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Review on Lock-in Amplifier

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Abstract— **The main objective of this paper is to review design and fabrication of various types of lock-in amplifier systems. The key specifications of lock-in amplifier systems for signal recovery and signal characterization are analyzed and it is shown how these can be implemented. The configurations of several systems are discussed briefly. The analog and digital lock-in amplifier systems are also discussed. The designing of lock-in amplifier by using sophisticated systems such as DSP, microcontroller, and PC is reviewed and the performance of these lock-in amplifier systems is presented.**

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Index Terms— **Lock-in amplifier, phase, amplitude, noise, spectral inversion.**

I. INTRODUCTION

The precise and accurate measurement of physical, chemical and biological parameters plays an important role in unraveling the mysteries of nature. Modern measuring instruments play an important role for studying the nature closely and clearly. New discoveries in science provided new instruments for the study of nature and these studies in turn give feedback to develop sophisticated instruments. Lock-in amplifier is one such instrument. In many scientific and industrial applications, a situation exists where one needs to measure the signal whose amplitude is much smaller than the noise component presents in the environment. In such cases the lock-in amplifier is very essential. It is both powerful measurement device and useful tool for teaching the lock-in detection. Lock-in amplifier measures an AC voltage (or current) and gives an output in the form of DC voltage proportional to the value of the AC signal being measured. It is called an "amplifier" because the DC level at the output is usually greater than the AC level at the input and is termed "Lock-in" because it locks to and measures the particular frequency of interest ignoring all other signals at the input. If the output of any devices is very weak as compared to the noise then in that case lock-in amplifier is preferred. Lock-in amplifier is used to measure the amplitude of the signal, and phase difference between reference signal and measuring signal [1].

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II. BASIC PRINCIPLE OF LOCK-IN AMPLIFIER

The basic lock-in amplifier consists of a reference signal, an amplifier, a phase sensitive detector (PSD), and a low pass filter. The reference signal is passed through an unknown system that produces a modification of the signal phase and magnitude. The system also adds noise to the signal. This signal is amplified to a level adequate for the PSD, which multiplies it by the internal reference. The result of this product is the sum of a component with the double frequency, a component of zero frequency, the noise that was added in the system. Filtering the ac frequencies and only keeping the dc component, the level of the signal that has exactly the same frequency and phase as the reference signal can be measured[2].

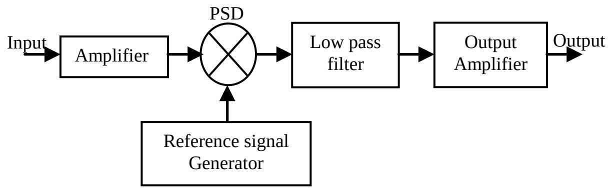

Fig 1. Basic block diagram of lock-in amplifier

III. ANALOG LOCK-IN AMPLIFIER

A. *Junction Impedance Measurement of Diodes by simplified lock in amplifier*

A lock in amplifier with most parts of its functional components substituted by integrated circuits is described by Juh Tzeng Lue [3] in his work. This amplifier is far from expensive and is free from the troubles arising from the temperature compensation and impedance matching's. This instrument operating at frequencies 20Hz to 100KHz has a noise rejection ratio of 40 DB and is suitable for junction capacitance and resistance measurement of diodes under reverse or forward bias. To determine the junction capacitance of a reverse biasing diode, a convenient bridge methods is adequate. This method is difficult to apply when the diode is forward biased. When the loss angle of the diode becomes large and a large current is flowing. This problem can be avoided by using lock in amplifier, which has the ability to measure in-phase and quadrature signals at the same time. To implement this measurement we have a lock in amplifier which is suitable for phase detections.

