Proceedings of the 5th WSEAS Int. Conf. on Power Systems and Electromagnetic Compatibility, Corfu, Greece, August 23-25, 2005 (pp280-285)

Remote Assessment & Monitoring of Flicker Indices in a Large Power System

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Abstract: - In a deregulated electricity industry, new concerns have emerged regarding the quality of power supply as each company involved will focus on its own objectives and interest. One of the main concerns regarding the quality of power supply is the voltage fluctuation. This paper addresses a method for monitoring the voltage flicker using state estimation (FSE). The method is based on WLSM (weighted least squares method) of voltage. IEEE 14 bus grid is considered as the test network for the validation of the new FSE algorithm. The new FSE algorithm can be used by operators as well as distribution companies to monitor the flicker severity throughout the network.

Key-Words: - Power Quality, Voltage Flicker, Flicker-meter, State Estimation

1 Introduction

Power quality monitoring is necessary to characterize electromagnetic phenomena at a particular location on a power system. In some cases, the objective of the monitoring is to diagnose the incompatibilities between electric power source and load. In still others, monitoring may be used to predict the future performance of load equipment or power quality mitigating devices, however there are several important reasons to power quality monitoring. The primary reason underpinning all others is economic, particularly if critical process loads are being adversely affected by electromagnetic phenomena. Effects on equipment and process operation can include disoperation, damage, process disruption and other such anomalies. Such disruptions are costly since a profit-based operation is interrupted unexpectedly and must be restored to continue production. In addition equipment damage and subsequent repair cost both money and time. Product damage can also result from electromagnetic phenomena requiring that damaged product either recycled or discarded, both of which are economic issues. In addition to resolving equipment disruption, a database of equipment tolerances and sensitivity can be developed from monitored data. Such a database can provide a basis for developing equipment compatibility specifications and guidelines for future equipment enhancement. As per most power contracts, power quality indices such as flicker and harmonic shall be maintained in an acceptable range. In particular flicker and harmonics are of real concern to utilities when other consumers are nearby and can be adversely affected.

Sources of voltage flicker are numerous. Arc furnaces and arc welders head the list. Motor starting, fans, pumps, elevators and switching of power factor capacitor are among the most common cause of voltage flicker. Cyclic voltage flicker exist when there is a slow change in the voltage magnitude with frequencies between 0.5 to 30 Hz which appears as a superimposed signal on the fundamental signal. The superimposed signal, which is generated due to the voltage flicker, appears as a change in fundamental signal envelope and is commonly known as “Instantaneous Flicker Level (IFL)”.

Many techniques were proposed in literature for the evaluation of flicker level such as FFT technique [1], least absolute value “LAV” sate estimation [2, 3], wavelet [4, 5]. Leakage effect error is one of the major problems associated with FFT application. As the system frequency deviates from the nominal value, the leakage effect error may be very serious

To overcome such disadvantage wavelet transform were proposed. “LAV” method proposed the application of a least absolute value state estimation to measure voltage flicker magnitude and its frequency. The models presented in the references are a linear model of voltage flicker magnitude, its phase angle and frequency deviation. Linearizing the system equation may lead to inaccurate result in environments with high noise and bad data. Envelope tracking were proposed in [6], [7], [8] using ADALINE, Genetic algorithm and Teager

Energy Operator (TEO). These methods suffer the sensitivity to high frequency components (TEO) or high computational burden (GA and ADELINE). After all none of the above mentioned references provide P_{st} (Short term flicker level) and P_{lt} (Long term flicker level) indices that are more useful in flicker assessment and monitoring rather than flicker magnitude and its frequency.

In order to have an accurate monitoring of power quality indices, some measurements from grid are strongly required, however full measurement of the system states and extracting flicker indices and sending them to central control room, is prohibitive for a large system. This is why state estimation can be widely used to alter raw measurements to precious database. State estimation has been played a big role in power flow studies since the late 1960s. It is now an essential part in energy management system. Recent contributions [9-12] have extended the concept to harmonic state estimation (HSE) and identification of harmonic sources. Many of power quality indices such as P_{st} and P_{lt} are combination (often weighted) of individual states and are not suited to direct state estimation. Instead only harmonic (or inter-harmonic) or instantaneous voltage and current are normally state estimated and those indices are then calculated from these estimates.

