

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

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Abstract—PMU are vital in modern power grid due to advancement in operation and control. Here in this report description of a PMU being developed using OMAP-L137, its testing and verification using a Full Spectrum Simulator (FSS) is discussed. The tests and its standardization reference is taken from smart-grid standard C37.118-2011. While developing the PMU, a custom high speed ADC board is designed, it is interfaced to OMAP using EMIFIA - a new interfacing method available in OMAP-L13x processors, is used. This setup will be hooked up to mini-FSS which will provide different test signals. through this experiment we also want to see the usability of FSS in different scenario.

Index Terms—Wide Area Measurement System(WAMS), Phasor Measurement Unit, IEEE C37.118, Full Spectrum Simulator, OMAP-L137,

I. INTRODUCTION

Day by day power system is becoming more and 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 countermeasure has become a complex task, which requires a reliable, fast-acting and absolute technique to deal with the challenge. This is where the Phasor Measurements Unit (PMU) comes into 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.

Just like all other engineering devices PMU's reliability, accuracy and precision are very crucial for its application and hence different kinds of test are done to validate its performance. Hence just like other measuring devices PMU standards are defined which states minimum performance requirement(s). All device should at least meet the requirement stated by the standards, according their application.

So, here with this project we are exploring the application of miniaturised Full Spectrum Simulator as a Hardware -in-loop-

testing device for PMUs and the implementation of standards on indigenously developed PMU . We will see the feasibility as well as effectiveness of the platform and how it can be adjusted to make it suitable for C37.118 compliance testing. This report is largely divided in two parts via three sections 1) C37.118 standard 2) Tests and its explanation and 3) Implementation. The *compliance* section provides theory background of the topic and basis of tests. Implementation section provides insight about the intended test-setup, hardware detail and the approach taken.

A. Background Theory

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

$$x(t) = X_m \cos(\omega t + \varphi) \quad (1)$$

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

$$\mathbf{X} = \frac{X_m}{\sqrt{2}} \exp^{j\phi} \text{ or } \mathbf{X} = X_r + jX_i \quad (2)$$

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 definitions 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 given 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. C37.118 STANDARD COMPLIANCE

Every PMU should be able to calculate the value of phasor estimate accurately. The estimate will include positive sequence or single phase values, phase difference, frequency and ROCOF. So it is important 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:

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

The ROCOF is defined as:

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

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:

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

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 compliant 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 compensated properly or not. *Latency in reporting* is the time taken between the occurrence of event in power system and that being reflected in the output of the PMU. This parameter largely depends on the class of PMU and the sampling and filtering algorithm

used. Which brings us to the classification of the PMU, they are divided in two parts:

- 1) **Protection Class (P class):** This PMU is used for protection purposes and hence its response time should be as much less as possible.
- 2) **Measurement Class (M class):** This PMU class emphasizes on the accuracy of the reported data and hence timing requirement are not as stringent as P class PMUs.

On the basis of above class PMU's TVE tolerance limit is set, as described in above points protection class is for application requiring fast response and M class is for application requiring higher accuracy. TVE norms for P class are more stringent compared to M class.

B. Validation & Testing

To get the TVE, compliance tests are performed and during the test only the quantity under test is varied from the reference condition as per the test and other relevant quantities are maintained at reference condition. There are following kind of compliance tests:

- 1) Steady-state compliance
 - a) Steady-state synchrophasor measurement requirements
 - b) Steady-state frequency and ROCOF measurement requirements
- 2) Dynamic compliance
 - a) Synchrophasor measurement bandwidth requirements using modulated test signals
 - b) Ramp of system frequency
 - c) Step changes in phase and magnitude

The TVE tolerance for each case wont be mentioned here as those tables can be looked into the standards.

