PMU Measurements as Basis of System WAMS in Czech Transmission Power System

Analysis, Parameters Calculations and State Estimations

Neuman Petr
SCADA department
CEPS, Inc.
Prague, Czech Republic
neuman@ceps.cz

Sadecky Bohumil
EMS department
CEPS, Inc.
Prague, Czech Republic
sadecky@ceps.cz

Abstract **— The digital protections SEL are equipped by synchronization units GPS in the selected and suitable substations of Czech Transmission System CEPS. These complex units realized the measurement of synchrophasors PMU (Phasor Measurements Unit). This paper is aimed to analyse of synchrophasors and also to calculation of parameters of 400 kV line, V430 – „HRD-CHR", which is measured on both ends. The data filtration and analyse is perform on commercial available SW toolboxes of MATLAB, e.g., Spectral Analysis is perform on Signal Processing Toolbox. The equations for calculation of lines parameters (impedance Z, admittance Y, lines temperature T) are perform directly on MATLAB. The next development steps are procedures of protections, local automatons, etc. The theory and algorithms are take from available technical documents of company SEL. The presented results are basis for contractual documents and building up the (inter)national WAMS (Wide Area Monitoring System) and/or WAPS (Wide Area Protection System).**

Keywords: Czech Transmission System; protections SEL; GPS Synchronization Units; PMU; Calculated Lines Parameters; WAMS; WAPS

I. INTRODUCTION

Standard Unsynchronous Measurements: We were using the classical measurements connected with Dispatch Control System TRIS supplied by Czech company ELEKTROSYSTEM, till this time .

Advanced Synchronous Measurements: During 2009 the digital protections SEL421 [1] were equipped by synchronization units GPS in the selected and suitable substations of Czech Transmission System CEPS. These complex units realized the measurement of synchrophasors PMU (Phasor Measurements Unit). This paper is aimed to analyse of synchrophasors and also to calculation of parameters of 400 kV line, V430 – „HRD-CHR", which is measured on both ends.

Phasor measuring units (PMUs) enable a number of different applications to improve the efficiency in power systems. This paper describes some of the applications devised by the Czech Transmission System Operator (CEPS). Examples reviewed include:

Dynamic Behavior Monitoring of System: Power system enlargement is creating small signal oscillations. Given the decreasing stability margins, knowledge of the dynamic behavior of the system is critical for proper operation. Using PMU readings from different points of a system, allows characterizing potential oscillations. This knowledge helps planners to devise corrective actions, increasing damping techniques and establishing defense procedures for unstable oscillations.

Sequence Impedance Calculations for Transmission Lines: traditional calculations based on line constants can result in significant errors, especially for zero sequence impedance. These errors will translace into incorrect settings on distance relays, fault locators, etc. Calculations based on measures by PMUs located on both ends of power lines provide a simple solution to obtain more accurate calculations [2]. One of possible these applications is calculation of **Ampacity**, i.e. practically the average temperature of wire lines.

Static and Dynamic State Estimation: different versions with using of synchronous phasors (Postproccessing, Hybrid Method, etc).

Fault Location for Mixed Lines: variations on zero sequence impedance in cables reduce the efficiency of traditional fault locators. Fault location based on measures by PMUs located in both ends of a mixed power line (combination of overhead and underground cable) gives more precise results.

To test the algorithms described, simulations could be run in a **RTDS system (Real Time Digital Simulator)**. The SW realization of control algorithms could be verified by method of „HW - In - the Loop" (HIL).

II. DYNAMIC BEHAVIOR MONITORING OF TRANSMISSION SYSTEM

This new environment creates the need for improving the knowledge of such dynamic behavior. This can be achieved by direct observation as well as additional system analysis via system modeling. A prepared pilot project is underway, using phasor measurement units (PMUs) in an application to determine the following modal characteristics:

- Modal frequency
- Amplitude of different modes
- Damping
- Phase

Based on this system and with the data provided by the PMUs, CEPS would be able to:

- Study potential damping problems in the system, identifying local and inter-area oscillation modes. This requires continuous monitoring of the amplitude of the oscillation modes and its damping. The systems scheme with two relays and one Synchrophasor Vector Processor (SVP) is depicted in Fig.1.

