Hardware-In-the-Loop Testing of Phasor Measurement Unit using Mini-Full Spectrum Simulator

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I. INTRODUCTION

DAy by day power system is becoming more nad more complex, which makes it impossible to operate it without automation for higher reliability. Due to wider geographical distribution of the grid, timely detection of faults and taking preventive/corrective counter measure has become a complex task, which requires a reliable, fast-acting and absolute techniqe to deal with the challenge. This is where the Phasor Measurements Unit (PMU) comes in to the picture. Phasor is a complex number which represents both magnitude and angle of an AC quantity. And the synchronized sampling/ measurement of this phasor at a precise reference (time) is called **synchrophasors** [1]. Using these synchrophasor measurements, different quantities are derived like phase angle, frequency, rate of change of frequency (ROCOF) etc. Frequency is computed as the first derivative of the synchrophasor phase angle, and ROCOF is computed as the second derivative of the same phase angle.

A. Background Theory

Phasor representation of sinusoidal signals is commonly used in AC power system analysis. The sinusoidal waveform defined in Equation (1):

$$x(t) = X_m cos(\omega t + \varphi) \tag{1}$$

is commonly represented as the phasor as shown in Equation (2):

$$\mathbf{X} = \frac{Xm}{\sqrt{2}} \exp^{j\phi} \, or \, \mathbf{X} = X_r + jX_i \tag{2}$$

The *synchrophasor* representation of the signal $x(t)$ in Equation (1) is the value X in Equation (2) where φ is the instantaneous phase angle relative to a cosine function at the nominal system frequency synchronized to UTC. Before we go into the compliance theory we will go through the basic definations for clarity:

phasor: A complex equivalent of a sinusoidal wave quantity such that the complex modulus is the cosine wave amplitude, and the complex angle (in polar form) is the cosine wave phase angle.

UTC: Its is the time of day at the earth's prime meridian.

ROCOF: It is the measure at which the frequency changes in a give instance of time.

Rate of change of Frequency Error (RFE): The measure of error between the theoretical ROCOF and the measured ROCOF for the given instant of time.

Frame:a data frame or a frame of data is a set of synchrophasor, frequency, and ROCOF measurements that corresponds to the same time stamp.

II. STANDARD COMPLIANCE

EVery PMU should be able to caluculate the value of phasor estimate accurately. The estimate will include positive sequence or single phase values, phase difference, freqnency and ROCOF. So it is importnat to keep in mind that the measurements are actually estimates of certain values.

Now, for a given input wave the computation for estimating the desired quantity are given below: For estimating frequency:

$$f(t) = \frac{1}{2\pi}\frac{d\psi(t)}{dt} \tag{3}$$

The ROCOF is defined as:

$$ROCOF(t) = \frac{df(t)}{dt} \tag{4}$$

important thing to note here is that phasors are always computed in relation to the system nominal frequency (f_0). Here $\psi(t) = \omega_0 t + \varphi(t)$

A. Measurement Evaluation

To validate the estimation coming from PMUs they are compared with the theoretical results. As results consists of amplitude and phase difference both they are considered combinedly and this quantity is called *total vector error* (TVE). TVE is an expression of difference between "perfect" sample of a theoretical synchrophasor and the estimate given by the unite at the same instant of time [1]. The value is normalized and expressed in PU of the theoretical phasor:

$$PVE(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{X_r(n)^2 + X_i(n)^2}} \tag{5}$$

Here $\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the estimated values of the given phasor and X_r and X_i are the theoretical values. to be complient with standard, PMU shall provide synchrophasor, frequency, and ROCOF measurements that meet the requirements as per the standards at a given time instance *n*. Similarly for freq and ROCOF the validation will be done using following equations:

$$FE == |f_{true} - f_{measured}| = |\Delta f_{true} - \Delta f_{measured}| \quad (6)$$

$$RFE == |(df/dt)_{true} - (df/dt)_{measured}| \quad (7)$$

Apart from the above 3 quantitative parameters other three important parameters to be considered are measurement response time & delay and reporting delay. *Measurement response time* is the time to transition between two steady-state measurements before and after a step change is applied to the input. *Measurement delay time* is defined as the time interval between the instant that a step change is applied to the input of a PMU and measurement time that the stepped parameter achieves a value that is halfway between the initial and final steady-state values [1]. The reason of measuring time delay is to verify that the time tagging has been compensatated properly or not. *Latency in reporting* is the time taken between the occurance of even in power system and that being reflacted in the output of the PMU. This parameter largely depends on the class of PMU and the sampling and filtering algorithem used. Which brings us to the classifiction of the PMU, they are divided in two parts:

1) Protection Class
2) Measurement Class

References

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