STM JOURNALS

Journal of Power Electronics & Power Systems
ISSN: 2249-863X (Online), ISSN: 2321-4244 (Print)
Volume 7, Issue 3
www.stmjournals.com

Design of a Wireless Protection Scheme for Smart-Grid-Based Industrial Systems

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Abstract
This paper illustrates the design of an alternative current measuring method which can be used for the protection of electrical machines, especially generators and motors, used in oil and gas industry. A comparison is made between the use of Hall effect sensors and current transformers for fault current detection. Also, different wireless communication methods that can be used in accordance with Hall effect sensors for detecting faulty conditions are discussed. Three case studies are presented: first, a simple ANACOM kit is used to send and receive amplitude modulated (AM) signal. Next, a test circuit is constructed that transmits and receives Frequency Modulated (FM) signal. Improvements are observed in terms of range and reliability. Finally, a digital transmission and reception test circuit is built and it is observed to provide the best results in comparison to the other two arrangements.

Keywords: *Protective relay, current transformer (CT), Hall-effect sensors, smart grid, ANACOM AT02 set, AM and FM technique*

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INTRODUCTION

Oil and gas represents one of the fastest growing opportunities in the energy sector. Efficient transport of oil and gas can help the world meet its increasing need for energy. But, while gas and oil offers substantial rewards, it also poses significant challenges; one of the biggest being safety hazards. Faults in electric power systems may lead to severe damages of the expensive equipments used in the industrial system and harm the working personnel or the environment.

As industrial and commercial operations processes have become more complex and extensive, the requirement for improved reliability of electrical power supplies has also increased [1]. Over the years, many improvements have been proposed based on specific requirements for specific industries. For oil and gas industry, where the risk of ignition from leakage is accompanied by natural risk factors such as storm and snowfall or the involvement of local wildlife, an intelligent way to improve safety and security may be to use a wireless protection system for generators and motors instead of the conventional wired system. Implementation of wireless technology offers many advantages over wired, e.g. low installation cost, mobility, remote location coverage, rapid installation, etc. [2].

It is mandatory that each and every part of a power system be incorporated with protective relaying. The main purpose of using protective relaying is that when any part of the power system undergoes a small or major disturbance condition, it should isolate the faulty portion from rest of the healthy system. The intensity of protection depends upon different factors such as, type and rating of the equipment that is needed to be protected, type of fault, location of the faulty area, etc. Requirements of satisfactory protection depend on several criteria such as selectivity, sensitivity, speed, cost optimization and system security [3].

A popular and widely used equipment for the fault detection in factories and industries is the current transformer (CT). A traditional CT consists of a magnetic core. Therefore, it usually encounters problems such as direct current (d.c.) and alternating current (a.c.)

saturation and permanent magnetization. These problems are caused by the effect of hysteresis. When faults occur in power systems, the fault currents usually contain large d.c. offsets, which may cause the iron cores of CTs to be saturated. This may cause distortion of the current waveforms in the secondary windings, resulting in false responses in current detection and protective devices. These problems severely affect the safety and reliability of power systems [4]. To overcome these problems, the traditional CT would require redesigning but that can be quite an expensive and complex process. An easier alternative is using a Hall effect sensor.

The Hall-effect sensor is based on the Hall-effect principle proposed by Edwin Hall in 1879 which is represented as in Eq. (1)

$$v = \frac{IB}{nqd} \tag{1}$$

Where, *v* is the voltage, I is the current through the conductive material, B is the magnetic flux density, *n* is the carrier density, *q* is the charge of the current carrier, and *d* is the thickness of the sheet [5].

Hall-effect sensors use small, current-to-voltage transducer that respond to magnetic fields and are therefore useful for monitoring both d.c. and a.c. The transducer produces a voltage output that is proportional to the magnitude of the applied field. The response time is in the 10 µsec range making the transducer capable of measuring high order harmonics from 50 and 60 Hz sources. This type of enclosure provides for simple installation on live wires in harsh environments without the necessity for removing equipment from service. If the measurement and timing errors are low, the voltage outputs from the sensor become accurate representations of the currents being monitored. Thus, using the Hall-effect sensors to monitor major substation equipment is very much in line with today's smart grid initiatives [6].

A smart grid is a form of electricity network utilizing digital technology. Smart grid delivers electricity from suppliers to consumers using two-way digital communications to control appliances at consumer level. This saves energy, reduces costs and increases reliability and transparency [7]. Traditional power grid is a one-way information system that lacks interaction with the users. It is a rigid system that has low flexibility in power source as well as transmission. It is hard to form real-time, configurable, relocatable system. Moreover, it is weak in self-healing and self-recovery capability. The new generation smart grid would make further improvement in system flexibility, network visibility, self-healing capability and the two-way interaction ability with the users [8].

