PERFORMANCE ANALYSIS, CALIBRATION, AND TESTING OF MICRO PROCESSOR BASED DIGITAL FAULT RECORDER WITH PHASOR MEASUREMENT UNIT (PMU)

Krish Narendra,

ERLPhase Power Technologies Ltd.
Winnipeg, Canada

George Punnoose

Easun Reyrolle Ltd.
Bangalore, India

Abstract - **With the increase interest in the Wide Area Monitoring, Control and Disturbance Analysis, and to minimize the future black outs caused due to the cascade tripping, there is a growing interest in the microprocessor based relays and disturbance recorders to provide an additional Phasor Measurement Unit (PMU) measurement and reporting [1,2,3,4]. The recent IEEE C37.118 [5] standard on the synchrophasors outlines certain stringent requirements in terms of how to precisely measure the phase angle with respect to the global time reference – the coordinated universal time (UTC), and how to report the phasor information. The standard also specifies the Total Vector Error (TVE) allowed in evaluating the phasor for different compliance level to allow interoperability between different vendor PMUs. The purpose of this paper is to discuss the calibration, testing and performance analysis of a Micro Processor Bases Digital Fault Recorder (DFR) with a PMU. The analysis is carried out as per the C37.118 for different compliance levels. The paper discusses various challenges encountered in calibrating the PMU, and comparative analysis of different manufactures test set and how to carry out the calibration process. Sources of errors and their effect on the PMU reporting will also be discussed. The DFR described in this investigation is a multi-time frame recording system used to monitor electrical power systems. It can record up to 36 analog channels and 64 digital (status) channels and store up to 1000 recordings.**

Index Terms – Digital Fault Recorder (DFR), Phasor Measurement Unit (PMU), Calibration, Coordinated Universal Time (UTC)

1.0 INTRODUCTION

Phasor measurements with phase angles referenced to a global time standard – coordinated universal time (UTC) – have been used in limited scope by electric power utilities around the world for well over a decade as a means of measuring and predicting dynamic stability of the power grid. Recently, growing concern about the stability of the power system has increased interest in the use of synchrophasors on a broader scale. The formulation of a new standard to define the evaluation and transmission of synchrophasors in real time (IEEE C37.118 – 2005) [1], and the launch of a major synchrophasor project on the eastern North American power grid (North American Synchro Phasor Initiative (NASPI) [2] – formerly EIPP) have solidified the requirement for devices which can provide synchrophasor measurements in real time. With the recent blackouts that have occurred in the US, and other parts of the world, the concept of wide area protection using synchrophasor measurements is gaining considerable momentum.

The key components in successfully implementing a wide area protection are the PMUs. The PMUs are precision level measurement units installed at various substations within an area to implement an area of wider protection.

The recent synchrophasor standard C37.118 mandates compliance levels (level 0 and / or level 1) for the PMU under steady state conditions. This paper discusses some of the challenges of testing the PMU - a software module available with the DFR, as per the new standard. The possible sources of errors and the current state of the art of the testing equipment which qualifies for PMU testing will be discussed.

A number of references are available [1],[3],[4],[5],[8] which explains the meaning , convention and communication aspects of the PMU. Very few literatures are available on the calibration and testing of PMU. The NASPI [2] is actively involved in improving the concept of understanding the PMU behaviour during dynamic conditions under a number of task forces. One of the Performance Requirement Task Team (PRTT) is involved in addressing the calibration and testing of the PMUs. This paper focuses on the performance analysis, calibration and testing of PMU with a Micro Processor Based DFR.

2.0 MICRO PROCESSOR BASED DFR WITH PMU

The DFR used in this investigation is a multi-time frame recording system used to monitor electrical power systems. It can record up to 36 analog channels and 64 digital (status) channels and store up to 1000 recordings. Up to four recorders can be operated as a cooperative group to achieve greater numbers of channels. The DFR can record data simultaneously in three time domains: high speed transient fault (upto 384 samples/ cycle), low speed dynamic swing (upto 30 minutes), and continuous trend (10 second to 1 hour intervals). A wide variety of triggers are available to initiate recording. The recording system consists of a recorder, analog input isolation modules and Graphical User Interface (GUI) software. There are various analog input isolation modules available to interface to signal sources. Modules are available to connect to standard signals found in a typical electric power substation including secondary ac voltage and current and low level dc voltage and current signals. These modules can generally be installed up to 300 meters from the recorder unit, allowing them to be located near the source of the signals being monitored. The GUI software provides tools to configure the recorder, trigger, retrieve and manage records and display real time measured values. The GUI software also includes a graphical record display and analysis software sub module. An optional data retrieval and management data base program is available to automatically collect and store records from multiple DFRs (refer Figure 1).

