Application of Phasor and Node Voltage Measurements to Monitor Power Flow and Stability

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Abstract— This paper presents the applications of Phasor Measurement Unit (PMU) for monitoring the stability of wide area interconnected power system and node voltage measurement for monitoring the power flows inside a building. Wide area measurement system for the power system stability which has been developed by our group is installed at the power outlets in some university campuses in Japan. The system was also applied to Singapore-Malaysia power system. Others, the power flows on the wiring lines in a building are monitored by simultaneous measurements of node voltage at power outlets. Some results are shown in this paper.

Keywords: Power system stability, power flow monitoring, phasor measurements, smart power monitoring

1. Introduction

Electric power supply and distribution systems are continuously growing along with expansions of power systems. Accordingly, these large scale interconnections of power system cause power system inter-area stability degrading toward lower level. The power system in West Japan has a longitudinal structure due to its geographical constraints. The instability arises as a problem of low-frequency oscillation with weak damping characteristic originated from this power system structure. There are some examples of longitudinal power system such as Italy, Malay Peninsula and so on. In this paper, a global monitoring system of power system dynamics by using the Phasor Measurement Units (PMU) installed at demand side outlets is presented.

A number of PMUs are located in different universities in Japan, as shown in Figure1, and data are collected automatically via the Internet. By installing PMUs at multiple locations in a power system, time synchronized measurements with accuracy within ±1μs can be achieved by the use of GPS signal. Measured data from PMUs clearly show local frequency variations and phase difference between areas. From the information, low-frequency oscillations and power system stability that are useful for analyzing power system dynamics can be investigated and examined. With a proposed method, we can analyze the changes of power system stability in West Japan power system over the years since the stability characteristic may be shifting toward lower level with the increase of power demands associated with the social economy.

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In our phasor measurements the wall outlets are used. In the PMU research we just use the phasor of voltage. On the other hand, the information on the voltage magnitude is also useful. During the data analysis on PMU research we noticed that the voltage magnitude slightly drops when some electric appliance is switched on. Thus, inside a building voltage magnitudes are possibly utilized as a useful signal to estimate the active power flows. Then we investigated a method to measure the power of wiring line just from the voltage magnitudes of outlets. In this case we do not need a current sensor or a power meter to monitor the power flow but

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inexpensive voltage meters (no need of a phasor measurement function) are available for this purpose. In this paper a set of voltmeters dispersedly installed at wall outlets is presented as a monitoring system for power distribution inside of building or house. As a result, indoor power consumption was estimated with inexpensive and easy way by applying the proposed estimation method.

2. Monitoring of Wide Area Power System Dynamics by PMU

A. Campus WAMS in Japan

Figure 1 shows PMU locations developed by our group in Japan power system, in which the monitoring system is call as the "Campus WAMS" since the installation of PUMs are in the university campuses, and presently we have installed 12 PMUs: 9 of them are installed in the supply area of Western Japan 60-Hz system and another 3 in the supply area of Eastern Japan 50-Hz system (T. Hashiguchi. et al., 2008). The phasor measurement system employs a commercial PMU product, which is Network Computing Terminal Type-A, NCT2000 (Tsukui, R. et al., 2001). The PMU measures the single-phase voltage phasor of 100V outlets, and corrects its clock based on the time stamp of GPS. The phase angle of the measured voltage is accumulated in the PMU as the time sequential data. The PMU records the calculated phasor every 40 or 33 ms (2 cycles) and for every 20 minutes, the measured data is saved in a data file. The measured phasor data are transmitted via the internet to server at Kyutech.

From the measured phasor data of the Campus-WAMS, two kinds of useful signals can be computed: voltage phase difference between two locations and frequency deviation of each location. Increasing phase angle represents that the frequency of the observed voltage is higher than the system normal commercial frequency, 50-Hz or 60-Hz. Decreasing phase angle means that frequency of the observed voltage is lower. The time derivative of phase angle corresponds to the deviations of system frequency, which can be calculated by

$$\Delta f_n = \frac{\delta_{n+1} - \delta_n}{360 \Delta t_n} \tag{1}$$

where, Δt_n [s] is the sampling interval of sequential phase data δ_n and n is the number of accumulated phase angle data. And the frequency variation can be observed by the PMU with accumulating the sequential frequency deviations Δf_n .

