BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LVII (LXI), Fasc. 1, 2011
Secţia
ELECTROTEHNICĂ. ENERGETICĂ. ELECTRONICĂ

ENHANCED REI EQUIVALENTS WITH PHASOR MEASUREMENTS

BY

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Received: June 22, 2010
Accepted for publication: December 4, 2010

Abstract. This paper presents a new static network equivalence technique which takes into consideration the influence of events that occur in the reduced part of the system, by using based on voltage phasor measurements taken by phasor measurement units installed in the external system. Study cases prove that using real-time measurements provided by PMUs installed in the external system can considerably improve the results of the simulations, compared to traditional REI equivalents, for the considered operating conditions in the internal power system.

Key words: static network equivalent; REI equivalent; phasor measurements.

1. Introduction

At present, static network equivalents are often used as an efficient tool in on-line applications such as contingency analysis or in off-line planning and development studies, for large or very large power systems, whose on-line or off-line analysis and control often requires a heavy computational burden. The first type of equivalent network was proposed by J.B. W a r d (1949) in the mid of the 20-th century. In the late 1970s, P. D i m o (1982) developed the REI

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type equivalents, which are still considered as one of the most efficient network reduction techniques. A REI equivalent replaces the external power system by one or more fictitious REI buses, in which are grouped one or more different external buses.

The traditional grouping methods for the REI equivalent use a single REI bus for the entire external system or two buses, a PQ bus for all the PQ buses and a PV bus for all the PV buses from the external system. But other grouping methods are available in the literature. For instance, in (Singh et al., 1981), the external buses are not grouped by their type, but by sensitivity indices computed amongst pairs of buses, with respect to each PV bus from the system, when bus loads vary by a defined quantity.

At present, GPS synchronized phasor measurement (SPM) data can be used as supplementary input data in the traditional system models (Nuqui, 2001). Phasor measurement units (PMUs) are installed at the buses of transmission substations to measure bus voltage and branch current phasors in the substation and on the outgoing branches. The synchronization *via* GPS enables the PMUs to provide high-accuracy results, with a sampling rate of up to 1 μs (Electric Power Group, 2006).

This paper proposes a new REI model which, beside the traditional REI buses, uses as individual REI buses, nodes from the external power system continuously monitored by PMUs.

2. Static System Equivalents

The structure of the experimental model of the HEV is presented in Fig.1. The internal combustion engine (ICE) is a diesel F8Q with 1.9 L capacity. The coupling with the motor/generator system is assured by a clutch, a gearbox and a belt transmission.

The system equivalents divide the original system into an internal system (IPS) and an external system (EPS), separated by a small number of boundary buses (BB). The IPS is the observed portion of interest and its structure and characteristics remain unchanged. The EPS is replaced by an equivalent one connected at the boundary buses.

The REI equivalent replaces the EPS by one or more fictitious REI buses, that group together different external buses into equivalent buses using a fictitious, linear and lossless network called the *Zero Power Balance Network* (ZPBN). The procedure of building the ZPBN consists in the following steps:

1. Choose the number of REI buses.
2. Associate each bus from the EPS to a REI bus.
3. For each group "EPS buses – REI bus", a fictitious ground bus is introduced, which is connected in a radial manner to the REI bus and the reduced EPS buses.
4. The radial networks obtained in the previous step are linearized by replacing bus power injections, S_p, with current injection, $I_{p,0}$, computed using bus voltages, U_p, from the reference operating conditions.

5. The admittances from the ZPBN are computed with relation

$$\underline{y}_{p,0} = \frac{\underline{S}_p^*}{U_p^2}, \quad \underline{y}_{R,0} = \frac{\underline{S}_R^*}{U_R^2}, \tag{1}$$

where R is the REI bus, p is one of the buses to be eliminated, and 0 is the fictitious ground bus. The power injection from the REI bus, S_R , is the sum of apparent power injections from the buses associated to the REI bus. REI bus voltage, U_R , is computed from the power, S_R , and equivalent current injections, I_p,

After building all ZPBNs associated to the equivalent REI buses, the network is reduced applying a traditional Gauss reduction technique, which aims to bring the nodal equation of the modified system,

$$[\underline{Y}]\cdot[\underline{U}]=[\underline{I}], \tag{2}$$

to a partially triangular form. When all the lower diagonal elements from the columns of matrix [$\underline{Y}$], corresponding to the external and REI buses, have been annulled, the submatrix corresponding to the internal and boundary buses is the admittance matrix of the equivalent network (Eremia, 2006).