III. LITERATURE SURVEY

Apart from studying IEEE C37.118 for the purpose of tests and the standardize condition, a literature survey was also done. Papers refering to the topics like Dynamic testing, IEEE standards were taken into consideration for a broader view and dipper understanding. Herewith presenting a brief discussion on selected papers: One of the goal of this experiment is to access the feasibility of FSS as a HIL testing platform for PMU so in that context a very similar paper was found “**Development of a Smart Grid Test Bed and Applications in PMU and PDC Testing**” which discusses the development of “smart-grid” testbed. In the given paper the activity is carried out using RTDC as a platform. This paper tries to present the scenario of how one can model a smart power system within laboratory and how that setup can be used for testing of synchrophasors and phasor data concentrators. The *test setup* consisted of RTDC by Opal-RT which houses the power system model, aroudn which, system was created which had a SEL GPS module, which provided time reference to whole setup, an array of different relays having different charactersitics in conjunction of communication device. The output of RTDS is given to other relays and the PMU under test via current and voltage amplifiers. which boosts the low voltage signals to normal power level. For the purpose of

reliable testing, PMU was coupled with RTDS as well as PMU TESTER POM2-6143[5]. PMU tester has accuracy of 0.01 % as per the reference. Tests performed on PMU were of 4 kinds 1) Balance Condition 2) Unbalance Condition 3) System at Off-nominal Frequency and 4) System with harmonics component. Each test was first conducted using PMU Tester, readings were taken and then it was repeated using RTDS. Both of these results were then compared. Apart from testing PMU this test-bed also evaluated the capabilities of PDC, this was possible due to embedded PDC and data logging facilities in SEL® relays, which were connected through PC. The characteristics evaluated were 1) Data Validation 2) Data Re-Sampling 3) Data Alignment 4) Data Recognition 5) Data Retrieval 6) Data Truncation.

Another interesting paper studied was **Dynamic PMU Compliance Test under C37.118.1aTM-2014** by R. Ghiga, this paper present flexible testing methodology for dynamic compliance test for PMUs [6]. Three different PMUs are taken and tests are conducted on them using laboratory hardware setup and comparative study is presented. This setup used Doble F6150 Power System Simulator, which is used for retesting, this device acts in standalone mode and generates 3 - ϕ AC voltage and current signals with varying amplitude and frequency. PMUs can be connected directly, without the amplification stage or so, which resolves the accuracy concerns and in addition more than 1 device can be connected at a time, which enables testing of all 3 devices at a time! Tests were conducted on the basis of the PMU standard which are Amplitude Modulation, phase modulation, freq ramp, amplitude step and phase step. The results presented were quite interesting. An important note to make over here is that only dynamic tests are performed and the test signals given to the PMUs are not time triggered. As per the C37.118-2011 the step-input test signals requires to be UTC synchronised. So this implementation is considered to quite similar to ours.

Another wonderful paper and one of the first paper to be published on compliance testing stated by PMU standard in 2011 was **Dynamic Performance Evaluation and Testing of Phasor Measurement Unit (PMU) as per IEEE C37.118.1 Standard** by Krish Narendra, Dinesh Rangana Gurusinghe and Athula D. Rajapakse. This paper gives a fundamental understanding of the compliance testing and then newly introduced concept of TVE and compliance testing. In this paper

IV. IMPLEMENTATION

Overview of the test setup can be seen in FIGURE, Implementation can be divided in three parts

- 1) **Full Spectrum Simulator (FSS):** Which will have the power system model, through which different test conditions will be given
- 2) **PMU:** Which will consist of a ADC interfacing board and OMAP-L 137 EVM
- 3) **PC:** It will have a Phasor Data Concentrator (PDC), which receives data from the PMU and record it for future analysis.

During the initial phase of the project intention was to use indigenously PMU developed C-DAC but due to the hardware

issues and lack of documentation and support, it was decided that a minimalistic PMU will be developed by ourself.

A. Full Spectrum Simulator:

As per the requirement of the implementation, miniature-Full spectrum Simulator will be used for this purpose. FSS is a card based, multi CPU - parallel processing hardware. It uses TI's MSP430 DSPs as building block. It was developed by IIT Bombay and CDAC for both, offline & real-time simulation purposes in Power Electronics and Power Systems.