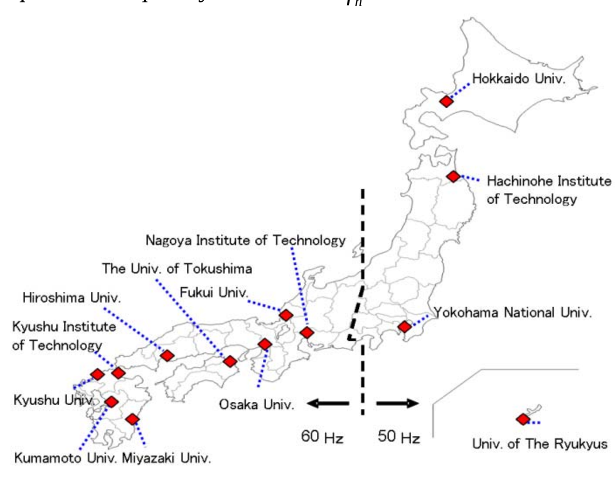

Figure 1. Assignment of Phasor Measurement Units in Japan.

B. Application to Singapore-Malaysia System

By collaborations with Universiti Sains Malaysia and Nanyang Technological University, Singapore, we applied the Campus WAMS to the power system in Malay Peninsula. The map of Campus WAMS in Malay is shown in Figure 2

Figure 2. PMU installations in Malay Peninsula

The tie-line between Malaysia and Singapore is linked by AC and the tie-line between Malaysia and Thailand is by DC, so the power system in Malay Peninsula is one large AC interconnected system with a longitudinal structure which is similar to the West Japan power system. In such a longitudinal power system a low-frequency power oscillation mode around 0.3 - 0.5 Hz is observe, which is the dominant mode among some electro-mechanical oscillations.

3. Data Procssing for Wide Area Power System Stability Analysis

In this chapter a method to evaluate the stability of dominant mode based on the observed data from Campus WAMS by using the phase data of Nagoya Institute of Technology (Nagoya) and Miyazaki University (Miyazaki) located at both ends of power system in Western Japan.

A. FFT Analysis for Low-Frequency Oscillation Mode

Result of FFT analysis of phase difference between Nagoya and Miyazaki is shown in Figure 3.

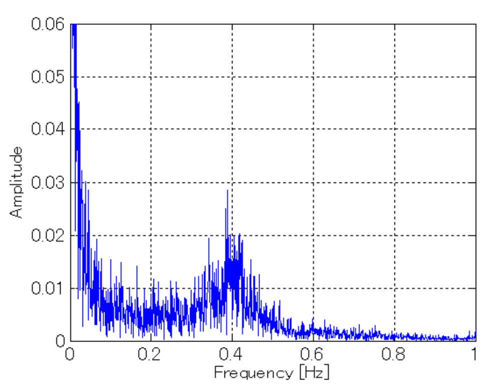

Figure 3. FFT Analysis of Oscillation Modes

We can observe the low-frequency oscillation mode around 0.4[Hz] in the result of FFT analysis of phase difference between both ends of power system in West Japan.

B. FFT Filtering for Extracting Low-Frequency Oscillation

In order to focus our attention to the low-frequency oscillation for the analysis of the stability, the FFT filtering method is available. The FFT filtering is a method to extract the frequency components we want in the FFT domain by replacing all of unused data with zeros and the inverse FFT method is applied to the extracted FFT data. After proceeding the FFT filtering, an oscillation waveform just associated with the dominant frequency can be extracted.

Figure 4 shows the original phase difference waveform after a power system disturbance occurred. Extracted phase difference waveform after the FFT filtering is applied is shown in Figure 5, and an oscillation with exponential damping can be observed, which is corresponding to the low frequency mode with around 0.4 Hz.

C. Simplified Oscillation Model for Eigenvalue Estimation

Eigenvalues can be estimated by using oscillation components extracted by using FFT filtering via simplified oscillation model as shown in (2).

