Current Phasor Measuring Device for Three Phase Distribution Lines

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Abstract: *Protection and reliability are the most paramount considerations in the power system. Current measurement of distribution lines is essential for the power and quality evaluation purposes. The current measuring devices are used for controlling, monitoring and protection purposes. While the measurement of current at an end connected to a substation can be carried out without too much trouble, intermediate current measurements cannot be carried out with ease. Further instantaneous phase angle differences need to be measured to be able to evaluate power flow in distribution lines. Thus, at present power loss calculations are approximately carried out by the utility. So, the power quality analysis, switching operations and load transferring in distribution lines are not much accurate. The use of a flux concentrator and hall-effect sensor, with a filter, has demonstrated that a sinusoidal current waveform, with the correct phase angle, can be obtained. The use of the device on an existing line does not need disconnection, nor a separate earth connection to obtain the magnitude and phase angle of the current accurately. The data from the transducer is transmitted to the operator using radio signals rather than wi-fi.*

Keywords: *Current Phasor, Hall Effect Transducer, Magnetic Flux, Current Transformer, Zero Crossing Detection.*

1. Introduction

With the necessity of a device to measure the current passing through the distribution lines, implementing of a portable as well as non-contact device, was taken into consideration. So, the utilities can have a rough idea about the amount of current passing and power flowing through the sections of lines. In medium voltage distribution lines, load transferring and switching operation are currently carried out approximately. The load balance is achieved by load transferring among feeders in distribution systems, as system losses are increased by the load imbalances. The load imbalance is solved by switching operations and switching operations are aimed at line and load dispatching operations. In power systems, the load flow is monitored to collect active and reactive power, to identify whether the load flow is exceeded. So, if there is any method to have a good idea about the amount of current passing through any point of the medium voltage distribution lines, it would be easy or an accurate system operation (Selva et al., 2015).

A. The existing current measuring method in distributionlines and its drawbacks.

Generally, Current Transformers are used to measure currents in conductors. Normally, to measure the current in a medium voltage distribution line, a pole should be erected,and a large current transformer should be installed. So, it takes more time. Another drawbacks of Current Transformers (CT) are accuracy issues because of the droop, limitations of the duty factor and the inability to sense DCcurrents. CTs are used to measure Alternative Current (AC) currents. If the CT is operated without a load on the secondary, it will causeinsulation breakdowns due to the high voltage. Moreover, the need to repair the CTs is not an easy task, and the testing equipment is expensive and time consuming (Karthick, 2015).

The present work has identified some research that has been carried out, and the methods developed in order to measure the current in distribution lines based in the Hall-effect.

B. Hall effect based current measuring technique.

With the development of modern technology, there are various methods that can be used for current measuring in distribution lines (Chen, Guo and Ma, 2018). Nowadays, the Hall Effect sensor has become very attractive for current measuring purposes. By using hall sensors, the overall size of traditional CTs can be decreased. Hall Effect sensors can measure AC and DC currents without a supply interruption. The sensor is smaller in size compared to the CT, with noise-immunity, and less power consumption. It is also cost effective, has accuracy and linearity. Quick response ensures better performance of these Hall Effect based current measurement methods (Wu et al., 2021).

C. Working principle.

The major relevant laws in electromagnetic fields are.

1) Biot-Savart's law:

where,

B - Magnetic flux density

I - Current carrying in the cable.

μo - Permeability in the free space

r - Distance

$$B = (\mu o\ I)/2R$$
(1)

The electrical and magnetic fields are coupled together to solve Maxwell's equation (Biot-Savart Law, no date).

2) Ampere's circuital law: The magnetic field surrounding a single current carrying conductor is given by the line integration of magnetic flux intensity, H round the path equal to the total current as given in equation 2.

$$\oint ▒ 〖H.dl = I〗$$
(2)

For a.c. fields, the measured value of B is averaged or rms value taken to obtain the rms current (Ampere's Law, no date).