As shown in Fig: 2 above it is a card base setup which contains:

- System Interface Card (SIC)
- Intra Rack Control Card (IRC Card)
- Three CPU Cards (CPU 0, CPU 1 and CPU 2), each having 3 digital signal processors on it. So there are total 9 processors allowing for parallel computation.
- One Analog Output Card (AO Card), having 6 analog output channels (10 V range).
- One Analog Input Card (AI Card), having 6 differential analog input channels (10 V range).
- One Digital Input/Output Card (DIO Card), having 24 digital inputs and 24 digital outputs (0 - 5 V).
- One Back Plane PCB.

• System Interface Card: It is called SIC, it acts as a communication layer between host PC and the CPUs in the CPU rack. It consists of TUSB chip which connects the device to host PC, real-time simulation software is downloaded to from the host computer to SIC over this USB interface for distribution over different CPUs. It communicates to other CPUs in the rack over backplane through Gun Transistor Logic Plus (GTLP) transceivers. A TMS320 chip is also there to interface SIC with IRC card and a MSP430 to have RS-232 interfacing.

• Inter Intra Rack Communication Card: IIRC is designed as a master controller card, which controls other cards, peripheral communication, timer triggered execution and host pc communication. Further more IIRC card handles analog as well as digital input-output also. Apart from that IIRC processor also controls the simulation execution using it's timer on the respective CPU card. IIRC card has protocol implemented to communicate between CPU cards and SIC so that simulation can be controlled and it's result can be sent to respective peripheral and/or can be downloaded to host PC. The communication to and from the I/O system over a high speed fiber optic network is also controlled by the IIRC cards using 2 Altera make FPGAs.

• CPU card: mini-FSS has 3 CPU cards, each having TI's MSP430 DSPs. These cards are heart of FSS. They handle all the mathematical algorithm associated with the simulation. Data flowing from and to the cards are controlled by IRC card via **back plane** PCB.

FSS having card base architecture with multiple CPU makes it a very viable platform for modeling purposes, as the system can be split across multiple process threads and concurrent



Fig. 1: Mini-FSS setup in laboratory

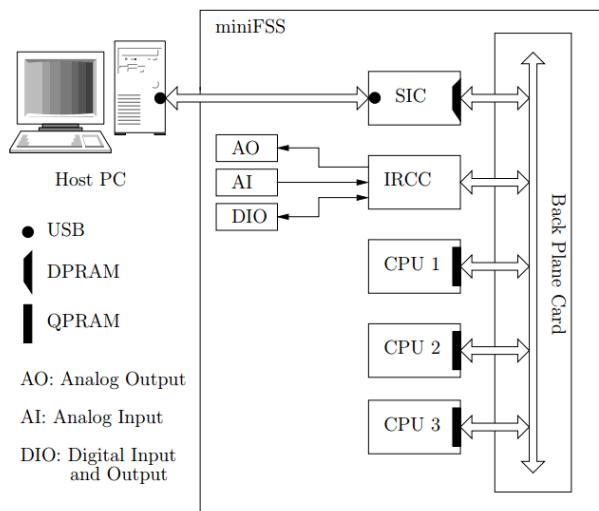


Fig. 2: FSS architecture

execution can be done. This feature makes it extremely suitable for Power system and power electronics application as there different system cutset can be made to execute on each processor and hence results can be computed/ solved very fast. This feature is explored for the PMU testing as the system model is implemented over several cores/processors.