The first two steps of this procedure have a major influence over the accuracy of the REI equivalent. For real-time analysis purposes the grouping procedure is a question which should take into account its influence over the accuracy of the IPS operating conditions computed using the REI equivalent for different contingencies that can occur in the system.

3. Synchronized Phasor Measurements

The SPM technology has emerged in the latest years as one of the most promising advances in the field of real-time monitoring and control of electric

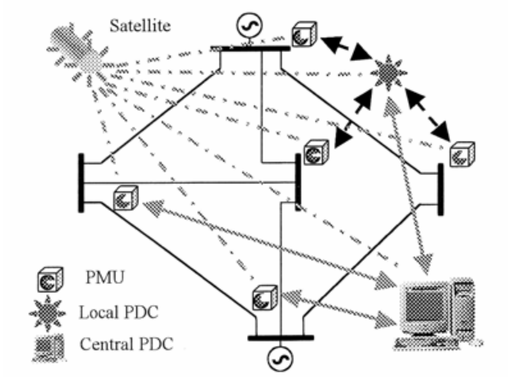

Fig. 1 – The structure of a monitoring system based on SPM (PMU –Phasor Measurement Unit, PDC – Phasor Data Concentrator).

power systems (Electric Power Group, 2006). PMUs are high-performance digital devices that can measure the AC waveforms at the system's buses and convert them in real time, using specific algorithms, into voltage and current phasors, synchronized using the GPS technology. Several interconnected PMU devices installed in the system can provide real-time "snapshots" of the state of the power system (s. Fig. 1), which can be used in monitoring and analysis system, in applications like phase angle, voltage stability and overload monitoring and control, state estimation, congestion management, system restoration and adaptive protection.

4. Enhanced REI Equivalents with SPM

In the traditional model of a REI equivalent, contingencies occurring in the EPS can be represented only through a complete recalculation of the REI equivalent, after the contingency has occurred.

The new approach assumes that, by installing one or more PMUs in certain buses from the EPS and by continuously monitoring the voltage phasors in these buses, it is possible to model the reaction of the external system to different operating conditions for both the IPS and the EPS. In this paper, only important contingencies in the EPS, such as loss of a large generating unit or switching off of a highly loaded transmission line, have been considered.

The method performances were assessed using error indices for the complex power flows and voltage phasors only in the IPS

$$dS = \frac{1}{\mathrm{NC} \cdot \mathrm{NB}} \cdot \sum_{k=1}^{\mathrm{NC}} \sum_{b=1}^{\mathrm{NB}} \left| \underline{S}_b^{\mathrm{ref}} - \underline{S}_b^k \right|, \quad [\mathrm{MVA}], \tag{3}$$

$$dU = \frac{1}{\mathrm{NC} \cdot \mathrm{NN}} \cdot \sum_{k=1}^{\mathrm{NC}} \sum_{n=1}^{\mathrm{NN}} \frac{\left| \underline{U}_n^{\mathrm{ref}} - \underline{U}_n^k \right|}{\left| \underline{U}_n^{\mathrm{ref}} \right|} \cdot 100, \quad [\%], \tag{4}$$

where: NC is the number of contingencies considered in the system; NN – the number of buses from the IPS; NB – the number of branches from the IPS; $\underline{U}_n^{\mathrm{ref}}$ – the voltage phasor in bus *n*, for the reference conditions; $\underline{U}_n^k$ – the voltage phasor in bus *n*, for the contingency *k*; $\underline{S}_b^{\mathrm{ref}}$ – the complex power flow on branch *b* for the reference conditions; $\underline{S}_b^k$ – the complex power flow on branch *b* for contingency *k*.

5. Case Study

Numerical simulations with the proposed method were performed on the IEEE 14-bus test system (http://www.cnr-cme.ro…, 2008). The IPS, BBs and EPS were chosen as follows: buses #1, #2 and #3 for the IPS, buses #4 and #5 for the BB, and buses #6 to #14 for the EPS. Since all buses in the original EPS are PQ buses with small load values, the contingency was simulated in bus #13, converted to a PV bus with an active and reactive generation of 100 MW and 30 MVAr, respectively.