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ a_1 & a_2 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} \tag{2}$$

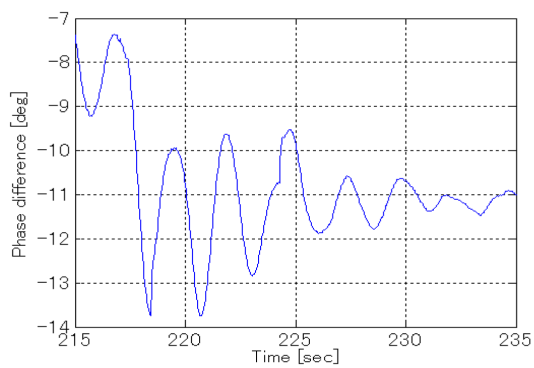

Figure 4. Phase difference of original data during

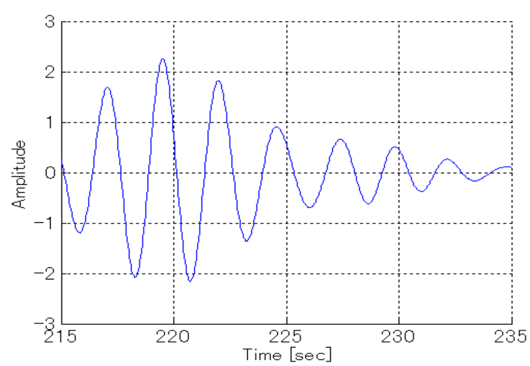

Figure 5. Extracted low frequency mode

where $\Delta\delta$ is the low-frequency oscillation component extracted from the phase difference data between two locations, $\Delta\omega$ (= $\Delta\dot{\delta}$) is the derivative of $\Delta\delta$, and $\Delta\dot{\omega}$ is the second derivative of $\Delta\delta$. System equation (2) can be evaluated using the least squares method based on the extracted mode waveform data. Eigenvalues of the power system at steady state condition are estimated by a couple of complex conjugate eigenvalue of (2). Real part of eigenvalue indicates the damping coefficient in 1/s (corresponding to the power system stability index) and imaginary part shows the angular velocity in rad/s of the dominant oscillation mode.

D. HHT (Hilbert-Huang Transform)Method and Hilbert Marginal spectrum

This part will introduce another method named Hilbert-Huang Transform and Hilbert Marginal spectrum. As mentioned before, the FFT filtering is a method to extract the frequency components we want in the FFT domain by replacing all of unused data with zeros and the inverse FFT method is applied to the extracted FFT data. However, FFT method itself has limitation, that is, FFT cannot be applied to non-stationary and non-linear data. Actually, the power system oscillation should change in frequency from location to location, and time to time, even within one oscillation cycle. It is a nonlinear and non-stationary system. In order to solve this problem, HHT is applied to analysis low frequency-oscillation, which is a fully adaptive time-frequency analysis methods, not only both suitable for nonlinear and non-stationary signal analysis but also for linear and stationary signal analysis (Huang Norden E., et al, 2005). It applied empirical model decomposition (EMD) to decompose the low frequency oscillation signals to get Intrinsic Mode Function (IMF). And then calculate the instantaneous parameters including power system low frequency and frequency energy change of every model component with Hilbert transformation.

The Hilbert spectrum offers a measure of amplitude contribution from each frequency and time, while the marginal spectrum offers a measure of the total amplitude (or energy) contribution from each frequency value. The marginal spectrum represents the cumulated amplitude over the entire data span in a probabilistic sense. The frequency in marginal spectrum has a totally different meaning from the Fourier spectral analysis. In the Fourier representation, the existence of energy at a frequency means a component of a sine or a cosine wave persisting through the time span of the data. Here, the existence of energy at the frequency means only that, in the whole time span of the data, there is a higher likelihood for such a wave to have appeared locally.

In fact, the Hilbert spectrum is a weighted non-normalized joint amplitude-frequency-time distribution. The weight assigned to each time frequency cell is the local amplitude. Consequently, the frequency in the marginal spectrum indicated only the likelihood that an oscillation with such a frequency exists. The exact occurrence time of that oscillation is given in the full Hilbert spectrum.