- Model validation. Continuous monitoring of the system dynamics will provide the necessary data to validate models of the different operating conditions of the system. The model simulations could be run in a **RTDS** – see Fig.2.

- Improvement of system security. Analyzing the phasor data will be possible to establish corrective action plans against instable oscillations.

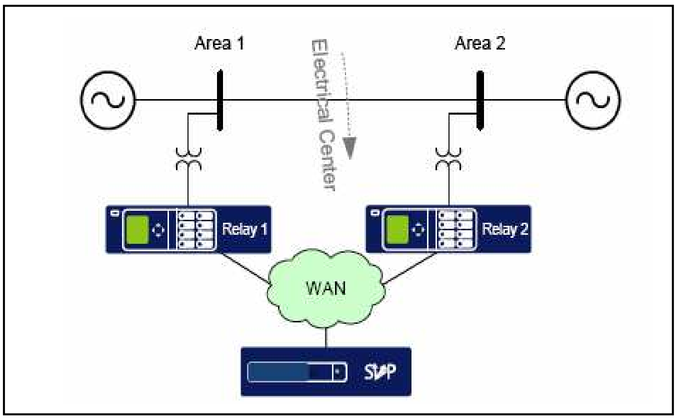

Figure 1. Two-area power systems that uses two **relays** and one **SVP**

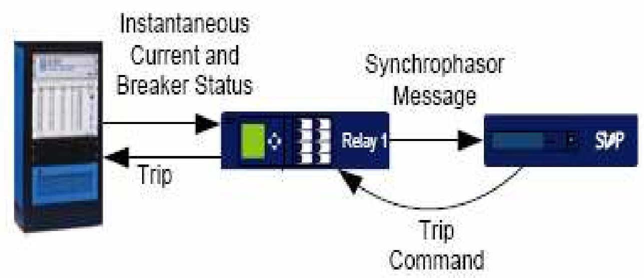

Figure 2. Interconnection of the power system simulator **RTDS**, **relay**s, and **SVP**

III. Surface Discharge Fault Location

Example - from date 9th, February 2010 (Fig.3) was calculated special spectrogram results – see Fig.4.

This transient phenomenon could be surface discharge, or some other phenomenon (partial discharge, surge discharge, etc.). There are many states, which rise difference of nominal voltage harmonics. These states could be following:

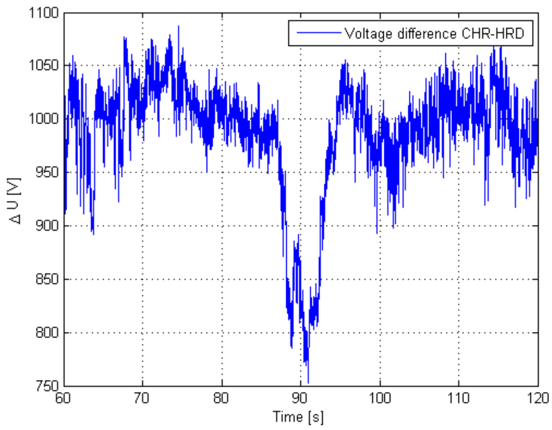

Figure 3. Detail data for calculation of next spectrograms

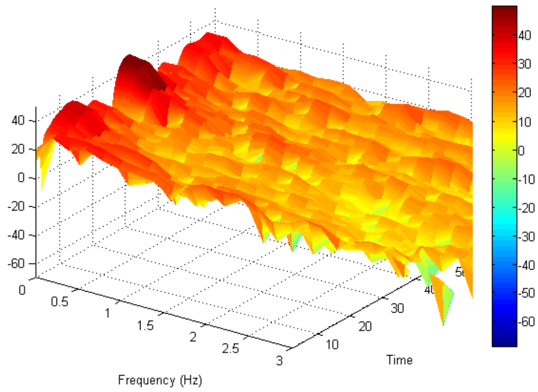

Figure 4. Example of voltage difference spectrogram

A. Short time voltage decline

It expresses oneself by sinking of effective value of voltage. The time duration of it is from halfperiod of line voltage to 60 sec. This discharge rises most often in connection with switch-on of greate consumer or as a result of short-circuit in power system.