The results are presented in Tables 1 and 2, for the parameters *dS* and *dU*. When a PMU-bus is considered in the EPS, the best results are obtained when the PMU is located in the same bus where the contingency is considered (bus#13), where the average values of both *dU* and *dS* are the smallest. However,

Table 1
Power Flow Errors, [MVA], *in the IPS, Computed with Eq. (2), for Different Levels of Nodal Contingency (Loss of Generation Unit in Bus #13) and Different Location of 1 PMU, Compared with the Reference Case (w/o PMU)*

Contingency level, [%]	Reference, w/o PMU	1 PMU in bus:						
		13	12	14	10	11	6	9
–100	29.110	2.199	6.921	4.208	4.635	4.175	4.277	2.237
–90	26.000	2.048	6.283	4.020	2.377	2.982	3.683	2.261
–80	22.939	1.884	6.136	3.944	1.387	2.445	3.171	2.446
–70	19.928	1.617	5.713	3.836	1.148	2.135	2.892	2.485
–60	16.968	1.434	5.251	3.708	1.383	2.182	2.561	2.502
–50	14.053	1.236	4.680	3.461	1.620	2.246	2.205	2.419
–40	11.182	1.021	4.000	3.088	1.763	2.188	1.823	2.230
–30	8.355	0.790	3.204	2.580	1.743	1.980	1.412	1.920
–20	5.570	0.544	2.284	1.923	1.508	1.591	0.973	1.474
–10	2.831	0.282	1.226	1.090	0.996	0.976	0.500	0.866
Average		1.305	4.570	3.186	1.856	2.290	2.350	2.084
Configuration rank		1	7	6	2	4	5	3

Table 2
Voltage Errors, [%], *in the IPS, Computed with Eq. (3), for Different Levels of Nodal Contingency (Loss of Generation Unit in Bus #13) and Different Location of 1 PMU, Compared with the Reference Case (w/o PMU)*

Contingency level, [%]	Reference, w/o PMU	1 PMU in bus:						
		13	12	14	10	11	6	9
–100	0.417	0.225	0.627	0.320	0.462	0.191	0.352	0.170
–90	0.363	0.208	0.606	0.355	0.190	0.157	0.322	0.199
–80	0.313	0.189	0.579	0.360	0.067	0.129	0.289	0.218
–70	0.256	0.161	0.528	0.346	0.047	0.157	0.259	0.221
–60	0.215	0.142	0.477	0.331	0.063	0.176	0.224	0.222
–50	0.176	0.122	0.417	0.305	0.097	0.182	0.188	0.214
–40	0.140	0.100	0.350	0.268	0.116	0.175	0.151	0.196
–30	0.108	0.077	0.275	0.221	0.119	0.155	0.114	0.167
–20	0.078	0.053	0.193	0.162	0.104	0.121	0.076	0.127
–10	0.050	0.027	0.101	0.091	0.069	0.073	0.038	0.074
Average		0.130	0.415	0.276	0.133	0.152	0.201	0.181
Configuration rank		1	7	6	2	3	5	4
Fig. 3 legend		——	— · · —	= = = = =	═══	·······	— · —	– – –

a good approximation accuracy was obtained for all cases when one PMU is installed in the EPS and Tables 1 and 2 show that the values of *dU* and *dS* are similar, hence using one or another of these performance indices is optional.

This can also be seen by comparing the average, *dS* and *dU*, values, computed for all 10 contingency levels simulated for bus #13. The best PMU placement ranking is almost identical for the two deviation types (power flows and voltages), as shown by values from "Configuration rank" lines in Tables 1 and 2. The only difference in hierarchy is for buses #11 and #9, which shift positions.

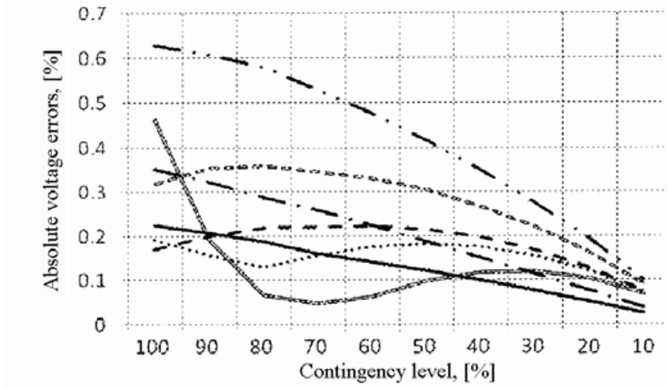

Fig. 2 – Voltage errors in the IPS, for different levels of bus contingency and different location of 1 PMU (for legend, see Table 2).