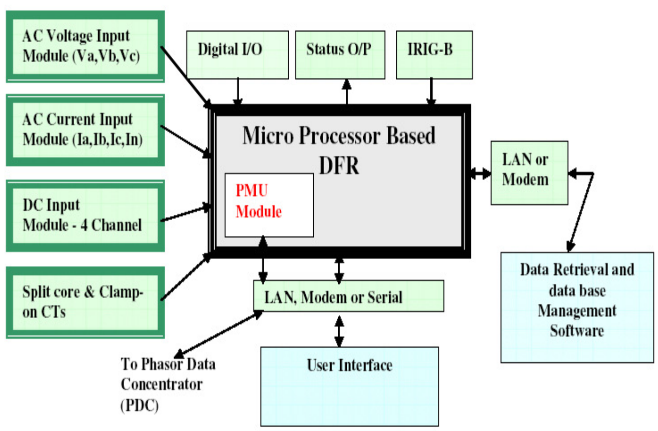


FIGURE 1: SCHEMATIC VIEW OF A DFR WITH PMU MODULE

PMU functionality is an optional software product feature on this DFR. The PMU functionality will comply with IEEE C37.118 – 2005 [1]. Up to 12 user selectable phasors - as individual phase quantities or three-phase positive, negative or zero sequence phasors or summated phasors - can be transmitted via Ethernet, Serial port, or Modem at rates up to 60 frames each second. The PMU functionality is designed to work simultaneously with the existing DFR features such as triggering, recording, and trending. This means, simultaneously you can connect to the DFR using the GUI software and view metering quantities, modify configuration settings, transfer records over Modem and stream PMU data over Ethernet or vice-versa.

In order to reliably transmit the PMU data, it is required to connect IRIG-B signal from a reliable Global Positioning System (GPS) clock or receiver to the DFR through standard BNC (Bayonet Neill Connector) connector. The GPS signal must comply with the specification as mentioned in the IEEE C37.118 standard [1].

3.0 PHASOR MEASUREMENT AND REPORTING-SOURCES OF ERROR

This section explains the various sources of errors that contribute to the phasor measurement calculations and reporting (Figure 2). The primary analog input (voltage and current) to the DFR will be from the station CTs and PTs through the input modules as shown in Figure 1. There will be an inherent error associated with the CTs and PTs, and need to be compensated.

From the primary transducers (CTs / PTs) and input module, the signal passes through anti-aliasing filter (AA-filter) before it is sampled - this is another source of error. The A/D converter, ADC count bit error and channel-to-channel skew can introduce magnitude or gain error and channel phase shift, which can introduce phase angle error. Later, once the sampling is done, the signal processing will be carried out to evaluate the phasor magnitude and phase angle. There is a possibility that the signal processing may introduce some error in the phasor calculations. Since the phase angle needs to be reported with respect to the global time reference (synchronized with UTC), the poor quality IRIG-B signal may introduce some error. The cable delays can cause some errors. Components aging and wide variation of operating temperatures can cause errors over time. The standard [1] mandates the compliance level 0 and/ or level 1 for the PMU under any conditions.

