International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 22 (2017) pp. 12395-12402

Reactive Power Monitoring and Compensation in a Distribution Network of Modern Power System

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Abstract

The paper presents a modern technique for capturing and processing the real-time signals in the power system. A model has been proposed by using a Smart Grid Prototype hardware and LabVIEW software to monitor and acquire the data related to power factor and reactive power in a distribution network. FPGA-based embedded system architecture of the model enables the processing of multiple data signals in parallel.

A case study is done at one of the distribution substation with existing infrastructure to check online reactive power compensation method executed by local utility company. Current work focuses on effective use of capacitor bank for reactive power compensation using the prototype model.

The paper focuses on the broad objective of mitigating the current power grid towards a modern power system so that occurrence of voltage imbalances or any fault may be detected in real-time and the remedial measures may be taken in time.

Keywords: Smart Grid (SG), Phasor Measurement Unit(PMU), Reactive Power, Power Quality.

INTRODUCTION

Management of reactive power leads to improvement in the performance of ac power systems. Compensation has two aspects, (a) Load Compensation which increases the power factor, balance the real power drawn, compensate voltage regulation and eliminate current harmonics of the system. (b) Voltage Support decreases the voltage fluctuation at any given terminal of a transmission line. Therefore, Reactive power (VAR) compensation improves the stability of ac system by increasing the maximum active power which can be transmitted.

Reactive power has a negative impact in the distribution network [1] and is compensated by widely used Capacitor banks. The section focuses on the objective to make the voltage stable in a power system with variable reactive power due to various types of load and Distributed Generation (DG) sources [2].

For getting a high degree of DG penetration with increase in efficiency of power system and low environmental impact, the existing transmission and distribution system needs to be more interactive along with their usual role[3]. Such type of network is a Smart Network or a Smart Grid. The Smart Grid concept includes real time monitoring and data acquisition, analysis of acquired data and fast implementation in a wide area network. For the purpose of voltage control by reactive power compensation, capacitor banks are being used.

Apart from being an essential part of power, reactive power has a negative impact in the distribution network. In present scenario, the reactive power is compensated by widely used Capacitor banks. The paper focuses on the objective to make the voltage stable in such a power system with variable reactive power. Next section in the paper gives overview of reactive power in the power system followed by description of various aspects of technology used *i.e.* FPGA and LabVIEW FPGA Real Time Architecture. The subsequent sections give the detail about the case study and problem formulation followed by the result and conclusions.

REACTIVE POWER IN POWER SYSTEM

Reactive power is considered an essential part of power system but it is seen as a major hurdle in getting a quality power and a consistent voltage. The source of reactive power can be anything from inductive loads, peak load, power theft or connection of various distribution generation units to the grid. Hence, during day to day operations the voltage at different buses across the system increase or decrease during daily operation [4].

During off peak conditions, the line generates net VAR which is absorbed to obtain voltage stability [5]. While, during peak load conditions shunt capacitor bank generate lagging VARs at the receiving end to obtain voltage stability.

The voltage at the receiving end depends on reactive power in the system as shown in power angle diagram [6] in Figure 1.

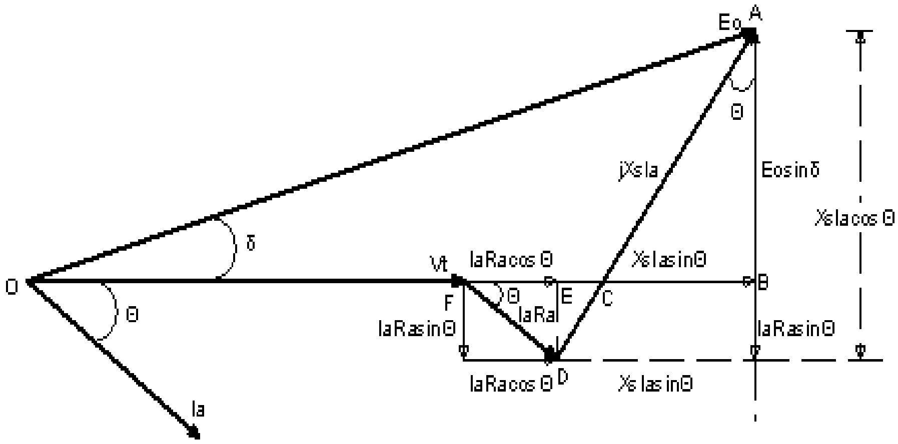

Figure 1: Power angle diagram

Mathematically, (E-V= XQ/V) where, E is receiving end voltage, V is sending end voltage in volts, X is reactance of the line in ohms and Q is reactive power in VAR.

