INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2020, VOL. 66, NO. 4, PP. 775-780
Manuscript received June 7, 2020; revised October, 2020. DOI: 10.24425/ijet.2020.134040

The Use of PMU Data for Detecting and Monitoring Selected Electromagnetic Disturbances

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***Abstract*—Power quality (PQ) monitoring is important for both the utilities and also the users of electric power. The most widespread measurement instrument used for PQ monitoring is the PQM (Power Quality Monitor) or PQA (Power Quality Analyzer). In this paper we propose the usage of PMU data for PQ parameters monitoring. We present a new methodology of PQ parameters monitoring and classification based on PMU data. The proposed methodology is tested with real measurements performed in distribution system using dedicated PMU system.**

***Keywords*—electrical disturbances; phasor measurement unit; power quality; distribution system**

I. INTRODUCTION

THE issue of power quality (PQ) is present at every step of electric energy supply process, both in transmission and distribution, but also in the usage of energy by end-point consumer.

PQ is understood in many different ways. Distributor of energy will define power quality differently from a client or equipment producer. According to [1] one of the most accurate definition of PQ is a definition introduced by Advisory Committee for Electromagnetic Compatibility (ACEC) IEC: “Power quality is a set of parameters describing the characteristics of the process of energy supply to the user under normal operating conditions, determining the continuity of supply (long and short interruptions in supply) and characterizing the supply voltage (value, asymmetry, frequency, shape of the time waveform)”

Suppliers sell energy, characterizing its quality with selected indicators which values cannot always be fully controlled. Numerical quality indicators are degraded under the influence of consumers through transmission and distribution of energy, but also consumption and production. Distributed energy sources can also be significant source of quality indicators degradation.

The most widespread measurement instrument used for PQ monitoring is PQM (Power Quality Monitor) or PQA (Power Quality Analyzer). Nowadays there is a high number of PMUs installed in transmission and also distribution systems, and further increase of PMU number is expected. New functionalities of PMU data, including PQ are now being investigated, and it is expected that PMU data will provide a new insight into PQ monitoring in distribution system [2-3].

PQM consists of three main functional blocks: 1) signal acquisition, 2) computational part and 3) communication layer. PMUs are made of similar functional blocks. PMU reports the amplitude, phase, frequency and frequency change ROCOF (Rate of Change of Frequency) for fundamental component of the measured voltage or current.

The possibility of using PMU as PQM depends on the characteristics of the analog input circuits as well as the speed and resolution of the signal acquisition. If the phasor is calculated by software and the hardware platform has the appropriate computing power, any PQ indices can be determined simultaneously with the phasor.

PMU measurements can be integrated with the PQ measurement system. In distribution networks with PQ analyzers and SM devices (Smart Meters) installed, PQ measurements carried out by PMU introduce redundancy, which increases the reliability of measurements [12].

USM (Unbundled Smart Meter) devices and their newer versions NORM (Next Generation Open Real-Time Smart Meters) integrate SM, PMU and other units on one platform [13]. Due to the benefits of measuring Synchrophasors, new intelligent IED (Intelligent Electronic Devices) systems can work as PMUs. Devices such as DFR and PMU are integrated into MPPs (Multipurpose Platform) with the PQ analyzer, event recorder and PMU functionality [13].

In this work a methodology of PQ parameters motoring and classification using PMU is presented based on three phase analysis with special interest in asymmetry motoring.

II. THE USE OF PMU FOR DETECTING AND MEASURING OF TYPICAL PHENOMENA IN POWER SYSTEM

Continuous time sinusoidal signal is given with

$$x(t) = a(t)\cos(\omega_0 t + \varphi(t)) \tag{1}$$

where: $\omega_0 = 2\pi f_0$ is a nominal pulsation in rad/s, f_0 is a nominal frequency in Hz, $a(t)$ is time-varying amplitude and $\varphi(t)$ is a time-varying phase in radians, the phasor is defined as [4-5]

$$p(t) = \frac{a(t)}{\sqrt{2}} e^{j\varphi(t)} \tag{2}$$

The phasor should be estimated 10, 25 or 50 times per second for nominal frequency f_0=50. A synchrophasor is a phasor referred to universal time.

