of the bus numbers can improve the results, leading to a higher number of sets with a minimum of PMU number. At this aim the symmetric reverse Cuthill-McKee permutation of the admittance matrix and of the network nodes, seems to lead to the best results.

b) Research of alternative patterns

The sets obtained by the preliminary spanning tree generation are subsequently elaborated for a further improvement, as depicted in Fig. 3. One at a time, each PMU of each set is replaced at the buses connected with the node where a PMU was originally set. This kind of "small signal" variation proved to provide some other equivalent minimum sets that may present practical advantages for the physical allocation of PMU's. Along with a search of alternative equivalent solutions, PMU's that were located on buses connected to the grid by single lines, are replaced on the neighbouring buses. This operation provides more direct current measurements, which should reduce the error variance.

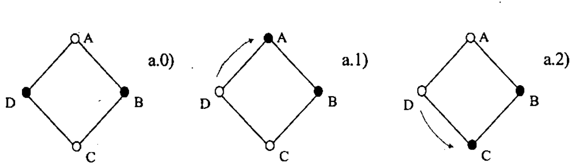

Fig. 3. Graphical representation of alternative pattern search. Solution a.0 is the one determined by the previous positioning algorithm.

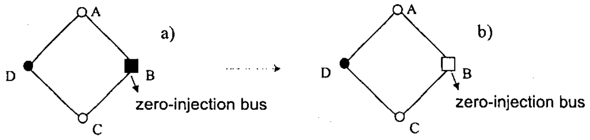

Fig. 4. Graphical representation of filtering in case of pure transit nodes.

c) Reducing PMU number in case of pure transit nodes

If no pure transit nodes are present in the network, the procedure ends at the previous step. Otherwise, a last filtering of the actual sets is performed, by means of eliminating one PMU at a time and verifying if the network remains observable, as depicted in Fig. 4. In order to save simulation time, this procedure proved to be effective when applied only to the sets which present the minimum number of PMU's.

IV. SINGLE SHOT SECURITY N ALGORITHM

A second method that attempts to allocate PMU's is depicted in Fig. 5. The algorithm is based only on topological rules, and provides a spanning tree by means of a "single-shot" technique. Each bus is associated with an *osservability index w* which is set to zero at the beginning of the procedure. Observability indexes are used as flags for possible measurement and/or pseudo-measurement of node voltage magnitudes and phase angles, according to the PMU's monitoring properties. First, the buses interconnected to only one other bus (*interconnection index h* = 1) are searched and the PMU is set on the latter buses. Whenever a PMU is set on a bus, at that bus the observability index is set to a high number (e.g. 100 in the flow chart), and the observability index is augmented by one at the neighbouring buses.

Then, an iterative search of nodes with the higher interconnection index is performed. For each interconnection degree, PMU's are placed at those buses which presents $w = 0$,

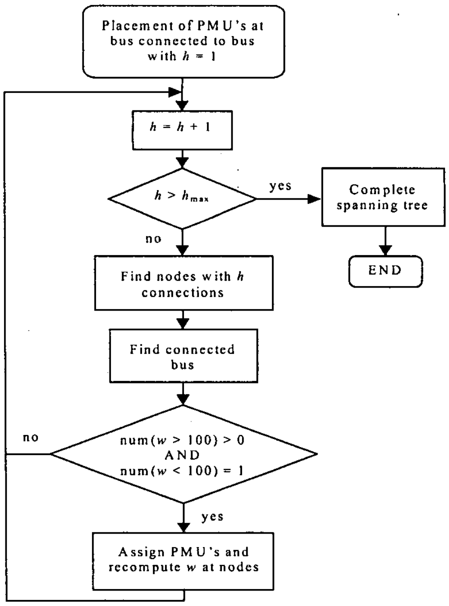

Fig. 5. Single shot algorithm for *N* security.

whose neighbouring buses present no PMU's and, among them, at least one has $w = 0$. These choices avoid considering multiple connected buses located in completely unobserved zones, and leads to ignore buses connected to areas already observed by previously installed PMU's. When the maximum degree of interconnection is reached, the algorithm ends, and a final placement of PMU's at those buses which are not still observable is completed. Finally, the PMU placement is revised by means of the techniques described in subsections III.b and III.c for searching alternative sets and filtering redundant PMU's in case of pure transit nodes.