This paper presents the FSE technique for the on-line assessment of voltage flicker. The framework of flicker state estimation is illustrated in Fig.1. On the basis of the network topology, an instantaneous state estimator is formulated from the system admittance matrix in time domain and the placement of measurement points. Measurement of instantaneous voltage and current at selected bus bars and lines are sent to a central workstation for the estimation of bus voltages. These estimated voltages then applied in a flicker-meter software to extract P_{st} and P_{lt} [13]. Measurement placement shall make all the buses observable. The implementation of this technique will, in practice, be limited by poor synchronization and accuracy of conventional instrumentation scheme, lack of continuity of measurement or lack of processing speed. The FSE can be implemented continuously in real time if the measurement is continues and the processing speed fast enough. Potentially, the measurements instruments and estimator can then be integrated into one existing supervisory control and data acquisition (SCADA) system. The performance of the proposed technique is tested by IEEE 14 bus sample grid. Results are obtained and discussed. This paper is divided into five sections. State estimation is introduced in section 2. Building up the measurement matrix is demonstrated in section 3. The example is given in section 4. Finally, section 5 concludes the paper.

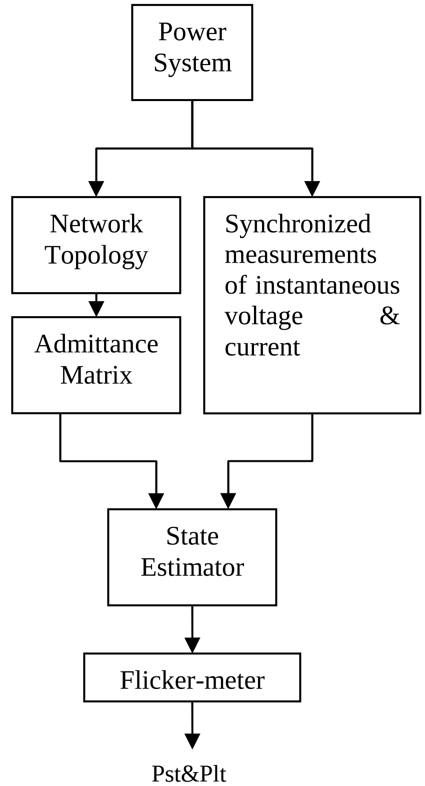

Fig1. Framework for flicker state estimation

2 Measurements and State Variable Model

The task of state estimation is to generate the best estimate of voltage from limited measured line currents or bus voltages, corrupted with measurement noise. The three issues involved are the choice of state variables, some performance criteria and the selection of measurement points and quantities to be measured. State variables are those, if known, completely specify the system. The instantaneous voltages at all buses are chosen, since they allow all branch currents, shunt currents to be determined.

Various performance criteria are possible; the most widely used being the Weighted Least Squares (WLS). This method minimizes the weighted sum of the squares of the residuals between the estimated instantaneous voltage and actual voltage measured. This can be shown to be the maximum likelihood estimate assuming that the noise distribution is Gaussian. For a given measurement set and system topology, the basic circuit laws lead to the following measurement equation:

$$Z = h(x) + \varepsilon \qquad (1)$$

Minimize $J(x) = \frac{1}{2}[Z - h(x)]^T R^{-1}[Z - h(x)]$ (2)

Where Z and x are the vectors of measurements and state variables, respectively, and ε is the measurement error vector which is assumed to be made of independent random variables with Gaussian distribution. Although in general, the measurement equation can be nonlinear, by choosing the bus voltages as state variables and real and reactive power as measurements, line currents and bus voltages measurements make Equation(1) linear. In this case, the task of estimating x given Z measurements in the presence of noise ε is expressed as:

$$Z = [h]x + \varepsilon \qquad (3)$$

In which $[h]$ is the measurement matrix. State estimation can be classified as over-determined, completely determined or under-determined on whether the number of independent measurement equation are greater, equal or less than the number of unknown state variables. A unique solution (Equation 4) is only possible for over determined and completely determined systems.

$$x^{est} = [[h]^T [R^{-1}][h]]^{-1}[h]^T [R^{-1}]Z^{meas} \qquad (4)$$

Matrix R is a diagonal and contains the covariances of the measurements (if they are known). This permits applying higher weightings to measurements that are known to be more accurate. The measurement matrix $[h]$ has more rows than columns but $[h]^T[R^{-1}][h]$ (known as the gain matrix) is a square matrix and can be easily solved using standard techniques. If not solved, there is a non-observability for given measurements.