Juh Tzeng Lue explained a lock in amplifier, with its extremely narrow equivalent bandwidth, which is capable of measuring a periodic signal buried in noise and is becoming increasingly useful in scientific instrumentation. The fundamental operational principle is that an input signal is demodulated by a synchronous reference signal to produce in-phase or out-of-phase signals by a phase sensitive detector. The random phase components (noise) are smeared

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by an integrator, leaving only the zero-beat signal where the input and reference signal have the same frequencies. With this lock in amplifier can measure the junction R_t and capacitance C_t by measuring the in-phase and 90^o out-of-phase signals across the reference resistor, which represents the magnitude of the current passing through the diode.

B. A Frequency-Domain Description of a lock-in amplifier:

John H. Scofield [4] in his paper described the basic principles behind the operation of a lock-in amplifier. The lock-in amplifier is an extremely important and powerful measuring tool, it is also quite simple. Particular emphasis is placed on looking at the frequency components of the signal present at the various stages of the lock-in during typical measurement. The block diagram of a lock-in amplifier is shown fig2. The lock-in consists of five stages.

1. An AC amplifier called the signal amplifier.
2. A voltage controlled oscillator (VCO).
3. A multiplier called the phase sensitive detector (PSD).
4. A low pass filter
5. A DC amplifier

The signal to be measured is fed into the input of the AC amplifier. The output of the DC amplifier is a DC voltage proportional to V_0.

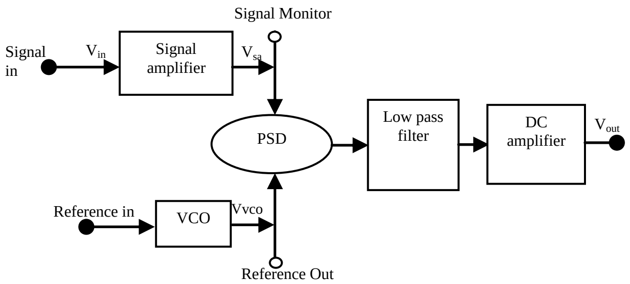

Fig2. Schematic Diagram of Lock-in amplifier

The AC amplifier is simply a voltage amplifier combined with variable filters. The voltage controlled oscillator is just an oscillator except that it can synchronize with an external reference signal both in phase and frequency. The phase sensitive detector is a circuit which takes in two voltages as inputs V1 and V2 and produces an output which is the product V1*V2. That is, the PSD is just a multiplier circuit. The low pass filter is an RC filter whose time constant may be selected. The DC amplifier is just a low-frequency amplifier similar to those frequently assembled with op-amps. It differs from the AC amplifier in that it works all the way down to zero frequency (DC) and is not intended to work well at very high frequencies, say above 10 KHz. A Hewlett Packed dynamic signal analyzer was used to measure the power spectral density of the voltages present at the various stages of the LIA. The function of the various stages has been illustrated by locking at power spectral densities of signals present at each of them during a typical measurement.

IV. Digital Lock-in Amplifier

A. Personal Computer based Lock-in Amplifier

1. Lock in amplifier response simulation using mathcad

Guinon et al., [5] described in all measurements a certain amount of noise is found along the desired signal. Sometimes the signal is so large compared with the noise amplitude that its presence is hardly noticed. However, in other experiments the noise is so large that the signal cannot be found at all. When the signals are weak, the amount of noise can be so great as to cover the signal completely. That is, the AC fluctuations in the meter will greatly affect the DC deflection from the signal so that it will be impossible to find and measure the DC signal. In order to improve the signal the signal-to-noise(S/N) ratio, different techniques such as signal averaging and integration, analog filter, digital filter and Fourier transform are used. A lock-in amplifier is basically a device for the measurement of amplitude of AC signals in the presence of noise. A lock-in amplifier uses a synchronous detector, phase sensitive detector, PSD to improve the signal-to-noise(S/N) ratio in AC experiments. The PSD requires that the signal be modulated at some reference frequency. The lock-in amplifier than amplifies only the component of the input signal at reference signal frequency and filters out all other frequencies, i.e noise. The main components of a lock-in amplifier are 1) modulation and amplification system 2) phase shifter 3) multiplier (PSD) and 4) low-pass filter fig.3.