This technique, even though highly inexpensive in comparison to the method described in Section III, presents the drawback of not providing very minimum PMU placements. This fact, anyway, leads to negligible extra number of PMU's as the network dimension increases.

V. RECURSIVE AND SINGLE SHOT SECURITY N-1 ALGORITHMS

The minimal PMU placement is based on the assumption of a fixed network and on the complete reliability of the measurement devices. Actually, an optimal PMU positioning should accomplish a complete state estimation also in case of changes and/or component outages in the transmission system. These changes can be summarised as follows:

- Modification of node injection, loss of generation or load shedding;
- Modification of branch admittance, up to zero in case of connection outage;
- Loss of a measurement device.

In case of power injection variations, the observability obtained by an N security criterion is not lost, and the event could be even detected by means of measurement variations. More, a total generation or load loss would provide an additional pure transit node, which could improve measurement redundancy. On the other hand, changes in network topology can lead to the loss of observability of some area of the network. This fact can be a severe drawback when state estimation is used for taking corrective actions, e.g. for transient or voltage stability assessment and control. Finally, when a PMU failure occurs, the complete grid observability is certainly lost, because of the construction of the minimum spanning tree, and the associated inaccuracy depends on the specific location of the device.

In order to overcome line outages, a rather simple criterion would be ensuring a redundancy of each voltage measurement, i.e. a node is said to be observable, with an N-1 security, if at least one of the two following conditions applies:

Rule 1: a PMU is placed at the node;

Rule 2: the node is connected at least to two nodes equipped with a PMU;

Rule 2 could be ignored if the bus is connected to the grid by a single line. In this case, one could accept that the bus were observed by only one PMU, since, if the connection is lost, there is no interest in measuring the voltage of the resulting islanded bus.

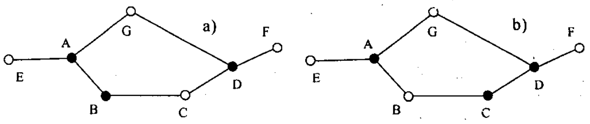

Fig. 6. PMU placement with an N-1 criterion

Fig. 6 shows a graphical representation of an N-1 security placement. For a minimal placement, positioning a PMU at nodes A and B would be enough for obtaining a complete spanning tree of the network. But, if line A-B (or C-D) is lost, the voltage of node B (or node C) can not be estimated. An additional PMU should be added either at B or C, to ensure an N-1 observability. Note that if lines A-E or D-F are lost, buses E or F are non longer observable, however the remaining network is still fully observable.

The previous rules 1 and 2 ensure a complete observability only in case of line losses, and are generally not sufficient for overcoming also PMU outages. However, in the most of the cases, an limited number of additional PMU's, either on some new buses or as redundant devices on buses already equipped by one PMU, can accomplish a complete N-1 security criterion. With regard to the simple example of Fig. 6, it is quite easy to see that adding two redundant PMU's at buses A and B would provide a complete N-1 security in case of one PMU outage.

The simple example of Fig. 6 suggests that a possible strategy for defining a spanning tree for an N-1 security, is to search the minimum PMU placement that realises a "one white-one black" pattern, i.e. alternatively one node with PMU and the following connected one without PMU.

Figs. 7 and 8 depict two possible algorithms for obtaining the N-1 security placement, by means of a modified depth first search and a single-shot method respectively. In the first method, the procedure is a slightly different version of the recursive technique described in Section III. The procedure starts from one bus and builds the spanning tree assigning a PMU at the closest bus connected to the buses already observed. The procedure is than repeated starting from each bus of the network and finally selecting the minimal PMU placement sets. As for the security N algorithm, also in this case a search of alternative patterns is performed for finding possible multiple solutions.

