

# Applications of a Robust State Estimator to the EEF Power System

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**Abstract** – The EEF utility, which is headquartered in Fribourg, Switzerland, is planning to install in its new energy management system a robust Schweppe-type Huber GM-state estimator (SHGM) as described in [1]. Prior to the installation, the iterative algorithm that implements the estimator has been upgraded to meet the specifications and extensive off-line simulations have been carried out on the EEF power network. This system consists of 3 islands and 33 substations that are interconnected by 60kV subtransmission lines. The islands may from time to time be interconnected. Simulations revealed that the SHGM algorithm exhibits excellent convergence properties and is robust to bad measurements, be they leverage points or not. Installation of the state estimator on the computer facilities located at the new EEF control center will take place in the summer of 1998, followed by its full real-time testing.

**Keywords:** EEF system, robust state estimator, projection statistics, leverage points, bad data identification.

## 1 - INTRODUCTION

Today, a broad acceptance is witnessed among the power community of the need of a state estimator to create a complete and reliable database for security monitoring, security analysis and control of a power system [2-7]. To this end, the state estimator requires the availability of a redundant set of real-time measurements that observes the system state along with a topology processor that determines the system topology from the telesignalings of circuit breaker statuses.

The Entreprises Electriques Fribourgeoises, known as the EEF electric utility and headquartered in the city of Fribourg, Switzerland, decided to install the Schweppe-type Huber GM-estimator (referred to as the SHGM-estimator), as described in [1], in their energy management system (EMS). This decision was made after clear evidence was demonstrated of the superiority of the SHGM-estimator over the conventional WLS

method, which were previously used by the EEF. Cases were demonstrated for which the WLS-based procedure [8] fails to pinpoint bad data due to the masking effect, whereas the SHGM-estimator properly rejects them.

Extensive off-line simulations on the EEF system showed that the iteratively reweighted least squares (IRLS) algorithm that solves for the SHGM-estimator exhibits excellent convergence properties, even in presence of multiple bad data with large gross errors. The algorithm typically converges in three iterations while rejecting gross measurements. When using real-time EEF data files, the SHGM-estimator has confirmed a discrepancy in sign conventions at the tie lines. It also consistently rejected certain power flow measurements, prompting a study into the parameters of a line and the bias in its metered values.

The algorithm has been upgraded to meet the EEF specifications. The new version is able to handle parallel lines, multiple bus voltage measurements, transformers and the independent treatment of active and reactive measurements. Once the algorithm was proven capable of making estimations on the real EEF network, a topology processor was created that transforms real-time files into a super-bus model for the estimator. The estimator's output includes a formatted file compatible with the EEF load flow program for use in contingency analysis and a text file that may be inspected upon request by the system operators. This output includes estimated values for all power flows and injections in the system.

The paper is organized as follows. Section 2 describes the EEF system. Section 3 deals with the SHGM-estimator. Some simulations results are discussed in Section 4 and future work is outlined in Section 5.

## 2 - THE EEF SYSTEM

The EEF utility services the Swiss canton of Fribourg, with area of about 1,600km<sup>2</sup>. They have a peak load of 300MW and an installed generation capacity of 279MW, including 255MW of hydraulic units and 24MW of thermal units. The principle network consists of 33 substations interconnected by 600km of 60kV subtransmission lines, which is externally connected by one 130kV- and two 220kV-tie lines owned by the Swiss company EOS (Energie Ouest Suisse). These three tie lines allow the network to commonly be subdivided into three interconnectable islands, which supply energy to loads through 17kV distribution systems. The tie lines are located at the Monteynan, Botterens and Villarepos substations, in order of decreasing number of busses typically attached to each tie line. For our purposes we will name the islands after their respective tie line substations. The Monteynan and Botterens islands are



Here,  $\lambda$  is a cutoff value fixed at 1.5 and  $w_i$  are weights based on the projection statistics as described in [1]. They take values smaller than one for those measurements whose projections on the space spanned by the rows of the weighted Jacobian matrix are distant from the bulk of the point cloud, the so-called leverage points. The estimate  $\hat{\underline{x}}$  is a solution to  $\partial J(\underline{x}) / \partial \underline{x} = \underline{0}$ , namely to

$$\sum_{i=1}^m w_i \underline{\ell}_i \psi(r_{Si}) = \underline{0}. \quad (4)$$

In (4),  $\underline{\ell}_i^T$  is the  $i$ th row of the weighted Jacobian matrix,  $\sqrt{\underline{R}^{-1}} \underline{H}$ , and  $\psi(r_{Si})$  is the derivative of  $\rho(r_{Si})$  with respect to  $r_{Si}$ . It is given by

$$\psi(r_{Si}) = \begin{cases} r_{Si} & |r_{Si}| \leq \lambda \\ \lambda & \text{elsewhere} \end{cases}. \quad (5)$$