3 Building up the Measurement Matrix

Each line current measurement adds a row to the measurement matrix. The measurement for a line connected between buses *i* and *j*, as shown in Fig.2 has two possible non-zero entries. Quantities being measured (in this case line current) are themselves functions of other variables that we wish to estimate (in this case bus voltage). If the sending-end line current is measured then:

$$i_s(t) = i_c(t) + i_{RL}(t) \qquad (5)$$

$$i_s(t) = \left(\frac{2c}{\Delta t(1+\alpha)} + \frac{1+\alpha}{\frac{2L}{\Delta t} + (1+\alpha)R}\right)v_i(t) - \left(\frac{1+\alpha}{\frac{2L}{\Delta t} + (1+\alpha)R}\right)v_j(t) - i_{hc} + i_{hRL}$$

(6)

In which i_{hc}, i_{hRL} are history terms of capacitive and inductive components of the line respectively and α is the compensating factor that shows how much the integrating method is close to Euler($\alpha = 1$)or Trapezoidal ($\alpha = 0$)rule with Sample time Δt. i_{hc}, i_{hRL} can be calculated as follows:

$$i_{hc} = \frac{2c}{\Delta t(1+\alpha)} v_i(t-\Delta t) - \frac{1-\alpha}{1+\alpha} i_c(t-\Delta t) \qquad (7)$$

$$i_{hRL} = \frac{1-\alpha}{\frac{2L}{\Delta t} + (1+\alpha)R}(v_i(t-\Delta t) - v_j(t-\Delta t)) + \frac{\frac{2L}{\Delta t} - (1-\alpha)R}{\frac{2L}{\Delta t} + (1+\alpha)R} i_{RL}(t-\Delta t)$$

(8)

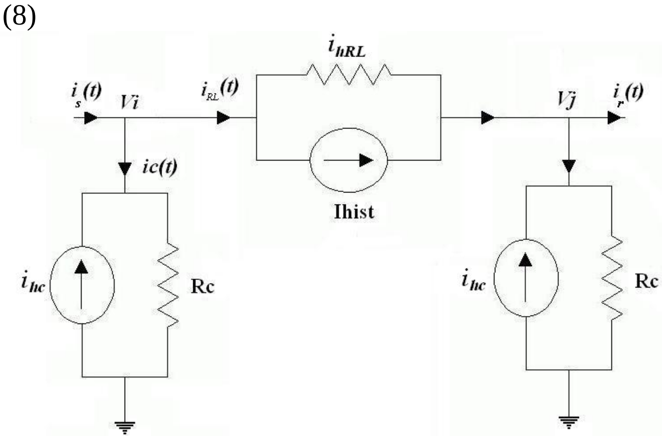

Fig2. Time domain equivalent of a branch

Equation (6) can be written for all branches and shown in matrix form as below:

$$I_s(t) = hV(t) + I_{hist} \qquad (9)$$

If there are N_m measurements and N_s states (bus voltage) then $I_s(t)$ is a $N_m \times 1$ vector of measurements, h is a $N_m \times N_s$ measurement matrix, $V(t)$ is a $N_s \times 1$ vector of bus voltages and I_{hist} is a $N_m \times 1$ vector of history term combination. Now equation (9) is the same as equation (3) and bus voltages can be calculated by equation (4).