4. The basic principle to estimate active power Flows in a Building Using Node Voltage

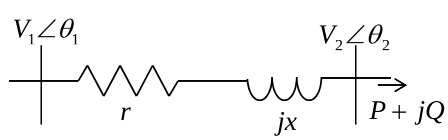

Figure 8. One line diagram of wiring line

Consider a part of the power distribution lines, as shown in Figure 8 where r and x are resistance and reactance of the line, V_1 and θ_1 are the supply side voltage and phase angle, V_2 and θ_2 are the outlet side voltage and phase angle, P and Q are the active and reactive power of the line, respectively.

Phasor relationship of the voltage of the supply side and the outlet side voltage are represented as follows:

$$\dot{V}_1 = V_1 e^{j\theta_1} \tag{3}$$
$$\dot{V}_2 = V_2 e^{j\theta_2} \tag{4}$$

Then, active power P and reactive power Q are calculated from the relation of $P + jQ = \dot{V}_2 \bar{I}$. Because the resistance component is relatively larger compared with the reactive component in the wiring line, after eliminating x components the active and reactive power are represented by

$$P \cong \frac{V_2(V_1 - V_2)}{r} \tag{5}$$
$$Q \cong \frac{V_1 V_2(\theta_2 - \theta_1)}{r} \tag{6}$$

In equation (5), the active power P can be estimated only by voltage values of two points if the resistance value of the line is known. Since the voltage is almost constant the active power is almost proportional to the voltage difference, while the reactive power Q has less effect on the voltage difference. Therefore, power flow analysis of active power can be carried out by measuring the voltage difference of the line. So, by replacing $1/r$ with α/V_s, equation (5) can be rewritten as the following equation.

$$P = \left(\frac{V_2}{V_s}\right)\alpha_{12}(V_1 - V_2) \tag{7}$$

Here, α_{12} is defined as the rate of change in voltage difference against the changes in the load power consumption when a known load (we call this as a reference load) is connected to the outlet and α_{12} is referred to as a conversion factor to power P from the voltage difference between two nodes. In other words, it is the percentage of voltage drop by resistance of line between two measurement points when the load is connected to the outlet. And, V_s is the reference voltage before the reference load is connected. P can be estimated from only information of voltage difference by using these voltage values when any kinds of load are connected. In addition, a voltmeter can be installed together with a connected appliance, which means that the appliance needs not be disconnected from the outlet because this estimation method for active power uses only voltage information. Therefore, this technique can measure the active power without measuring the current.

Actual wiring lines have more complicated connections with some bifurcations. In such a case we need a method to estimate the voltage at the bifurcated point. Then, the above-mentioned manner is applicable in general.

5. Results from the Campus WAMS

A. Analysis of Lowr FrequencyOscillation Mode

By using some filtering method such as wavelet transformation or FFT filtering we can extract the low frequency mode clearly. Since data are time-synchronized the geographical

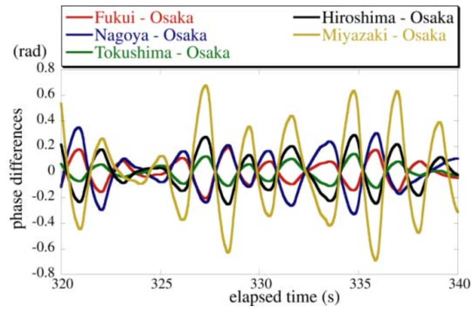

Figure 9. Extracted low frequency mode

mode shape of the oscillation can be analyzed. Figure 9 shows comparison of the waveforms of the low frequency mode referred to the phasor at Osaka observed at various places in West Japan power system. The result shows that Nagoya and Miyazaki, which are the both ends of West Japan system, swing in reverse phase.

B. Response of Frequency Drop afer Large Disturbances

Since the all data are time-synchronized by GPS we can evaluate the propagation of frequency drops. Here are some results when some large power plants were shut down due to protective actions against large events such as earthquakes, short circuits in transmission line and so on.

