Assessment of Time Synchronization Requirements for Phasor Measurement Units

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***Abstract*—This paper assesses time synchronization sources suitable for Phasor Measurement Unit (PMU) applications in power systems. The paper investigates PMU phase error due to time source inaccuracy in the presence of current and voltage transformers. This paper also shows that in practical on-field applications of commercial PMUs, the accuracy of the time source should be around ten times better than the 31.8μs limit mentioned in the IEEE Standard for Synchrophasor Measurements for Power Systems C37.118.1-2011.The test set-up is discussed in brief.**

***Index Terms*—Phasor Measurement Unit (PMU), Time Synchronization, Total Vector Error (TVE).**

I. Introduction

The modern power grid is a large complex and interconnected system. An event occurring at one part of the grid may affect the operation of the whole system. Understanding these events better, requires a way to compare the power systems response at the same point of time at different locations of the grid [1]. For this purpose, PMUs are being used to provide synchronized phasor measurements to feed wide-area monitoring, control, and protection applications [2].

A common and accurate timing with reference to the Coordinated Universal Time (UTC) is required by the PMUs for correct operation and required performance level [3]. Any inaccuracy in the PMU timing adversely affects the PMU estimation of phasor angles, which in turn increases the Total Vector Error (TVE) of a phasor estimate. The TVE is the difference between the theoretical phasor value of the signal and the phasor estimate of the signal from PMU. As stated in the IEEE C37.118.1-2011 standard for Synchrophasors Measurements for Power Systems [4], the time source should be accurate enough to keep the TVE within 1%.

Previously, work has been carried out to assess the TVE compliance criteria of PMUs in steady state conditions [5] [6]. These tests were performed using stand-alone relay test kits injecting the voltage and current signals directly to the PMUs. But in practical applications the PMUs receive signals via instrumentation channels consisting of current and voltage transformers (CTs and VTs) situated in the field and teh control cable connecting the CTs and Vts to teh PMus. These CT and VT signals are phase shifted to some extent and these phase errors will reflect upon phasor measurements of PMUs [7]. As a consequence, these phase errors will also affect the accuracy requirements of PMU timing. This paper discusses the effect of these phase errors on accuracy requirements of PMU timing sources in a controlled experimental environment.

The remainder of the paper is organized as follows: Section II details the available time distribution and synchronization methods for Intelligent Electronic Devices (IEDs). In section III, the timing requirements for PMUs and suitable options are discussed. Section IV assesses timing requirements of PMUs in a practical controlled experimental environment by means of real-time hardware-in-the-loop (HIL) tests. Conclusions are drawn in section V.

II. Time Synchronization Methods

The need of time synchronization has increased with modernization of IEDs. Over time, many methods providing accurate synchronized time to IEDs have emerged. The most common among the other present techniques are the Global Positioning System (GPS) as time source and the Network Time Protocol (NTP) as time distribution method [8]. Some other time distribution methods include standard radio transmission of time from ground based radio stations (like WWVB (US), DCF77 (Germany)), Inter-Range Instrumentation Group (IRIG) B coded time signals and IEEE 1588 Precision Time Protocol (PTP) [9]. A brief overview of these methods is discussed below:

- *GPS Time Source:* The accuracy of GPS is in the range of $\pm 10ns$ to $\pm 100ns$ [8]. Its sources of error include atmospheric delays (which cannot be compensated). Factors like antenna positioning and availability of full horizon view may also affect the accuracy [8]. But even with all the drawbacks the accuracy of the GPS makes it the most popular choice for high accuracy IEDs [8].
- *NTP Time Distribution:* The NTP network is made of time servers at different hierarchical levels called stratum. The topmost server is directly connected to high accuracy reference source like an atomic clock or time code receiver [8]. The accuracy of NTP depends on the network

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topology, operating system delays and the medium of communication and in the range of milliseconds [9].