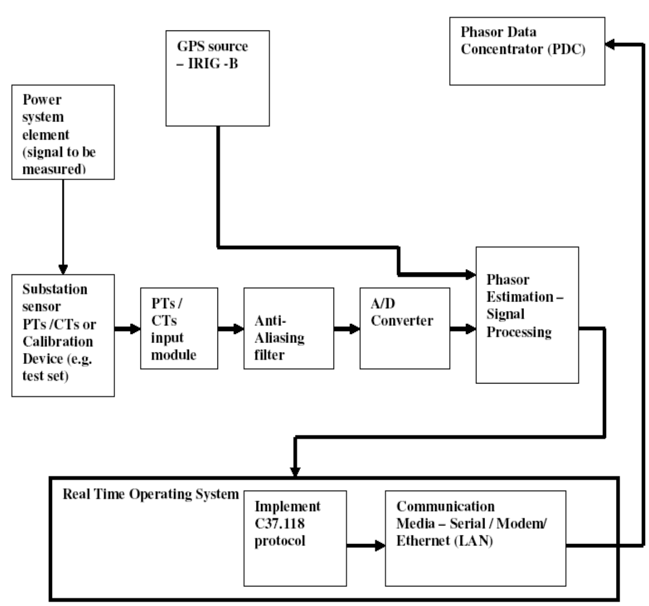


FIGURE 2: PHASOR ESTIMATION AND POSSIBLE SOURCES OF ERRORS

Before installing the DFR in the field, calibration has to be carried out using standard testing equipment. This testing equipment needs to be qualified as per the C37.118 to be considered as a calibration device. In this investigation, the input to the DFR is from a standard testing device (test-set) and any source of error in the magnitude and phase angle correction pertaining to the test-set and the sources of error, which has been described above must be compensated as per the standard [1] before it is available for reporting.

4.0 CHALLENGES OF TESTING PMU AS PER IEEE C37.118 STANDARD

As explained in the previous section, there are number of possible sources of error that needs to be addressed before the phasor information is transmitted. As per the definition of the standard [1], the phase angle of the phasor (cosine reference) must be reported with respect to the global time reference (UTC) as shown in Figure 3. For example, at time t1, the UTC intersects with the zero cross-over of the A phase signal and the theoretical reporting phase angles are -90, 150 and 30 degrees for A, B, and C phases respectively. At time t2, the UTC intersects at cosine reference of the A phase signal and the theoretical reporting angles are 0, -120 and 120 for A, B and C phases respectively.

The Total Vector Error (TVE) is an important criterion which must be < 1% under steady state conditions for Level 0 and Level 1 compliance Table 3 of standard [1]. For convenience, the definition is repeated as follows (Figure 4).

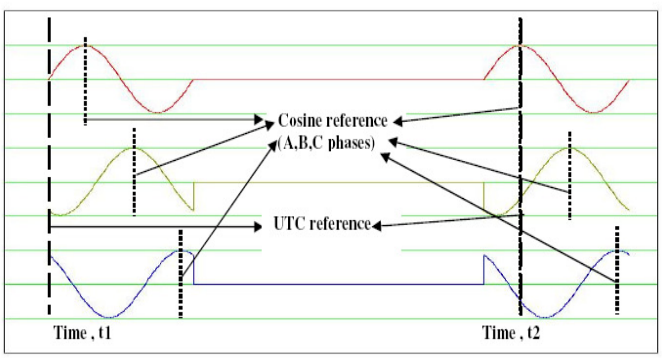


FIGURE 3: PHASE ANGLE REPORTING CONVENTION AS PER C37.118-2005

Unless specified, for all the test cases, standard test-set with 3 phase balanced voltages of 69 V rms and 3 phase balanced current of 5A rms has been considered for the analysis.

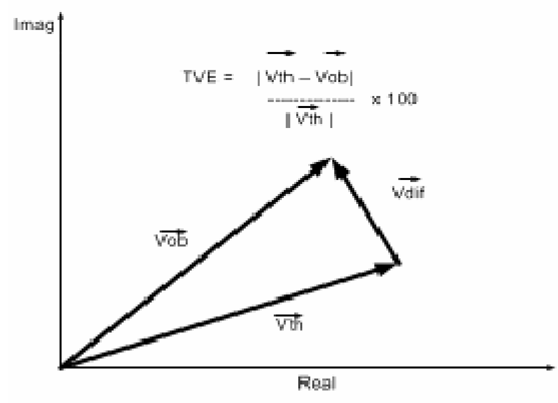
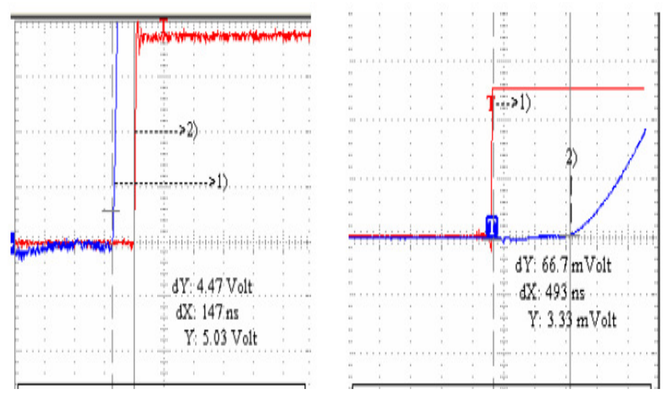