B. Short time voltage elevation

It rises, e.g., as a result of one-phase short-circuit in the phase without disturbance.

C. Voltage impulse as a result of lightning discharge

The lightning discharge takes usually about less than 0,2 sec, only in 10 % cases exceeds time 0,7 sec. The longest of these could take time as far as 1,4 sec – see [3]. The lightning discharge also express oneself by thermal influence. The heat developed by lightning current passage through the line wire increases the temperature of the line wire, and the electrical parameters are changed.

D. Provisional overvoltage

Provisional overvoltage with time of duration from 0,03 up to 3600 sec, which rises, e.g., during one-phase earth fault in power systems with insulated neutral. The overvoltage stay on up to despatch of earth fault, during which time the system could supply power in a mater of disturbance.

Generally the research of specific phenomenons based on synchrophasors must be realized with complementary monitoring of many other contemporary conditions and measurements. The next CEPS activities will be aimed, among others, into measurements, monitoring, analysis and calculation of special application functions.

IV. Sequence Impedance Calculations for Transmission Lines

Calculations of sequence and phase impedances based on synchronized readings from two PMUs, one at each end of the line, allow for a simple method to obtain accurate results. Positive sequence impedance can be obtained anytime, derived from positive sequence currents and voltages at both ends of the line. Results obtained at a given time from PMU readings can be used to set all the devices with operating principles based on impedance metering. Nevertheless, since sequence impedances are subject to changes depending on the weather conditions and the power flow it is possible to get calculation under different conditions, with a programmed schedule for positive sequence impedance and during ground faults in the system for zero sequence impedance. If noticeable variations are detected between calculated and set values, it is possible to change the settings group of relays or fault locators, adapting those settings to the current.

A. Identify the Headings Positive sequence and phase impedance calculations for line V430

The first Fig.6 depicts the principal scheme of PMU measurements. The second Fig.5 depicts the equivalent positive sequence PI circuit for a transmission line. The relationship among positive sequence currents and voltages at both ends of the line are included in the following equations:

$$V_{1R} = V_{1L} - (I_{1L} - V_{1L} \cdot \frac{Y_1}{2}) \cdot Z_1 \quad (1)$$

$$-I_{1R} = I_{1L} - V_{1L} \cdot \frac{Y_1}{2} - V_{1R} \cdot \frac{Y_1}{2} \quad (2)$$

From equation (2) is possible to calculate

$$Y_1 = 2 \cdot \frac{I_{1L} + I_{1R}}{V_{1L} + V_{1R}}$$

Substituting in (1)

$$Z_1 = \frac{V_{1L}^{\ 2} - V_{1R}^{\ 2}}{I_{1L} \cdot V_{1R} - I_{1R} \cdot V_{1L}}$$

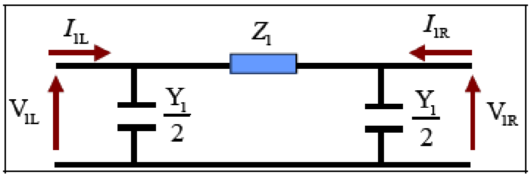

Figure 5. Positive sequence equivalent PI circuit for a transmission line

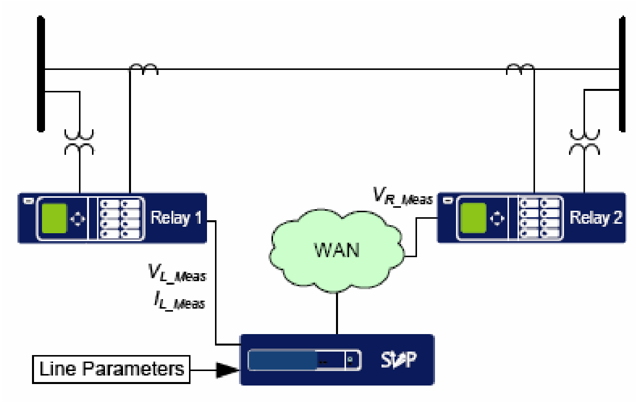

Figure 6. Scheme to supervise remote current and voltage measurements

B. Parameters of czech transmission lines

The nominal parameters of lines, recalculated on standard temperature 20 °C, are in Table I.