On 16th August, 2005 a large Nuclear Power Plants shutdown occurred in 50 Hz east power system in Japan. Since the frequency of 50 Hz system dropped in large amount (see Figure 10). After then an emergency action in Back to Back DC (BTB) system between 50 Hz and 60 Hz systems is taken to send a pre-determined amount of power from 60 Hz system to 50 Hz system. For the West 60 Hz system it was a kind of step response test. The responses in frequencies in local are shown in Figure 11.

C. Stability Analysis of the Low Frequency Mode Based on Eigenvalue Estimation

As it is mentioned eigenvalue analysis can be carried out using the phasor difference data between Nagoya and Miyazki. Especially, the real part of eigenvalue tells us the stability of the mode. We have continuously collected the data since 2004, so the variation of stability in the low frequency mode can be evaluated. Figure 12 shows the results year by year base.

Variations of real part of eigenvalues for one year estimated with proposed method using the phasor data between Nagoya and Miyazaki as shown in Figure12 informatively reveal that power system stability tends to decline during summer and winter which are the peak seasons of power demand, and recover through spring and fall. In the winter of 2008 the price of oil raised sharply. As a result electricity as a cheaper resource was used for heating by heat pumps, which increased the electricity power demand. In September, 2009 Lehman shock decreased the electricity demand and the price of oil dropped down. Thus, with the proposed method, relationships between electric power demands and power system stability are well explained.

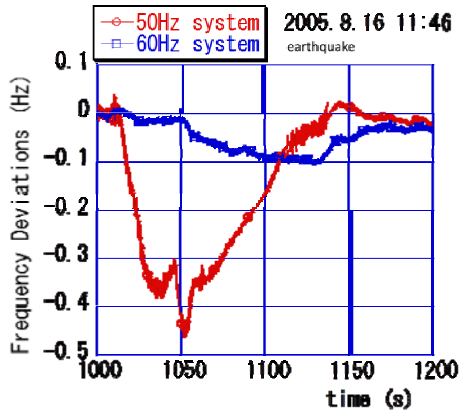

Figure 10. Frequency deviations in 50 Hz and 60 Hz systems after a large nuclear power plant shutdown in 50 Hz system

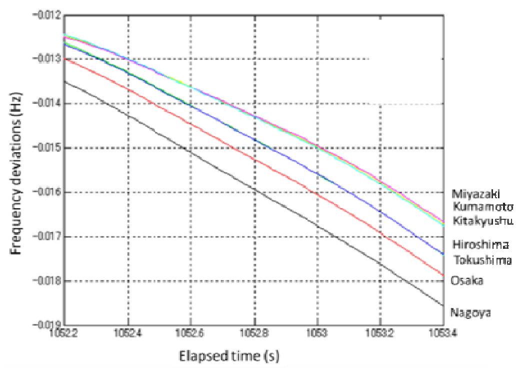

Figure 11. Response of frequency deviations.

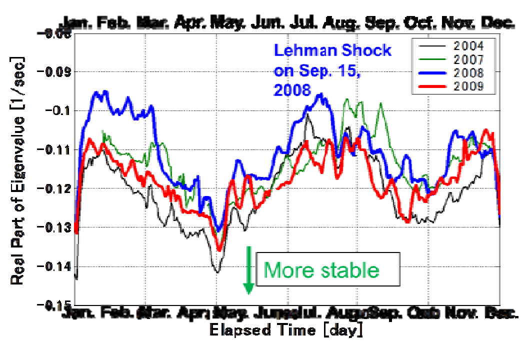

Figure 12. Variations of real part of eigenvalue in the low frequency mode

D. Analysis of the Low Frequency Mode Based on HHT Method and Hilbert Marginal spectrum

By using HHT method we can extract the frequency oscillation as shown in Figure13. The frequency's order of c1, c2…c8 is from high to low. This means that one of the local frequency