4 Numerical Example

IEEE 14-bus grid is used as an example. Data can be found in Ref. [14]. Fig.3 shows the grid with measurement in all sending-end of the lines. Voltage of bus 1 is measured as well as 17 current measurements. One of the transformers between buses 4 and 9 is ignored for simplicity and as a result 14 buses are reduced to 12. Actual values are gathered from simulation of the grid in time domain with time step 0.1 m-sec for 10 minutes. As per standard, this time interval is required for *Pst* calculation. Arc furnace is modeled as a variable current source as in Equation 10 and connected to bus 10.

$$i_f(t) = (1 + 0.025 \times \cos(\omega_f t))\cos(\omega t) \qquad (10)$$

In which $\omega_f = 2\times\pi\times 9$ and $\omega = 2\times\pi\times 50$. These values are optional and can be changed by user. Result from the simulation were used at the measurement location and supplied to FSE algorithm. All measured quantities are then polluted with Gaussian noise with zero mean and $3\sigma = 0.1\%$ and applied in state estimation. Measurement matrix [*h*] is constructed by means of grid data and $\alpha = 0.15$. This factor shows that the integrating method is closer to Trapezoidal method rather than Euler for more accurate results. Equation (9) is written for all the branches. The FSE estimated the unmeasured quantities to be compared with the exact solution. As it is clear only 12 measurements would be enough to determine the bus voltages however the more measurements would result in the more accurate values. The estimated instantaneous voltages are then fed to flicker-meter simulation in order to obtain IFL. Flicker-meter has two main tasks, first to classified flicker sensation levels according to their value, thus obtaining their frequency distribution, second to establish cumulative probability function (CPF) when the observation period expires. This method has been called" Time at level classification". The foundation of the CPF concept is that time at a given level (class) gives the more useful indication. Class width can be selected by user in both simulation and real flicker-meter. Here it is considered to be 0.1. For the mentioned location of measurements, the results of the simulation are shown in Figures 4 to 7.

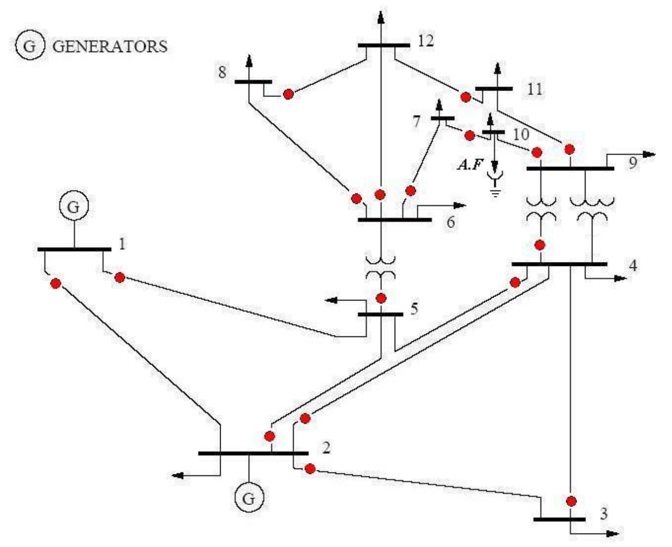

Fig3. IEEE 14-Bus as the test system

While maximum voltage error in Fig.4 is under 3.5%, IFL is oscillating in the class between 0.4 and 0.5. Real and estimated IFL in bus 6, are compared in Fig.5. Estimation has been done in two different situations, with and without measurement noise. The differences between real and estimated values are due to the applied noise and the integrating method; however values are still in the same class. Being in the same class, causes the CPF (Cumulative Probability Function) of the real and estimated IFL to be similar as it is shown in Fig.6. This figure shows that each class is exceeded with corresponding probability. The difference is in class 6; however its probability is less enough and does not affect the P_{st} values largely. Fig.7 shows the P_{st} in all the network buses. Bus 10 experiences higher P_{st} since arc furnace is there. Buses 7 and 9 are in adjacent and suffer next. Buses 1, 2, 3, 4, 5 are in safe area. P_{lt}, which is a P_{st} average in 2 hours, also can be calculated if measurements are continuously available.