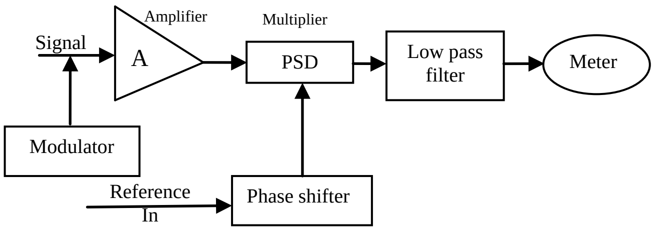

Fig3. Schematic Diagram of Lock-in amplifier

One of the inputs to the lock-in amplifier is the modulated signal (converted to AC). The modulation is made with a chopping wheel or electronically with a function generator so the signal formally the magnitude of a voltage is unaltered and remains only the white noise. The signal is further amplified to a given value. Other input to the lock-in amplifier is the reference signal. This signal is passed to the phase shifter that changes the phase difference between the input signal and reference signal. The multiplier or PSD is an electronic device that in fact multiplies both signals, the input times the reference signal. That is when the reference waveform is positive, the input signal is passed unchanged; when the reference waveform is negative the input signal is inverted. The lock-in amplifier amplifies only the component of the input signal at reference signal frequency, and filters out all other frequencies, i.e., noise. The PSD output is fed through a low pass filter, filtering out the high frequency signal and passes only the DC component of the signal that reaches to meter.

The Mathcad is one the most widely used software. The ease with which Mathcad lets type formulae and text, nearly exactly as we would write them down on paper, and its capability for creating complex graphs, it makes Mathcad a powerful and flexible tool to develop a variety of instructional designed programs to promote knowledge. In this paper we report the use of Mathcad software for the simulation of a lock-in amplifier. The mathematical principles for operation for a lock –in amplifier are described. The effect of the time constant of low pass filter and the phase difference on the ability of the system signals are also analyzed. Finally different animations are included to visualize the dynamic behavior of the lock-in amplifier.

2. High performance modular digital lock-in amplifier

Fabrizio Barone et al., [6] in their paper described an efficient and robust digital implementation of a lock-in amplifier, based on the classic quadrature technique and on a mathematical algorithm for error signal extraction. The digital lock-in amplifier scheme is as shown in fig4. Both the hardware and the software architecture are modular. The hardware consists of a VME bus (IEEE 1014) standard crate. In which commercial VME boards (the CPU. The ADC and DAC) are housed. The software is written in standard C language for probability and easy integration also within complicated software architectures. The software algorithm implementing the lock-in amplifier can be particularized by the user on the basis of the needed performances and on the available hardware. Numerical and experimental tests on lock-in amplifier prototype have shown by Fabrizo Barone perform as theoretically predicted.

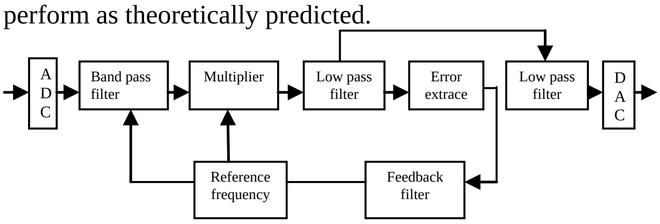

Fig4. Digital lock-in amplifier scheme

Fabrizio Barone has implemented a prototype of the digital lock-in amplifier using a standard modular hardware and software architecture. The standard architecture do not often permit one to reach the maximum performance of the assembled components, but Fabrizio make it easy to upgrade the system, simply replacing the obsolete modules(h and s). It is always possible to design a dedicated hardware architecture for the implementation of this lock-in amplifier, if max performance are required. The hardware architecture of this digital lock-in amplifier is based on a VME-bus standard crate, in which commercial VME board are housed. The advantage of such a modular choice becomes plain when the digital LIA will be pact of more complex digital system within this architecture, the lock-in amplifier is simply made by a CPU board, on ADC board and a DAC board. With this hardware architecture the throughput rate of the ADC board (50 samples/s) is the real limit to the speed of the digital LIA.