3) Hall effect: When a magnetic field is applied at right angles to the current in a thin film, an electric field is generated which is mutually perpendicular to the current and themagnetic field and which is proportional to the product ofcurrent density and the magnetic induction (equation 3) (Hall Effect, no date).

$$\mathrm{VH} = IB/nqd$$
(3)

where,

VH – Hall voltage through the conductive plate

I – Current passing through the plate

B – Magnetic flux density

q – Magnitude of the charge carriers

n – Number of charge carriers per unit volume

d – Thickness of the sensor columns.

2. Methodalogy

A. Selecting the Sensor Details

Initially, testing has been done using the 49E Hall Effect Transducer, but it was observed that it saturates quickly due to its limited linear region and only provides a perfect sinusoidal wave within a small range of current (1-2A). Hence, the linear Hall Sensor DRV 5053 from Texas Instruments, shown in Figure 1 was selected to give a linear output with high sensitivity stability.

Figure 3: DRV 5053 Hall Effect Sensor (DRV5053 data sheet, product information and support | TI.com, 2017)

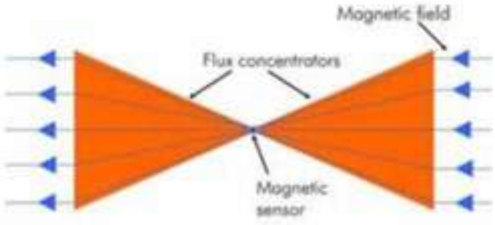


Figure 2: Magnetic Field Lines in Flux Concentrator ('Future Directions for Magnetic Sensors: HYBRID MATERIALS Achieving Better Sensitivity, Smaller Size, Lower Cost, & Lower Power Use', 2015)

B. *Constructing the flux concentrator*

In this study, the current is measured using the magnetic flux generated when the current is passing through the conductor (Figure 2). A flux concentrator is used consisting with a hall effect transducer to convert the flux into a voltagesignal.

C. *Testing the Hall Effect sensor*

The flux concentrator in Figure 3 is a conically shape solid made of steel, and enhances the intensity of the magnetic field.

Figure 4: Flux Concentrator

In the analysis, the peak–peak voltage was obtained by giving different current values to the apparatus as given in table 1. The current is supplied through 30 turns of a coil to the device.

Table 1. Testing of Flux Concentrator

Step	Supply Current × Turns = Current (A)	Peak-Peak Voltage (mV)
1	1.0 A× 30 = 30 A	180
2	1.50 A× 30 = 45 A	200
3	2.5 A× 30 = 50 A	250

Figure 5: Testing the Sensor on Test Bench

The voltage from the transducer is converted to 0-5V range, as it is the sensing voltage of the Arduino. The input voltage is measured while giving maximum current. The Gain of the Amplifier is calculated from the peak-to-peak voltage as in equations 4 and 5.

V p-p = 5 × 2 = 10 V (4)

Gain x 2 = Vp-p
(5)

D. Testing the Coupling Effect

When gathering flux from one conductor, there will be an effect from the flux generated by the other two conductors. Thus the flux measured is a function of three currents in three phasors as shown in the equation 6, 7 and 8.

$ø_a = f(i_a, i_b, i_c)$
(6)

$ø_b = f(i_a, i_b, i_c)$
(7)

$ø_c = f(i_a, i_b, i_c)$
(8)

This magnetic field interference is caused by mutual and self- coupling. The self-coupling can beignored if the mutual coupling is low. Both self and mutual coupling exist if the mutual coupling is high. To calculate the coupling factors, the equations are arranged in a matrix as shown in equation (9) (Zhang et al., 2022).

[■(ø_a@ø_b@ø_c)
= [■(K_aa&K_ba&K_ca@K_ab&K_bb&K_cb@K

(9)

However, it can be shown both theoretically as well as experimentally that a considerable coupling effect cannot be obtained from this Hall Effect based current measuring device.

E. Calculating the conductor currents

By solving the mutual transfer matrix of the matrix shown in equation 9, the currents passing through the three conductors i_a, i_b, i_c can be calculated. Since the interference is negligible, the error occurring due to coupling effect can be neglected.