Voltage Change is $\Delta V = \frac{RP+XQ}{V}$ (1)

and

power angle, $\delta = sin^{-1}(\delta V / E)$ (2)

where, $\delta V = IXcos\theta - IRsin\theta$ (3)

Since the resistance may be assumed negligible for a Transmission line,

So, $\Delta V = \frac{XQ}{V}$ (4)

and $P = \frac{EV}{X} sin\delta$ (5)

System voltage is a function of reactive power and frequency is a function of active power.

Reactive power has a negative impact in the distribution network [7]. The devices which supply reactive power at the load bus in distribution system are known as reactive power compensating devices such as Capacitor banks [8]. For Reactive Power Compensation, there are various compensators available such as Shunt compensation, Static VAR Compensators and Static Compensators. Besides voltage control, the compensating devices have some additional effects such as decrease in system copper loss, decrease in investment per kW of load supplied and improvement in system power factor which helps in achieving better economy in power distribution.

Ensuring a stable and constant voltage to consumers is always a challenge. Different methods and technologies are used to ensure voltage stability. In most of cases where the voltage is below the specified level, the reactive power produced is compensated by the capacitance viz. Synchronous condensers, Shunt, Series Capacitance, Tap Changing Transformers. While in the cases of over voltage where the voltage is above the specified level, reactive power produced is compensated by inductance viz. Shunt Reactors, Static VAR compensators, Tap Changing transformers. The capacitor banks are generally used by majority of utilities to compensate reactive power i.e. Synchronous condensers and Static capacitors or Capacitor Bank. Static capacitor bank are further subdivided into shunt capacitors and series capacitor.

In distribution networks, utilities use shunt capacitor banks for reactive power compensation and power factor correction. A shunt capacitor reduces the reactive components of load and thereby improving the power factor of the system. On the other hand the method used mostly in EHV lines is Reactive power compensation by use of series capacitor which improves the impedance of the system since it is in series with the line.

Capacitor bank is installed primarily at high voltage bus system instead of installing at every load point. At high voltage bus at a substation, capacitor bank is connected on the secondary side of the transformer. In capacitive compensation by using capacitor banks, the reactive power supplied by the capacitors are given by

$Q = 2\pi fCV^2$ MVAR/phase (6)

where, f, C and V are frequency, capacitance and voltage per phase respectively.

FPGA Embedded System Architecture

Smart Grid prototype cRIO by National Instruments along with LabVIEW FPGA Real Time Architecture has been used to make the proposed model prototype [9]for monitoring the required acquired data.