TABLE I. THE NOMINAL PARAMETERS OF LINES

no. of line	max current	length	R1	X1	B1
	[A]	[km]	[Ω]	[Ω]	[µS]
V430_	1968	82.44	2,02	24,85	318

C. Statistics of phasor synchronous data

The first measurements - 14th January 2010 (1 p.m.)
- outside temperature at Plzeň – CHRast: -0.38 [°C]
The second - 9th January 2010 (12 a.m.): -5.35 [°C]

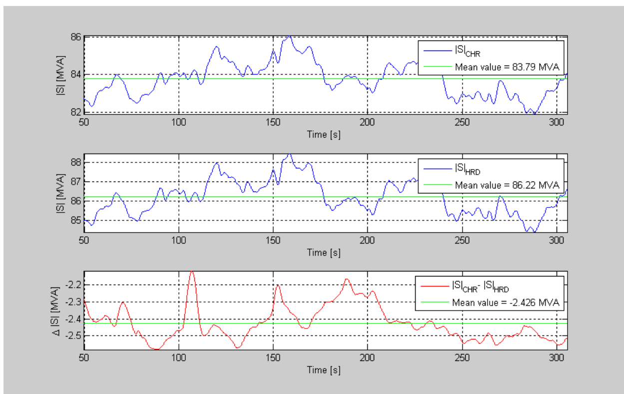

Figure 7. Trends of lines apparent power S

The results of statistics data analysis are in Table II.

TABLE II. THE CALCULATED STATISTICS OF PHASOR SYNCHRONOUS DATA AND PARAMETERS OF LINES V430, PHASE C, JANUARY 14, 2010

Data analysis	without filtration
Mean value of voltage [V] CHR:	239759.165404
Mean value of voltage [V] HRD:	239958.862861
Mean value of current [A] CHR:	289.510512
Mean value of current [A] HRD:	295.163243
Mean value of voltages difference [V] CHR-HRD:	-199.697457
Standard deviation of voltages difference [V] CHR-HRD:	38.668058
Mean value of currents difference [A] CHR-HRD:	-5.652730
Standard deviation of voltages difference [A] CHR-HRD:	0.430894
Mean value of power [MW] CHR:	69.412469
Mean value of power [MW] HRD:	70.826750
Mean value of power difference [MW] CHR-HRD:	-1.414281
Mean value of real part of admittance Y [S]:	0.000008
Standard deviation of real part of admittance Y [S]:	0.000000
Mean value of imaginary part of admittance Y [S]:	0.000318
Standard deviation of imaginary part of admittance Y [S]:	0.000000
Mean value of real part R_C of impedance Z_C [Ω]:	1.879204
Standard deviation of real part R_C [Ω]:	0.007519
Mean value of imaginary part X_C of impedance Z_C [Ω]:	23.468927
Standard deviation of imaginary part X_C [Ω]:	0.034246

D. Results of analysis calculation

The variables trends from measurements 9th, February 2010 are gradually depicted on Figures 7., 8., 9., 10.

