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NEW MODELS FOR POWER SYSTEMS STATE ESTIMATION

Ovidiu IVANOV, Mihai GAVRILAŞ, Bogdan VICOL[1]

The operation and real time analysis of large power systems require fast and reliable tools for state estimation. Classic state estimation algorithms can take advantage of the recent technology advances, and use more reliable measurement sources such as the SPM/PMU technology. This paper presents a new approach for improving the results of the standard WLS estimator based on PMU measurements, and distributed estimation algorithm for evaluating the power flows on interconnection lines.

Keywords: state estimation, phasor measurement units, distributed estimation.

1. Introduction

The static state estimation plays a major role in real time operation and control of power systems. In network control centres, the state of the system is assessed and the desired level of operation safety is maintained using the Energy Management System (EMS), built on the state estimator or state estimation (SE).

The state estimation algorithm assesses the state of the system at a given moment, using an available set of measurements provided by dedicated metering and communication systems. The system's state is fully described by a set of state variables, conveniently chosen, usually the bus voltage magnitude and angle phasors. After the state variables are computed by the SE algorithm, other variables can be derived: branch power flows, branch currents, losses etc.

The classic SE algorithms use as measurements branch power flows, bus power injections and bus voltage magnitudes, complemented by other information such as transformer tap settings and breakers' open/closed state. A drawback is, however, is the lack of measuring precision and absence of information regarding neighbouring systems. The recent advances in phasor measurement technology now allow including in the SE input measurement set of voltage angle values.

Recent approaches on this subject are the use of synchrophasor measurements (SPM) and of distributed estimation (DE) algorithms. [1] proposes a new state estimation model in which, if a voltage PMU measurement is present, its value is never recomputed and it is considered as the estimated value. This assumption means fewer calculations and has positive effects on convergence and

[1] Technical University "Gh. Asachi", Iaşi, Romania

speed. [2] describes in detail the positive effects of using PMU measurements in state estimation and the use of PMU measurements as state variables. For the distributed estimation problem, [3] uses a hierarchical wide area systems state estimation, which allows a coordination between estimations obtained from the constituent subsystems. [4], on the other hand, proposes a DE algorithm which splits the global estimation into local estimations. The local estimators are running on independent machines, communicating through a system partitioning module.

This paper presents two new approaches for the static state estimation problem, based on the SPM/PMU technology. The first method describes a hybrid SCADA/PMU solution for an isolated system, while the second uses DE as a tool for assessing the overloading of interconnection branches.

2. State Estimators

The state estimator, which is the core of the EMS systems in command centres, computes estimated values which have not been measured, based on data read across the system. Basically, the state estimation is an optimization problem, which can be solved by means of numerical algorithms [5, 6, 7]. Most SE algorithms used today are developed from computing the solution of over determined non linear equations systems solved using the weighted least square (WLS) model [6], which linearizes the equations:

$$[z] = h([x]) + [e] \tag{1}$$

where $[z] = (z_1, z_2, ..., z_m)$ is the measurements' vector, $[x] = (x_1, x_2, ..., x_n)$ is the state variables' vector, $h_1, h_2, ..., h_m$ are non-linear functions which express the measured quantities as a function of the state variables, and $[e] = (e_1, e_2, ..., e_m)$ is the measurements' error vector, which follows a normal distribution. The state variables vector $[x]$ contains the $U_1, U_2, ..., U_n$ voltage magnitudes and $\theta_1, \theta_2, ..., \theta_n$ voltage angles from the *n* buses in the system. θ_1, the voltage angle of bus #1, is considered 0, as reference for the entire system.

The WLS method minimizes the following goal function:

$$J([x]) = \sum_{i=1}^{m} [z_i - h_i([x])]^2 \cdot w_i = [[z] - h([x])]^T \cdot [W] \cdot [[z] - h([x])] \tag{2}$$

in which $[W]$ is a diagonal matrix of w_i weights associated to each z_i measurement. The best choice for the $[W]$ matrix is its inverse $[R]$ where each σ_i^2 diagonal element is the standard error deviation for the z_i measurement. An interesting aspect is the weighing procedure used by (2), which can be considered as a measure of the trust associated with each measurement.