To solve (4) for  $\underline{x}$ , let us divide and multiply  $\psi(r_{Si})$  by  $r_{Si}$ , yielding

$$\sum_{i=1}^m \frac{1}{\sigma_i} \underline{\ell}_i r_i q(r_{Si}) = \underline{0}, \quad (6)$$

where  $q(r_{Si}) = \psi(r_{Si})/r_{Si}$  is called the weight function. Defining  $\underline{Q} \equiv \text{diag}(q(r_{Si}))$  and putting (6) in a matrix form, we obtain

$$\underline{H}^T \underline{R}^{-1} \underline{Q} (\underline{z} - \underline{h}(\underline{x})) = \underline{0}. \quad (7)$$

Substituting in (7)  $\underline{h}(\underline{x})$  by a first order Taylor series expansion around  $\underline{x}^{(k)}$  given by

$$\underline{h}(\underline{x}) = \underline{h}(\underline{x}^{(k)}) + \underline{H}(\underline{x}^{(k)}) (\underline{x} - \underline{x}^{(k)}), \quad (8)$$

we get

$$\Delta \underline{x}^{(k)} = (\underline{H}^{(k)T} \underline{R}^{-1} \underline{Q}^{(k)} \underline{H}^{(k)})^{-1} \underline{H}^{(k)} \underline{R}^{-1} \underline{Q} \underline{r}^{(k)}, \quad (9)$$

where  $\Delta \underline{x}^{(k)} = \underline{x}^{(k+1)} - \underline{x}^{(k)}$ . The foregoing expression defines the so-called iteratively re-weighted least squares (IRLS) algorithm. Unlike a Newton-type algorithm that involves divisions by the second derivative of the  $\rho(\cdot)$  function, which may vanish, the IRLS algorithm has proven to be numerically stable while exhibiting good convergence properties.

#### 4 – SIMULATION RESULTS

The IRLS algorithm that implements the SHGM-estimator was developed and adapted for the EEF system with extensive off-line testing. In all simulated cases, the algorithm converges in three iterations. These simulations have revealed that the EEF system is challenging from a state estimation viewpoint. For example, the typical topology for Monteynan island shown

in Figure 1 consists of two meshed sub-networks connected by a single link, which is made up of two transformers. In addition, each sub-network contains very short lines, inducing extreme leverage points in the power measurements. Another feature of these networks is that they are provided with power flow measurements on both sides of every branch, but have very few power injection measurements.

In this section, we describe some simulation results carried out on the Monteynan island. This sub-network has 57 voltage measurements, 54 pairs of real and reactive power flow measurements, one pair of real and reactive power injection measurements, and 2 pairs of zero injections, yielding a total of 171 measurements. Artificial metered values were generated from load flow calculations with Gaussian noise added. The noise generator is based on the Box-Muller method as described in [10].

The Monteynan sub-network consists of 20 busses, 2 transformers and 26 lines, four of which are very short with relatively small reactances. These lines are OELB-MAIG, OELB-STL2, HV11-HV31 and HV12-HV32. As seen in Table 1, the projection statistics of all the power measurements on these lines are large, yielding small weights  $w_i$ . Recall that the latter are used to calculate the standardized residuals  $r_{Si}$ , which are given by (3). Note that the weights  $w_i$  are fixed to 0.01 whenever they take values smaller than this lower bound.

Six pairs of P and Q bad data on power flow measurements have been introduced in the system. Three of these are bad leverage points, which are flow measurements on line HV31-HV11, HV32-HV12, and OELB-MAIG. Two other pairs are conforming bad data located on line COUR-SCHI whereas the last one is a pair of bad power flows on line CRES-KERZ. The IRLS algorithm that solve for SHGM-estimator has been applied to the network, the state estimated and the weighted residuals calculated. It took 3 iterations for the IRLS algorithm to converge and provide the results summarized in Table 2. As seen, all 12 bad data have been rejected with large weighted residuals.