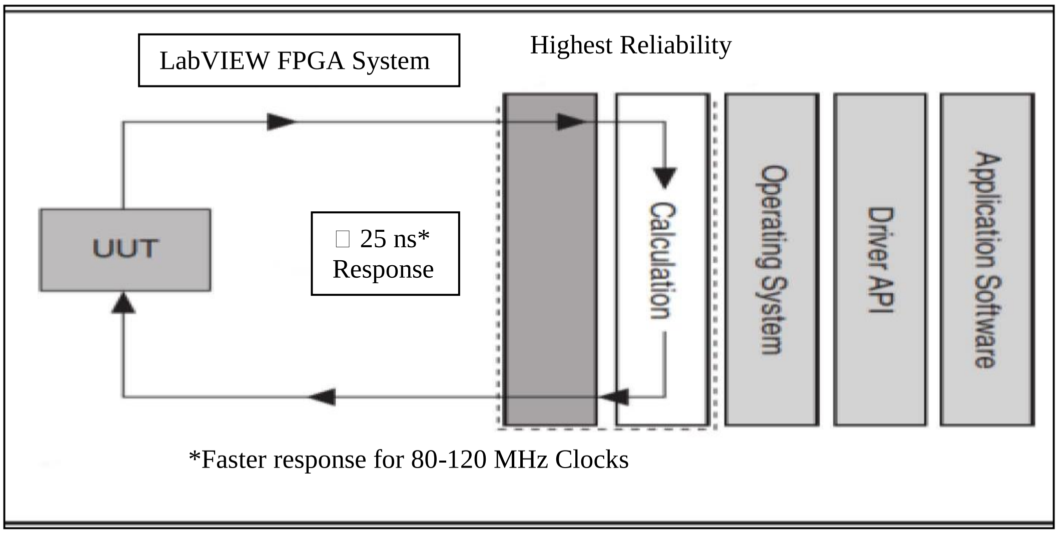

Figure 2: FPGA Software and Hardware Layers

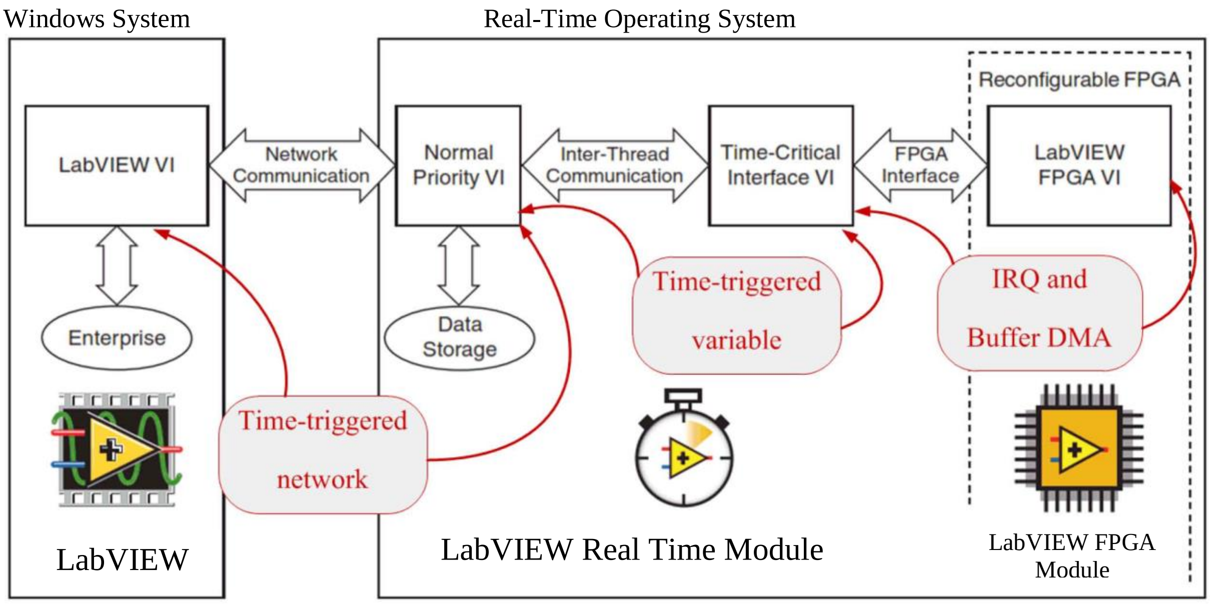

Figure 3: Lab VIEW FPGA Architecture for Real-Time [11]

The response rate of traditional measurement system is in milliseconds to microseconds level while LabVIEW FPGA system with a clock rate of 40 MHz, responds to digital signals within a single clock cycle i.e. within 25 ns. The configuration is shown in Figure 2.

In NI cRIO, each I/O module is directly connected to the FPGA in the chassis (as shown in Figure 4) which helps in minimizing the time for customization and I/O signal processing. The current signal and the voltage input signal are acquired with the help of NI-9227 and NI-9225 modules respectively [10-11]. Data from FPGA are received by the application software to calculate from them different parameters i.e. Power factor, Active and reactive power. The LabVIEW FPGA architecture is shown in Figure 3.