- *Standard Radio Distribution:* In standard radio distribution of time the receiver device periodically synchronizes its clock to the real atomic clock whose time is transmitted using radio waves. Propagation delay of the radio waves affects the time accuracy and can cause a delay up to $30ms$ [9].
- *IRIG-B Distribution:* IRIG-B is a standardized set of time-code formats and has become a popular format for time distribution to IEDs. IRIG-B provides time once a second containing information from second of the minute to the day of the year in a binary-coded decimal (BCD) format. All the information With GPS as source, IRIG-B can distribute time with an accuracy of $\pm 500ns$. IRIG-B is used from short to medium distance applications [9].
- *PTP Time Distribution:* IEEE 1588 PTP is capable of achieving accuracy levels up to $\pm 500ns$ with the support of dedicated hardware for precision time stamping [9]. Implementation of PTP based time distribution requires the network infrastructure (all Ethernet switches) to have the hardware support for high-precision time stamping. The hardware support in relays and other substation IEDs still remain limited [9].

III. PMU Time Synchronization

The TVE for an operational PMU under steady-state should not exceed 1% [4]. 1% TVE corresponds to a phase angle error of 0.573°, provided no other errors are present. This is about $31.8\mu s$ at system frequency of $50Hz$ ($26\mu s$ at $60Hz$). The time source for PMUs should be accurate enough to keep the TVE below 1%. It means PMU's timing error should be less than $31.8\mu s$ in a $50Hz$ system. Looking at the timing error associated with the above discussed timing solutions, it can be stated, that as for now, only GPS and IEEE 1588 PTP are suitable for synchrophasor applications. Although hardware support for PTP in the substation IEDs and Ethernet switches in the network remains a bottleneck in the implementation of PTP based timing in substations. IRIG-B is a suitable high precision timing distribution solution and along with a GPS source, could be used effectively to distribute time to PMUs in the sub-microsecond level accuracy.

