Improved real time measurement of amplitude and frequency deviations in power systems to ensure the traceability of synchrophasors.

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Abstract: Traceability of synchrophasors may be constrained to the measurement of reduced variations of frequency and amplitude; if the combined effects of amplitude or frequency modulation on the measurement results are not correctly ascertained. An improved technique is proposed in this work for the real-time measurement of simultaneous deviations of frequency and voltage amplitude at a given node in a power system. Knowledge of the instantaneous value of the amplitude and frequency in a power system provides an enhanced capability for monitoring of dynamic failures of the system allowing taking corrective actions from their inception.

Keywords: amplitude and frequency modulation; real-time measurements.

1. INTRODUCTION

Providing measurement traceability for synchrophasor technologies for its use under non-stationary conditions as usually occurs in interconnected power systems is a challenge for national metrology institutes. The IEEE Std. C37.118.1-2011 [1] provides some tests for PMU instruments for static and dynamic conditions of electric power systems aiming to describe and quantify the performance of this kind of measuring instruments which may be deployed to monitor power grids.

The recently published amendment 2014 to this standard, the IEEE Std. C37.118.1a-2014 [2], addresses some important issues. Table 5 of this document, Bandwidth requirements using modulated test signals, proposes to individually test either the amplitude or the phase angle. The work referred in [3] was devoted to the measurement in real time of the instantaneous frequency of signals in power systems. Enhancement of the analysis stage of amplitude and frequency combined effects in the measurement technique has rendered the measurement of instantaneous variations of the amplitude that signals in a power system may undergo during dynamic conditions. As it will be shown in this work, the developed measuring technique overcomes the need of individually testing the amplitude or phase angle of the input signal as proposed by Table 5 in the IEEE C37.118.1a-2014 amendment [2].

The concurrent measurement of off nominal deviations amplitude and frequency of electric signals in a given node in a power system may be regarded as the modulation of amplitude and phase (frequency) of the signals.

This work offers a measuring method for the simultaneous measurement of amplitude and frequency of electric signals observed during dynamic conditions in power systems, providing traceability of measurement to synchrophasor technologies.
2. THE TIME EVOLUTION OF AMPLITUDE AND FREQUENCY DURING DYNAMIC CONDITIONS OF A POWER SYSTEM

Equation (1) may be used to describe the evolution in the time domain of a signal taken at a given node in a power system, which may undergo simultaneous modulation of its amplitude and frequency.

\[ v(t) = V_1(t) \cos(2\pi f_1 t + \theta_1(t)) + \sum_{h=2}^{H} V_h(t) \cos(2\pi f_h t + \theta_h(t)) + r_A(t), \]

(1)

where \( V_1(t) \) and \( \theta_1(t) \) describe the amplitude and frequency modulation of the fundamental frequency component; the second term accounts for the time variation of the amplitude and frequency of harmonics, and the last term stands for additive wideband noise. Equation (1) deserves making some remarks: i) the equation may be regarded as describing a nonstationary causal signal; ii) this analytic model is representative of the kind of waveform that an electric signal taken at a given node in an electric power system may exhibit when the system is undergoing dynamic conditions; iii) the frequency modulation term in equation (1) may be identified with the concept of the instantaneous frequency of mono frequency signal, thus, the frequency of the fundamental in equation (1) is not constrained to the conventional zero-crossing definition of frequency of a time signal. Without loss of generality, the fundamental frequency of the signal in equation (1) may be expressed as the time derivative of the first term in equation (1):

\[ f_1(t) = \frac{1}{2\pi} \frac{d}{dt} (2\pi f_1 t + \theta_1(t)) = f_1 + \frac{1}{2\pi} d\theta_1(t) \]

(2)

3. MEASUREMENT OF AMPLITUDE AND FREQUENCY MODULATION

The proposed measurement technique works as follows: 1) the orthogonal band-pass filters extract the fundamental frequency component of the input signal \( v(t) \), allowing to the fundamental frequency component and filtering out any DC, harmonic and out-of-band additive noise components. The technique proposes an adaptive algorithm for correcting the gain of the orthogonal filters as the frequency of the fundamental component may change during the time of measurement.