Case Study

Grid substation of OPTCL 220/110 kV located at Kapilaprasad, Bhubaneswar, Orissa, India and a 11kV/420V Distribution Transformer Bay has been taken for case study. The single line diagram of the distribution transformer bay where reactive power and power factor are recorded is shown in Figure 5. It consisted of a distribution transformer whose specifications are mentioned in the Table 1 along with air circuit breakers and switches. The measurement is recorded at one of the branches on the secondary side of the transformer.

Figure 4: (a) NI cRIO-9082Controller with 1.33 GHz Dual-Core CPU and LX150 FPGA chassis without any I/O modules [10]

Figure 4: (b) NI cRIO-9082 chassis with all the I/O modules [10]

Table 1: Distribution Transformer specification

Transformer Rating	2000kVA
Type of Cooling	ONAN/ONAF
Phase	3
R(pu)	0.001
X(pu)	0.04
Nominal HV Voltage(L-L)	11kV
Nominal LV Voltage(L-L)	0.415kV
Rated Current (HV)	131.2A
Rated Current (LV)	3478A
Frequency	50 Hz

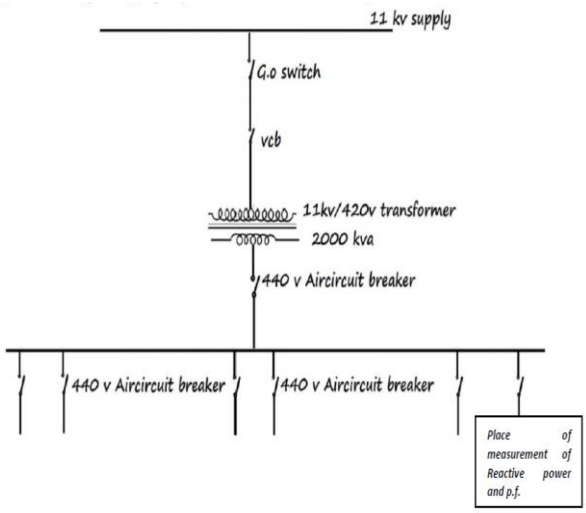

Figure 5: Single Line Diagram of 11kV/420V Distribution Transformer Bay

The problem formulated is stated as Reactive Power Compensation in a AC distribution network by calculating capacitance of capacitor banks used by using $C = Q/2\pi fV^2$ and finding the value of active and reactive power using $P = VI\cos\theta$, $Q = VI\sin\theta$, where, $\cos\theta$ is the power factor.

SOLUTION METHODOLOGY

The real sample of data for reactive power and power factor acquired from the substation was fed to the cRIO for 100 minutes and the same is plotted in graphs using LabVIEW software. The graphs for reactive power and power factor are given in Figure 6(a) and Figure 6(b) respectively.

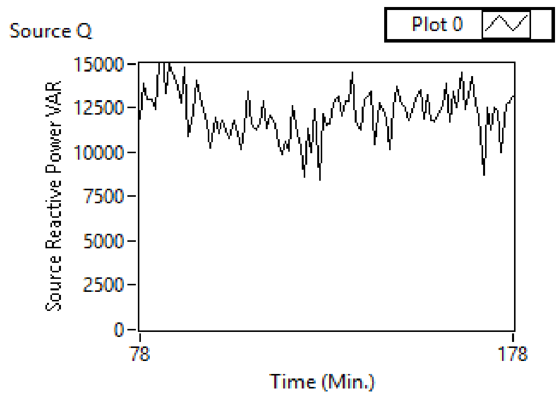

Figure 6: (a) Reactive power (in VAR) for one phase as monitored by cRIO

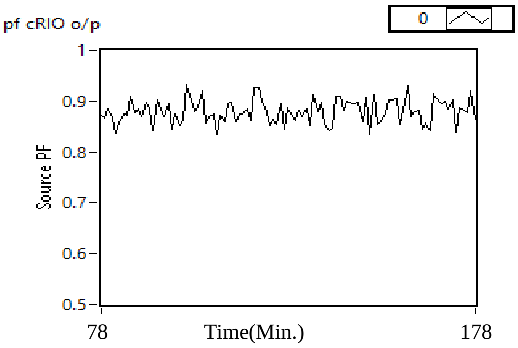

Figure 6: (b) p.f. for one phase as monitored by cRIO

The data acquired was for every one minute time period and a sample data is given in Table .The monitoring system takes the required data at one of the distribution transformer bay in the substation. The schematic diagram transformer is given in Figure 7.