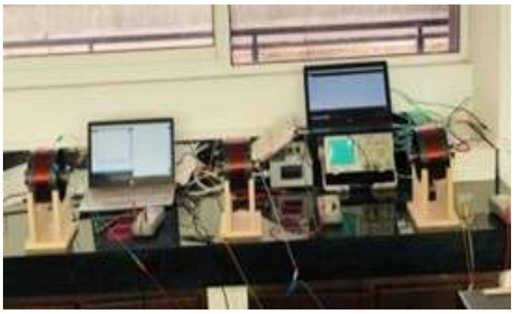


Figure 6: Testing the Coupling Factors

F. Circuit for obtaining measurements

1) The Signal conditioning circuit: Analog filters and an instrumentation amplifier are used to condition the analog signals before converting into digital signals. The higher harmonics starting from fifth are blocked by this circuit. The application of this circuit is for changing the input voltage and get the offset and the voltage reference of Analog to Digital Converter (ADC).

2) Op- amp rectification: Rectifiers measure the strength of the signal and convert the AC to DC. Diode and an operational amplifier can be used as the rectifier to get currentflow in one direction.

3. Experimental Design

1) *Phase angle measurement*: Phase angles are obtained from the zero-crossing detection of current and voltage waveforms. The small signal which comes from the Hall effect sensor has a low amplitude with noise and it goes to the instrumentation amplifier through the low pass filter. The low-pass filter minimizes the noise and the signalinterference. It improves signal to noise ratio and the accuracy. The filter is placed closer to the amplifier. The signal then goes to the rectifier bridge, and the waveform is rectified. Next, an opto-coupler passes the square shaped pulses to the micro controller.

Phase angle between the current and the voltage waveform is measured by Zero Crossing Detection (ZCD), as shown in Figure 6. The output from the ZCD is a square shaped waveform which goes through the RC series circuit. The time difference between the sine wave and thereference signal is detected by ZCD. If the input passes the zero and if it is in negative direction, V_{out} goes to positive saturation.

2) *Designing and implementation the circuits:*

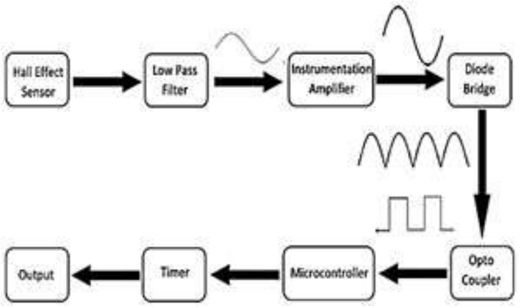


Figure 7: Measuring the phase angles

Implementing the first order low pass filter

The low pass filter is used to remove noise with a cut-off frequency chosen as 500Hz.

$F\backslash C = 500Hz$ (10)

The capacitor and the resistor are then chosen according to the cut-off frequency given in equation 11.

$F = 1/2\pi RC$
(11)

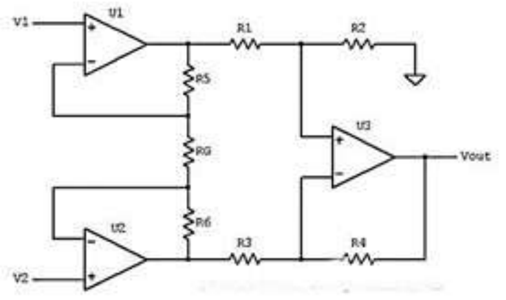
This gives the value as R = 21kΩ and C = 10nF.

Implementing the Instrumentation Amplifier

The LM 324 IC consisting of 4 op amps is used and saturates at VCC of 1.5 V. The instrumentation amplifier has a good sensitivity to dc offset errors due to the common mode. It increases the amplitude which comes fromthe sensor.

The resistors are selected as it is given gain of 6. The Gain of the instrumentation amplifier is calculated as in equation 12.

$\text{Gain(Av)} = V\_0/(V\_2 - V\_1) = (1 + 2R\_5)/R\_g \times R\_2/R\_1$ (12)



3) *Obtaining the zero crossings of the current:*

Figure 8: Instrumental Amplifier Circuit

The Vo output is given to the full wave diode bridge connected to the opto-coupler. The output is obtained from the collector of the opto-coupler. When the AC sinusoidal wave crosses zero, the collector of the transistor goes high giving square shaped pulses at 0^{o}, 180^{o},360^{o}... Since the amplitudes are changed with the current, this ZCD is complicated for the current measuring circuit than the Voltage measuring circuit.