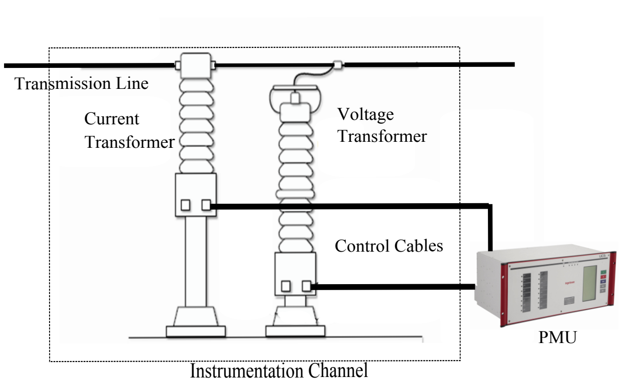

Fig. 1: PMU and Instrumentation Channel

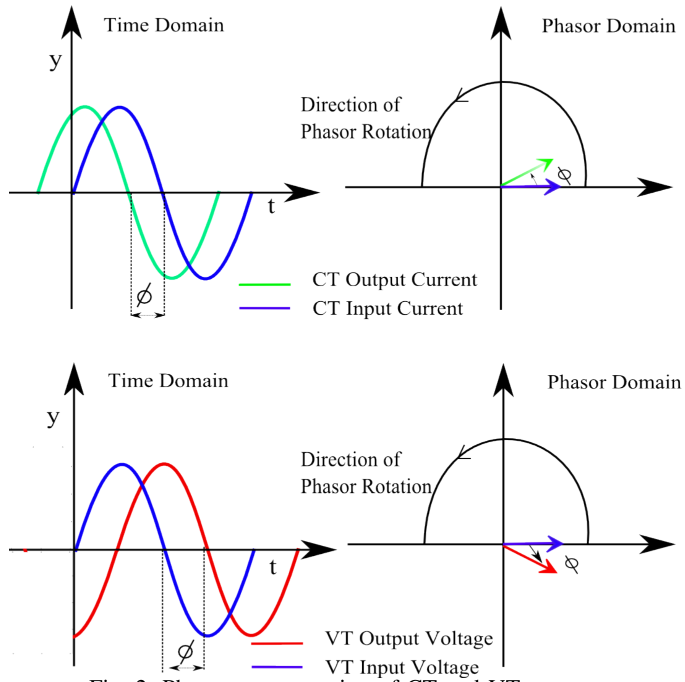

Fig. 2: Phsors representation of CT and VT outputs

The accuracy of a phasor estimate by a PMU is measured in terms of TVE. The TVE is composed of errors in both phase and magnitude estimates. PMU timing accuracy will directly affect the phase errors of the PMU and in turn the required 1% TVE accuracy puts a cap on the timing error. Phase error in PMU estimates is composed of various components like time source error, phase error or delay in PMUs signal processing unit (which includes analog to digital converters and step down transformers) [1]. But these are not the only source of phase error in the PMU estimates. In substations, a group of devices referred as the instrumentation channel feeds the scaled replica of the high power current and voltage signals to the PMUs. In practical conditions this instrumentation channel also degrades the original signal in terms of phase and magnitude. This could be termed as TVE caused by instrumentation channel (TVE_{IC}). So the total TVE (TVE_{Total}) of final phasor estimate by the PMU would be the sum of the TVE_{IC} and TVE_{Total}.

Testing and analysing a PMU in the lab using stand-alone relay test sets such as Freja-300 gives us the phase error due to PMUs signal processing unit. This is not the ideal case for the PMU being fed via the instrumentation channel. These CTs and VTs feed an already phase shifted signals to PMUs. Phase angle error for VTs is in the range of $\pm 4°$ and for CTs in the range of $\pm 2°$. In high accuracy instrument transformers, the phase angle varies between $\pm 0.1°$. These errors increase significantly during transients especially for Capacitive Voltage Transformers (CVTS) as characteristics parameters of the components deteriorate for frequencies other than the fundamental [10]. Control cables used for connecting the instrument transformers to the PMUs and relays along with isolating switches and various non-linear burdens also impacts the over all accuracy of the instrument channel. The