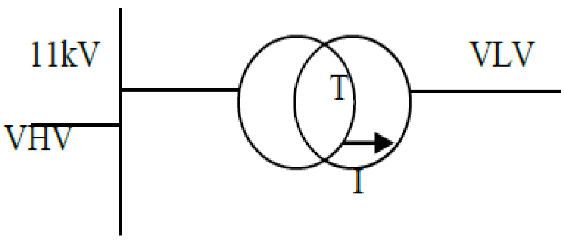

Figure 7: Schematic diagram of Distribution Transformer bay

Per unit system is incorporated so that the transformer can be represented as p.u. of resistance and inductance. The transformer model is shown in Figure 8.

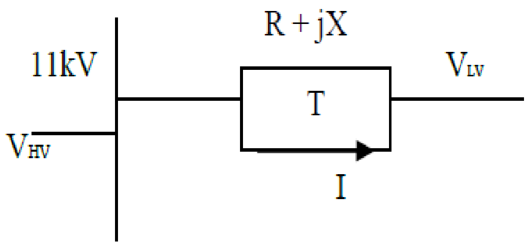

Figure 8: The Transformer model for a single phase.

By using the above transformer model, the relationship of low voltage side voltage V_{1LV}, low voltage side current I_1, high voltage side voltage V_{HV} and the bus-bar high voltage side current I of the transformer are given as in (7)

$$V_{HV} = V_{1LV} + I_1(R + jX) \quad (7)$$

Data acquisition by the cRIO and collecting the same from two modules of the cRIO are done as per the LabVIEW FPGA program shown in Figure 9which receives the data sent by the cRIO prototype for online monitoring.

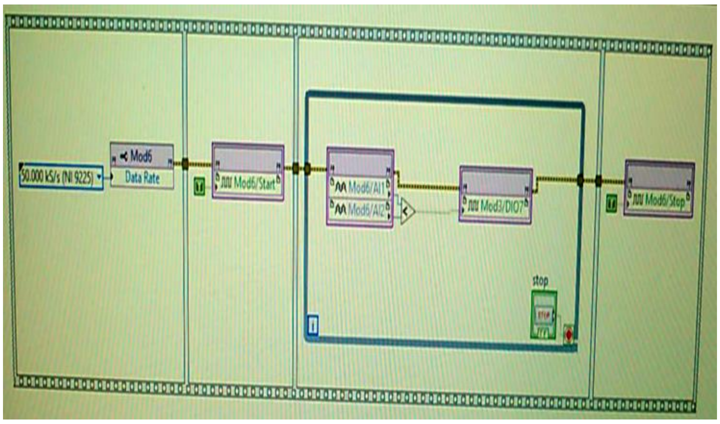

Figure 9: The data acquisition program on LabVIEW FPGA

After the IP address is configured, the live data can keep on streaming in the program without break. The following steps have been made to analyse the data on a LabVIEW platform.

(a) Data Acquisition

(b) System Initialization

(c) Per unit calculation

(d) Voltage calculation

(e) Power Calculation

The sub-programs for the steps followed are shown in the Figure 10.