The instantaneous frequency f_{in} of (1) is the 1st order time derivative of cosine argument in (1):

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$$f_{in}(t) = f_0 + \frac{1}{2\pi}\frac{d\varphi(t)}{dt} \tag{3}$$

and the rate of change of frequency (ROCOF) is the 2nd order time derivative of the cosine angle

$$ROCOF(t) = f\,\frac{1}{2\pi}\frac{d^2\varphi(t)}{d^2t} = \frac{df_{in}(t)}{dt} \tag{4}$$

There is a number of synchrophasor measurement methods which differ by their response time, accuracy and disturbance rejection [6-8]. Figure 1 represents a generic phasor measurement model.

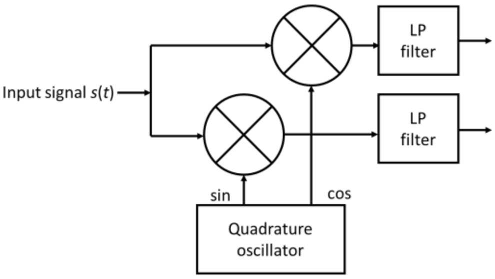

Fig. 1. Phasor measurement model].

The PMU unit can be equipped (extended) with additional functionalities:

- the availability of the time waveform of the measured voltage or current,
- phasors for harmonic frequencies [6],
- residual signal availability, i.e. the difference between the sinusoidal signal reconstructed based on the phasor and the measured signal,
-measurements of environmental quantities such as temperature, sunlight, wind strength, humidity, smoke, pressure, etc.

Based on the phasor, residual signal and time waveform, it is possible to determine all indicators of electric energy quality available in PQ analyzers, and also to monitor power flow in the system as well as to detect and locate emergency conditions [9]. Harmonic synchrophasors can be used to monitor harmonic power flow and harmonic impedance estimation.

Table I summarizes the possibility of using phasor technology to detect and measure phenomena occurring in the power system and affecting the quality of the electricity, listed in the IEEE standard [11]. In case of the PMU recorder, which additionally provides the time course of the measured signal, residual signal and supports the calculation of the harmonic phasor, it is possible to determine the parameters of all disturbances defined in [11].

In [11] a summary of operational requirements for the use of synchrophasor technology in the distribution network is presented. The resolution of measurement data, measurement accuracy, delays and continuity of transmission as well as the location of PMUs in the distribution network are considered. The basic distinction between PMU applications relates to the steady state and the dynamic state of the power system. For the steady state, e.g. when estimating the system state, comparisons of synchrophasors measured at different points are important. In this application, the absolute error should be small compared to the measured value, even at the level of 0.0001 p.u. [11] gives the requirements regarding the accuracy of voltage and phase measurement for state estimation, model validation, error location and control. In the dynamic state, time changes are observed and momentary resolution is more important.

TABLE I
POSSIBILITY OF USING PHASOR TECHNOLOGY TO DETECT AND MEASURE TYPICAL PHENOMENA OCCURRING IN THE POWER GRID.

Disturbance	Standard PMU	Extended PMU
Transients (surge) Impulsive transients Oscillatory transient (low-frequency, medium-frequency, high-frequency)	NO	YES Residual signal required. In the case of high-frequency, a sufficiently high sampling rate is required. A dedicated application is required to determine the parameters of the disorder.
Short-duration rms variations voltage dips (sags), swells (rises) interruptions (instantaneous, momentary, and temporary)	Detection YES	YES For instantaneous measurement of parameters requires the availability of a time course.
Long-duration rms variations Overvoltage, Undervoltage, Sustained interruptions	YES	
Voltage imbalance (unbalance)	YES If each phase is recorded	
Waveform distortion DC offset Harmonics Interharmonics Notching Noise	NO	YES Residual signal and harmonic phasor are required.
Voltage fluctuations (light flicker)	YES	
Power frequency variations	YES	