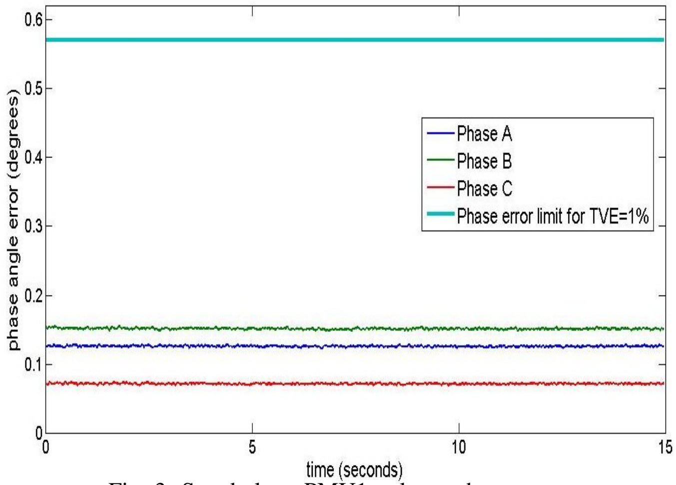

Fig. 3: Stand-alone PMU1 voltage phase error

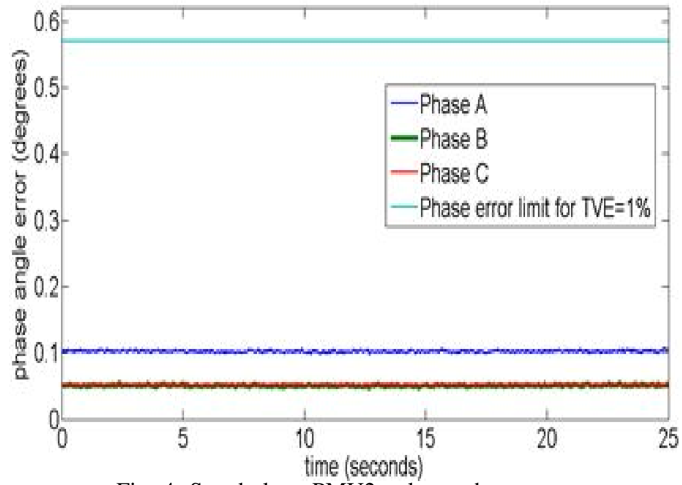

Fig. 4: Stand-alone PMU2 voltage phase error

output voltage of VT lags the original voltage waveform and the phase error is taken to be positive. Similarly, the CT output current leads the actual current and the phase error is assumed to be negative. These phase angle errors incurred in the instrumentation channels reduce the margin for timing errors as contribution of both the errors should not exceed the 1% TVE limit. The phase errors introduced by PMU signal processing unit together with phase errors caused by CTs and VTs reduces the margin of error in time source to be less than the $31.8\mu s$ limit specified in IEEE C37.118.1-2011. The following section presents the tests and the results to support this.

IV. Assessment of PMU Time Requirements

In order to investigate the effect of instrumentation channel and assess the timing accuracy required by PMUs, three test scenarios were performed on two commercial PMUs. The first test results in identification of phase angle errors introduced only by the PMU itself. The second test introduces an instrumentation channel emulated by amplifiers (representing VT and CT) and find out the phase angle error introduced by the combination of PMU and amplifiers. In the third test, incremental inaccuracy was imposed in the time source feeding PMU to show the reduced margin of the time source error.

A. Test case 1: Stand-alone PMU

In this test case, the phase error of PMUs due to their signal processing unit was measured. Freja-300 relay tester kit was used to inject current and voltage signals. Balanced three phase current and voltage signals were injected into the PMU terminals. PMU Time synchronization was provided by distributing high accuracy IRIG-B signals originating form a GPS based sub-station clock. Synchrophasor data generated by the PMUs was sent to Phasor Data Concentrator (PDC) over Ethernet. Saved data on PDC was then taken for further analysis on the phase error using MATLAB.