FIGURE 4: DEFINITION OF TVE, V_{TH}, V_{OB} , AND V_{DIF} ARE THE THEORETICAL, OBSERVED AND DIFFERENCE VECTORS

4.1 IRIG-B RECEIVER SIGNAL VARIATIONS

The challenge was to find the right source of the IRIG-B receiver signal as an input to the DFR and the testing equipment, which synchronizes with the UTC time with a requirement as mentioned in the standard [1]. A study was conducted to determine the variations of 1 PPS signal with 3 different manufacturers. A calibrated Tektronix digital oscilloscope (THS720A) was used for this purpose and a number of triggers were analyzed. A sample result is depicted in Figure 5.



a) 1- TESTA-SET 2- Clock A b) 1) TEST-SET 2-Clock B

FIGURE 5: GPS SIGNAL COMPARISON – TEST-SET 1PPS WITH OTHER CLOCK S A, AND B

The relative comparison of the above shows that the clock B has wider difference in their reading in the range of 500nS, compared to clock A, which is 150nS. The test-set 1 PPS signal was consistent with Clock A 1PPS signal and varied between 147ns to 150nS and with respect to Clock B it varied between 490nS to 500nS. More information on GPS signal can be found in [6].

4.2 Modulated vs Unmodulated IRIG-B Signal

From the point of view of accuracy and the stringent requirements of the standard, it is recommended to use unmodulated IRIG-B signal compared to the modulated IRIG-B signal. A test was conducted to verify the results and a significant difference in the TVE was found between modulated and unmodulated signal. Table 1 below summarizes a sample study result.

	Nominal Signal	Unmodulated – TVE %	Modulated – TVE %
1	69V rms A, B, C phase	0.01, 0.01, 0.011	0.86, 0.85, 0.84
2	5A rms A, B, C phase	0.036, 0.041,0.013	0.86, 0.91, 0.83

TABLE 1: COMPARISON OF TVE FOR UNMODULATED AND MODULATED IRIG-B SIGNAL

4.3 Reference signal variations

As per the standard [1], the reference signal generated from the test set should meet the criteria of 0.25% TVE in order to qualify as a calibration or testing equipment. This is important because the reference signal from the test set will be considered as the theoretical signal for evaluating the TVE. Three different manufacturers test equipments were studied to check the accuracy of the calibration or test signal. In all the cases a number of trials were carried out to verify the accuracy of the phase angle generation with respect to the 1 PPS signal.

In the case of manufacturer A, there was an inconsistency in SineWave startup (point-on-wave) time with respect to the 1PPS. Also, the 60Hz nominal system frequency was varying (even though the variation was 0.0001 Hz),as a result of this variation the phase angle was monotonically increasing (fourth decimal place), and over a period of time this would result in a significant error. Hence manufacturer A's test set could not be used as a calibration device for PMU analysis. Sample observation of manufacturer A signal generation with respect to 1PPS signal is shown in Figure 6a.

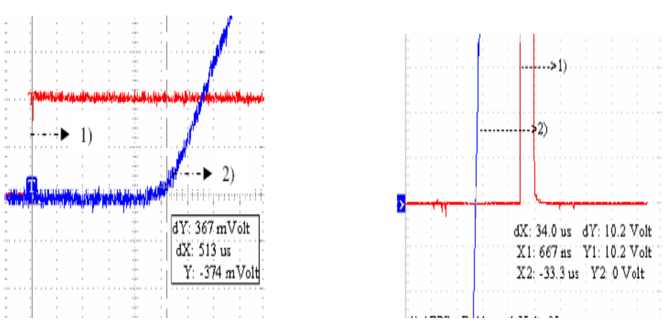


FIGURE 6: SINEWAVE GENERATION (POIN-ON-WAVE) WITH RESPECT TO 1PPS

A comparison of test-set SinWave startup scenario for the same test conditions is shown in Figure 6b.