The core component of the technique is a dual band-pass filter, which performs an orthogonal decomposition on the input signal \( v(t) \), allowing to extract the fundamental frequency component and filtering out any DC, harmonic and out-of-band additive noise components. The technique describes measures the simultaneous variations of amplitude or frequency that the fundamental frequency component may undergo as given by equation (3):

\[ v_{filt}(t) = V_{AM}[1 + k_a \cos(2\pi f_M)] \cos(2\pi f_1 t + k_f \cos(2\pi f_M t - \pi)). \]

(3)

Equation (3) describes the fundamental frequency component in terms of the modulation factors of amplitude or frequency. Regarding the fundamental frequency component of the input signal, in equation (1) \( V_{AM} \) is the peak amplitude; \( f_1 \) is the fundamental frequency; \( k_a \) is the amplitude modulation factor; \( k_f \) is the frequency modulation factor and \( f_M \) is the modulating...
frequency. For a real and causal signal $f_M < f_1$. For a three phase electric signal taken at a given node in a power system, the first term of equation (1) may be expressed in terms of a positive sequence signal [1]:

$$V_1(t) \cos (2\pi f_1 t + \theta_1(t)) \rightarrow X_1 [1 + k_a \cos (w_M t)] \times \cos (w_1 t + k_f \cos (w_M t - \pi)),$$

(4)

where $X_1$ is the amplitude of the positive sequence signal; the constants $k_a$ and $k_f$ are the amplitude and phase angle modulation factors, respectively; $w_M$ is the frequency of the amplitude and frequency modulation factors.

4. EXPERIMENTAL WORK

The measuring technique was tested for simultaneous deviations of amplitude and frequency as shown in Table 1.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Testing parameters</th>
<th>Reference condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$k_x = 0.5$</td>
<td>$F_{\text{nominal}} = 60 \text{ Hz}$</td>
</tr>
<tr>
<td></td>
<td>$k_a = 0.5 \text{ radian}$</td>
<td>Signal magnitude = 100 % rated.</td>
</tr>
<tr>
<td></td>
<td>$f_M = 1 \text{ Hz}$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$k_x = 0.5$</td>
<td>$F_{\text{nominal}} = 60 \text{ Hz}$</td>
</tr>
<tr>
<td></td>
<td>$k_a = 0.5 \text{ radian}$</td>
<td>Signal magnitude = 100 % rated.</td>
</tr>
<tr>
<td></td>
<td>$f_M = 1 \text{ Hz}$</td>
<td>$F_{\text{fundamental}} = 180 \text{ Hz}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amplitude of 3rd harmonic = 20%</td>
</tr>
</tbody>
</table>

Table 1. Tests for the measuring technique.

Figure 3 shows the waveform of a signal for test 1 in Table 1, whereas Figures 4 and 5 show the measurement results. This test is for a mono frequency component signal. For test 2, Figure 6 shows the waveform and a caption. Figures 7 and 8 show the measurement results. This test is for a fundamental plus third harmonic signal, with both frequency components modulated in amplitude and frequency.

Figure 3. Waveform of a signal for test 1 in [1].

Figure 4. Measured amplitude of the waveform shown in Fig. 3.

Figure 5. Measurement of the fundamental frequency of the waveform shown in Fig. 3.
5. DISCUSSION OF RESULTS

For test 1 and as shown in figs. 4 and 5, the measuring technique correctly measures the individual deviations of the amplitude and of the fundamental frequency. The amplitude deviations in the testing waveform do not affect the measurement of the fundamental frequency. Results of Test 2, as in figs. 7 and 8, show that the technique is not prone to measurement errors under the third harmonic whose amplitude equals 20% of the fundamental.

As discussed in section 2, the proposed technique provides an adaptive tracking of the fundamental frequency even if this deviates from nominal values. The FIR nature of the filters allows estimating the delay time of the algorithm in order to comply with the latency requirements of the IEEE Standard as in [1].

6. CONCLUSIONS

The simultaneous deviation of amplitude and frequency in a signal is considered a remarkable endurance test for measuring techniques, as pointed out in the amendment to the IEEE Std. 118.1a.2014 [2]. The enhanced technique for the measurement of amplitude and frequency of signals, as proposed in this work, has proven to provide a reliable reference of traceability for synchrophasor measurements.

In the Conference, some measurement tests carried out on signals taken in an interconnected power system in Mexico will be presented.

7. REFERENCES