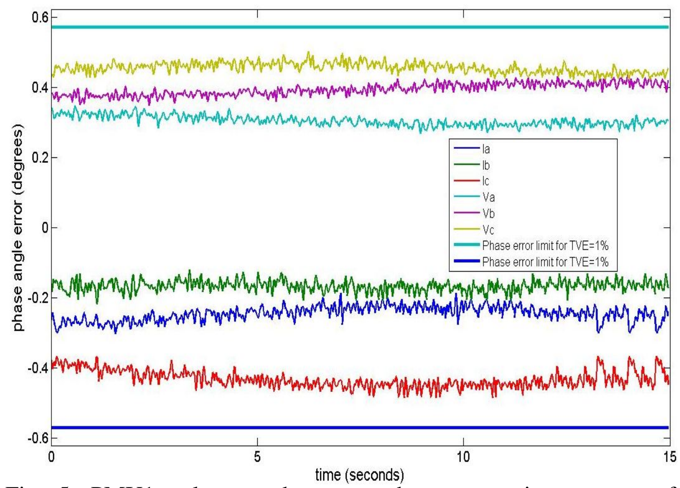

Fig. 5: PMU1 voltage and current phase errors in presence of amplifiers

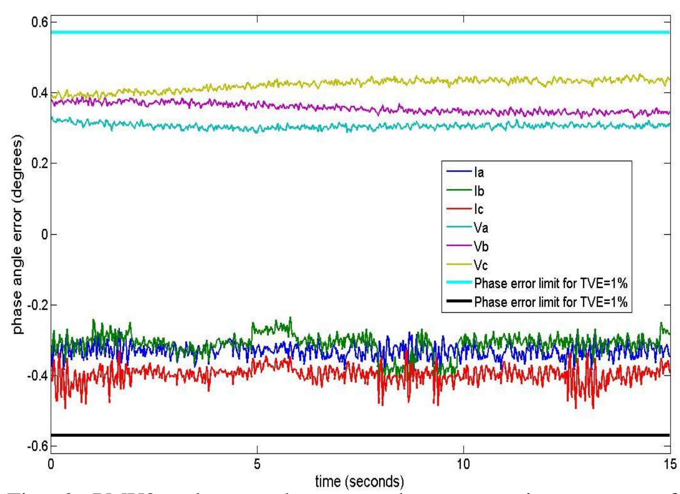

Fig. 6: PMU2 voltage and current phase errors in presence of amplifiers

Figures 3 and 4 show the phase angle errors for the voltage phasors calculated by PMUs. As shown in the figures, phase angle errors for PMU1 and PMU2 were in the range of [0.07°-0.1247°] and [0.05°-0.1°], respectively. These errors are well within the limit of 0.573° for which TVE becomes 1%. Both PMUs fulfill the requirements for TVE.

B. Test case 2: PMU and Amplifiers

In this test case, the phase angle errors for phasors calculated by PMUs receiving input signals from CTs and VTs (represented by Megger amplifiers) are investigated. Balanced three phase voltage and current signals were simulated in real-time OPAL-RT simulator and were fed to the PMUs through the Megger amplifiers. Similar to test case 1, accurate time source was provided to the PMUs. Synchrophasor data were recorded in the PDC and analysed for phase error. Phase errors measured during this test are shown in fig. 5 and 6. As shown in the figures, the phase angle error for both PMUs increased. Although the time distributed was accurate up to 500ns, voltage phase angle error was observed in the range of [0.332°-0.46°] for PMU1 and [0.32°-0.45°] for PMU2. Phase angle errors for currents were observed in the range of negative [0.187°-0.465°] for PMU1 and negative [0.240°-0.494°] for PMU2. This is due to the phase angle shift caused by the current and voltage transformers inside the amplifiers which are substituting for the on-field CTs and VTs. The polarities of the measured current and voltage phase errors are opposite. As mentioned above, this is due to the fact that the voltage output form the VT lags lags the original voltage by some degrees and the output current from the CT leads the original current by some degrees. With the original phase as reference, the lagging phase error is assumed to be positive and the leading phase error is assumed to be negative. The errors are still under 0.573° limit but there is very less margin of error due to timing inaccuracies. Depending upon the phase errors associated with CTS and VTs, the TVE of a PMU could could break the limit of 1%.

C. Test case 3: PMU, Amplifiers, and Time Inaccuracy

For the last test, a user controllable IRIG-B time singnal was simulated in real-time using OPAL-RT simulator. Controlled time errors were imposed in the simulated IRIG-B signal being supplied to the PMUs. Starting with zero error, the errors were imposed in steps of μs at the points in time marked by A,B,C,D and E in the figures. At each step the timing error was raised by $10\mu s$. The effect of both time advancement and time delay errors were investigated. Similar to test case 2, the voltage signals were supplied through Megger amplifiers. The phase angle errors were analysed from the stored data. It should be noted that varying the time error in the IRIG-B signal, caused the PMU to give unstable incorrect phasor estimates for a few seconds before settling down. Therefore, the unstable part has not been included in the figures.

Figs. 7 and 8 show the effect of time advancement in steps of $10\mu s$ on the voltage and current phase errors for PMU1. If fig 7,the errors in steps of $10\mu s$ were introduced at point A(t=9.6s) and B(t=46.6s). As the voltage signal input to the PMU was already lagging the original signal, the advancement of PMUs's clock increases this phase error. This leads the TVE to cross 1% mark for all the phases caused by a total timing error of $20\mu s$. For the current signals something a bit