Table 2 summarizes the ten iterations of reading obtained using Tektronix digital oscilloscope (THS720A) during the SinWave startup between the manufacture A and the test-set.

Ideally, the difference between the SineWave startup instance and the 1PPS tick should be zero. As shown in Table 2, both manufacturers startup time with respect to 1PPS signal varied but test-set startup showed much better consistency compared to Manufacturer –A and also the Test-set system frequency remained extremely stable throughout the testing period

Test	Manufacturer – A – Startup w.r.t 1PPS (difference in micro seconds)	Test-set Startup w.r.t 1PPS (difference in micro seconds)
1	502	36
2	518	34
3	503	34
4	438	34
5	462	34.7
6	502	36
7	444	34
8	467	36
9	479	34.7
10	520	34.7

TABEL 2: SUMMARY OF SINEWAVE START UP WITH RESPECT TO 1PPS SIGNAL BETWEEN MANUFACTURER - A AND TEST-SET

4.4 Off-nominal frequency performance test

As per the standard [1] the off-nominal frequency test must be carried out depending on the level of compliance and the TVE must satisfy < 1% requirement. The challenge here was to generate a reliable off-nominal signal based on the 1PPS and keep track of the phase angle variation of signal due to the change in the frequency. The following relationship exists between the reporting rate of the PMU messages and the off nominal frequency variation.

Phase Angle Rotation (Degrees / frame) = (f - f0)*360.0 / R

Where, f = Off-nominal frequency (e.g. 61 Hz)
f0 = nominal system frequency (e.g. 60 Hz)

R = PMU reporting rate (e.g. 10 frames/sec)

In the above example, the phasor rotates with the phase angle of 36 deg per frame as shown below in Figure 7.

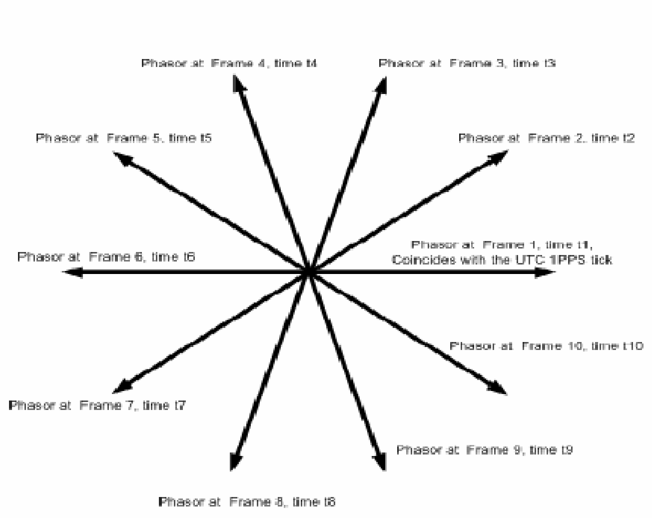


FIGURE 7: PHASOR VARIATION UNDER OFFNOMINAL FREQUENCY 61 Hz WITH 10 FRAMES PER SECOND PMU REPORTING RATE

Hence, for the calculation of the TVE for a corresponding frame, proper phase angle rotation must be used. Also, the initial phase angle reporting time tag must synchronize to the beginning of the UTC time (1PPS tick). The difficulty here was to generate a synchronized signal at off-nominal frequency. For example, with Test-set, this can be achieved by changing the system frequency to 61 Hz (for the above case) or to any desired off-nominal frequency to achieve the accurate calibration off-nominal frequency signal, and not just by changing the applied frequency of the signal to 61 Hz.