The second method, instead, is a variant of the algorithm described in Section IV, and differs only in the criterion used

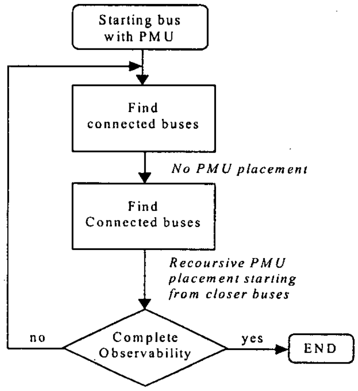

Fig. 7. Recursive algorithm for N-1 security PMU placement.

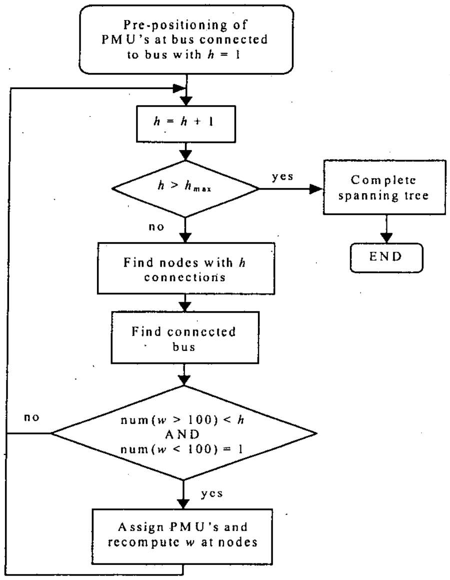

Fig. 8. Single shot algorithm for *N*-1 security.

to assign the PMU's at the buses. Since this method does not ensure necessarily that each bus is observed at least by two PMU's, a final fulfilment of the resulting spanning tree is needed. While being very fast, this procedure generally leads to slightly higher PMU numbers than the first method does.

For the N-1 security methods, it is not performed a search for alternative patterns as described in Section III.b, thus, the single shot method will provide only one solution in this case.

As a final remark, it has to be noted that in the construction of the spanning tree for the *N*-1 security, pure transit nodes are not considered, since rule 2 of the *N*-1 criterion does not allow estimating bus voltages by means of the Kirchhoff current law.

VI. RESULTS

The described methods are applied to some networks, i.e. the IEEE 14, 39, 118-bus test systems and the 173-bus WSCC network, for which minimal PMU placement sets obtained by the simulated annealing technique were already available [6]. Tests on some 400 kV Italian grids, i.e. the Southern Italy (22 buses), the Central Southern Italy (38 buses), the whole Italy (129 buses) and the simplified Italy (76 buses) networks, are also investigated for additional comparisons.

Results for all the methods, included the simulated annealing are shown in Table I. In each column, the end left quantities show the minimum number of PMU's that was determined by the respective algorithm in order to achieve the spanning tree of the network. Best results are from the simulated annealing and the recursive security *N* methods. The single shot method seems to provide generally slightly higher number of PMU's (about 10%). However, the simulated annealing becomes extremely lengthy as the number of nodes increases, since its computations increases with the factorial of this number. Furthermore, differences between the simulated annealing and the proposed methods are limited to few units and tend to be negligible for bigger networks. As an example, Fig. 9 depicts the whole 400 kV Italian grid with the indication of PMU positions as results from the recursive security *N* approach.

In Table I, italic numbers indicate how many different sets of PMU's were found, being the total number of PMU's the same. It has to be noted that also the annealing method could find more than one solution, but only by running the algorithm many times. Clearly this would imply a very expensive computational effort.