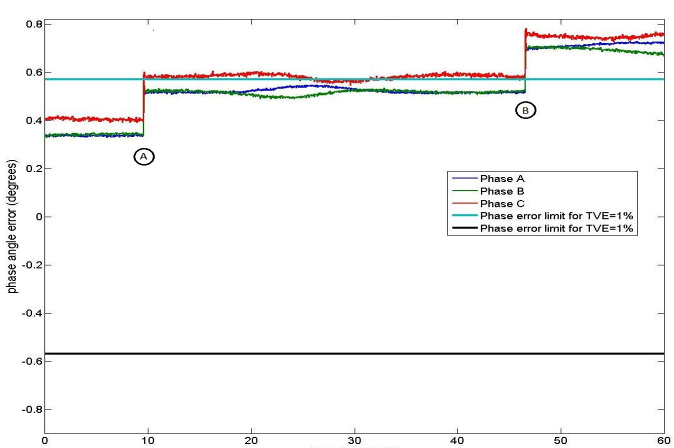

Fig. 7: PMU1 voltage phase errors due to time error in form of time advancing ahead the correct time

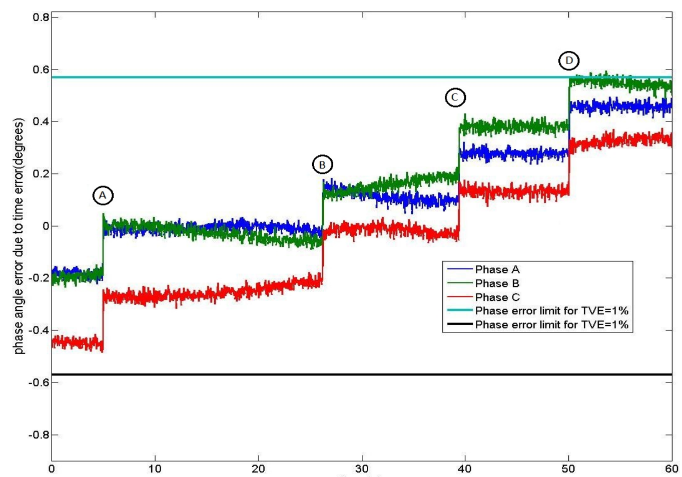

Fig. 8: PMU1 current phase errors due to time error in form of time advancing ahead the correct time

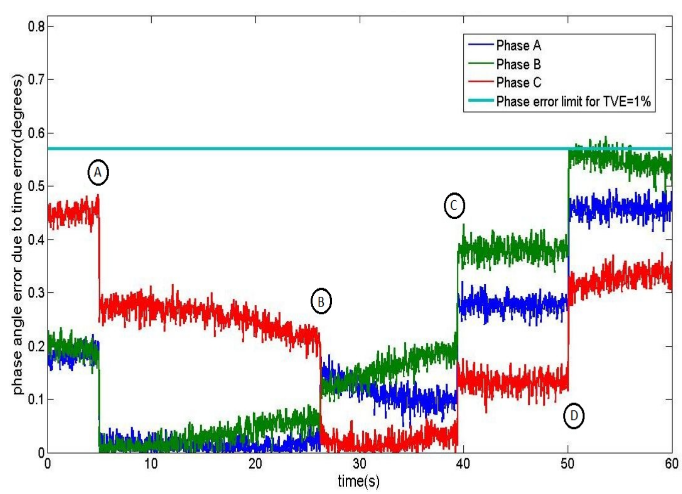

Fig. 9: PMU1 absolute current phase errors due to time error in form of time advancing ahead the correct time