V. Microcontroller based Lock-in Amplifier

A. A Simple microcontroller based digital lock-in amplifier for the detection of low level optical signals.

Adrian A.Dorrington et al., [7] in their paper presented a small and simple digital lock-in amplifier that uses a 20 bit current integrating analog to digital converter interfaced to a microcontroller. The conceptual illustration of proposed digital lock-in amplifier is as shown in fig5. The sample rate is set to twice the reference frequency placing the sampled lock-in signal at the inquest frequency allowing the lock-in procedure to be performed with one simple algorithm. This algorithm consists of a spectral inversion technique integrated into a highly optimized low-pass filter. Adrian demonstrated a system with a dynamic range of 103 db recovering signals upto 85db below the interference. However he reported the process of accumulating samples during reference signal half cycles is still an option. It can be considered as a down sampling process reducing the sample rate to twice the reference frequency. The reference signal and detected modulated signal correspond to the nyquest frequency. The principle of an analog lock-in amplifier can be applied using the well known technique for spectral inversion of a sampled signal which is swapping the sign of every second sample. A digital low pass filter can then remove the noise that now resides in the vicinity of the Nyquist frequency.

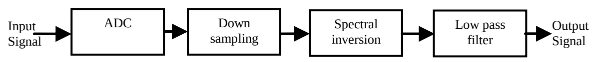

Fig5. Conceptual illustration of proposed digital lock-in amplifier.

Adrian for this optical lock-in detector system chose an 89c 8252 8-bit microcontroller and is interfaced to the ADC DDC112. This microcontroller was chosen for its on-chip EEROM program memory ease of interface to the DDC112, and compatibility with industry standard 8051 development tools. Filtering the sampled data in real time requires highly optimized algorithm. A single pole 2.5 Hz Betterworth low pass filter was selected because its co-efficient are all multiples of 1/256, which is an easy division for the microcontroller. The expression for this filter is

$$y_n = \frac{x_n}{256} + \frac{x_{n-1}}{256} + y_{n-1} - \frac{y_{n-1}}{256} - \frac{y_{n-1}}{256} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where Y is the output, X is input and ‘n’ is sample number. To conserve processor time the spectral inversion was integrated into filter algorithm by using two filter expressions each with one of the input terms negated. The expression is

$$y_n = -\frac{x_n}{256} + \frac{x_{n-1}}{256} + y_{n-1} - \frac{y_{n-1}}{256} - \frac{y_{n-1}}{256} \ldots\ldots\ldots\ldots (2)$$

and

$$y_n = \frac{x_n}{256} - \frac{x_{n-1}}{256} + y_{n-1} - \frac{y_{n-1}}{256} - \frac{y_{n-1}}{256} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

are used alternatively as a complete digital lock-in amplifier. The result is then sampled by averaging 200 samples providing an output with a rate of 10Hz.

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Adrian has successfully developed a simple, high sensitivity, small, low cost digital amplifier for the detection of low level optical signals, which has a dynamic range of 103dB and is capable of recovering input signals in the pico-ampere range. The design contains novel solution to problems arising from the use of a microcontroller as the central processor. Flexibility and configurability are good reasons for using a microcontroller, but the disadvantage is the poor signal processing performance. A highly optimized lock-in algorithm, based on a one sample per reference half cycle principle, has been implemented including a divide by 256 algorithm that requires minimal processor time.