For the *N*-1 security methods, the quantities in square brackets indicate the additional PMU's required for accomplishing a complete observability also in case of measurement device outages. These results were obtained after the determinations of the PMU sets, taking out, one at a time, each PMU and determining if the network would remain still observable. When this is not the case, a new PMU can be placed either on the same bus or on a neighbouring bus. As it can be noted, these numbers are at least about the half of the PMU's needed for an *N*-1 security which covers only line losses. However, it has also to be remarked that in about the 50% of the cases, taking out one PMU does not affect the complete observability of the network, while in the 45% of the cases only one bus results not observable. Thus, when planning a PMU placement, it should be evaluated if the advantage of adopting a complete *N*-1 security criterion would pay back the installation costs.

Fig. 10 depicts again the Italian network and reports the PMU position determined by the recursive *N*-1 approach. Additional PMU's needed for overcoming measurement device outages, are also shown. For the choice of these PMU's, it has been chosen to apply a redundancy to the existing ones rather than set PMU's on different buses. As it can be seen, buses connected to the network by a single line are lost when the line is out of service.

Summarising, the *N* security criteria lead to PMU sets about the 25-30% of the total bus numbers, while in case of *N*-1 security, the percentage is about the 50%, which may increase up to the 75% when considering also PMU outages.

TABLE I.
COMPARISON AMONG PMU PLACEMENT METHODS

Grid Name	**Nodes**	**Simulated Annealing**	**Recursive Security N**		**Single shot Security N**		**Recursive Security N-1**		**Single shot Security N-1**
			# PMU	**# Set**	**# PMU**	**# Set**	**# PMU**	**# Set**	
IEEE 14-bus	14	3	3	*1*	4	*2*	8 [+0]	*10*	8 [+2]
IEEE 39-bus (New England)	39	8	9	*2*	10	*2*	18 [+4]	*4*	18 [+4]
IEEE 118-busi	118	29	31	*6*	34	*1*	63 [+10]	*6*	72 [+10]
WSCC	173	34	34	*5*	38	*6*	84 [+26]	*3*	87 [+28]
Southern Italy	22	6	6	*4*	6	*1*	9 [+4]	*1*	10 [+4]
Central Southern Italy	38	10	10	*2*	11	*5*	17 [+8]	*1*	18 [+6]
Italy	129	35	36	*3*	38	*1*	64 [+31]	*1*	67 [+28]
Simplified Italy	76	19	19	*11*	20	*1*	38 [+20]	*9*	39 [+15]

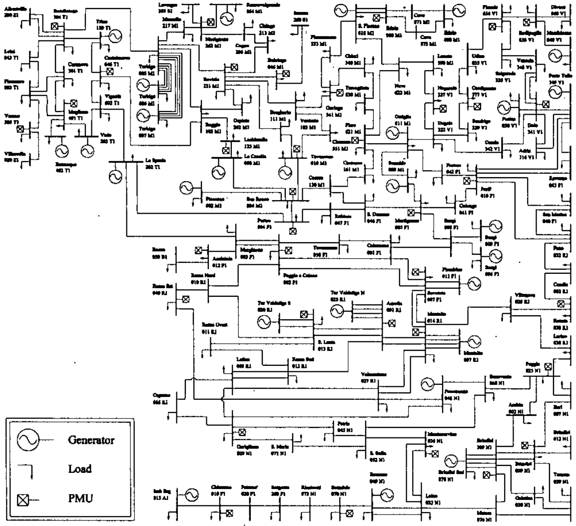

Fig. 9. PMU positioning set, as obtained by the recursive security *N* method, for the 400 kV 129-bus Italian grid.