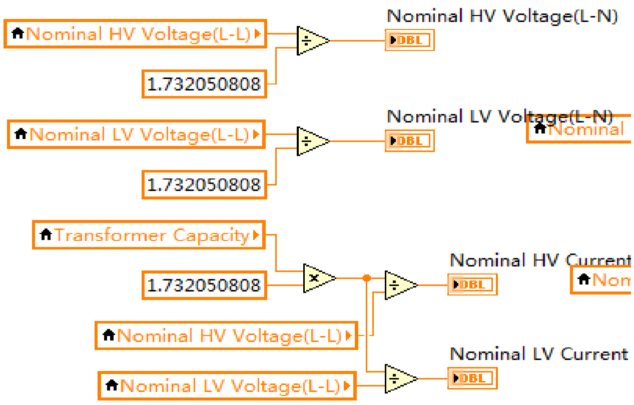

Figure 10: (a) Nominal value calculation

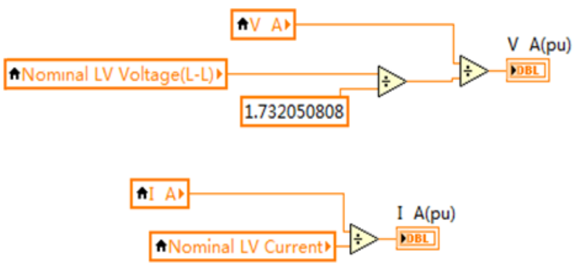

Figure 10: (b) Acquired data conversion to per unit values

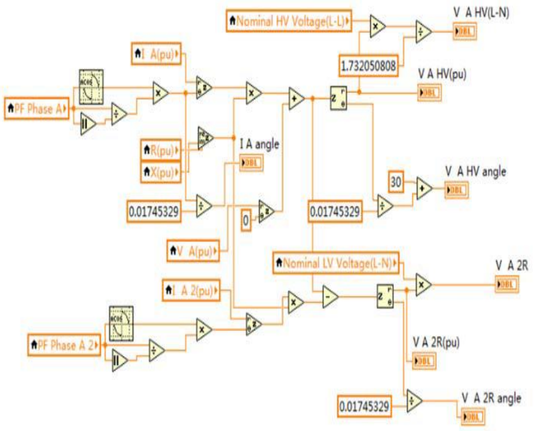

Figure 10: (c) Voltage calculation for one of the phase (A) on HV and LV sides of transformer

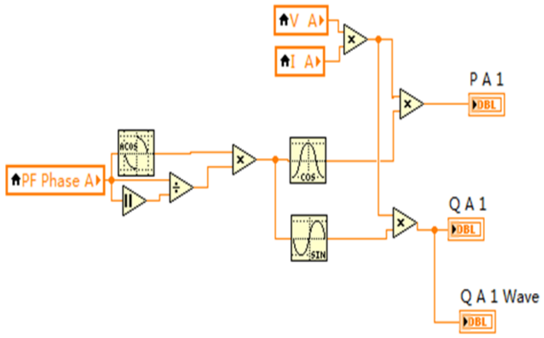

Figure 10: (d) Active and Reactive Power calculation after compensation

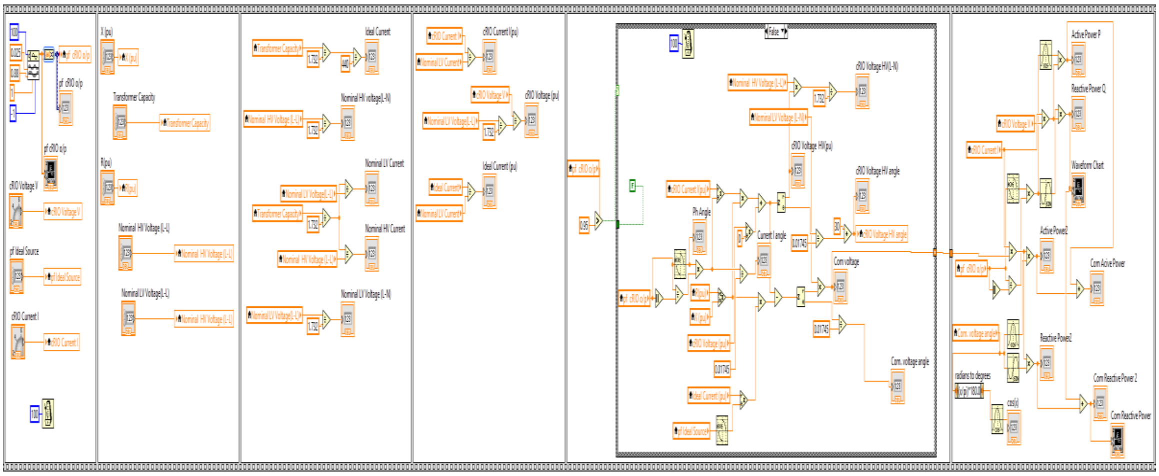

Figure 11: LabVIEW main program

The main LabVIEW program (Figure 11) is made by using the sequential structure where all the subprograms are kept in sequential manner for execution.