Smart grid systems enrich overall system management since they have better control over the transmission system and thus boost up system reliability [9]. The primary goals of a smart grid are to confirm user's data security, maintain user's demand at any time and fulfill two-way communication [10].

RELATED WORK

Several studies highlighted the benefits of using the Hall-effect sensors to diagnose problems and identify root causes of equipment failures. The studies were conducted at generating plants, switching stations and at distribution substations. If certain criteria such as appropriate enclosures, recording instruments and accurate resolution and sampling rates can be achieved, the Hall-effect sensors could be made useful for a wide range of equipment monitoring applications including capturing relay targets, timing circuit breakers, measuring in-rush currents, and diagnosing DC control circuits. The future for using Hall-effect sensors to monitor major substation equipment is very promising. Therefore, many researches related to improving the output of Hall effect sensors are ongoing within the power industry in recent years [4, 6]. In the past, wireless technologies had comparatively slow acceptance in power industries due to low data rates, interference related issues, security concerns, etc. However, due to its various advantages, several activities have already been initiated to address the wireless technical issues and identify suitable wireless technologies, especially for smart grid [2, 7, 11].

CT is one of the most common protecting devices that have been used to detect fault current for the protection of electrical machines like generators and motors. Figure 1 shows the advancement of a signal from analog to digital form. The relay auxiliary transformer converts the CT secondary current to a predetermined voltage level. The anti-aliasing low pass filter removes any high frequency present in the waveform and the ADC converts the signal to a digital value of a current at a typical sampling rate of 16 samples per cycle. The purpose of a digital filter is to reject all harmonics and to extract the magnitude of the fundamental content of the signal [12]. In this paper, a different current measuring method is proposed that involves Hall-effect sensors instead of CT and fault signal is transmitted through a wireless system. The schematic diagram of proposed system is shown in Figure 2.

PROPOSED METHOD FOR WIRELESS COMMUNICATION

In this paper, different methods of wireless technologies have been studied and the potential issues related to each have been highlighted. To investigate these different technologies, prototypes have been built. The prototypes are used to test the idea in a laboratory environment to ensure that the components suggested may work in an actual industrial system. Firstly, a simple amplitude modulated analog signal is sent and received using the ANACOM AT02 kit. The range and reliability of the signal is observed. Then, a frequency modulated signal is transmitted using a built prototype circuit (Figure 7). The range and reliability is again observed and compared to that of the AM signal. These two steps of testing analog signals act as a base for building a much-improved digital circuit system (Figures 9 and 10).

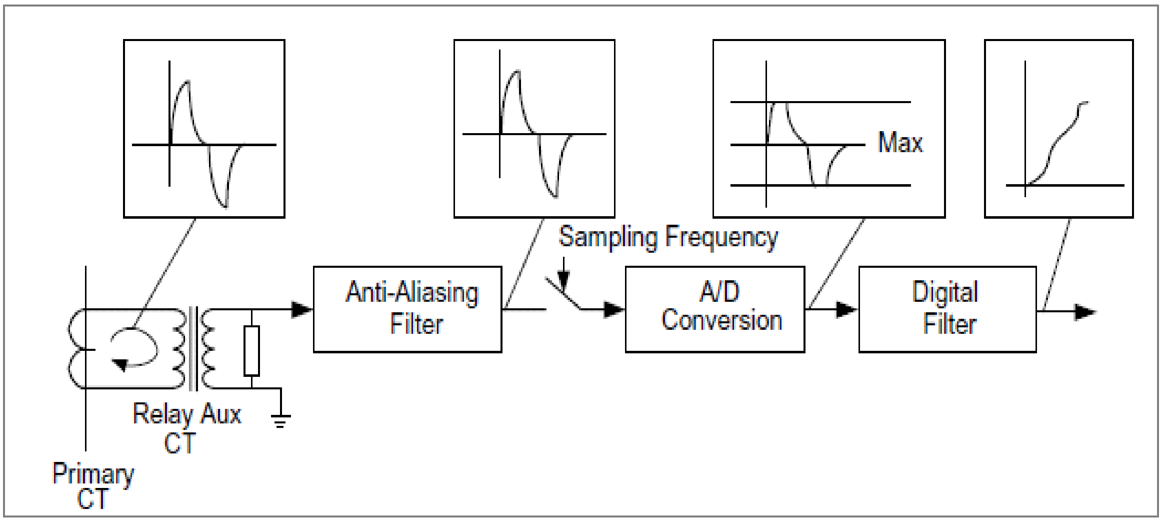

Fig. 1: *Schematic Diagram of the Microprocessor-based Relay Showing the Progression of a Signal from Analog to Digital Form [10].*