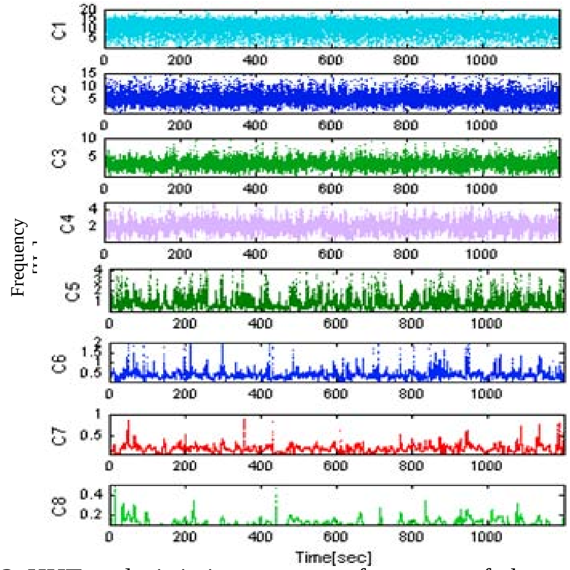

Figure 13. HHT analysis in instantaneous frequency of phase difference

of the c1 higher than same local frequency of c2 which also reflects the strong localized nature of the EMD algorithm. The characteristics of frequency of EMD from highest to lowest also mean that it can be used to de-noise. This is because Low-frequency oscillations are generator rotor angle oscillations having a frequency between 0.1 -2.0 Hz and are classified based on the source of the oscillation (P. Kundur, (1994). In this example, c1 to c4 and c8 can be removed from the original signal. Figure14 just shows the HHT spectrum instantaneous frequency of c5, c6 and c7, because that the center frequency of these three is mainly between 0.1-2.0 Hz. We can know that HHT preserves both good temporal and frequency resolutions; the instantaneous energy content and frequency variations are easily observed over the time axis for c5, c6 and c7. There are energy changes at 940 seconds (c5). It is easily to turn back the detail original signal as shown in Figure 15. A disturbance around 944 seconds is found.

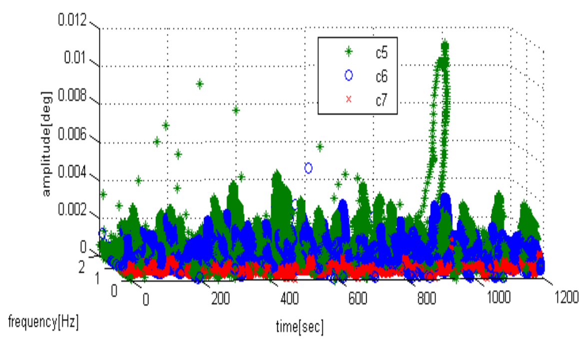

Figure 14. HHT spectrum in instantaneous frequency

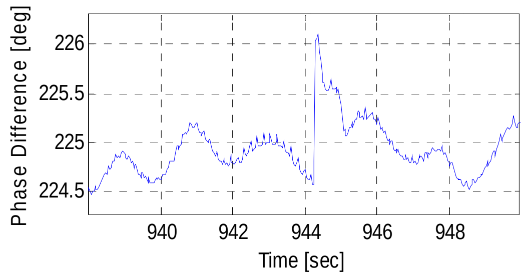

Figure 15. Phase difference at steady state

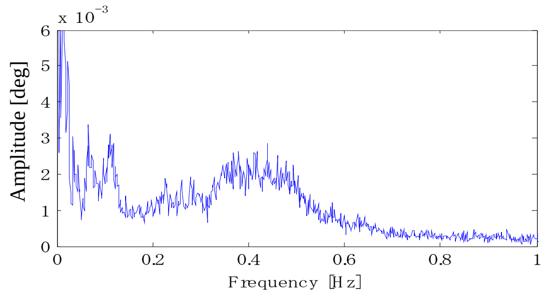

Figure 16. HHT marginal spectrum

The marginal spectrum as shown in Figure16 represents the cumulated amplitude over the entire data span in a probabilistic sense. That is the existence of energy at the frequency means only that, in the whole time span of the data, there is a higher likelihood for such a wave to have appeared locally. In this example, the range of frequency from 0.2 to 0.5 Hz is higher than other part means that the oscillation likelihood of the range is higher than other frequency' in cumulated amplitude over the 20 mins.