Using the present design, alteration related to monitoring of any other target or change in any parameters can be done.

The equations used behind the functional blocks are:

$$V_{LN,base} = V_{LL}/\sqrt{3} \qquad (8)$$

When data collection is complete, nominalization is done so that per unit model can be established. All the LV data is between phase and earth. The program for one of the phase A uses the following equations in the programming block.

$$I_{A.pu} = {}^{I_A}/_{I_{base}}, \quad V_{A.pu} = {}^{V_A}/_{V_{base}} \qquad (9)$$

Voltage Calculation is an expression of the transformer substation model and the ideal source for fault voltage revision. It's given as:

$$V_{HV} = V_{LV} + I(R + jX) * \text{angle } \theta \qquad (10)$$

Power calculations for active and reactive powers are given by equations below are used in the LabVIEW programming block.

$$P = VI\cos\theta \quad \text{and} \quad Q = VI\sin\theta \qquad (11)$$

RESULT

The reactive power obtained after capacitive compensation is more stabilized and the power factor is also uniform in nature (Figure 12) with respect to original data (Figure 6).The model worked at efficiency of 80% which is better comparedto60-70% efficiency by traditional methods used in utilities. The data was processed by hardware model cRIO with LabVIEW at a speed 1000 times more than that of traditional methods due to processing speed of the model. A sample of compensated data with respect to acquired data for ten minutes is given in the Table 2.

Table 2: Acquired and compensated values of reactive power and power factor

Time in Minutes	Date and Time	Acquired Values			Compensated Values	
		Reactive Power (kVAR)	p.f.		Reactive Power (kVAR)	p.f.
78	17-08-2016 13:00	11470.03221	0.88		1134.185577	0.927977
79	17-08-2016 13:01	10218.25825	0.90		1930.764528	0.925748
80	17-08-2016 13:02	8358.072837	0.90		1133.75448	0.9293
81	17-08-2016 13:03	6072.111409	0.90		1929.781102	0.9274
82	17-08-2016 13:04	6868.842713	0.89		1134.649641	0.925977
83	17-08-2016 13:05	9035.68737	0.90		1929.598174	0.919634
84	17-08-2016 13:06	10710.70733	0.87		1133.734853	0.9191
85	17-08-2016 13:07	11728.42537	0.86		1930.533291	0.92
86	17-08-2016 13:08	11990.2782	0.90		3581.199979	0.92
87	17-08-2016 13:09	11470.18542	0.92		1133.986007	0.9237