For our purposes in the beginning FSS will be used a real-time player only. A simulation will be developed in a Elector Magnetic Transient Program (EMTP) for a sample system,

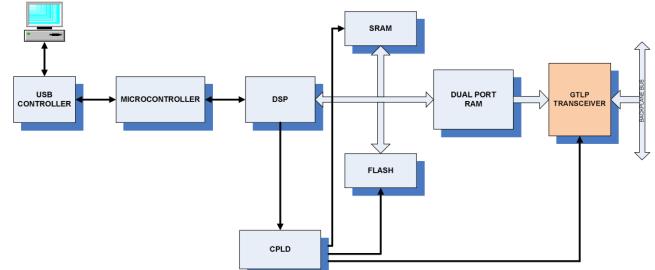


Fig. 3: SIC block Diagram

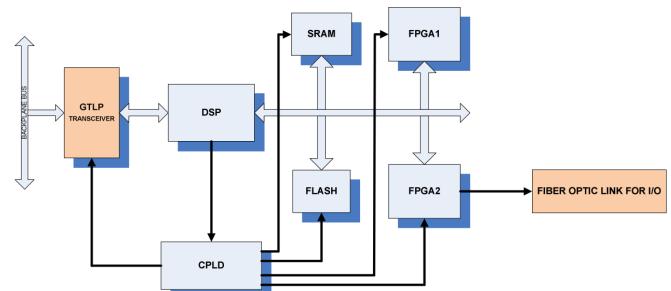


Fig. 4: IIRC card Block Diagram

and it's data will be taken. This data will be used to create a output pattern to be played in real-time to the PMU. Latern on as the concept evolves A model of a small system (say 4 bus or more) will be implemented which will use multiple CPU cards and processors, which will used as an input to the

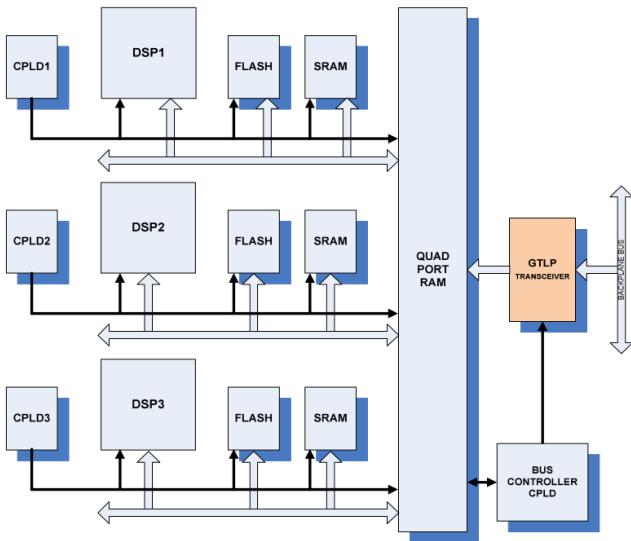


Fig. 5: CPU card Block Diagram

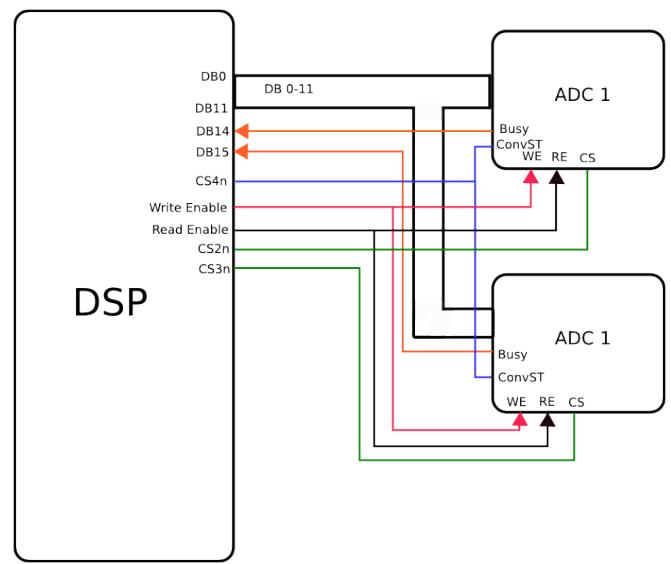


Fig. 6: ADC Board block diagram

PMU. Different kinds of transient conditions can be created using this, which can be later used for testing of the PMU.

Though as of now it has been observed that simulation having anything more than 2 bus is not possible to run due to step size and other technical aspects. But later on a more thorough effort will be made to implement it.