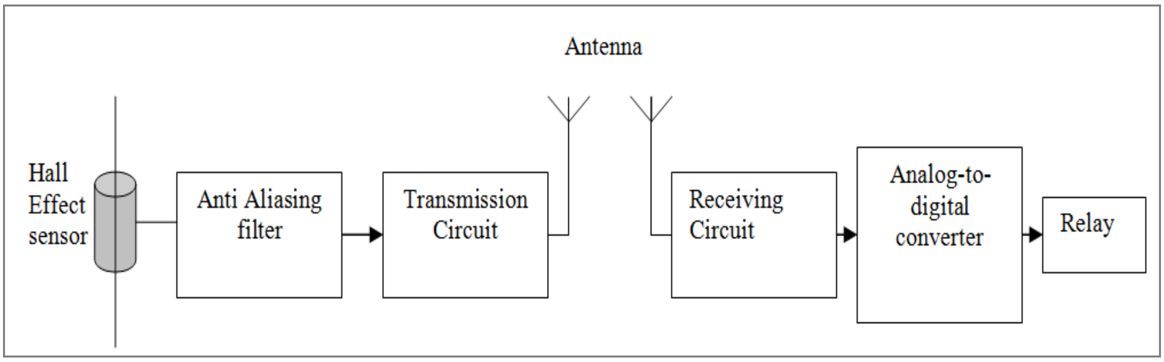

Fig. 2: *Schematic Diagram of Proposed Hall Effect Sensor-Based System with Wireless Transmission and Reception Circuit.*

Analog Transmission Using Amplitude Modulation (AM) Technique

For testing this technique, a function generator that will represent the output obtained from a Hall-effect sensor after passing through an anti-aliasing filter, an ANACOM AT02 set and an ADC have been used. The transmission circuit consists of various filters as shown in Figure 3. The signal is first modulated using a balanced modulator. In the next stage, a ceramic bandpass filter is used to obtain the necessary frequency range. After obtaining necessary frequency range, the signal is passed through another stage of modulation and filtering (balance modulator + bandpass filter circuit-2) and sent to an amplifier circuit and transmitted. The transmitted signal is then received by an analog receiving circuit.

The receiving circuit on the other hand consists of various amplifiers as shown in Figure 4. The first step is to send the signal through an interconnected system of radio frequency (RF) amplifier, tuner, local oscillator and mixer. Then, two intermediate stages of amplification take place. This amplified signal is sent to both a diode detector and a product detector. The diode detector is the simplest form of demodulation circuit which operates by detecting the envelope of the incoming signal (by rectification). To obtain a signal of double the frequency of the intermediate frequency (IF) signal, the product detector mixes the IF signal with a locally derived carrier (beat frequency oscillator). The automatic gain control circuit makes the output signal smoother. In the last step, signal from diode detector and product detector is amplified and sent to an ADC and the output signal of ADC is sent to relays. Figure 5 shows the resultant receiving circuit using ANACOM AT02 kit.