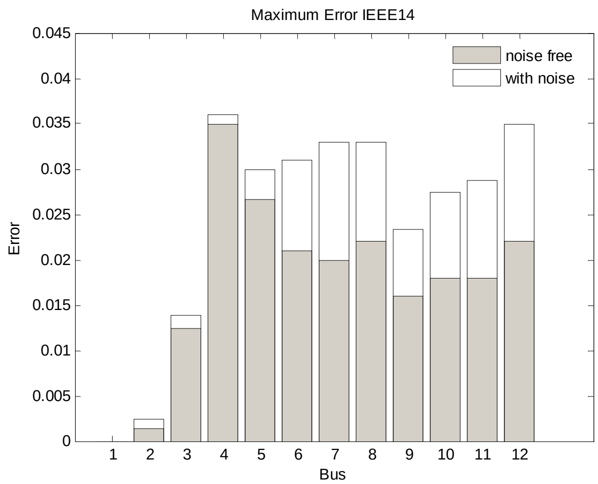

Fig4. Maximum Error in voltage

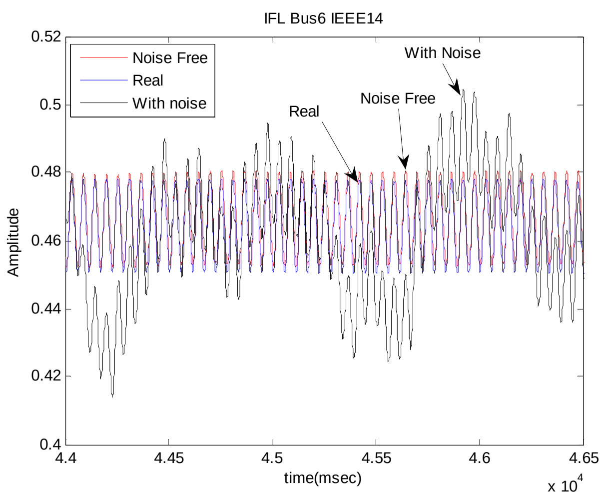

Fig5. IFL comparison in Bus 6

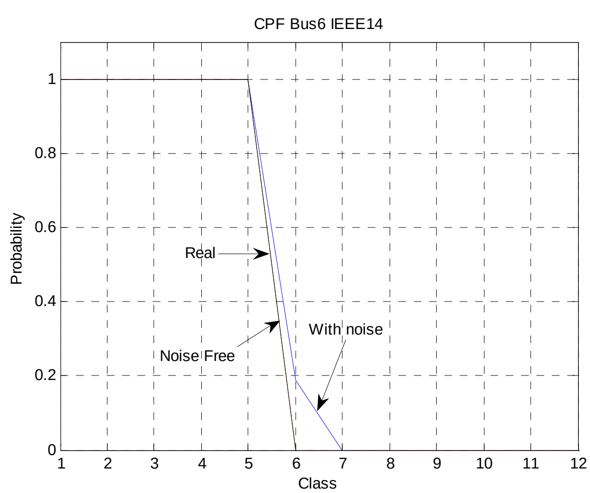

Fig6. CPF comparison in Bus 6

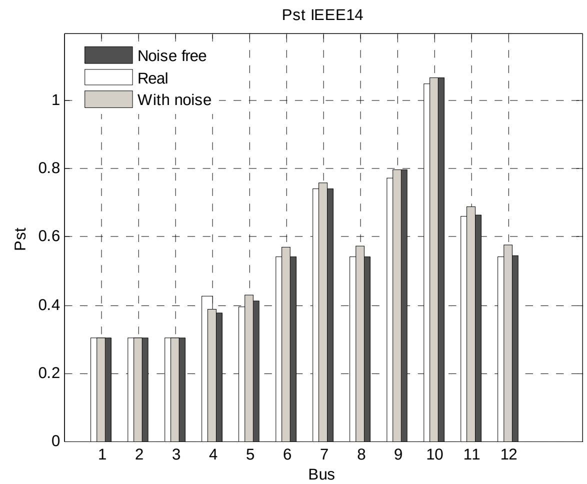

Fig7. Pst comparison in all grid buses

In comparison to other methods, it is clearly observed that computation burden is very light. Because receiving end of each branch has not been considered and only sending end was considered. This reduces the number of involved equations; though they may lead to more accurate solution. Not any flicker model or any arc furnace model is required, besides no Linearizing is imposed into equations.

5 Conclusion

In this paper a new technique for widely flicker monitoring in a large power system has been proposed. Flicker index P*st* was calculated using instantaneous voltage in a large power system. By means of line current measurements and state estimation method (WLSM), instantaneous voltage was estimated. These estimated values are then applied to flicker-meter to extract P*st* in all the network buses. No flicker model is required in this technique and it is suitable for every kind of flicker disturbance. Results show that the P*st* can be estimated accurately while computational burden is less than simulation. Beside, not any kind of Linearizing has been considered.

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