4) *Obtaining the voltage measurements:* The current (i) is passed through a load (e.g: motor, water heater) to the test the apparatus. From the 230V AC waveform, 4.5V is obtained using a step-down transformer,. The signal is obtained by varying the voltage by a variac and given toAnalog 1 pin of the Arduino.

5) *Establishing the communication system*: When utilities request the current phasor readings of a specific point, the server will transmit the relevant data to the utility. Ubidots is the dashboard which displays the data on computer screen. The dashboard is displayed as shown in the Figure 13.

4. Results

1) *Coupling Effect Calculation*: A considerable coupling effect was unable to be obtained from

this hall effect based current measuring device experimentally. Hence, the interference of the magnetic field of the conductors were calculated theoretically to check the reliability.

The apparatus was placed as in the same gap (0.7m) between the conductors in 11kV MV distribution lines as shown in the Figure 8.

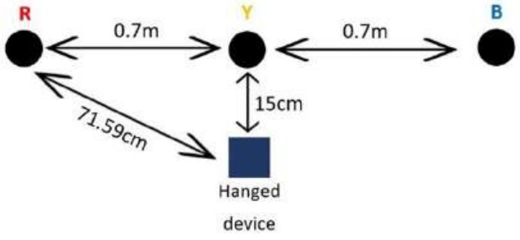


Figure 9: Arrangement of Three Conductors and the Device

From the equation (1), $B = (\mu o I)/2\pi R$; Tesla

A) Magnetic field strength from R or B conductor to the placed device,

μo- $4\pi \times 10^{-7}$ Hm^{-1}

Permeability in copper medium; μ – 1.25×10^{-6} Hm^{-1}

$B = (4\pi \times 10^{\wedge}(-7))(1.25 \times 10^{\wedge}(-6))200/2\pi(71.59 \times 10^{\wedge}(-2)) = 6.98 \times 10^{-11}$ T

(Approximately 200A passes through 11kV distribution line)

B) Magnetic field strength from Y conductor to the placed device,

$B = (4\pi \times 10^{\wedge}(-7))(1.25 \times 10^{\wedge}(-6))200/2\pi(15 \times 10^{\wedge}(-2)) = 33.33 \times 10^{-11}$T

Interference of Magnetic field strength from three conductors to place the device,

$B= 2(6.98 \times 10^{-11}) + 33.33 \times 10^{-11}$ T $= 47.29 \times 10^{-11}$ T

As the magnetic field strength is negligible, it was proved that, a considerable coupling effect cannot be obtained from this hall-effect based current measuring device experimentally as well as theoretically. Therefore, the magnetic field interference from other conductors can be neglected when measuring the current in one conductor. Hence, it's a significant improvement of this project.

2) *Obtaining Waveforms*: The signals which comes from the sensor is passed through an inverting instrumentational amplifier to amplify the signal. The signal with the amplified signal is shown in the Figure 9.

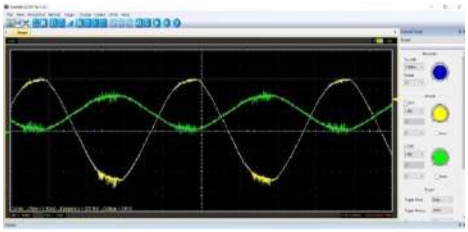


Figure 10: Current Waveform from the Sensor and the Amplified Waveform

When AC wave crosses zero crossings, the collector of the transistor in Opto-coupler goes high, thus gives poles 0-5V at 0^{o},180^{o},360^{o} as shown in Figure 10.

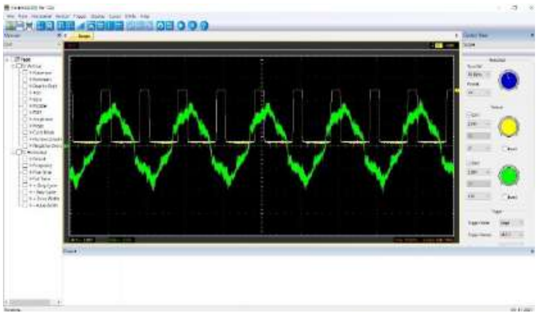


Figure 11: Zero Crossing Outputs from Opto-Coupler

The phase angle is measured from time shift of the current and the voltage waveforms. It is obtained from the current and voltage zero crossing waves in Figure 11.