4.4 Harmonic Distortion Test

As per the standard, any harmonic (up to 50^{th}) at 1 or 10% of signal magnitude should not result in TVE exceeding 1 %. This test was difficult to conduct using normally available test sets since most of them support upto 20^{th} harmonic signal generation. Even though COMTRADE file can be generated to test the contents of the harmonics but it was difficult to track the synchronized fundamental frequency variation due to the digital nature of the generation (round-off error accumulation etc.). For this case, signal from two different manufacturers test set was used to arrive at a meaningful calibration signal.

4.5 Out-of-band interfering signal

The standard [1] does not specify the nature of interfering signal – what kind of interference should be considered. For example, additive, subtractive or multiplicative interferences are possible with the input signal. Testing for each case and with theoretically infinite possibilities, it is impractical to generate calibration signals for all these conditions. The nature of low frequency interference in the power systems swing happens in the range of 0.3 to 5 Hz. Therefore, a discrete number of calibration signals were generated to test this condition and cover the broad range of interferences.

4.6 Communication issues

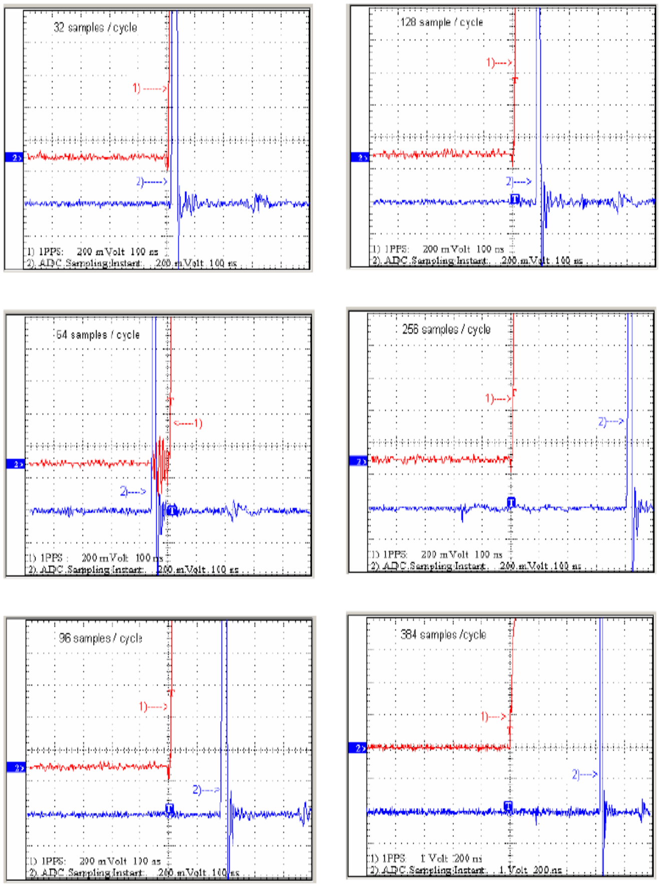
Although the standard [1] requires the phasor information to be transmitted in a particular protocol format, it does not impose on the choice of communication media. The authors have done testing with TCP/IP, UDP and Serial mode communication media. In all the cases, the Tennessee Valley Authority (TVA) free PMU connection tester program was used as a Phasor Data Concentrator (PDC) [7]. More elaborate testing needs to be done to have better insight into PMU data communications.

5.0 TIME SYNCHRONIZATION ACCURACY

The PMU uses synchronized sampling scheme to record the data samples. It may not be necessary to report the PMU magnitude and phase angle based on the synchronized sampling [8], but there are advantages to have synchronized sampling scheme to analyze the data recorded from similar devices during wide area disturbances.

The ADC (Analog to Digital Conversion) sampling instant will be synchronized on every occurrence of the 1 PPS signal. The basic principle of this scheme is to discipline the ADC acquisition time instant with that of the 1 PPS signal. This is achieved by very gradually adjusting the time period of the acquisition clock (1 part per 1000 to 1 part per 15000 depending on the sample rate) thereby reducing the time difference between the instant of 1PPS and the ADC acquisition instant through a special software algorithm. The objective is to keep the time synchronization error within 1 micro second with respect to the 1 PPS signal.

Figure 8 shows the test cases conducted to verify the time synchronization accuracy of the PMU for different sample rates. The ADC sampling instant and the 1PPS signals are measured at their respective hardware interrupt outputs using calibrated Tektronix digital oscilloscope (THS720A). The two interrupt signals were captured a number of times to check the accuracy of synchronization.