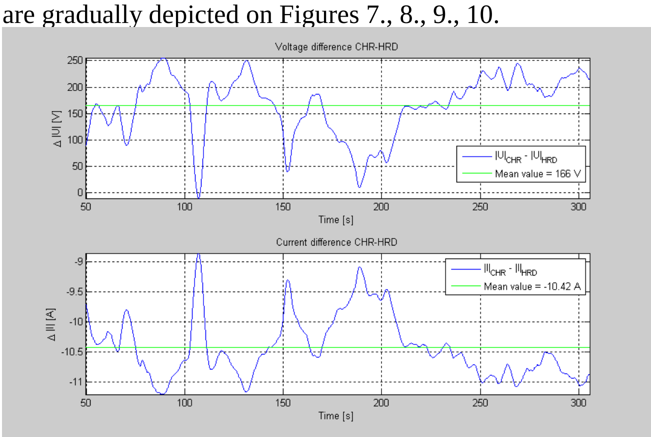

Figure 8. Trends of lines difference voltages

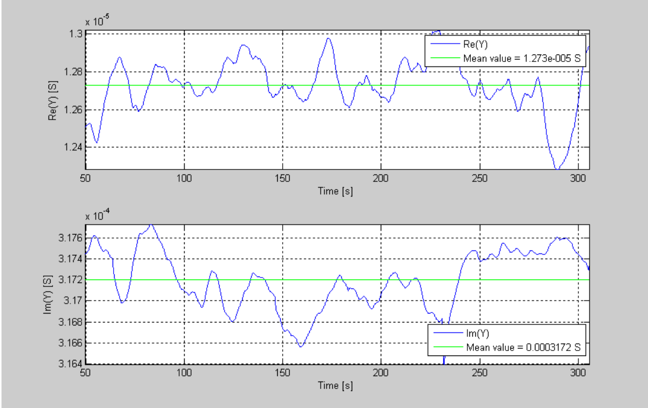

Figure 9. Trends of line admittance Y [Re(Y)=G...conductance, Im(Y)=B...susceptance]

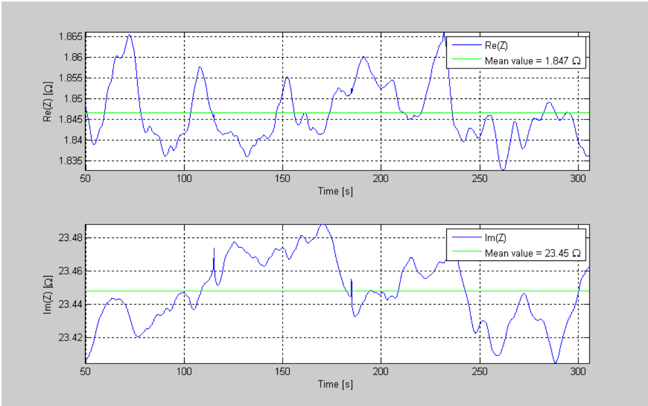

Figure 10. Trends of line impedance Z [Re(Z)=R...resistance, Im(Z)=X...reactance]

V. NOMINAL ELECTRICAL PARAMETERS OF OVERHEAD LINES

The nominal parameters were measured during switch-off state by using of OMICRON. The values of these parameters are well known and therefore the comparing with parameters calculated from synchrophasors is possible [3].

The values of positive-sequence impedance and leading susceptance measured by OMICRON are following:

$$Z1 = (2,02 + j24,85)\Omega$$
$$B1 = 318\mu S$$

A. Determination of lines parameters from synchronous phasors

The phasors of voltages and currents were measured during January 14, and February 9, 2010, with sampling rate 50 pattern per second. The average values of calculated lines parameters are following:

a) Phase B, date January 14, 2010 (without correction on the temperature):

$\mathbf{Z_B = (1,46 + j\ 24,48)}$ **[Ω]**

$\mathbf{B_B = 319}$ **[uS]**

b) Phase C, date January 14, 2010 (without correction on the temperature):

$\mathbf{Z_C = (1,87 + j\ 23,46)}$ **[Ω]**

$\mathbf{B_C = 318}$ **[uS]**

c) Phase B, date February 9, 2010 (without correction on the temperature):

$\mathbf{Z_B = (1,40 + j\ 24,56)}$ **[Ω]**

$\mathbf{B_B = 319}$ **[uS]**

d) Phase C, date February 9, 2010 (without correction on the temperature):

$\mathbf{Z_C = (1,84 + j\ 23,44)}$ **[Ω]**

$\mathbf{B_C = 317}$ **[uS]**

VI. AMPACITY OF TRANSMISSION LINES

Current load capability (ampacity) of overhead lines is not constant, but it is influenced by climatic conditions (outside temperature, flow of wind – the most influence, sunrise intensivity – the low influence), temperature of line wire and operation conditions. Generaly the ampacity is determine by maximal operation suferable wire temperature, which is done by type of line wire. The ampacity dependents on regime of loading, which could be following:

- Steady state

Steady state is normal operation conditions, when the heat power done by load transit and sunny radiation is egual as power head eliminating by convection and radiation. The electric current, wire temperature as well as actual wheather are suggested invariable during steady state.