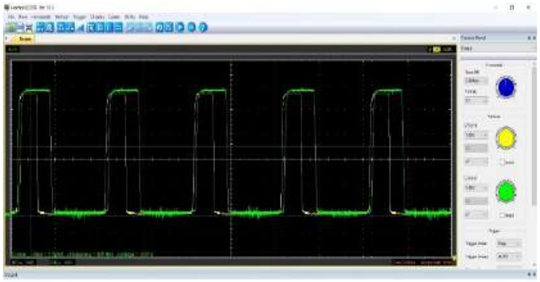
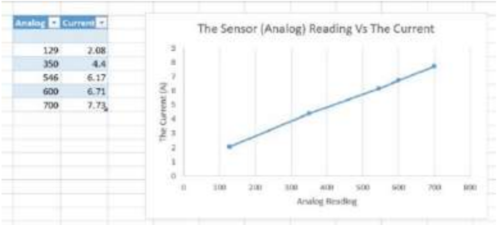


Figure 12: ZCD of current and voltage waveforms

The current measurements according to the Analog readings which come from the Hall sensor as Magnetic Flux are shown in this graph. This Graph proves the linearity of the Hall Sensor. Hence, it has been shown that results are accurate.



Analog	Current
129	2.08
350	4.4
546	6.17
600	6.71
700	7.73

Figure 13: Graph of the Sensor (Analog) Reading vs the Current

The current, voltage, power, and power factor values are displayed on the Dashboard Application as per the utility's requirements is shown in the Figure 14.

Figure 14: Dashboard Application

Figure 15 shows the designed circuit. In particular the relevant parts of the circuit are labelled.

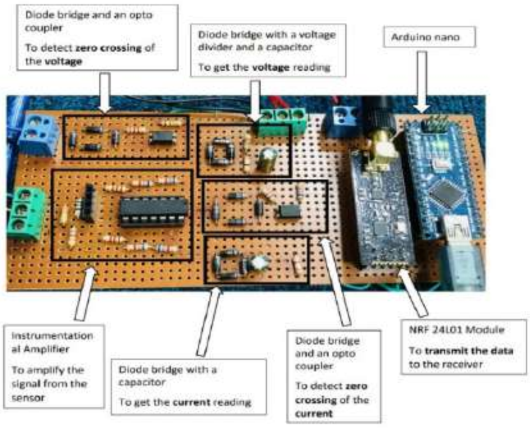


Figure 15: Designed Circuit

Figure 16: Fabricated Prototype

5. Discussion

This paper gives an effective solution for the current measuring purpose in distribution lines using hall effect sensor method. The research has demonstrated stable sinusoidal waveforms by using the Hall-Effect sensor with filters. The linearity of the sensor is used to compute the currents from magnetic flux considering the coupling effect. The low-pass filter is minimized the noises and it gives better output waveforms and also the signal conditioning circuit converts them to proper signals before processing. Therefore, the systemaccuracy will be high.

6. Conclusion

The proposed non-contact device can measure current phasors by hanging the device on the conductor. The readingsare obtained from this device without disconnecting the power to that particular area. The coupling effect is considered when getting the magnetic flux readings. However, it was observed that a considerable coupling effect cannot be obtained from this hall effect based current measuring device experimentally as well as theoretically.

The proposed method can be improved by using more signal conditioning circuits to obtain more accurate and reliable data. Rechargeable batteries can be added to the device which can be charged from the induced conductor current according to the low power theories. To increase the data communication range, Lora modules canbe used due to its high range.

Moreover, an apparatus for voltage measurement can be implemented. By placing a Copper plate parallel to the medium voltage distribution lines, the voltage can be obtained relative to the ground. So, it is like a capacitor between the ground and the copper plate. Then, the real time voltage data can be transmitted as the zero-crossing pulses.

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