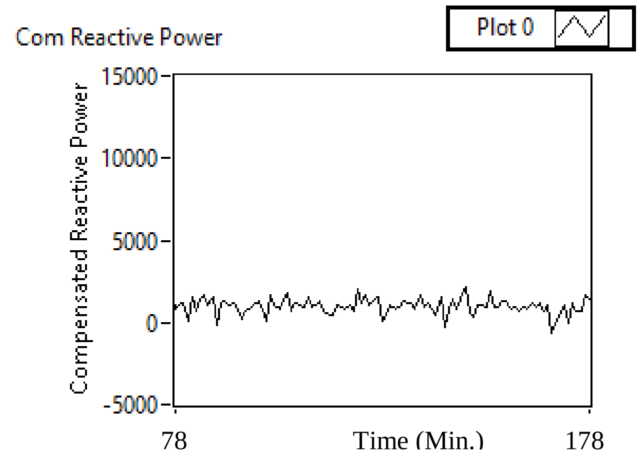

Figure 12: (a) Compensated Reactive power (VAR) for one phase

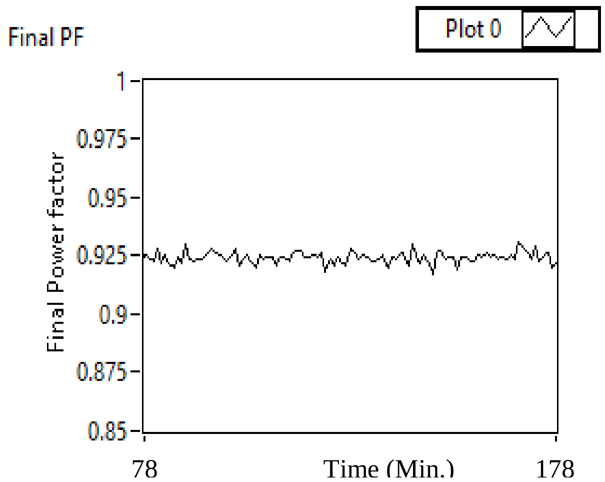

Figure 12: (b) Compensated p.f. for one phase

Further, the capacitive compensation improves the power factor in the system to a stabilized value of approximately 0.92 which reduces losses and increases the efficiency of the power system.

The use of such technique is to improve the efficiency of capacitor bank switching which will result in the desired voltage stability.

CONCLUSION

The work presents a modern technique of capturing and processing of the real-time reactive power data in a distribution network. It is concluded that the hardware model cRIO with LabVIEW FPGA processed data at a speed 1000 times more than that of traditional methods used by the utilities. Further, it is concluded that the capacitive compensation for reactive power compensation in the hardware model using LabVIEW works with an overall efficiency of 80% approximately and able to provide uniform values of power factor which is stabilized to a value 0.92 which helps in improvement of voltage stability in the system.

REFERENCES

[1] Dugan, Roger C, and Roger C. Dugan. Electrical Power Systems Quality. New York: McGraw-Hill, 2003. Print.

[2] V. C. Gungor, B. Lu, and G. P. Hancke, “Opportunities and challenges of wireless sensor networks in smart grid,” IEEE Trans. Ind. Electron.,vol. 57, no. 10, Oct. 2010, pp. 3557–3564.

[3] Rejc M.; Davidov S.; Pantos, M., "Probabilistic analysis of dispersed generation and smart grid technologies on electric power distribution networks," in European Energy Market (EEM), 2015 12th International Conference on the , vol., no., pp.1-6, 19-22 May 2015.

[4] Shang Li; Xiaodong Wang, "Cooperative Change Detection for Voltage Quality Monitoring in Smart Grids," in Information Forensics and Security, IEEE Transactions on ,vol.11,no.1,pp.86-99,Jan.2016.

[5] Gao, Cheng, and M. A. Redfern. "A review of voltage control in smart grid and smart metering technologies on distribution networks." Universities' Power Engineering Conference (UPEC), Proceedings of 2011 46th International. VDE, 2011.

[6] T. Eastham, "Reactive Power Control in Electric Systems," New York: Whiley, 1982.

[7] Sen, Kalyan K., and Mey Ling Sen. "SMART Power Flow Controller for smarter grid applications." Power & Energy Society General Meeting, 2015 IEEE. IEEE, 2015

[8] Yang Qiu,Min Zhang, Shuping Dangand Mielanie Whitefield, " Analytical Methodology of Smart Grid-based Capacitive Compensation Using cRIO" 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 2014.

[9] Pallares-Lopez, V.; Munoz, A.M.; Gil-de-Castro, A.; Santiago-Chiquero, I., "FPGA-based embedded system architecture for power quality measurements," in Harmonics and Quality of Power (ICHQP), 2012 IEEE 15th International Conference on , vol., no., pp.507-511, 17-20 June 2012

[10] National Instrument, "OPERATING INSTRUCTIONS AND SPECIFICATIONS CompactRIO NI cRIO-9081/9082" 2014.

[11] National Instruments, "Getting Started with LabVIEW," 2014