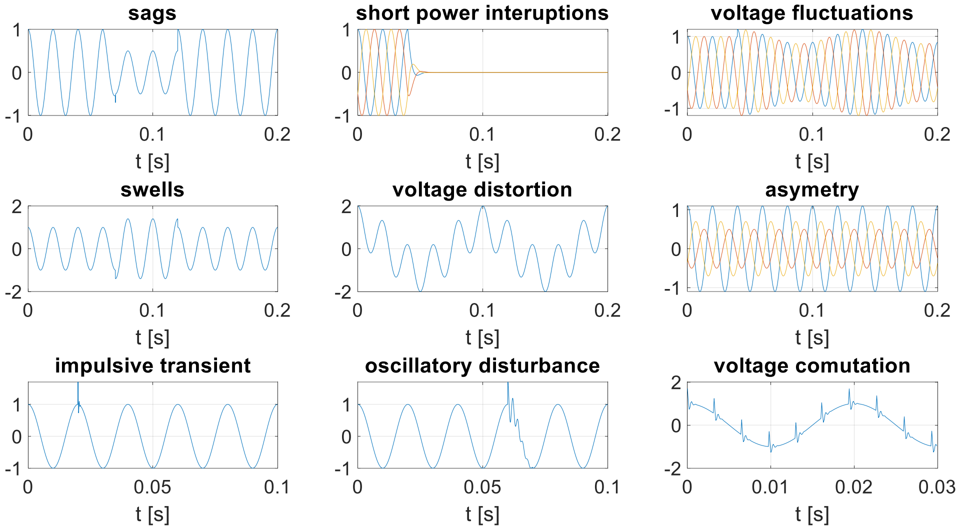

Fig. 2. Examples of electromagnetic disturbances [1].

In [11] greater tolerance to absolute errors is seen when used for event detection, voltage variation measurement, topology detection, phase identification and DG (Distributed Generation). When analyzing the phenomena observed by means of PMU, it should be considered that although the timing of synchrophasors is very accurate, their reporting is usually equal to the nominal frequency of the system. Thus, in case of a 50 Hz system, the measurement resolution is 20 ms.

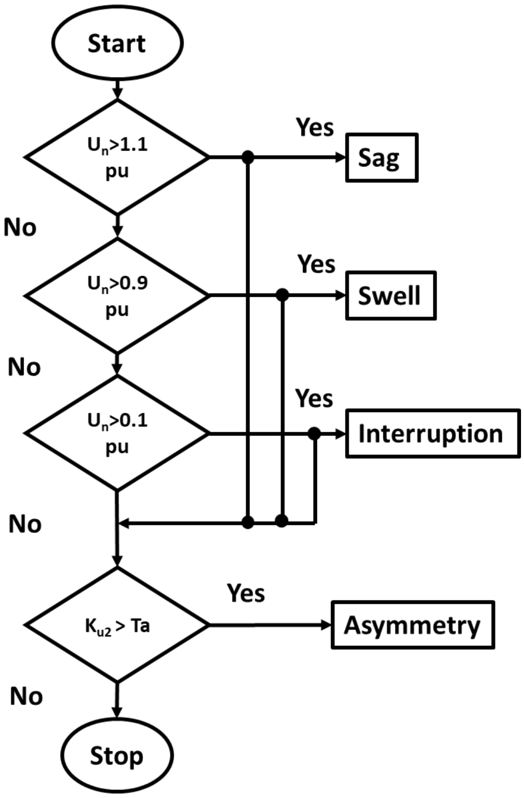

Fig. 3.Methodology of threshold-based rules for PQ distortions at the fundamental components (where U_n is module of specific case, K_{u2} is asymmetry indicator and T_a is chosen asymmetry indicator threshold).

Figure 2 presents examples of disturbances occurring in power supply networks [1]. According to the IEC classification, most of them belong to the category of low-frequency phenomena (up to 9 kHz).

Figure 3 presents the proposed threshold-based methodology for PQ distortions at the fundamental component. In the first three steps of algorithm each phase voltage magnitude is compared with a threshold chosen according to the IEEE Standard 1159, like it was introduced in [2]. In the last step asymmetry is calculated and compered with the chosen threshold.

There are multiple definitions of asymmetry indicators [11, 14, 15] which use different types of voltage parameters. PMU often provides only phase voltages, thus as an asymmetry calculation method, a method prosed in IEEE 1159 standard was used [11]:

$$K_{2u} = \left|\frac{\underline{U}_{L1}+a^2\underline{U}_{L2}+a\underline{U}_{L2}}{\underline{U}_{L1}+a\underline{U}_{L2}+a^2\underline{U}_{L2}}\right| \cdot 100\% \qquad (5)$$

where $a = e^{j\frac{2}{3}\pi} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$ and $a^2 = e^{j\frac{4}{3}\pi} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$.