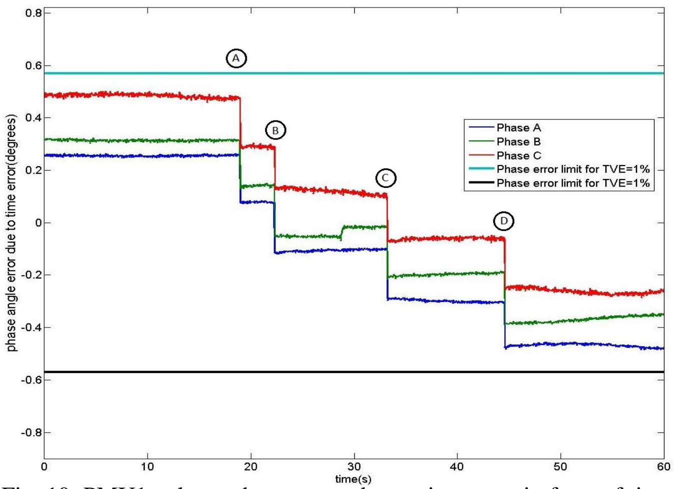

Fig. 10: PMU1 voltage phase errors due to time error in form of time lagging behind the correct time

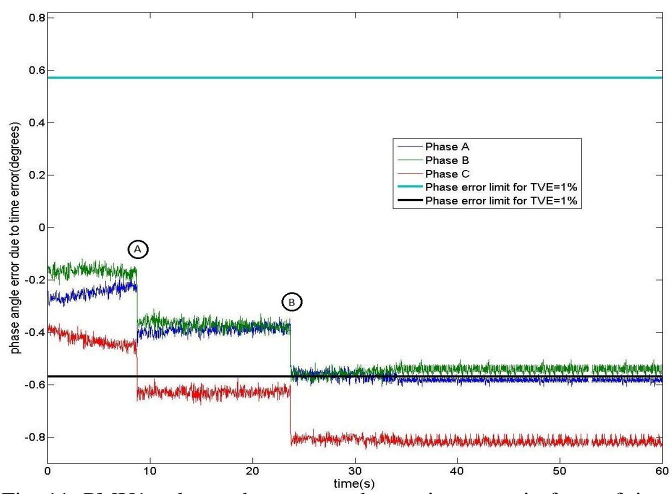

Fig. 11: PMU1 voltage phase errors due to time error in form of time lagging behind the correct time

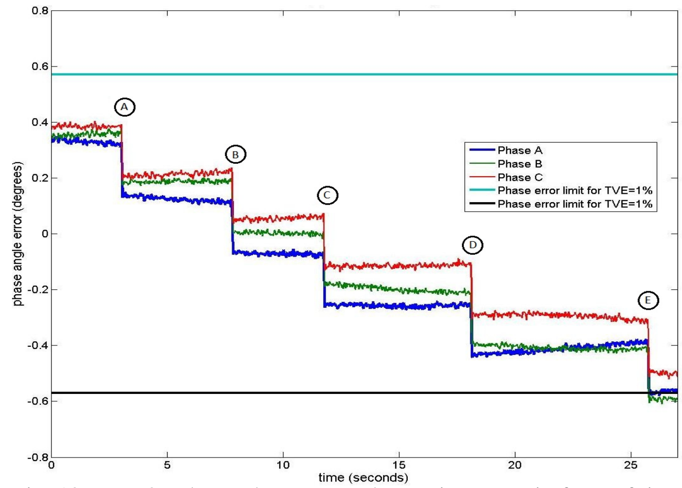

Fig. 12: PMU2 voltage phase errors due to time error in form of time lagging behind the correct time

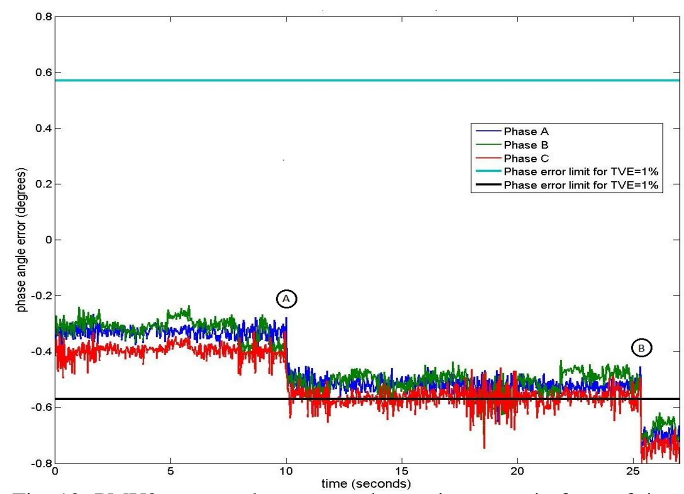

Fig. 13: PMU2 current phase errors due to time error in form of time lagging behind the correct time

