AN IMPLEMENTATION OF TWO-STAGE HYBRID STATE ESTIMATION WITH LIMITED NUMBER OF PMU

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Abstract

State estimation is an important tool for power system supervision and control and the related applications. Based on the redundant measurements taken in the network, state estimation provides the most likely state of the power system. Conventional measurements were collected by the SCADA system and the measurement chain did not allow measurement synchronization. A disadvantage is that due to the communications delay measurements inherit an additional error and simultaneously voltage angle measurements are not available. With the advent of phasor measurement units (PMU's), synchronized phasor measurements are possible. It allows to enhance the performance of state estimators. Expecting the gradual penetration of PMUs this paper discusses possible hybrid SE methods, integrating partial PMU measurements into the classical SE systems.

1 Introduction

The secure operation of power system must be ensured by the Control Center operators, and a primary need of the operators is reliable information. Establishment of Supervisory Control And Data Acquisition (SCADA) systems was an important achievement. However, data obtained from SCADA is not always correct containing e.g. measurement or circuit breaker status errors. Moreover, not all the measurements are available in the Control Center.

These concerns were first recognized by Fred Schweppe, who proposed and investigated State Estimation (SE) methods [13] likely state of power system from possibly limited raw measurement data.

Nowadays, state estimation is an important and a widely used control center tool [9] , [2], [6]. It forms the basis for a number of applications, such as:

- System observation;
- Security assessment;
- Optimal power flow;
- Transmission system usage billing.

The performance and reliability of SE thus have economic implications [3] and are getting a great attention.

The next technological breakthrough has came with the development of phasor measurement units (PMUs) by Phadke [10] and the revolutionary formulation of the linear state estimation with PMU measurements. Due to the large dimensionality and thus the long time constants for the exchange of the power systems equipment, the question of gradual implementation of the phasor measurements units becomes essential.

State estimation accuracy and reliability could benefit also from the partial availability of PMUs [4]. The control center algorithms has to be modified correspondingly. Two groups of methods can be distinguished:

- direct implementation in SE;
- non-invasive implementation, decoupling PMU measurements from classical SE.

Direct methods would have an advantage of improving the classical state estimator overall performance, first of all, robustness. While the second group of methods contributes mostly to accuracy and bad data detection capability. It does not require to change the main SCADA software package and can be easily implemented [8].

This paper studies non-invasive PMU implementation methods, evaluates the advantages brought by those on theoretical examples supported by the simulations, as well as discusses an implementation and tests of the proposed algorithm on an analogue power system model [14], [15].

2 Theoretical Background

2.1 Classical State Estimation procedure

Let us first review the classical state estimation procedure. Majority of the state estimators (SE) nowadays rely on the bus-branch transmission system model obtained by the topology processor from the detailed model including switches and those states. We assume model parameters including phase shifting transformers and the high voltage dc line to be known. The model and the measured values are passed to the state estimator that involves the mapping of the states x to measurements z with measurement errors e:

$$\begin{aligned} z_i - h_i(x) &= e \\ &\text{with } x = (\theta_1\theta_2\ldots\theta_n U_1\ldots U_n)^T, \end{aligned} \tag{1}$$

where $h(x)$, known as the *measurement function*, relates the system state vector x containing voltage angles and magnitudes to the measured quantities - voltage magnitudes V_i, bus power injections P_i, Q_i and branch power flows P_{ij}, Q_{ij}.

The measurement errors are assumed stochastic with a Gaussian probability distribution, zero mathematical expectation values and mutual independence. Therefore, equation (1) can be solved giving the most likely values of the state variables based on the given measurements.

Since the measurement error expectation values have been assumed to be zero, the most likely estimation in this case corresponds to the states minimizing the following objective function [13], [2]:

$$J = \sum_{i=1}^{m} W_{ii} \left[z_i - h_i(x) \right]^2 . \tag{2}$$

The weights W_{ii} are inversely proportional to the measurement error variance $W_{ii} = 1/\sigma_i^2$.

The minimum of J can be determined using the first order optimality conditions $g(x) = \frac{\partial J(x)}{\partial x} = 0$. Expanding $g(x)$ in Taylor series around $x^{(k)}$ and neglecting higher order terms, we obtain:

$$g(x^{(k)}) + \frac{\partial g(x^{(k)})}{\partial x}(x - x^{(k)}) = 0. \tag{3}$$

Thus, the Gauss-Newton iterative solution scheme [5] can be employed to find x satisfying Equation (3).