Assuming that the phase voltage (L1) is located in the real axis, the complex values of phase voltages is given by:

$$\underline{U}_{L1} = U_{L1}\underline{U}_{L2} = U_{L2}e^{-j\alpha}\underline{U}_{L3} = U_{L3}e^{-j(\alpha+\beta)} \qquad (6)$$

where α is the angle between $\underline{U}_{L1}$ and $\underline{U}_{L2}$ and β is the angle between $\underline{U}_{L2}$ and $\underline{U}_{L3}$.

Asymmetry causes additional energy losses and affects the work of many electrical loads, especially: induction motors, synchronous generators and power electronics. For induction motors, this can be, for example, increased heating of the stator windings. In case of power electronic inverters, this can be, for example, uncommon harmonics generation for a given inverter topology [1].

III. MEASUREMENT SYSTEM AND DISTURBANCES CLASSIFICATION

Measurements were carried out with the use of PMU units produced by Power Standard Labs connected in the medium voltage network in Poland. Sampling rate for the instrument operating in the 50 Hz systems is 25.6 kHz. Reporting rate is 100 Hz. PMU operates in high accuracy mode compliant with IEEE C37.118.1 Standard [4].

PMU recorded voltage magnitudes, phases and frequencies. Four events were chosen for analysis and tests for presented methodology.

In figures 4, 5, 6, 7 and 8 magnitudes of three phase voltages, frequency of phase L1 and asymmetry are presented.

Table II, III, IV, V and VI present results of detecting three selected power quality disturbances: sags, swells and interruptions. Maximal value of measured asymmetry is also presented.

A. One phase short circuit

Figure 4 shows an example of one phase short circuit which is followed by second short circuit and oscillatory transient. Sag was recorded for phases L1, L2 and L3. Swell was recorded for phases L1, L2 and L3. Interruption was recorded for phase L3. Maximal recorded value of asymmetry equals 65%. One phase short circuit are a common cause for voltage sags. A sag in one phase caused a swell in two others phases.

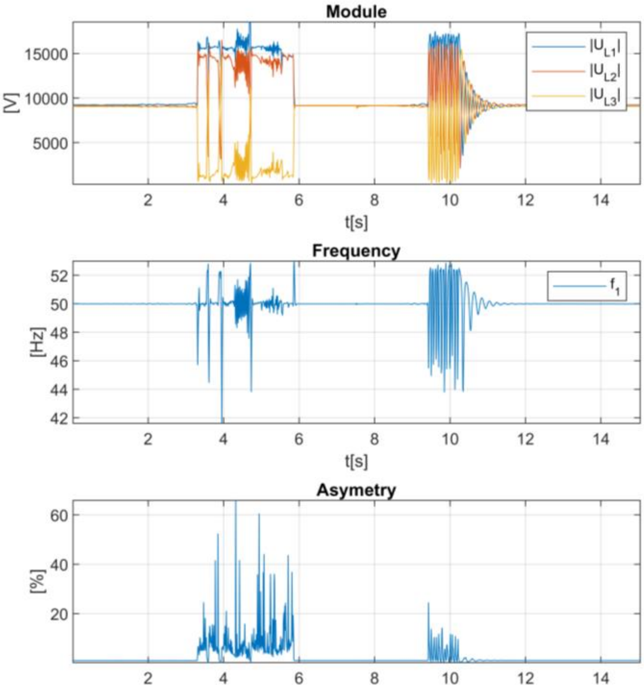

Fig. 4. Example of one phase short circuit.

TABLE II
RESULT FOR CASE A

Phase	Sag	Swell	Interruption	Max Asymmetry [%]
L1	YES	YES	NO	65
L2	YES	YES	NO	
L3	YES	YES	YES	

B. One phase short circuit

Figure 5 shows an example of one phase short circuit. Sag was recorded for phases L1, L2 and L3. Swell was recorded for phases L1 and L3. Interruption was recorded for phase L3. Maximal recorded value of asymmetry equals 37%. Presented phenomenon is similar to first part of A example.