- Dynamical state

Dynamical state occurs during step change of current. It is, e.g., switch-on of transmission line or sudden current change influenced by failure of next branch of line. Typical example of dynamical loading is double current in the correct branche of dual line, when the failure occurs in the adjacent branche. During new steady state the wire would be overheated, however owing to heat inertia is possible to overload the line. The new steady state will not be reached.

- Transients

Transients occurs during transit of short-circuit or lightning current. This is very fast transient and hence there are no heating exchange with surroundings. Under this situation the adiabatic conditions are thinking over.

A. *Estimation of average temperature of line wire from synchronous phasors*

Resistance (R)

The resistence of wires is depending of its temperature. Therefore if we know one specific value of resistance with known appropriate wires temperature then we could estimate the real temperature according to appropriate equation, on the base of this specific value of resistance calculated from measured synchronous phasors.

The temperature coefficient of electric resistance for aluminium is $\alpha = 4{\cdot}10^{-3}\ K^{-1}$ and for ferrum $\alpha = 5{\cdot}10^{-3}\ K^{-1}$. Because the rate between intersection of aluminium and ferrum is for wires AlFe8 equal 8, then resulting temperature coefficient of electric resistance for wires AlFe8 will be equal $\alpha_{AlFe8} = 4{,}11{\cdot}10^{-3}\ K^{-1}$.

- Wires, strips, ropes (multi wiring material – AlFe)

$$R_{DC01} = \frac{\rho_0}{S} \quad \left(\Omega\cdot m^{-1}; \Omega\cdot m, m^2\right)$$

$$\text{cca } R_{DC01} \in (0{,}05\,;2)\,\Omega\cdot km^{-1}$$

- Influence of temperature line into resistance R (equation of the 1st order),

$$k_T = 1 + \alpha_1(T_2 - T_1) \quad [-\,; K^{-1}, K]$$

material	Cu	Al	Fe (steel)
α_1	$3{,}93.10^{-3}$	$4{,}03.10^{-3}$	$4{,}5.10^{-3}$

respectively (equation of the 2nd order):

$$k_T = 1 + \alpha_1 (T_2 - T_1) + \alpha_2 (T_2 - T_1)^2$$

where $\alpha_1 = 4{,}11\ .\ 10^{-3}$

material	Cu	Al	Fe (steel)
α_2	$0{,}45.10^{-6}$	$1{,}1.10^{-6}$	9.10^{-6}

$$\mathbf{R_1 = R_{DC01}\ .\ K_T}$$

B. *The temperature correction*

The value of currents difference (cross section AlFe 3 x 450 [mm^2] , max current: Imax = 1968 [A], scope of working lines temperature <20, 80 [°C]>) :

	CHR current	HRD current
14.1.2010	356.839214	369.197825/18%
9.2.2010	289.510512	295.163243/15%
current difference	67.3287	74.03458
T=f(I) – “nomograms”	**31** [°C] - jan.	**29** [°C] – feb.
temp. difference		3 [°C]

Instead of “nomograms” there is possible to measure at least one “reference” temperature of line in one operation point, then is possible directly to calculate the parameters and temperature in the scope of operation range.

B.1 - The calculation of strip temperature difference (January):

$(T_1–T_2) = 1/\alpha_1 \,.\, (R_1–R_2) / R_1 =$
$0{,}2439.10^3 \,.\, (\mathbf{1{,}879204} – \mathbf{1{,}846623}) / 1{,}846623 = 4{,}3$ [°C]

The corrected line temperature:
$dT_p =$ **31** + 4,3 = **35,3** [°C]

B.2-The calculation of strip temperature difference (February):

$(T_1–T_2) = 1/\alpha_1 \,.\, (R_2–R_1) / R_2 =$
$0{,}2439.10^3 \,.\, (\mathbf{1{,}846623} – \mathbf{1{,}879204}) / 1{,}879204 = - 4{,}2$ [°C]

The corrected line temperature:
$dT_p =$ **29** + 4,2 = **33,2** [°C]

dTp … recalculated temperature difference of the strip, according to real currents, for measurements “january” and “february”.