different happens. Initially when the time error was increased by advancing the time, the measured phase error decreased. As the timing error was further increased the measured phase error crosses zero and starts to increase in the opposite polarity. This is shown in fig. 7. This is due to the fact that the current signal input to the PMU was leading the original signal, so when the time is erroneously advanced till a certain value, the PMU makes a better estimate of the phasors. At a certain time advancement error, the error in phasor estimate due to wrong timing cancels out the error in phasor estimate due to CT ratio error. After that value of timing error, any increase in timing error, the phase angle error will start to increase again but in opposite polarity.

In fig. 7, the timing error was increased in steps of $10\mu s$ at points A,B,C and D. The errors decreases, cross zero phase error and increase towards 1% TVE mark. At the point D after $40\mu s$ timing error one of the phases crossed the 1% TVE mark. The absolute value of the phase errors were plotted in the figure 9. It could be seen that the TVE due to phase error initially decreases before increasing again.

In next step, the timing errors were imposed on PMU1 by delaying the time in steps of $10\mu s$. The effects on the phase errors of voltage and current can be seen in fig. 10 and 11. As the timing errors were imposed in the steps the voltage phase error decreased initially and increased in the negative polarity. This was due to the fact that the voltage signal input to the PMU via VT lags the original voltage and if the time is delayed, the measured phase error starts to move in negative direction, decreasing first and increasing after crossing the zero measured phase error mark. But the measured phase error of the current signal starts increasing form the first error in the negative polarity. Measured phase error for for one of the phases of the current signals crosses the 1% TVE mark at point A, with only $10\mu s$. Error is increased to $20\mu s$ and the measured phase error for all the phases cross the 1% TVE mark.

In both the cases of errors, it is seen that phase errors for either of the current or voltage signals violates the 1% TVE rule even before the timing error reaches the $31.8\mu s$ limit, set in [4]. Similar set of tests were repeated for PMU2. Figures 12 and 13 display the measured phase errors in the case of imposed timing delay errors. In this case, it can be seen that the phase error for the current signals reach the 1% TVE mark in negative polarity after $10\mu s$ error was introduced at point A. All the phases comfortably clear the mark after the second step of $10\mu s$ error at point B. The voltage phase error initially decreases then increases in the opposite polarity.

All the plot results indicate that PMUs require a time source with a better accuracy than the $31.8\mu s$ limit set in [4]. These results also confirm that in order to limit the TVE of PMUs below 1%, high accuracy time synchronization methods such as GPS and hardware supported PTP with sub-microsecond accuracy are required. Other available methods of time distribution such as NTP and standard radio are not suitable for PMU applications.

V. Conclusion

Different time distribution sources were discussed and compared for their usability as time sources for PMU synchronization. It was seen that GPS and hardware supported PTP are capable time synchronization solutions for PMU applications. To investigate the time source requirement of PMUs for practical applications, two commercial PMUs were tested for their phase errors by means of real-time HIL tests where amplifiers represented CTs and VTs. It was shown that for any commercial PMU the final phasor measurement could be quite large due to the instrumentation channel associated in the measurement. These factors of TVE errors would affect the accuracy of the PMU measurements and will also make the timing requirements more stringent. The tests showed that even a time source error of 10s could be sufficient to make TVE higher than 1%. $10\mu s$ is about one third of $31.8\mu s$ limit set by the IEEE Standard C37.118.1-2011. It has been concluded that to leave some margin for other errors, it is necessary to use a time source with accuracy about ten times better than the limit set by the standard.

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