Rearrangements lead to so called *Normal equations*:

$$G(x^k)\Delta x^{(k+1)} = H^T(x^{(k)}) \cdot W \cdot [z - h(x^{(k)})], \tag{4}$$

where

- $G(x) = \frac{\partial^2 J(x)}{\partial x^2} = H^T(x) \cdot W \cdot H(x)$ is the gain matrix
- $\Delta x^{(k+1)}$ is the update of the solution at iteration k, so $x^{(k+1)} = x^{(k)} + \Delta x^{(k+1)}$
- $H(x) = \frac{\partial h(x)}{\partial x}$ is the measurement Jacobian.

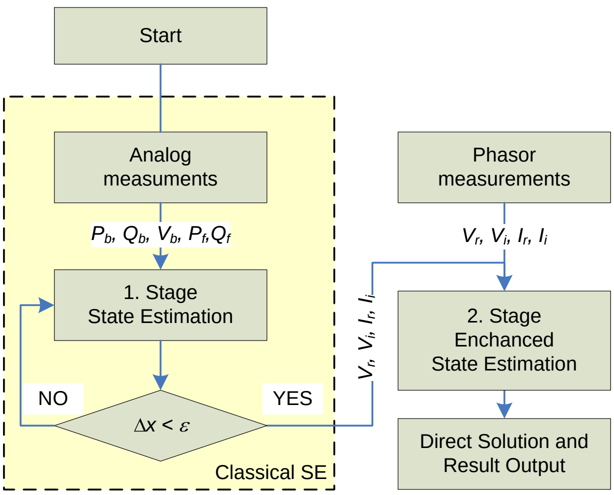

Figure 1: Flow chart of the implemented SE procedure.

Solving equation (4) for $\Delta x^{(k+1)}$ and iterating until the required accuracy ε is reached, i.e. $\Delta x^{(k+1)} < \varepsilon$, one will obtain the solution of SE.

2.2 Enhanced State Estimator with Phasor Measurement Units

In [8] a two-stage non-invasive PMU integration scheme is proposed, as in Figure 1. The classical SE gives estimated voltages as a pseudo measurement in addition to PMUs measurements to the second stage SE. The second stage involves, due to the formulation in rectangular coordinates, the linear measurement model:

$$M = H\hat{V} + \epsilon, \tag{5}$$

where M is a measurement vector, H is a measurement Jacobian matrix, $\hat{V} = [\hat{V}_r \hat{V}_i]^T$ is a state vector in rectangular coordinates and ϵ is the measurement noise.

In the extended form Equation (5) therefore, is given by:

$$M = \begin{bmatrix} \begin{bmatrix} V_r \\ V_i \end{bmatrix}^{se} \\ \begin{bmatrix} V_r \\ V_i \end{bmatrix}^{pmu} \\ \begin{bmatrix} I_r \\ I_i \end{bmatrix}^{pmu} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ \frac{\partial I_r^{pmu}}{\partial V_r} & \frac{\partial I_r^{pmu}}{\partial V_i} \\ \frac{\partial I_i^{pmu}}{\partial V_r} & \frac{\partial I_i^{pmu}}{\partial V_i} \end{bmatrix} \begin{bmatrix} \hat{V}_r \\ \hat{V}_i \end{bmatrix} + \begin{bmatrix} \epsilon_{Vr}^{se} \\ \epsilon_{Vi}^{se} \\ \epsilon_{Vr}^{pmu} \\ \epsilon_{Vi}^{pmu} \\ \epsilon_{Ir}^{pmu} \\ \epsilon_{Ii}^{pmu} \end{bmatrix}, \tag{6}$$

where V are the voltages, I are the currents, superscripts se and pmu denote the source of the information, subscripts r and i denote correspondingly the real and the imaginary components of the parameter and 1 is the identity matrix with ones at the diagonal and zeros otherwise.

The values of partial derivatives in Equation (6) can easily be obtained from the π-model of the network branch, which is linear in the complex form:

$$\underline{I_{km}} = (\underline{y} + \underline{y^{sh}})\underline{V_k} - \underline{y}\underline{V_m}, \tag{7}$$

where $\underline{I_k}$ is the complex current in the branch km at node k, $\underline{V_k}$, $\underline{V_m}$ are the voltages in the nodes k and m, $\underline{y}$ is the series admittance of the branch km, $\underline{y^{sh}}$ the shunt admittance of the branch.

Proceeding with transformations in rectangular form and the separation of the real and the imaginary part results in for example $\frac{\partial I_{kmr}^{pmu}}{\partial V_{ki}} = -(y_i + y_i^{sh})$.