#### 5 – FUTURE WORK

The SHGM-estimator as adapted for the EEF has thus far been tested on converted files captured from the newly installed SCADA system during its testing. Real-time implementation of both the topology processor and state estimator on the computers of the EEF control center will take place in the summer of 1998. At this time a number of tasks should be carried out in order to have the estimator installed and finely tuned. First, the general accuracy of each measurement should be captured in the form of a standard deviation  $\sigma_i$  of the entire measurement chain, from the metering device through the current or power converters and finally the analog/digital converter. For non-robust estimators, such as the weighted least squares estimator, the  $\sigma_i$  values need to be accurate. For robust estimators such as the SHGM, the accuracy of the  $\sigma_i$  is much less critical because the measurements are neither accepted nor rejected, but instead are smoothly downweighted when they have large standardized residuals.

**Table 1.** Projection statistics of real power flow measurements.

Real Power Measurement	Branch Reactance	Projection Statistic	Weight $w_i$
CORB - HV32	0.04234	1.866	1.000
CORB - VLR2	0.09442	3.230	1.000
CORB - CIG	0.03812	5.791	1.000
COUR - CIG	0.05179	3.836	1.000
COUR - VLR2	0.05555	6.561	1.000
COUR - SCHI	0.08349	2.347	1.000
CRES - KERZ	0.11665	1.452	1.000
CRES - MORT	0.04649	2.343	1.000
CRES - SCHI	0.04457	5.361	1.000
CRES - VLR2	0.06249	5.672	1.000
GIFF - MARL	0.08166	3.575	1.000
GIFF - SCHI	0.18870	1.394	1.000
GUTZ - STL2	0.06376	5.151	1.000
GUTZ - HV31	0.05345	2.272	1.000
GUTZ - MONC	0.01365	8.914	1.000
HV11 - MAIG	0.04806	4.606	1.000
HV12 - STL1	0.07548	5.866	1.000
HV12 - MARL	0.01924	10.106	1.000
HV32 - CORB	0.04234	2.653	1.000
HV32 - MTY2	0.12914	3.047	1.000
HV31 - MTY1	0.14016	2.735	1.000
HV31 - MONC	0.03671	6.618	1.000
HV31 - GUTZ	0.05345	2.272	1.000
HV31 - HV11	0.00270	<u>76.966</u>	<u>0.021</u>
HV32 - SCHI	0.15967	1.300	1.000
HV32 - HV12	0.00270	<u>76.923</u>	<u>0.021</u>
KERZ - CRES	0.11665	1.452	1.000
KERZ - VLR2	0.21621	1.381	1.000
MAIG - HV11	0.04806	4.606	1.000
MAIG - OELB	0.00795	<u>21.639</u>	<u>0.265</u>
MARL - HV12	0.01924	10.106	1.000
MARL - GIFF	0.08166	3.575	1.000
MONC - GUTZ	0.01365	8.914	1.000
MONC - HV31	0.03671	6.618	1.000
MORT - CRES	0.04649	2.343	1.000
MORT - VLR2	0.06130	4.565	1.000
MTY - MTY2	0.12914	3.047	1.000
MTY - MTY1	0.14016	2.735	1.000
OELB - MAIG	0.00795	<u>21.639</u>	<u>0.265</u>
OELB - STL2	0.02891	<u>14.586</u>	<u>0.583</u>
SCHI - COUR	0.08349	2.347	1.000
SCHI - HV32	0.15967	1.300	1.000
SCHI - CRES	0.04457	5.361	1.000
SCHI - STL1	0.06686	2.830	1.000
SCHI - GIFF	0.18870	1.394	1.000
STL1 - SCHI	0.06686	2.830	1.000
STL1 - HV12	0.07548	5.866	1.000
STL2 - OELB	0.02891	<u>14.586</u>	<u>0.583</u>
STL2 - GUTZ	0.06376	5.151	1.000
VLR2 - MORT	0.06130	4.565	1.000
VLR2 - CRES	0.06249	5.672	1.000
VLR2 - COUR	0.05555	6.561	1.000
VLR2 - CORB	0.09442	3.230	1.000
VLR2 - KERZ	0.21621	1.381	1.000

As a second task, it would be beneficial to install and execute an observability program before state estimation. This is particularly critical for the southern network, which is usually serviced by the Botterens tie line. This network has very poor measurement redundancy for the reactive measurements and may become unobservable from time to time. A third task would be to estimate the transformer tap positions [11] in