B. *A complete low voltage analog lock-in amplifier to recover sensor signal buried in noise for embedded applications:*

Gabal et al.,[8] in their paper they have presented a low-voltage 3v signal supply analog lock-in amplifier for processing small AC sensor signals buried in noise including those presenting a relative phase with respect to the reference signal. The block scheme is as shown in fig6. Reference and bias sensor signals are provided by a quadrature oscillator. In some conditions, sensor output signal can be some orders of magnitude smaller than the present electrical noise level. In those cases, linear filtering is not a suitable choice to extract signal information, making necessary the use of other techniques. An interesting possibility is the employment of lock-in amplifier which use the phase sensitive detection techniques to signal out the data signal at a specific reference frequency. In PSD based systems, noise signals at frequencies other than the reference signal are rejected, and thus do not significantly affect the desired signal information. The Gabal developed lock-in conditioning system consists of a quadrature oscillator and two parallel PSD, that eliminates the system phase dependence, thus enabling its use for both resistive and capacitive sensors. The variable frequency quadrature oscillator consists of two integrators and an inverter amplifier. The oscillator provides two 140 Hz sinusoidal waves with 90 degrees of phase shift and 1.5v dc level. The signals provided by the oscillator are used as exciting sensor signal and inputs for two comparators that provides the waves that control the mixer operation. The need of a DC offset level in the data signal due to the signal supply operation requires modifying the mixer operation. The system behavior is appropriate for a 50 Hz noise frequency while degrading its performance for the 100 Hz noise signal mainly due to the closeness of the noise and reference frequencies.

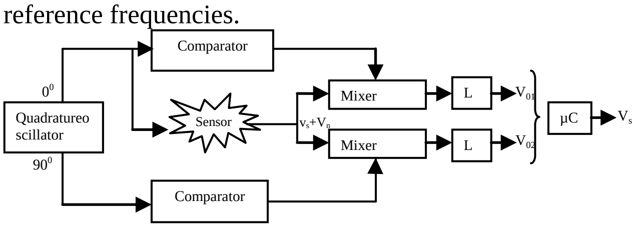

Fig6. Block scheme of the proposed lock-in system

Gabal lastly concluded that a complete signal supply lock-in amplifier targeting a processing system for embedded applications in low SNR environments it has the ability to process data signals provided by sensors that shift the signal phase value such as capacitive sensors. Gable shows experimental results confirm the capability of the proposed LIA to effectively recover information from signal-to-noise ratios below 0.025, with an error below 9%.

VI. DSP BASED LOCK-IN AMPLIFIER

A. *Signal Measuring Instrument lock-in amplifier*

Tasho Tashev[9] proposed in his paper, the signal measuring error caused by noises and non-linearity's in phase sensitive detector based analog lock-in amplifier and their improvement in digital signal processor. Design concept of digital lock-in amplifier is based on numerical manipulation of digitized reference and measuring signals. The measurements of low level AC signals are ever increasing in the field of Quantum Electronics spectroscopy and laser spectral analysis. In many cases it obscured by interference and noise or effect of DC drift make the recovery and measurement difficult, where precise measurement is critical. There are some special techniques which require basic understanding of actual measurement and instrumentation. Instruments for low level AC signals measurement are narrow band filter, spectrum analyzer, boxcar average and lock-in-amplifier. Also he proposed the most effective instruments lock-in amplifier for low level AC signal measurement.

In this paper DSP based lock-in amplifier system a 24-bit reference frequency sine wave is precisely multiplied by the digitized input signal inside digital signal processor. In the output section of the digital lock-in amplifier a multiplied signal is allowed to pass through the multiple stages of digital low pass filters. The working principle of digital lock-in amplifier is presented in fig7.

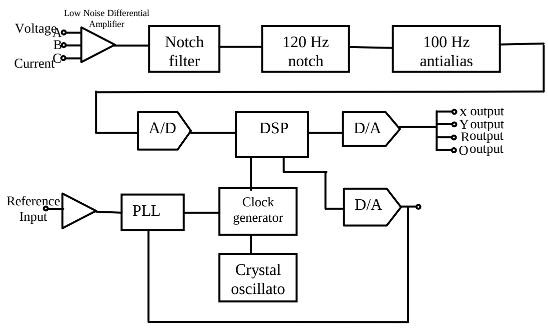

Fig7. Block Diagram of Digital Signal Processor Based Lock-in amplifier

Tasho Tashev stated that in compression to phase sensitive detection in analog lock-in amplifier and digital amplifier, digital lock-in amplifier provides extremely dynamic reserve, good harmonic rejection of reference frequency better phase resolution and stability.