1- ADC (Sampling) interrupt 2 – 1 PPS signal

FIGURE 8: HARDWARE INTERRUPT SIGNALS OF THE ADC SAMPLING INSTANT AND THE 1PPS SIGNAL FOR DIFFERENT SAMPLE RATES

Figure 9 depicts the error in time synchronization for different sample rates.

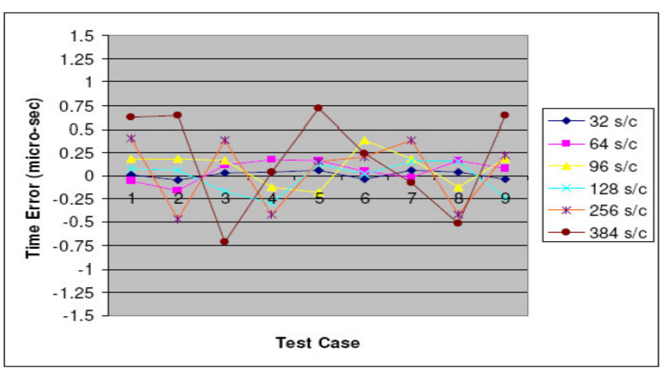


FIGURE 9: TIME SYNCHRONIZATION ERROR FOR DIFFERENT SAMPLE RATE

It can be observed that the maximum variation in the time synchronization error is within +/- 0.75 micro second. The reason that the accuracy varies with the sample rate is due to the limitation in the crystal frequency (30 MHz) of the clock (the base count available for each sample rate). The error can be further reduced if a high crystal frequency clock is chosen for the acquisition.

6.0 PMU RESPONSE UNDER STEADY STATE CONDITIONS

This section describes the PMU response under steady state conditions. As per the standard C37.118, level 0 and level 1 compliance specifies the TVE should be below 1% under all test conditions [1]. Figure 10 displays the magnitude and phase angle variations as calculated through Total Vector Error (TVE) for different sample rate.

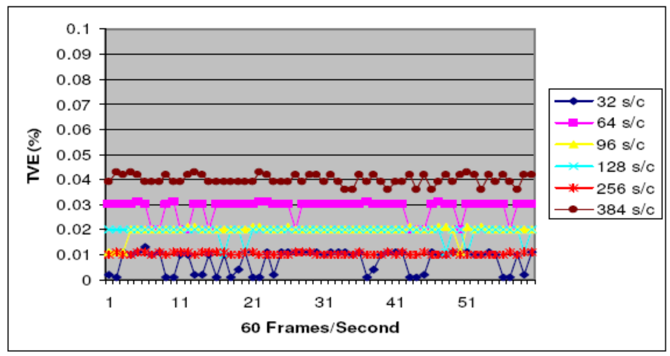


FIGURE 10: TVE UNDER NOMINAL VOLTAGE (69V RMS) AND FREQUENCY (60HZ) FOR DIFFERENT SAMPLE RATE AT 60 FRAMES / SECOND PMU REPORTING RATE

As discussed in section 5, the time accuracy translation is reflected in the TVE error. TVE is below 0.05 % and follows the same trend as seen in Figure 9. For off-nominal frequency the TVE error is as shown in Figure 11. It can be observed that the frequency compensation of the DFT algorithm is optimal near system frequency and diverges above and below the system frequency. In all cases, the TVE is below 1% as required by C37.118 [1].

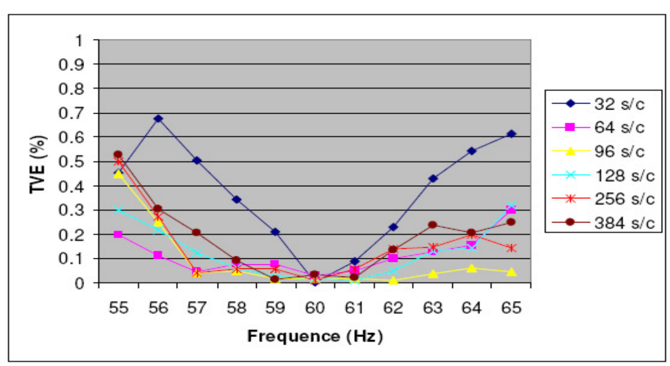


FIGURE 11: TVE UNDER OFF-NOMINAL FREQUENCY (55 Hz– 65 Hz) FOR DIFFERENT SAMPLE RATE AT 60 FRAMES / SECOND PMU REPOSRTING RATE