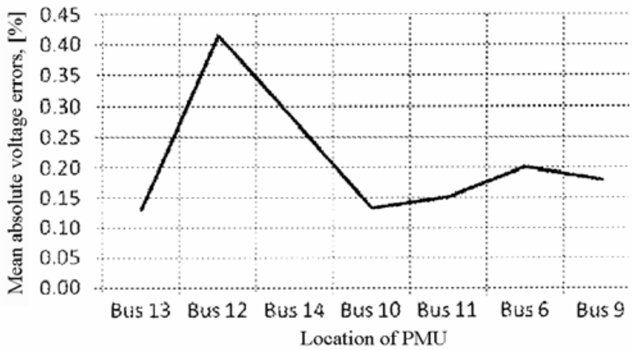

Fig. 3 – Average voltage errors in the IPS, for different levels of bus contingency and different location of 1 PMU.

Data from Tables 1 and 2 show a significant difference between the first and the last bus in the hierarchy and also that, even if from the standpoint of the *dU* values, the placement of a PMU in buses #13 or #10 has almost the same effect (*dU* = 0.130 *vs*. *dU* = 0.133), the two placement scenarios are clearly differentiated by the values of the power flow deviation (*dS* = 1.305 for bus #13 *vs*. *dS* = 1.856 for bus #10).

In Fig. 2, the variation of the *dU* values from Table 2 is represented, while in Fig. 3 the variation of the average *dU* value for the considered levels of contingency is plotted, value which is used to identify the optimal placement of the PMU. Higher values of the voltage deviations occur because, for some PMU buses and for some levels of contingency, the voltage deviations are worse than for the case when PMUs are not used.

If two or more PMU are installed on the buses of the EPS, their effect on the results produced by the REI equivalent, in the terms of branch power flow deviations, *dS*, are greatly influenced by their relative position in the network, sometimes the power deviations being higher than in the case when no PMU is used. This behavior could be explained by the fact that the original REI equivalent was computed using different operating conditions in the EPS, which can no more be reproduced in real-time conditions when voltages from PMU-buses are fixed. This behavior is not present if a single PMU is used, when the power deviations are always smaller.

Based on the above case study it can be concluded that the use of real-time measurements provided by PMUs installed in the EPS can considerably improve the simulation results produced by traditional REI equivalents. However, if measurement data from two or more PMUs installed in the EPS are to be used, then PMUs location must be optimized for better results. As a general rule, the use of a single PMU in the EPS is sufficient and its best location corresponds to the bus the most exposed to outages, which has a high value of generation or load.

6. Conclusions

A new static network equivalence technique that take into consideration the influence of changes occurring in the external network is proposed, which is based on voltage phasors measurements located in the external systems. The method was developed around the REI equivalent paradigm, but in principle it can be used with any other equivalence technique. Numerical simulations have shown that real-time measurements provided by PMUs installed on the buses of the external system can considerably improve simulation results produced by traditional REI equivalents.

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ÎMBUNĂTĂŢIREA CONFIGURAŢIEI ECHIVALENŢILOR DE REŢEA DE TIP REI CU AJUTORUL MĂSURĂRILOR FAZORIALE SINCRONIZATE

(Rezumat)

Se propune o nouă medotă de determinare a configuraţiei echivalenţilor de reţea, care ţine cont de influenţa schimbărilor ce au loc în partea echivalată a sistemului, cu ajutorul măsurătorilor furnizate de dispozitive pentru măsurări fazoriale sincronizate instalate în noduri situate în sistemul extern. Studiile de caz au demonstrat că utilizarea măsurătorilor preluate în sistem, în timp real, de către dispozitivele pentru măsurări fazoriale pot îmbunătăţi considerabil rezultatele echivalenţilor REI clasici, pentru un regim de funcţionare considerat al reţelei.