Similarly to Equation (2) the weighted least square problem can be formulated, as:

$$J = \left[M - H\hat{V} \right]^T W \left[M - H\hat{V} \right]. \tag{8}$$

The formulation of the first order optimality condition results in:

$$\left. \frac{\partial J(V)}{\partial V} \right|_{V=\hat{V}} = H^T W H \hat{V} - H^T W M = 0. \tag{9}$$

and the estimates V can be obtained as result of the non-iterative computation:

$$H^T W H \hat{V} = H^T W M. \tag{10}$$

The covariance matrix elements should be in this case expressed in rectangular components.

2.3 Implemented state estimation procedure with PMU

The state estimation scheme was implemented according to the method proposed by Nuqui [8] with the following modifications discussed below. Similarly to [8] in the first stage, the measurements are collected and processed by classical state estimation procedure as in [13]. The results of this first stage state estimation, namely bus voltages together with the PMU measurements are forming the measurement vector for the second stage state estimation.

The addition proposed by the authors to this algorithm is the introduction of supplementary current measurements on the second stage of state estimation. These current measurements are computed from the first stage state estimation results and introduced into the measurement vector of the second stage state estimator:

$$M = \begin{bmatrix} \begin{bmatrix} V_r \\ V_i \end{bmatrix}^{se} \\ \\ \begin{bmatrix} \vdots \end{bmatrix}^{pmu} \\ \\ \begin{bmatrix} I_r \\ I_i \end{bmatrix}^{se} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \\ \vdots & \vdots \\ \\ \frac{\partial I_r^{se}}{\partial V_r} & \frac{\partial I_r^{se}}{\partial V_i} \\ \frac{\partial I_i^{se}}{\partial V_r} & \frac{\partial I_i^{se}}{\partial V_i} \end{bmatrix} \begin{bmatrix} V_r \\ V_i \end{bmatrix} + \begin{bmatrix} \epsilon_{Vr}^{se} \\ \epsilon_{Vi}^{se} \\ \vdots \\ \epsilon_{Ir}^{se} \\ \epsilon_{Ii}^{se} \end{bmatrix}. \tag{11}$$

Such modification still allows to preserve decoupled structure of the classical SE and the PMU based one and, simultaneously, decrease impact of possible bias in the PMU current measurements. Thus, the estimation procedure is becoming more balanced.

3 Simulations and Results

3.1 Test System

The method was tested on the 4 bus model [14], [15], representing part of the swiss transmission network (Figure 2). The slack node Breite represents the connection to the 400 kV grid. It contains two phase shifting transformers and HVDC transmission line. System parameters are given

Line Nr	R_L [Ω]	X_L [Ω]	C [nF]
8	9.834	12.678	33
11	5.379	12.779	33
12	7.855	19.304	47
7	7.939	19.331	47
6	0.292	2.796	

Table 1: System parameters.

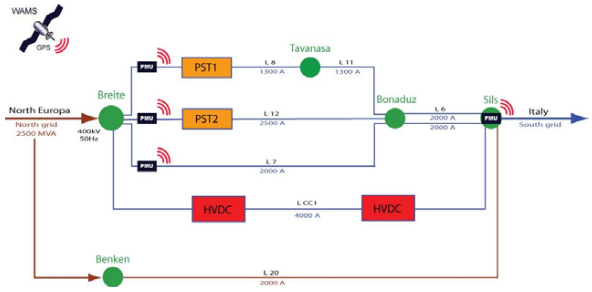

Figure 2: Single line diagram of the test system and location of the PMU.

in table 1. The capacitance was considered in the practical model in Section 4, and neglected in the software simulations. Transformation ratio of the phase shifting transformers were set to $1.05e^{j5^\circ}$ and $1.05e^{j10^\circ}$.

Measurement system consists of 2 synchronized voltage measurements, 3 synchronized currents and all the unsynchronized voltages and 1 flow measurement per branch. These measurement values were simulated by perturbing the values determined by the the power flow. Measurement noise [8] is normally distributed $N(0, \sigma)$ with the variance given by:

- $\sigma_{|V|} = 1.2\%$, $\sigma_{|I|} = 0.6\%$,
- $\sigma_{angle(V)} = 1.04^\circ$, $\sigma_{angle(I)} = 1.04^\circ$.

3.2 Results

For the power flow simulation a Newton-Raphson method was implemented [6] and converged in 3 iterations with the accuracy of 10^{-5}. Simulations were also verified by the Neplan software [7]. Comparison of the accuracy for the different state estimation algorithms is summarized in table 2. Here the mean of 100 trials of the total absolute deviations is given, i.e. comparison of the estimated states vs the power flow result. It can be observed that, generally, both hybrid method enhance SE accuracy, while hybrid method with additional estimated currents provide slightly higher precision.