B. PMU

OMAP-L137 EVM is being used as the platform to design PMU. OMAP-L137 EVM doesn't have Analog to Digital Converter on board hence an interfacing circuit is developed. While designing the ADC board following criteria were kept considered.

- Good sampling rate: 200 Samples/Sec
- No of channels: $3 + 3 = 6$ ($3 - \phi$ voltage and current)
- Interfacing type: It should be memory addressable and voltage level compatible to the EVM.
- Input type: FSS analog output is differential which can be configured as single ended, its voltage level is ± 10 V

Above Fig: 6 shows the design logic of ADC board. Two AD7864-1 are used as ADC chips due to their high sampling rate of 500 kspS and direct input voltage compatibility range of ± 10 V. AD7864 is a high speed 4 channel simultaneous sampling successive approximation ADC with *bi-polar* input having conversion time as low as $1.65\mu\text{sec}$. Chip's conversion sequence can be controlled through hardware as well as software, its default operating voltage is 5v but has a special output voltage shifter for interfacing it with 3.3v processors and controllers. This ADCs are fairly advance hence they have been interfaced with a special asynchronous peripheral interfacing architecture called EMIF-A, which is exclusively available in OMAP-L13x series processors. Extended Memory Interface (EMIF) has two parts A & B out of which EMIF-B is having *Enhanced Direct Memory Access* controller (EDMA3) which enables the processor for multi-threaded rapid memory access and hence it is exclusively for highspeed SDRAM

interfacing where as interface A (EMIF-A) is developed for generic purposes more details are given below:

1) *EMIF-A*: EMIF-A controller is a 16-bit databus based versatile controller [8], designed to interact with variety of devices like

- Single Data Rate (SDR) RAM
- Asynchronous devices like NAND & NOR flash memory and SRAM

It contains lot of features to ease and facilitate the usage of asynchronous devices. A functional block diagram is given here in Fig: 7 It is apparent from figure-7, that it has 4 cheap selects and, one read and write and 16 data channels. which makes it very convenient for interfacing multiple peripherals at a time.

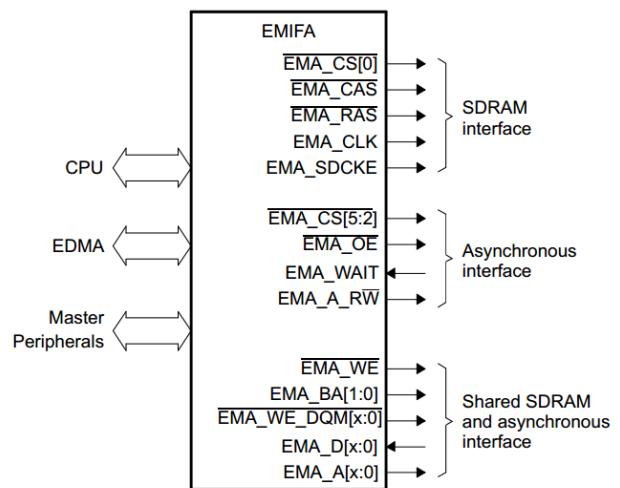


Fig. 7: EMIFA Block Diagram [8]

2) *ADC board Logic*: Due to EMIFA, interfacing of ADC board became quiet convenient rather than using pins in GPIO mode. So the logical flow of the board is as follows:

- 6 input channels are required hence 2 ICs are used
- Chip Select (CS), Read, Write, and databits from 0 - 11 are directly available from the EMIFA interface, and they are shared with both the chips.
- AD7864 has sequence selection which has been configured through hardware, and Clock source has been kept internal. because of this both the pins INT/EXT_CLK & H/S select
- AD7864 has 3 control output Busy, FIRSTDATA and EOC. Out of these only busy is observed via a data line (data bits 16 & 15). Data is **anded** is not read until data line 15 & 14 are not zero.
- AD7864 supports two kinds of data reading 1) Reading during the conversion 2)Reading after the conversion. Here we are going to use *Reading After the conversion*, below is the timing diagram of the chip for understanding the proper functioning of the circuit.