The value of power lines resistance with known resistance *r1* with lines temperature $\vartheta 1$ = 20°c of wires AlFe8. According to physical laws the lines temperature is proportionally dependent on outdore temperature.

Therefore the value of resistance is following:

a) For January 14, measurement

R1 = RDC01 . (1 + α1 (T2 – T1)) = 2,02 . (1 + $4{,}11.10^{-3}$. (**35,3** - 20)) = 2,14702366 = **2,15** [Ω]

b) For February 9, measurement

R1 = RDC01 . (1 + α1 (T2 – T1)) = 2,02 . (1 + $4{,}11.10^{-3}$. (**33,2** - 20)) = 2,12958904 = **2,13** [Ω]

On the base of these results is possible to express the engineers conjecture that contemporary accuracy of synchronous measurements is enough good for realization of some credibly applications in the operation [3].

VII. Static and Dynamic State Estimation

Changing conditions of distribution and transmission system operation induce new requirements to the software tools of their control systems including monitoring and state estimation. In transmission systems, it is the necessity of operation **security assessment** within a large interconnected grid, with regard to the energy market and new non-standard power sources. In distribution, the thing is massive **penetration of distributed generation**.

A. Hybrid Estimator

Formerly prevailing procedure, when the security has been checked primarily at the operation preparing level, is not sufficient. The accent is moving to the real time security assessment and therefore the importance of reliable and exact **state estimation** is growing significantly. Power system state estimation is generally considered as a critical application. Without estimation the security control in real time is impossible, particularly in states close to the maximal transmission capacity of lines. The accuracy of estimates heavily depends on the accuracy and synchronism of measurement inputs. The **WAMS (Wide Area Measurement System)** brings new possibilities of using synchronous measurement of voltages and currents from **PMU (Phasor Measurement Unit)** as new data inputs to the state estimation. Today is broadly recognized that phasor measurements give possibility of significant improving of estimation results accuracy and robustness.

In existing or planned projects of state estimation with phasor measurements the concept of **hybrid estimator** is prevailing. The second possible approach, when the PMU measurements are processed fully separately from classical SCADA measurements, is so far less frequent. This second method has bigger requirements to PMU installations. However there exists opinion that in the future phasor measurements installed through the whole network completely replace classical SCADA measurements. On the input of a hybrid estimator there is a measurement mixture of various origin: SCADA measurements with different delays, synchronous phasors of voltages and currents. Most estimators work with positive sequence component model and then it is necessary also from measured phasors to compute the positive sequence component used then on the hybrid estimator input.

B. Optimization of PMU placement

It is well know that not only the number but also the placement of PMU has great impact on the estimation quality, i.e. on the magnitude of estimation errors. The PMU placement may be optimized from the viewpoint of system observability or contribution to the estimation accuracy. Tests with dynamic estimation on the 14 bus IEEE model demonstrated, that including of phasors only in two buses decreased the estimation error of filtered voltage values from 0.5 % to 0.05 % and voltage angle error from 3 degrees to 0.5 degrees [4]. Similar reduction of estimation error after including phasor measurement has been found also in predicted voltages.

Furthermore it was stated, that with increased number of PMU the accuracy of the estimates does not increase markedly from a certain number of PMU, depending on the studied system. That means, always **it is necessary to find the optimal placement of PMU for the actual network from the viewpoint of observability, identifiability of measurement errors and accuracy of results.** Many methods of placement optimization exist, which eliminate also the occurrence of critical measurements [5]. The reliability of an estimator lies above all in its **robustness**, i.e. the ability of reliable function after large variation in the measurement set, after an outage or gross measurement error and after a topology change. It closely relates with the occurrence of critical measurements, whose outage leads to the observability loss. It is necessary to prove if the robustness criterion is fulfilled with given configuration of measurements and various grid topologies, and with given topology and various combinations of measurement outages. The usual result of robustness check is a proposal to completion of remote measurements in some nodes in the grid.