2. 1. State estimation using classic and PMU measurements

A current trend in state estimation analysis is using data originating from synchrophasor measurements provided by PMUs as auxiliary inputs for classic SE algorithms [1, 4]. Using PMU measurements, new SE models can be developed. In such cases, the mathematical model of the estimation problem becomes linear and easily solved [8]. However, using state estimators based exclusively on PMU measurements can be expensive, especially for large power systems. In such circumstances, a hybrid solution, which uses both classic and PMU measurements, must be considered.

If PMU measurements are to be added to the input data set, it is necessary to install a PMU in the reference bus of the system. Its phase angle measurement θ_0 will be used as reference for computing the other voltage angles in the system ($\theta_i' = \theta_i - \theta_0$). Then, other PMUs should be installed in the system, and their readings used as measurements, with voltage angles computed using the reference angle. The new estimation model must include two more equations (for voltage magnitude and for voltage angle) for each PMU bus. This is the only update required by the classic WLS SE model when using PMU measurements.

The estimation accuracy can be improved by conveniently selecting the PMU buses. For this purpose, the method presented in [9] can be used.

2.2. Distributed state estimation

For large power systems shared by several operators, each system operator can run independent state estimations for local analysis purposes, but estimation at global level requires an integrated approach. For local estimations, classic SE algorithms are used, in which phasor measurements are not mandatory.

The main difference between the various DE algorithms is the way each computes the global estimation, based on the local estimations. Most approaches found in literature [10, 11] use a third/party central entity which coordinates the results of the local estimations in order to improve their results, especially in critical locations in the system, such as interconnection branches.

The DE method used in this paper does not use a central coordinator. The correlation of the local estimation is achieved using PMU readings from the reference buses of the local subsystems. The method uses the following steps:

1. Divide the whole system into local systems
2. Run local estimations in each subsystem. The boundary buses of each subsystem are considered, but the interconnection branches are not included in the estimation.
3. One of the local subsystems, called subsequently studied or internal system, is extended to include the interconnection branches with its

neighbours. The system at the other side of will provide only the estimated voltages and power injections for its corresponding boundary buses

4. The estimation is performed again on the internal system, in order to estimate the power flows on the interconnection branches.

3. Case studies

The SE models were applied on a benchmark system taken from the Romanian 400-220 kV transmission grid (see Table 1), which covers the geographical area of Moldova and Dobrogea regions. The limits of separation are the Gura Ialomitei and Pelicanu buses to the Muntenia region and Gutinas and Gheorghieni buses towards the Transilvania region. Here, equivalent loads are used to simulate the remainder of the system.

This specific configuration was chosen so that the whole system could be divided in 2 subsystems or areas linked by two interconnection lines, in order to be used by the distributed state estimation algorithm presented in Section 2. For the WLS-PMU state estimation algorithm, the entire system is used. The interconnection lines are Focsani - Barbosi and Gutinas – Smardan.

As reference and measurements source for the state estimation algorithms, the results of the Newton-Raphson load flow algorithm performed on the entire system were used. To take into account the measurement errors, the load flow results were altered by adding a ±3% random noise.

3.1. State estimation with phasor measurements results

Prior studies carried out by the authors on the IEEE 14, 30, and 57 bus test systems [9, 12] concluded that adding voltage phasor measurements provided by PMUs to the measurement set used by a WLS SE algorithm improves the estimation precision. Even more, the improvement is greater when the PMUs are placed in the system using an optimization procedure.

Using this approach for the benchmark system considered above, in a first stage, the optimal placement in the system of one PMU was determined. The algorithm detailed in [9] identified bus Dumbrava as the optimal bus.

A comparison between the results of the WLS estimation algorithm when the PMU measurement is not available, and the estimation which uses this measurement, together with the deviation from the reference load flow results, measured in percent, is given in Tables 2 and 3. Table 2 shows the estimated bus voltage magnitudes and angles in the two instances, while Table 3 lists the line active and reactive power flows.