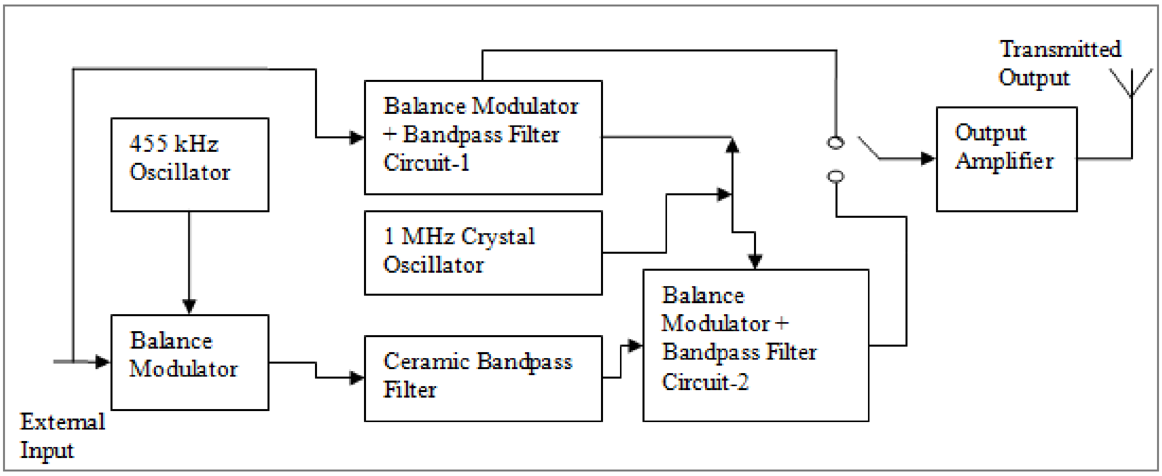

Fig. 3: *Transmission Circuit of ANACOM AT02 Set.*

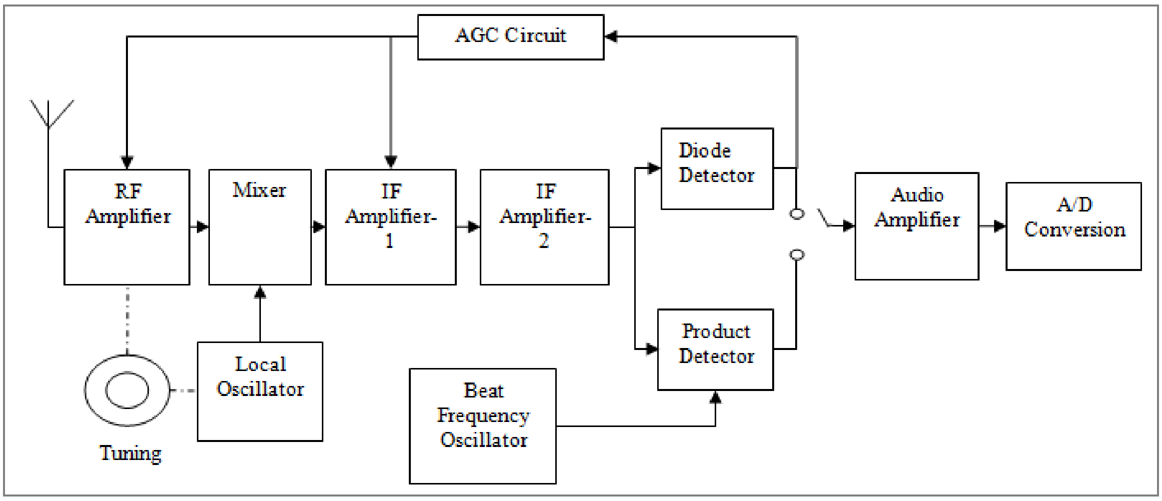

Fig. 4: *Receiving Circuit of ANACOM AT02 Set.*

Analog Transmission Using Frequency Modulation (FM) Technique

A prototype of transmission circuit for the FM technique has been built, the circuit diagram of which is shown in Figure 6. All the components of the circuit have been connected together on a PCB board as shown in Figure 7. The circuit is a type of RF oscillator that can be tuned between 70 and 120 MHz and operates at 9 V. The input signal is fed into the audio amplifier stage built around the first transistor. Output from the collector is fed into the base of the second transistor where it modulates the resonant frequency of the tank circuit by varying the junction capacitance of the transistor. The transmitted signal can be received by any compatible FM receiver. The approximate range of signal transmission is around to 20–30 m. The FM circuit is simple but surprisingly powerful despite its small components and low operating voltage and can be considered as a reliable option to send and receive fault signals.