**Table 2.** Weighted residuals provided by the SHGM-estimator.

Measurement	Real Power		Reactive Power	
	error/ $\sigma_i$	$r_{w_i}$	error/ $\sigma_i$	$r_{w_i}$
CORB - HV32	0.372	0.087	1.490	-0.780
CORB - VLR2	0.654	-0.617	0.237	-0.142
CORB - CIG	0.037	-0.304	1.612	0.661
COUR - CIG	0.044	0.297	0.071	1.054
COUR - VLR2	0.474	0.251	0.691	0.203
COUR - SCHI	<u>26.235</u>	<u>-24.349</u>	<u>35.234</u>	<u>-33.477</u>
CRES - KERZ	<u>17.100</u>	<u>13.725</u>	<u>30.000</u>	<u>29.578</u>
CRES - MORT	1.717	0.411	1.156	-0.900
CRES - SCHI	1.371	1.713	1.542	-0.201
CRES - VLR2	0.764	-2.421	0.181	-0.843
GIFF - MARL	1.724	-0.888	1.357	0.499
GIFF - SCHI	1.748	1.889	1.022	0.620
GUTZ - STL2	1.233	-0.051	0.459	0.950
GUTZ - HV31	1.710	1.210	0.323	-0.094
GUTZ - MONC	1.019	-1.039	0.243	0.103
HV11 - MAIG	0.562	0.003	0.158	-0.979
HV12 - STL1	0.343	-1.023	1.290	0.975
HV12 - MARL	0.093	-0.305	0.642	1.196
HV32 - CORB	0.708	0.247	0.361	-1.062
HV31 - MONC	0.913	-0.190	0.165	0.728
HV31 - GUTZ	0.645	1.147	0.488	-0.044
HV31 - MTY1	1.550	-0.733	0.709	0.717
HV31 - HV11	<u>145.187</u>	<u>-85.344</u>	<u>140.227</u>	<u>-66.354</u>
HV32 - SCHI	0.328	1.022	0.615	-0.456
HV32 - HV12	<u>148.360</u>	<u>-80.033</u>	<u>152.969</u>	<u>167.204</u>
HV32 - MTY2	1.772	0.884	0.822	-0.750
KERZ - CRES	0.157	3.196	0.522	-0.097
KERZ - VLR2	1.242	0.180	0.481	0.878
MAIG - HV11	0.007	0.550	0.535	0.303
MAIG - OELB	0.903	0.802	0.910	0.386
MARL - HV12	0.670	-0.457	1.693	1.146
MARL - GIFF	0.582	-0.257	0.228	0.671
MONC - GUTZ	0.903	-0.883	0.274	0.421
MONC - HV31	0.109	-0.611	0.419	-0.112
MORT - CRES	0.110	1.190	0.430	0.182
MORT - VLR2	1.055	-1.585	0.988	-1.251
MTY - MTY2	0.007	0.897	2.094	-0.407
MTY - MTY1	0.040	-0.774	0.068	-0.107
OELB - MAIG	<u>52.600</u>	<u>52.702</u>	<u>55.104</u>	<u>55.631</u>
OELB - STL2	1.522	0.336	1.040	-0.381
SCHI - COUR	<u>26.200</u>	<u>24.296</u>	<u>36.167</u>	<u>34.392</u>
SCHI - HV32	0.499	-0.199	1.228	1.111
SCHI - CRES	0.788	-1.134	0.603	-1.938
SCHI - STL1	0.224	-0.020	0.690	-0.984
SCHI - GIFF	0.489	0.349	0.409	0.074
STL1 - SCHI	1.036	-1.240	0.155	0.162
STL1 - HV12	0.165	0.514	0.144	0.489
STL2 - OELB	1.162	2.347	0.896	0.534
STL2 - GUTZ	0.767	-0.418	1.060	-0.331
VLR2 - MORT	0.243	0.287	1.233	1.515
VLR2 - CRES	0.213	1.441	1.222	1.900
VLR2 - COUR	0.071	-0.655	0.368	-0.505
VLR2 - CORB	0.880	-0.917	1.498	1.907
VLR2 - KERZ	1.745	0.320	0.494	0.164
CIG	0.015	-0.003	0.002	0.041
MTY1	0.043	-0.037	0.002	0.035
MTY2	0.057	0.044	0.003	-0.038
MTY	1.128	1.204	1.219	2.868
STL2	0.003	-0.013	0.040	-0.008
VLR2	0.020	-0.038	0.171	-0.064

addition to the nodal voltage magnitudes and phase angles. This may be done only if the local redundancy is improved in the vicinity of the transformers, for example by incorporating the current magnitude measurements on the 60/17 kV transformers into the state estimation model.

## 6 - CONCLUSIONS

The SHGM-estimator has been upgraded and tested on the EEF system. Simulation results showed that this robust estimator outperforms the conventional WLS-based method in that it exhibits excellent convergence properties while rejecting multiple bad data. The SHGM is not prone to the smearing and masking effects so characteristic of the WLS methods, making multiple bad data identification rather straightforward.

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