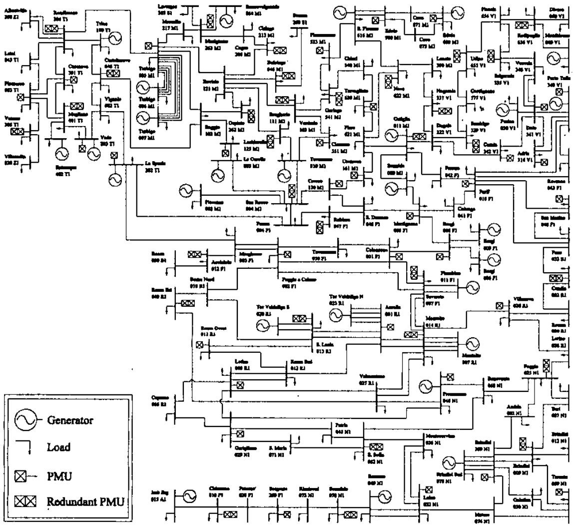

Fig. 10. PMU positioning set, as obtained by the recursive security *N*-1 method, for the 400 kV 129-bus Italian grid.

VII. CONCLUSIONS

This paper proposes four different methods for determining the minimum placement of Phasor Measurement Units with the aim of obtaining the linear static state estimation of transmission grids. First two presented techniques try to achieve in a faster but still efficient way (with respect to the methods used in the literature) the problem of positioning the minimum number of PMU's, being the network topology fixed. The latter two procedures explore the minimal placement with respect of a *N*-1 security criterion. At this regard, both line losses and measurement device outages are taken in account. Furthermore, all the techniques generally attempt to determine multiple solution at a time.

In our idea, estimation of phasors could be useful in transient conditions only if the measurement system is independent of network changes and/or component failures.

Furthermore, PMU ability of continuously providing voltage and current phasors makes these components a challenging opportunity for system monitoring and control. This characteristic appears particularly stimulating for applications in transmission grids like the Italian one which are currently facing electricity market and deregulation.

Future work will concentrate on PMU utilization and address the implementation of criteria for handling different transient phenomena, using selective remedial actions evaluated through PMU measured and calculated quantities.

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IX. BIOGRAPHIES

Gio Battista Denegri was born in Rocca Grimalda, Italy, on October 9, 1946. He received the degree in electrical engineering from the University of Genoa, Italy, in 1970. Until 1972, he worked as an R&D Engineer at ELSAG Corporation. He joined the Electrical Engineering Department of the University of Genoa in 1973, where he is now Full Professor of Electrical Machines and Drives. At present, his research interests are modelling of electrical machines, drive dynamics and computer analysis of electric energy systems. He is also a member of the Italian Electrical Society (AEI).

Marco Invernizzi was born in Genoa, Italy, on December 27, 1959. He received the degree in electrical engineering from the local University in 1984, and a PhD in power systems in 1989. Since 1990, he has been working at the Electrical Engineering Department of the University of Genoa, where he is now Associate Professor of Power System Analysis. He is presently engaged in modelling, simulation, management and control of electric energy system in deregulated environments and power system stability assessment.

Federico Milano received in March 1999 the Electrical Engineering degree from the University of Genoa, Italy. Since March 2000, he has been attending the Ph.D course at the Electrical Engineering Department, University of Genoa, in the field of power system control and operation. He is currently working at the Electrical and Computer Engineering Department of the University of Waterloo, Canada, as a visiting scholar. His research interests are voltage stability and electricity market.

Maurizio Fiorina was born in Genoa, Italy, on March 27, 1938. He received the degree in Electronic Engineering from the University of Padova, Italy, in 1964. After a year of academic experience he joined the Automatica Research Centre of the ENEL Research and Development Department, where was engaged in coding of measurement and control information and abatement of noise from power plants. Since 2001 he is with CESI S.p.A., where he is presently engaged in power system dynamic security assessment and control.

Pierangelo Scarpellini was born in Bergamo, Italy, on August 9, 1945. He graduated in electrical engineering from the Politecnico of Milan, Italy, in 1973. He joined ENEL in 1974. He gained his experience in power system dynamic modelling, incidents reconstruction, control actions in normal and emergency conditions. Since July 1994 he has been chief of Electric Power System Dynamics Division at Automatica Research Center of ENEL Research and Development Department. In 1999, the same department joint ventured with CESI S.p.A., becoming Electric Power System Business Unit. After retiring in December 2001, he presently acts as a private consultant.