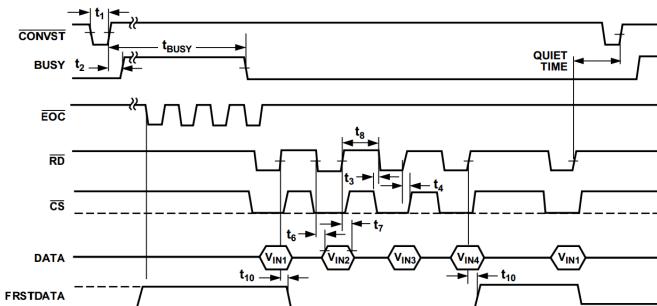


Fig. 8: ADC Reading After the Conversion timing

Now we will see the operation that takes place when sampling is to be done:

- Assert start of conversion (CONVST) is asserted via EMA_CS (4)
- Due to this chip will start the conversion processes which will make BUSY high,
- Status of BUSY will be checked via DB15 & DB14 pins of the EMIFA header, for both the chips until they are low again.
- The moment BUSY goes low, EMA_CS[2] and EMA_A_RE are asserted with which AD7864 starts putting data on data lines. this processes of asserting is repeated for 4 times, for each channel. The same is done using EMA_CS[3] for getting data from 2nd ADC chip.

3) *Computer*: It will have the Phasor Data Concentrator (PDC) program, which will collate the data coming from our PMU coming over serial bus. PDC usually has two functions one is to archive the data for historic reference and to send the data upward to higher level PDC for control actions and analytics. Here a PDC program developed by other M.Tech students is going to be used which is called **iPDC** [3]. iPDC has two parts, one part controls the data sources and the communication of configuration frame. The other part DBserver works as a data storage manager, which archives the data received at an given port. Configuration frame is first communicated before starting the transmission of data to know the number of channels, digital status word etc. Though for

existing setup config frame wont be required so program can be modified accordingly to function without it.

V. WORK DONE AND PLAN OF WORK

Work Done

- Initially the idea was to use an indigenously developed PMU in collaboration with C-DAC, Trivandrum and IIT Bombay. This PMU is a full functional device having capability of measuring six Voltage vectors and 6 Current vectors. It was having a signal conditioning stage (sensor module) which enabled the PMU to sense signals upto the voltage of 230 v. The device is show in the Fig-9. Its sampling circuit uses AD7606. The PMU has 8-channel, of 16-bits with bi-polar inputs at sampling rate of 200 ksp. So to use the hardware so that development time can be reduced the functioning and usage was understood and efforts were made to make it functional but after efforts of more than 1 month we discontinued it and decided to develop our own device
- Along with the above work related to hardware, study of IEEE C37.118-2011/14 standards along with literature survey was also done over the period of 3 months. During the literature survey different papers on Dynamic testing of PMU, test-beds for PMU, smart-grid test-bed topics were explored to get better insight of the "How-to" and "challenges" of the implementation of the experiment.
- AD7864 was chosen as an ADC chip and designing of ADC interfacing board was started. After rigorous study of OMAP-L137 EVM, EMIFA, AD7864 and schematics of C-DAC PMU, A proper strategy was laid down and logic was developed as explained in *implementation* section.

Future Plan of work

In upcoming months following activities are planned for the accomplishment of the experiment

- Test ADC board, check its performance after connecting it with OMAP-L137 EVM (15 Days)
- Interfacing of GPS module and DSP programming for time based signal sampling (15 - 20 Days)
- Implement and test DFT algorithm for the phasor estimation and reconstruction (1.5 months)
- Testing of whole setup along with simple test input from FSS (5 - 7 Day)
- Test PMU setup using FSS as real time player and analyse the result
- Implement a test system in FSS using multi-cores and do the testing (mentioned in compliance section) and analysis (2 - 3 months)

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Fig. 9: C-DAC, trivendrum PMU

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