6. Monitoring of Power Flow by Node Voltage Measurements

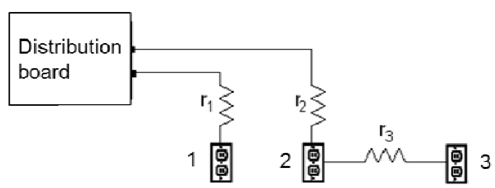

Figure 17. Configuration of wiring lines in a room.

Figure 17 shows the configuration of wiring lines and outlets from the distribution board in a room at Kyushu Institute of Technology. The proposed method has been applied to the active power flow measurement compared with the results by the use of power meter.

Figures 18, 19 and 20 compare the measured power at outlets 1, 2 and 3, respectively with the measurements by a power meter. There are good coincidences.

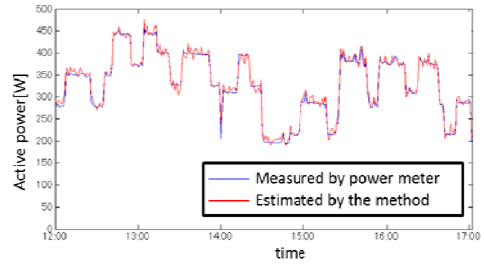

Figure 18. Comparison of power at outlet 1

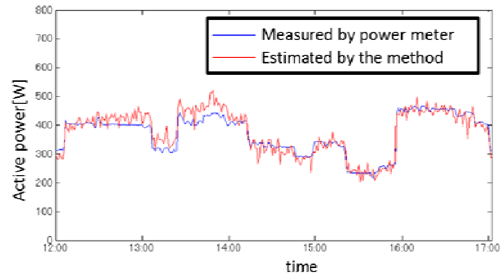

Figure 19. Comparison of power at outlet 2

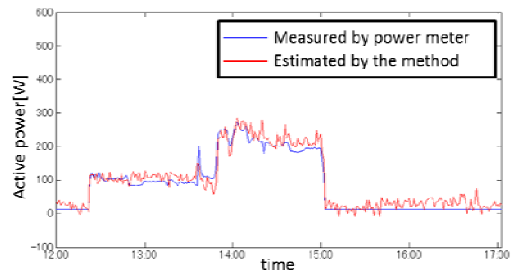

Figure 20. Comparison of power at outlet 3

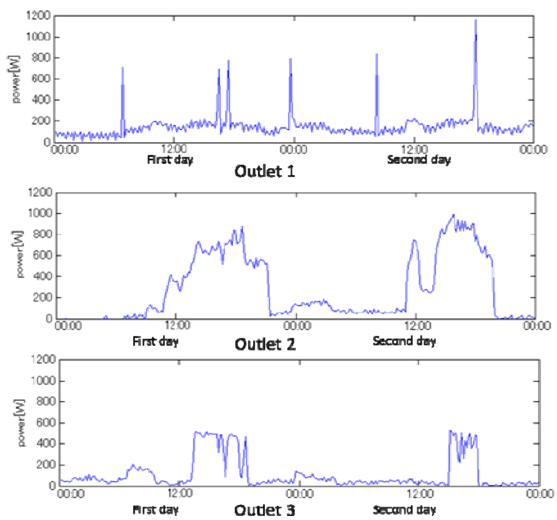

Figure 21. An example of measurements in two days

Figure 21 shows an example of power measurements by the proposed method. A refrigerator, a coffeemaker and an electric pot are connected at outlet 1. In outlets 2 and 3 many PCs and a printer are connected. We can see the detail operation of the refrigerator or the coffeemaker at outlet 1. There are some PCs which were not switched off during a night. On the second day some PC are shutdown or standby during the lunch time at outlet 2. Thus, we can have some findings of electric energy usages.

7. Concluding Remarks

In this paper a method to monitor the power system dynamics and stability by a synchronized phasor measurement and a method to monitor the active power flows in a building have been introduced. Since these methods are useful and easy to apply, they should be key devices in a future power system as a smart grid.

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