Phasor measurements have large importance also for making easier the detection of measurement errors and elimination of critical measurement in the nodes with small local redundancy. **Above all the phasor angles measurements support considerably the reduction of large errors impact on the neighbouring nodes** (effect of “error smearing”).

The accuracy of **line parameters** has also a substantial influence on the estimation quality. These values are usually considered as constant, although it is well known that parameters may vary during one year in the range of ± 10 % or more. The refinement of parameter values is possible with use of synchrophasors U and I at both ends of a line. It was discovered [6] that the difference in the voltage estimation at the level 400 kV using passport values of parameters or their computed values from PMU was as much as 1.5 % of voltage value.

VIII. CONCLUSIONS

- The parameter values shown in this paper are engaged as demonstration of possible calculation procedure for utilization of synchronous phasors.
- On the base of achieved results is confirme that accuracy of synchronous phasors measurements is sufficient for average values of calculated line parameters.
- The most important fact is not only accurate parameter values but also the trends of „on-line“ changes of its. These „on-line“ changes are depending of internal conditions (e.g. current loads) as well as external conditions (meteorologic, e.g. outdoor temperature, sunshine, wind).
- The payoffs attainable through including of synchronous phasor measurement into the input data of the state estimation are:
  - improving the accuracy of measurements
  - improving the grid observability
  - improving the estimator ability to find and correct erroneous and critical measurements
  - improving accuracy and reliability of estimation results
  - robustness of the estimator
- Estimation errors originate from three basic sources:
  - measurement (systematic, random) errors
  - topology errors
  - errors in parameters of branches

With use of phasor measurements in estimation it is possible to achieve significant decrease in the influence of these three error sources and in the ideal case their full elimination. Improvement of estimation and elimination of measuring chain errors is attainable with help of decentralized (distributed) estimation or so called “Supercalibrator” – see [7], where the task is decomposed into two levels.

- The next object of this paper will be using of synchrophasors for backup transmission line protection, e.g. for ground faults and power swing detection. The proposed protection approach complements protective distance elements and is suitable for single-pole and three-pole tripping applications. The next applications are safety local automats, prediction of emergency situations and also static state estimation and especially dynamic state estimation.

REFERENCES

[1] Guzmán, A., et al (2007): Using Synchronized Phasor Angle Difference for Wide-Area Protection and Control. Schweitzer Engineering Laboratories, Inc., 20070918 – TP6291-01.

[2] López, S., et al. (2006): Synchrophasor Applications of the National Electric System Operator of Spain, Schweitzer Engineering Laboratories, Inc., 20061214 – TP6272-01.

[3] Neuman P., M. Kanok, L. Hanka and J. Jirkovsky (2010): PMU Measurements in Czech Transmission Power System – Analysis, and Parameters Calculations as basis of WAMS, 9th Int. Conf. Control of Power Systems 2010, Tatranske Matliare – High Tatras, Slovak Republic.

[4] Amit Jain (2008): Phasor Measurements in Dynamic State Estimation of Power Systems, Int. Institute of Information Technology, Hyderabad, India.

[5] A.Z.Gamm, Yu.A.Grishin and I.N.Kolosok (2006): Reducing the Risk of Blackouts through Improved EPS State Estimation Based on the SCADA and PMU Data, 3.Int.Workshop “Liberalization and Modernization of Power Systems”, Irkutsk, Russia

[6] S.Skok, I.Pavic, A.Barta, I.Ivankovic, N.Baranovic, Z.Cerina and R.Matica (2008): Hybrid State Estimation Model Based on PMU and SCADA Measurements, Conf. Monitoring of PS Dynamics Performance, Saint Petersburg.

[7] A.P.S. Meliopoulos, G.J.Cokkinides, F.Galvan, B.Fardanesh, P.Myrda (2007): Advances in the SuperCalibrator Concept – Practical Implementations, Proc. Of the 40th Hawaii Int. Conf. on System Sciences, Hawai, USA.