B. *Implementation of high frequency digital lock-in amplifier*

Maximiliano o. Sonnaillon et al.,[10] proposed and validated experimentally a high frequency digital lock-in amplifier that uses non uniform sampling is shown in fig6. By using a random sampling strategy, it is possible to process periodic signals of frequencies several times greater than Nyquist

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frequency which is given by the sampling theorem. Authors implemented prototype of the LIA is based on 32-bit floating point DSP. The unknown system is exited by a reference signal generated by a direct digital synthesizer. The DSS if followed by a smoothing filter, which is formed by a 5-poll chebyshev passive filter with a cutoff frequency of 10 MHz. an amplifier stage provides gain and low impedance output. An op-amplifier with 38 MHz of gain bandwidth product and low noise used. The signal obtained at the unknown system output is amplified by a similar stage which is presents high impedance at the input in order to avoid disturbing the measured system. A 16-bit ADC is used for digitizing LIA input signal. The circuit has 6-bit presentable timer whose input clock is 5 MHz signal the timer end-of-count signal starts each ADC conversion when the conversion is finished ADC generates an external interrupt in the DSP. The interrupt service routine generates a new random sampling period and process the last sample converted by the ADC, which is reads through a 16-bit data bus. A JTAG interface is used to program the DSP, debug the software and read the measured data from a PC.

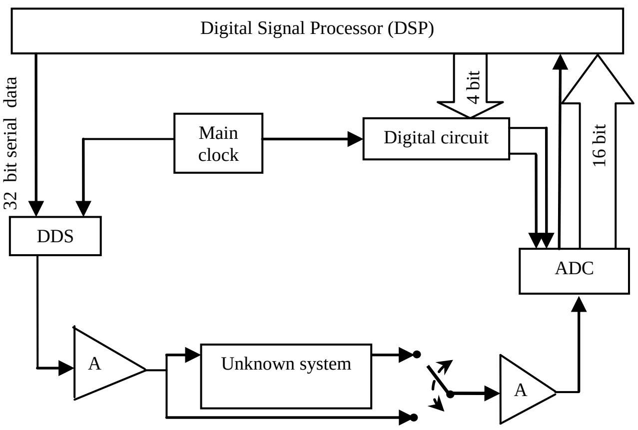

Fig 8. Block diagram of complete system

The LIA software implemented in the DSP has two main routines one is the initialization, which is run when the instruments is powered on. The second is the external interrupt service, which is generated by the ADC end-of-conversion signal.

In their research paper concluded that a high frequency DLIA that uses non-uniform sampling was proposed and experimentally tested. The application of this sampling strategy reduced significantly the speed requirements of the ADC and DSP. This reduces costs and makes possible the implementation of complete digital high frequency LIAs. It was shown experimentally that the implemented LIA can make measurements at much higher frequencies than the maximum sampling frequency, without decreasing its performance. Incrementing the number of averaged samples, the noise rejection can be raised, incrementing also the measuring time.

C. Implementing Digital Lock-in Amplifiers using the dsPIC DSC:

Darren wenn [11] reported the lock-in amplifier use phase-sensitive detection to measure the presence of small signals buried in large amounts of noise. By measuring the coherent system response from an incoming AC signal the digital lock-in amplifier can detect even minute changes. Both magnitude and phase can be used to characterize the system.