These tables show an obvious improvement of the estimation results when using a PMU measurement. The few high error values in branch power flows estimation occur on branches with low power flow. For instance, on the Smardan – Lacu Sarat branch, the 278% estimation error for reactive power is for an actual reactive power flow of less than 10 MVAr, when there is no congestion risk.

Table 1

System data for the test network

Buses:27		Transmission lines:31		Generators	Transformers
400 kV	220 kV	400 kV	220 kV	1	4
15	12	20	11		

Table 2

State estimation results (bus voltage magnitudes and angles) and estimation errors

Nod	classic WLS estimation		errors [%]		WLS+PMU estimation		errors [%]	
	U [kV]	θ [deg]	ε_U	ε_θ	U [kV]	θ [deg]	ε_U	ε_θ
Gutinas 400 kV	413.884	0.000	1.11	0.00	412.117	0.000	0.67	0.00
Gutinas 220 kV	237.699	-1.023	1.11	1.22	236.672	-1.032	0.68	0.35
BB 400 kV	414.756	-0.179	1.10	2.93	412.993	-0.181	0.67	2.06
BB 220 kV	235.913	2.725	0.94	0.92	235.066	2.741	0.58	1.52
Barbosi 220 kV	233.256	1.904	0.94	3.16	232.382	1.914	0.56	3.74
Cernavoda 400 kV	412.902	8.114	0.90	1.50	411.487	8.168	0.56	0.84
C-ta Nord 400 kV	413.209	5.891	0.93	1.60	411.783	5.930	0.59	0.95
Dumbrava 220 kV	233.692	-1.867	1.28	2.05	232.365	-1.885	0.70	1.11
Filesti 220 kV	233.618	2.078	0.93	2.80	232.749	2.090	0.56	3.38
Focsani 220 kV	234.804	-0.753	1.05	6.34	233.836	-0.761	0.64	5.35
Gheorghieni 220 kV	230.671	-2.378	1.34	2.55	229.271	-2.402	0.72	1.57
G. Ialomitei 400 kV	412.324	6.194	0.92	1.34	410.894	6.235	0.57	0.70
G. Ialomitei 400 kV	412.323	6.204	0.92	1.35	410.893	6.244	0.57	0.70
Iasi 220 kV	234.567	-4.410	0.90	2.75	234.036	-4.443	0.67	3.51
Isaccea 400 kV	413.891	3.893	0.93	1.59	412.487	3.918	0.58	0.96
Lacu Sarat 220 kV	235.905	2.723	0.94	0.82	235.056	2.739	0.58	1.41
Lacu Sarat 400 kV	412.139	3.912	0.94	0.59	410.689	3.936	0.59	0.03
Medgidia Sud 400	412.446	7.860	0.91	1.41	411.028	7.912	0.56	0.76
Munteni 220 kV	234.901	-3.880	1.13	2.10	233.880	-3.915	0.69	1.23
Pelicanu 400 kV	409.543	5.340	0.94	0.85	408.098	5.374	0.58	0.21
Smardan 400	411.702	3.356	0.84	1.40	410.288	3.377	0.49	0.77
Stejaru 220 kV	232.013	-2.121	1.32	2.26	230.629	-2.143	0.72	1.28
Suceava 220 kV	233.550	-4.608	0.90	2.51	233.017	-4.642	0.67	3.25
Suceava 400 kV	402.981	-1.777	1.11	2.34	401.259	-1.794	0.68	1.41
Tariverde 400 kV	413.186	5.558	0.94	1.50	411.767	5.594	0.59	0.85
Tulcea Vest 400 kV	413.788	4.450	0.93	1.52	412.381	4.479	0.58	0.88
Vulcanesti 400 kV	417.037	4.028	1.23	3.72	415.775	4.054	0.92	3.10
		max err	1.34	6.34			0.92	5.35
		min err	0.84	0.00			0.49	0.00
		avg err	1.02	2.20			0.64	1.75