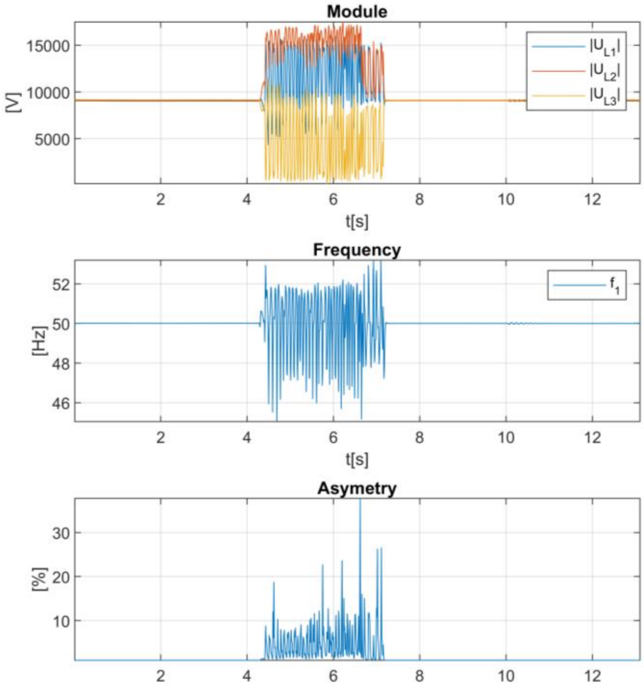

Fig. 5. Example of one phase short circuit.

TABLE III
RESULT FOR CASE B

Phase	Sag	Swell	Interruption	Max Asymmetry [%]
L1	YES	YES	NO	37
L2	YES	NO	NO	
L3	YES	YES	YES	

C. Oscillatory transient

Figure 6 shows an example of oscillatory transient. Sag was recorded for phases L1, L2 and L3. Swell was recorded for phases L1, L2 and L3. Interruption was not recorded. Maximal recorded value of asymmetry equals 1.57%. This phenomenon is supposedly an example of back-to-back capacitor switching. This kind of transient can occur when a capacitor bank is switched in close electrical proximity to another capacitor bank that is already energised.

TABLE IV
RESULT FOR CASE C

Phase	Sag	Swell	Interruption	Max Asymmetry [%]
L1	YES	YES	NO	1.57
L2	YES	YES	NO	
L3	YES	YES	NO	

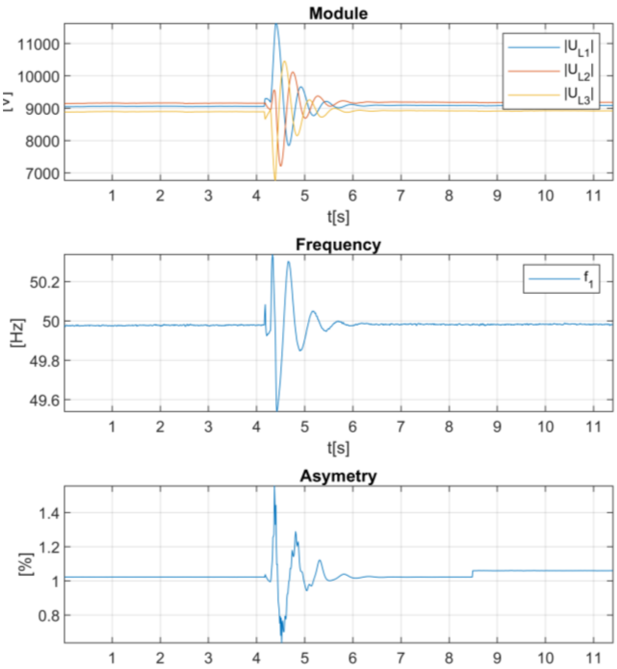

Fig. 6. Example of oscillatory transient.

D. *Probable overvoltage*

Figure 7 shows an example of overvoltage. Sag was recorded for phases L2 and L3. Swell was recorded for phases L1 and L3. Interruption was not recorded. Maximal recorded value of asymmetry equals 1.02%. This phenomenon could have been caused by a lightning.