7.0 CONCLUSIONS

Various aspects of performance analysis, calibration and testing of a Micro Processor Based DFR with a PMU module have been discussed in this paper. The challenges encountered during testing have been explained with several examples and test cases. It is emphasized that the role of calibration equipment such as the one considered in the investigation is important in achieving the required PMU accuracy to meet the different compliance levels of IEEE C37.118 standard. It is beyond doubt that the PMU technology can provide useful information to mitigate wide area disturbances, protection and real time control of power systems. In order to get meaningful phasor information from different PMU manufacturers, practical procedures to test the interoperability – especially under dynamic conditions should be established. The experience of testing the PMU functionality with a DFR indicates that the current state of the calibration equipments is not user friendly to conduct the compliance tests as mandated by the PMU standard [1]. With the ever increasing communication security implementations, it is even more challenging to cooperate and share the phasor information among different utilities. This technology can be best utilized with the wider participation from utilities, manufacturing industries and academic institutions. It is encouraging that several organizations (e.g. PSRC, NASPI – formerly EIPP) and utilities have already taken steps towards serious implementation of this technology in North America and other parts of the world.

8.0 REFERENCES

[1] "IEEE Standard for Synchrophasors for Power Systems", IEEE C37.118 – 2005.

[2] North American SynchroPhasor Initiative (NASPI) [Formerly, Eastern Interconnection Phasor Project (EIPP)] Performance Requirements Task Team (PRTT) - http://phasors.pnl.gov

[3] "Synchrophasors : Definition, Measurement, and Application", Mark Adamiak, William Premerlani and Bogdan Kasztenny, GE Multilin Publications, pp 1-13.

[4] "A New Measurement Technique for Tracking Voltage Phasor, Local System Frequency, and Rate of Change of Frequency", A. Phadke, J. Thorp, M. Adamiak; IEEE Trans. vol. PAS-102 no. 5, May 1983, pp 1025-1038.

[5] "Real Time Voltage Phasor Measurements for Static State Estimation", A.G. Phadke, J.S. Thorp and K.J. Karimi, IEEE Transactions on PAS, Vol. 104, No. 11, November 1985, pp.3098-3107.

[6] "The Perfect Time: An Examination of Time Synchronization Techniques", Ken Behrendt and Ken Fodero, Publication, Schweitzer Engineering Laboratories, Inc., pp 1-18.

[7] "Tennessee Valley Authority (TVA) free PMU connection tester program", http://phasors.pnl.gov under Resources/Tools

[8] "Implementation and Performance of Synchrophasor Function within Microprocessor based Relays", B. Kasztenny, M. Adamiak, 61st Annual Georgia Tech Protective Relaying Conference, May 2-4, 2007, Atlanta, Georgia, pp 1-43.

9.0 AUTHORS BIOGRAPHY

KRISH NARENDRA – obtained his B.E. (Electrical Engineering) in 1986 from University Visweswaraiah College of Engineering (UVCE), and Msc (E.E) , Ph.D. (E.E) with a specialisation in High Voltage Engineering from Indian Institute of Science, India in 1989 and 1993 respectively. He joined Electrical and Computer Engineering Department of Concordia University, Montreal as a Research Scholar in 1995. From 1996 - 2000 he was with APT Power Technologies as a senior software developer. In 2000 he joined NxtPhase T&D Corporation and since 2006 he is the Software Development Manager of Relay and Recorder division. He has about 15 years of software development expertise and about 16 publications to his credit. He is actively participating in the PRSC working groups and a member of the PRTT of NASPI. His areas of interests include Power Systems Disturbance Analysis, Protection, HVDC Controls, Neural Networks, Fuzzy logic, Phasor Technology (PMUs). He can be contacted at Knarendra@nxtphase.com.