Table 3

State estimation results (branch power flows) and estimation errors

Branch	classic WLS estimation		errors [%]		WLS+PMU estimation		errors [%]	
	P [MW]	Q [MVAr]	ε_P	ε_Q	P [MW]	Q [MVAr]	ε_P	ε_Q
Filesti - Barbosi	62.69	18.57	0.42	6.03	62.71	18.93	0.46	4.21
Cernavoda - Cta Nord	292.46	-52.50	0.51	5.87	292.43	-52.10	0.50	5.06
Cernavoda - Medg. Sud	123.35	9.62	2.24	7.34	123.35	9.72	2.24	6.39
Cta Nord - Tariverde	43.78	-21.81	1.42	1.89	43.76	-21.81	1.46	1.88
Cta Nord - Tulcea Vest	94.30	-49.49	0.01	0.91	94.28	-49.38	0.00	0.69
Dumbrava - Stejaru	21.01	21.64	1.72	4.30	21.16	22.42	1.04	0.84
Focsani - Barbosi	-65.71	16.24	1.84	13.91	-65.76	15.67	1.91	9.91
Gheorghieni - Stejaru	-10.33	-13.90	1.81	1.64	-10.33	-13.90	1.81	1.64
G Ialom. - Cernavoda	-281.91	3.62	0.21	9.73	-281.91	3.53	0.21	6.86
G Ialom. - Cernavoda	-270.49	1.53	0.21	20.07	-270.49	1.46	0.21	14.30
G Ialom. - G Ialom.	-272.22	3.64	0.43	175.88	-272.24	3.21	0.43	143.56
Gutinas - BB	26.40	-37.86	0.84	1.07	26.40	-37.72	0.83	0.71
Gutinas - Dumbrava	25.01	14.01	1.74	11.75	25.31	15.78	0.56	0.62
Gutinas - Focsani	-3.92	13.48	31.72	11.06	-3.97	13.06	33.30	7.64
Gutinas - Iasi	41.87	-11.02	6.63	8.30	41.63	-12.36	6.02	2.83
Gutinas - Munteni	57.56	-3.70	0.18	2.60	57.56	-3.70	0.18	2.57
Gutinas - Smardan	-216.23	11.07	0.05	518.55	-216.28	8.12	0.07	353.75
Gutinas - Suceava	78.34	-4.64	0.02	1.28	78.35	-4.64	0.03	1.28
Iasi - Munteni	-16.30	-5.18	73.11	121.41	-15.52	-1.61	64.85	31.32
Iasi - Suceava	4.58	-4.49	0.51	2.23	4.58	-4.45	0.52	1.36
Isaccea - Vulcanesti	-15.01	-74.81	30.15	28.96	-15.16	-76.14	29.46	31.26
Lacu Sarat - BB	-0.63	-1.12	0.00	19.27	-0.64	-1.20	0.00	13.36
Lacu Sarat - Filesti	56.80	32.56	2.53	4.54	56.80	32.80	2.53	5.33
Lacu Sarat - G Ialom.	-282.49	11.06	0.83	7.29	-282.51	10.90	0.82	5.68
Lacu Sarat - Isaccea	-0.96	-50.99	84.24	0.82	-1.11	-51.57	81.86	1.97
Pelicanu - Cernavoda	-272.12	-38.81	0.92	0.38	-272.12	-38.81	0.92	0.38
Smardan - Lacu Sarat	-144.83	-9.42	7.54	310.41	-144.52	-8.00	7.31	278.78
Smardan - Isaccea	-185.23	-95.00	0.03	1.37	-185.23	-94.96	0.03	1.34
Smardan - Isaccea	-185.23	-95.00	0.03	1.37	-185.23	-94.96	0.03	1.34
Tulcea V - Isaccea	171.61	-29.69	0.82	1.68	171.61	-29.73	0.82	1.79
Tulcea V - Tariverde	-144.41	8.05	0.47	10.15	-144.39	8.37	0.46	6.63
Gutinas TR1	111.46	32.79	0.98	2.88	111.48	32.83	1.00	2.74
Gutinas TR2	111.46	32.79	0.98	2.88	111.48	32.83	1.00	2.74
Lacu Sarat TR1	153.29	60.34	1.84	3.18	153.29	60.47	1.84	2.97
Lacu Sarat TR2	153.29	60.34	1.84	3.18	153.29	60.47	1.84	2.97
		max err	84.24	518.55			81.86	353.75
		min err	0.01	0.38			0.00	0.38
		avg err	7.61	38.38			7.25	27.75