Conventionally, lock-in amplifiers are complicated (and expensive) analog circuitry to perform the phase sensitive detection and filtering. However, modern digital signal controllers (DSCs) such as the plc3of and dsPlc33f families, can be used to remove large amounts of the analog circuitry by performing the necessary operations in software. This capability provides a number of additional benefits including increased reliability, resistance to temperature and aging effects, and the case with which the system can be modified in the field. By using the built in signal processing capabilities of the dsPlc33F, it is possible to perform high speed, high accuracy measurements on sensors such as strain gauges.

In the case of a digital lock-in amplifier most of the processing is performed in the digital domain using software and dedicated digital signal processing (DSP) hardware. The system still features a front-end amplifier; however, this is then followed by an anti-aliasing filter to remove any signal components higher than half the sampling frequency.

For dsPIC DSC-based solution, the sampling would be performed in 12-bit resolution at up to 400 KHz, so the anti-aliasing filter needs to be set to alternate any signals above 200 KHz.

The reference signal is generated internally or can be derived from sampling an external signal. The reference signal is also phase-shifted by 90 degrees. The reference and phase shifted reference values are multiplied directly by the DSP to generate the intermediate I and Q signals. Finally these signals are passed through digital low-pass filter to generate the final output values.

Once the input has been quantized by the analog-to-digital converter, there is no further loss of signal quality. Furthermore, since the reference signal can be digitally computed, it can be made to have a very low harmonic content.

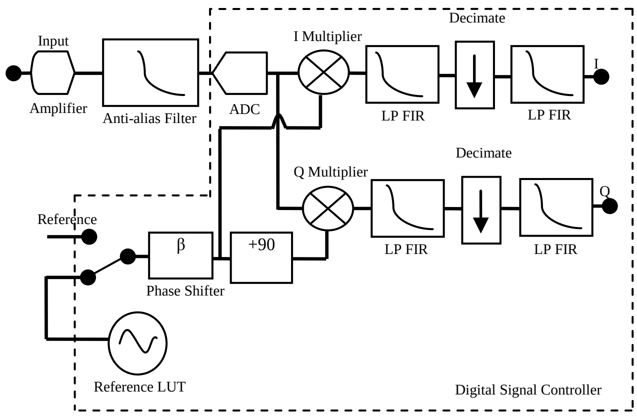

Fig 9. Digital Lock-in Amplifier

Most importantly, the deviations due to non-linear gain and phase of the analog components are removed in the digital lock-in amplifier and there will be no variations due to temperature drift or component aging. Similarly the offsets associated with real analog components are removed and the limitation on intermediate accuracy is purely down to the resolution of the processor and DSP engine. The digital lock-in amplifier is useful tool for measuring small signals. By translating the signal measurement to a high frequency. It is possible to avoid noise introduced at DC and low frequencies. It is possible to detect both amplitude and phase changes using the lock-in amplifier, it is possible to measure signal changes caused by devices with complex impedances, such as capacitive sensors. The dsPlc33f is a powerful digital signal controller and its capabilities are well suited to both the signal generation and processing tasks in this application. The high speed ADC and DMA allow for a high data throughput, while the efficient DSP engine can perform the multiple filtering stages with case.

VII. CONCLUSIONS

From the literature survey it is reviewed that various lock-in amplifiers are designed and tested on different systems. The most of the lock-in amplifiers are implemented on DSP and Microcontroller with DSP features. The deviations due to non linear gain and phase of analog components are removed in digital lock-in amplifier and there will be no variations due to temperature drift or components aging. The offsets associated with real analog components are removed and the limitation on intermediate accuracy is purely down to the resolution of the processor and DSP Engine. Some of the works reported on microcontroller implementation by using spectral inversion method to design a lock-in amplifier. The reason for using microcontroller is there flexibility and configurability in designing lock-in amplifier but the disadvantage is there poor signal processing. But by using the spectral inversion method the processing time can be reduced. It is concluded that the digital lock-in amplifier are good at signal processing and noise rejection can be raised their by improves the signal to noise ratio compared to the analog lock-in amplifiers.

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