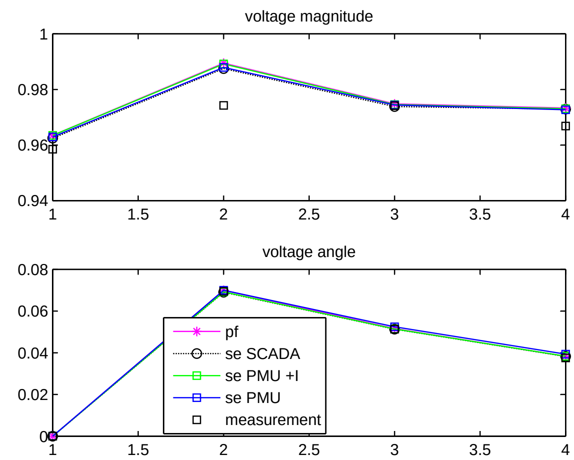

Figure 3: Comparison of the accuracies of the methods: bus voltage magnitudes and voltage angles vs bus number.

Figure 3 shows typical example of the performed trials. In addition, bad data identification procedure was implemented and verified.

State	SCADA	Hybrid PMU	Hybrid PMU with I_{SCADA}^{SE}
voltage magnitude	0.0204	0.0202	0.0199
voltage angle	0.0017	0.0015	0.0014

Table 2: Comparison of performance: mean of total absolute deviations

4 Implementation: Analog Simulation System

4.1 Reduced Scale Network Model

The reduced scale network model that has been used for the real time evaluation represents the 400 kV grid of Switzerland (see Figure 2 and Figure 4). The system parameters are the same as for the theoretical study. In addition, capacitance was considered in the practical model, but its influence was neglected in the state estimation. Transformation ratio of the phase shifting transformers were determined for each case by the multiobjective optimization procedure that seeks to minimize network losses, as well deviations of the voltages from the reference values.

This analog simulation environment has already been used for various wide area monitoring and control application studies [14], [15]. The network comprises several generators, built as synchronous machines. For system studies typical faults can be applied to the system at each node and / or on the lines at predefined locations. The scale of the model has been chosen with 1 KVA for 1000 MVA and 400 V for 400 kV on the voltage side. The impedances are adapted according to the typical voltage / power relationship.

In order to study the impact of all kind of fast network controllers the two power flow controllers (PFCs) have been set up on a UPFC basis [14], [11]. The series voltage capabilities

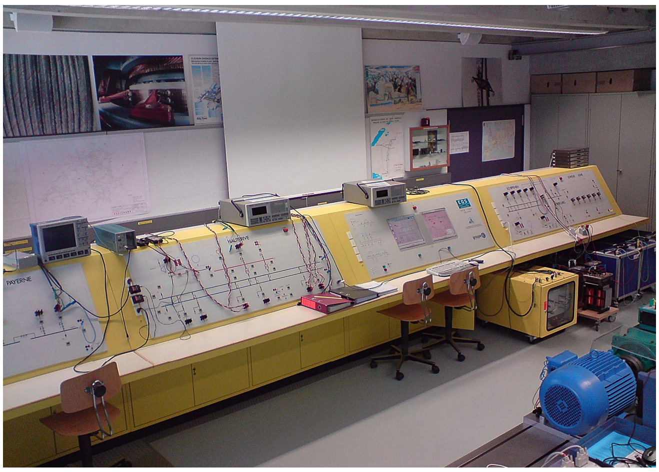

Figure 4: Laboratory setup for the analog power system model.

of the UPFC have been designed to be per phase at 7.5 A line current. The following operation modes are available:

- reactive power compensation (shunt source);
- open loop current control (fixed series source);
- closed loop current control (controlled series voltage with P and Q set points);
- special control software allows the UPFC to operate like a conventional phase shifting transformer since most of the power flow control applications in interconnected power systems are based on this type of device.

In order to study the behavior of embedded HVDC, one type of schemes has been integrated into the network. As reference for a parallel operation, a HVDC transmission line has been integrated between Breite and Sils.

4.2 Wide Area Control System

In the basic concept of a WAMS the PMUs are placed in substations to allow observation of a part of the power system under any operation condition. For the system supervision and control up to five PMUs have been used. They are integrated in the network model and synchronized by a conventional GPS signal. The data processing is based on the software PS Guard provided by ABB [12], [1]. The phasor information is provided to an application and control server, where the control algorithms and general analysis functions are executed.

The lab control is realized by LabView software; higher analysis and control applications are utilizing MATLAB environment. The control signals are distributed to the network controllers via a controller area network bus (CAN Bus).