3.2. Distributed state estimation results

The distributed state estimation model described in Section 2 was applied on the benchmark system divided in two interconnected areas as defined above.

The subsystem that covers the Moldova region was considered as internal system. The Dobrogea area was considered only with the measurements estimated locally in that subsystem for the boundary buses Smardan and Barbosi, as the primary goal of the distributed estimation is to determine the power flows on the interconnection lines.

The estimation results, as bus voltage magnitudes and angles and branch power flows, together with the percent error computed between the estimated and the reference load flow results, are presented in Tables 4 and 5.

While the estimation results for the entire system are comparable with the previous case, the estimation of active and reactive power flows on the interconnection branches is good. It should be mentioned that the 48% ε_Q error on the Gutinas – Smardan branch is for an actual Q flow of less than 2 MVArs, and the measurements received from the second subsystem for the global estimation are estimated values.

Table 4 and 5

Distributed state estimation results (bus voltage magnitudes and angles, branch power flows) and estimation errors

Bus	U [kV]	θ [deg]	ε_U	ε_θ
Gutinas	409.661	0.000	0.07	0.00
Gutinas	235.209	-1.042	0.05	0.59
BB	410.546	-0.184	0.08	0.11
Dumbrava	230.869	-1.900	0.05	0.33
Focsani	232.473	-0.772	0.05	4.00
Gheorghieni	227.787	-2.423	0.07	0.73
Iasi	232.706	-4.290	0.10	0.04
Munteni	232.562	-4.001	0.12	0.96
Stejaru	229.115	-2.162	0.06	0.40
Suceava	231.695	-4.496	0.10	0.02
Suceava	398.676	-1.850	0.03	1.68
Barbosi	231.123	1.889	0.02	2.36
Smardan	408.494	3.418	0.05	0.43
		max err.	0.12	4.00
		min err.	0.02	0.00
		avg err.	0.07	1.12

Branch	P [MW]	Q [MVAr]	ε_P	ε_Q
Dumbrava - Stejaru	12.36	22.61	0.73	0.30
Gheorghieni - Stejaru	-10.52	-13.68	2.92	0.95
Gutinas - BB	26.62	-37.46	0.02	0.52
Gutinas - Dumbrava	25.45	15.88	1.07	0.30
Gutinas - Focsani	-2.98	12.11	33.78	2.01
Gutinas - Iasi	39.27	-12.02	0.22	2.63
Gutinas - Munteni	57.67	-3.60	1.01	22.74
Gutinas - Suceava	78.32	-4.58	1.78	20.16
Iasi - Munteni	-9.41	-2.34	11.57	24.53
Iasi - Suceava	4.60	-4.39	1.33	0.90
Gutinas TR1	110.37	33.73	0.72	0.24
Gutinas TR2	110.37	33.73	0.72	0.24
Focsani - Barbosi	**-64.53**	**14.23**	**0.37**	**3.91**
Gutinas - Smardan	**-216.13**	**1.78**	**0.53**	**48.77**
		max err.	33.78	48.77
		min err.	0.02	0.24
		avg err.	4.05	9.16

4. Conclusions

This paper presents two new approaches for the static state estimation problem, based on the SPM/PMU technology. The first method describes a hybrid SCADA/PMU solution for an isolated system, while the second uses DE as a tool for assessing the overloading of interconnection branches. Both methods were tested on the Romanian 400/220 kV transmission system, with adequate results.

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