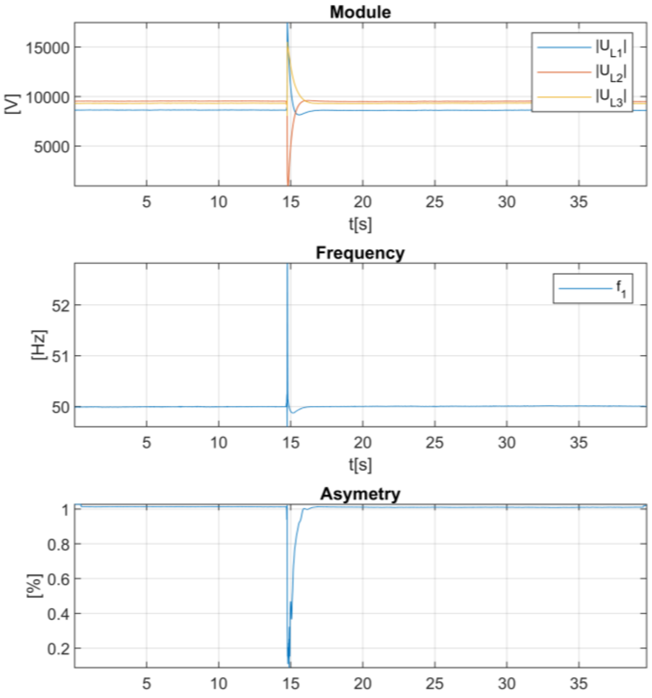

Fig. 7. Example of overvoltage.

TABLE V
RESULT FOR CASE A

Phase	Sag	Swell	Interruption	Max Asymmetry [%]
L1	NO	YES	NO	1.02
L2	YES	NO	NO	
L3	YES	YES	NO	

E. *Swell*

Figure 8 shows an example of swell. Sag was not recorded for any of phases. Swell was recorded for phases L1, L2 and L3. Interruption was not recorded. Maximal recorded value of asymmetry equals 1.03%. This phenomenon is an example of sag that could have been caused by the connection of significant three phase load.

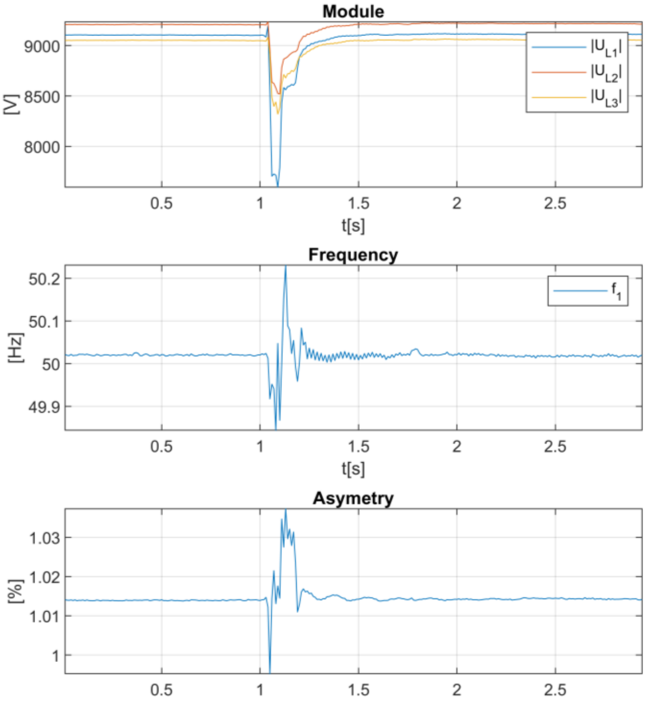

Fig. 8. Example of swell.

TABLE VI
RESULT FOR CASE A

Phase	Sag	Swell	Interruption	Max Asymmetry [%]
L1	NO	YES	NO	1.03
L2	NO	YES	NO	
L3	NO	YES	NO	

CONCLUSION

In this paper we propose the usage of PMU data for PQ parameters monitoring. A new methodology for PQ parameters monitoring and classification based on PMU data was proposed. A real data measurements carried out with the use of PMU in medium voltage network in Poland were performed. Four cases of different phenomena were analyzed. Presented results proved that PMU can be successfully used for PQ parameters monitoring. We believe that PMU measurements show an exceptional determinism and reporting rate that makes PMU a perfect instrument for detecting and monitoring of asymmetry indicator.

Asymmetry calculation next to PMU based harmonic impedance calculation can also lead to an efficient asymmetry localization method. In a future work a hardware implementation of the proposed methodology will be developed along side with the possible method of asymmetry source localization.

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