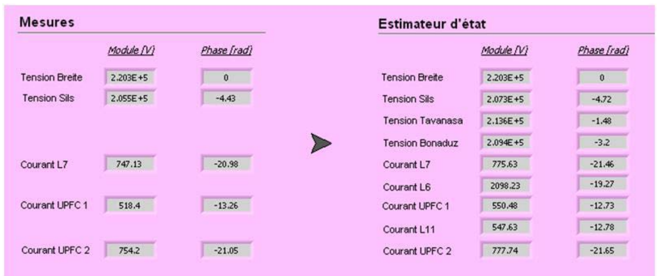

Figure 5: Results obtained by the state estimation without FACTS

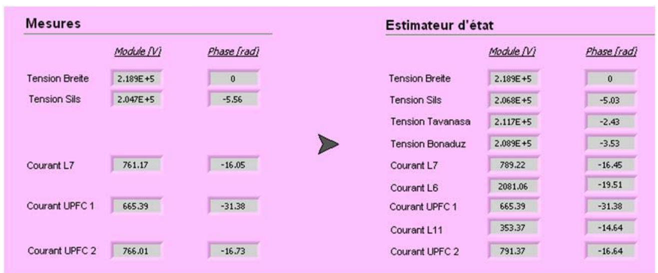

Figure 6: Results obtained by the state estimation with PST

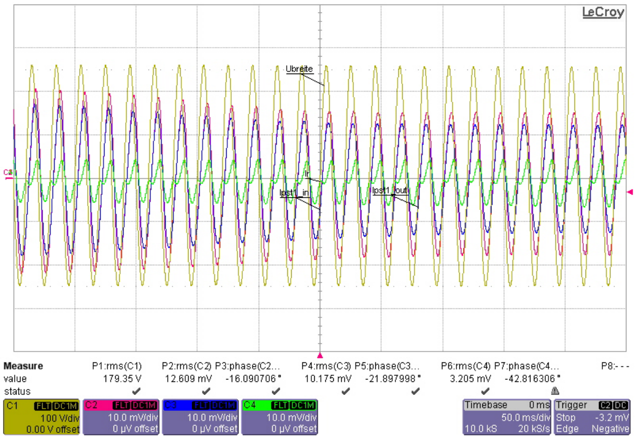

Figure 7: Recordings of current and voltage showing influence of low frequency oscillation. The full time scale is 500 ms.

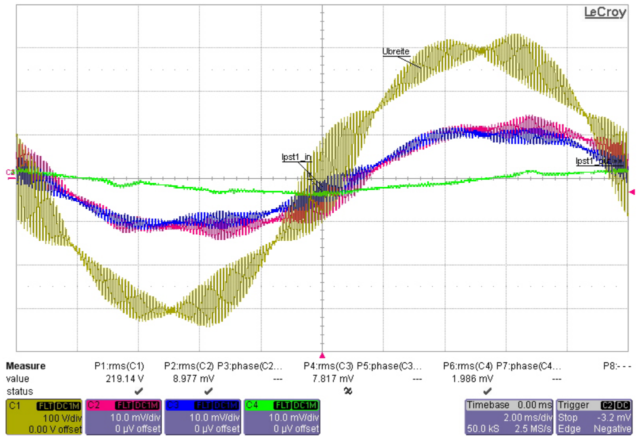

Figure 8: Recordings of current and voltage showing influence of high frequency harmonics. The full time scale is 20 ms.

4.3 Experiments

1) State estimation without FACTS: The state estimation applied to the reduced scale grid without FACTS is verified, see Figure 5.

2) State estimation with PST: The state estimation applied to the reduced scale grid with the first PST alone is verified, see Figure 6. Note that for current $L11$ the regulator of the UPFC1 (which is used here for representing the phase shifting transformer) has a low frequency oscillation (< 1 Hz), as shown in Figure 7. This produces a current difference between $L11$ and the output of the PST1. A further work will consist in stabilizing this low frequency oscillation.

3) State estimation with HVDC: The state estimation applied to the reduced scale grid with only the HVDC line is verified. The harmonics generated by the HVDC are more significant for a reduced scale model, compared to a 1 GW HVDC for example. A representation of the phasors is not anymore realistic with the distortion of currents and voltages, as in Figure 8.

4) State estimation with PST and HVDC: The state estimation applied to the reduced scale grid with the first PST and the HVDC line was performed. Here again the distortion prevents a full verification.

Conclusions

State estimation performance benefits from addition of the synchronized wide area measurements. Both non-invasive approaches tested in this paper show good results. The proposed addition of the estimated current to the measurement vector brings further small increase of the accuracy. In the analogue model the presence of the high frequency harmonics did not allow to obtain satisfactory results, however such harmonics are less significant in the real systems.

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