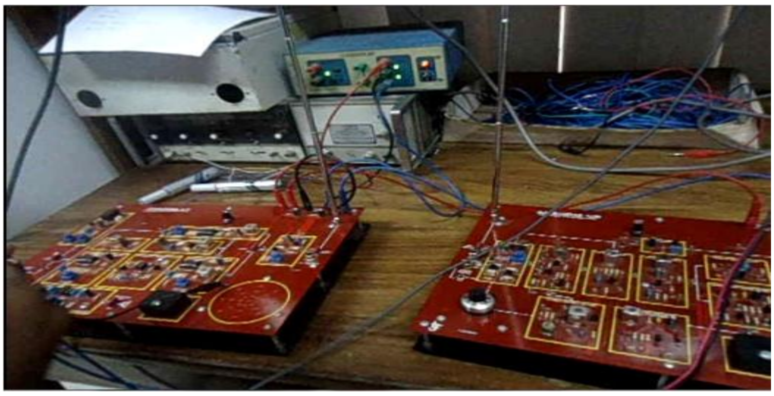

Fig. 5: *ANACOM AT02 Set.*

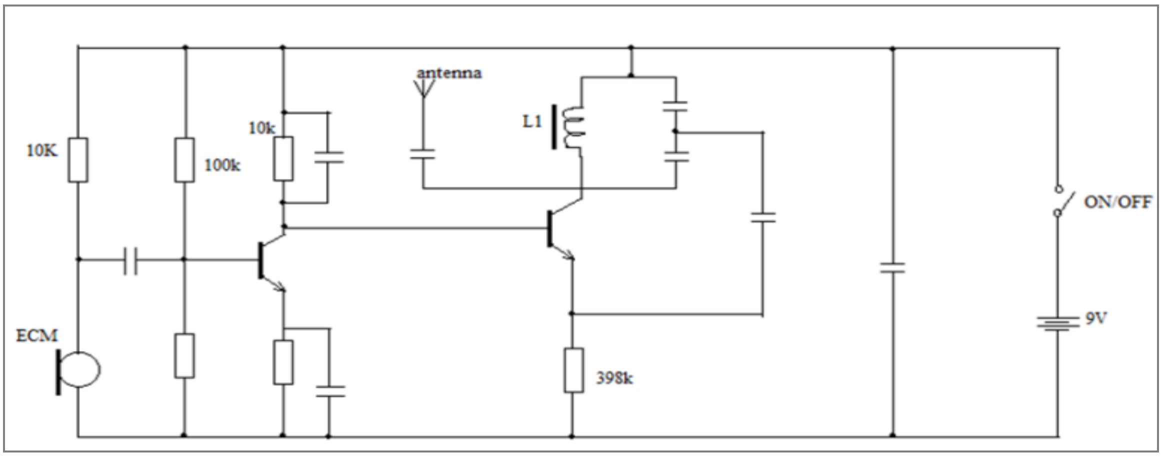

Fig. 6: *Circuit Diagram of the Prototype Used to Test Analog Transmission Using Frequency Modulation (FM) Technique.*

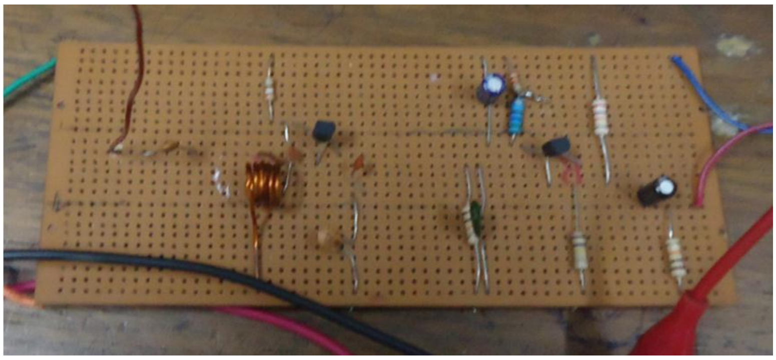

Fig. 7: *Prototype Used to Test Analog Transmission Using Frequency Modulation (FM) Technique.*

Digital Transmission Using Digital Modulation Technique

Figure 8 represents the relay schematic using a digital circuit. Two IC's are being used: HT-12E and HT-12D, and they are RF encoder and RF decoder respectively. The HT 12E Encoder ICs are a series of CMOS LSIs for remote control system applications. They are capable of encoding 12 bit of information which consists of N address bits and 12-N data bits. The HT 12D ICs are also a series of CMOS LSIs for remote control system applications. Operating voltage range of the ICs is 2.4 to 12 V. In the circuit, both the ICs, HT 12D and HT 12E are paired with each other. A pair of encoder/decoder with the same number of address and data format has also been used. If any disturbance arises, the Hall-effect sensor senses it and sends the signal to the comparator. There, the signal is compared with a reference voltage to check whether it is above or below the reference voltage. After the comparator detects the fault, it sends the signal to the IC HT-12E (RF encoder), where it is encoded and then transmitted using a RF transmission medium, i.e., through air. The signal is then received by the receiving circuit and passed to the IC HT-12D (RF decoder). The decoder receives the serial address and data from its corresponding decoder and gives output to the output pins after processing the data. The output pins D8, D9, D10 and D11 are connected to digital relays. The relays trip according to the signal they receive from the output pins of the IC. The transmission and receiving circuits using digital modulation have been implemented on the board with all the components shown in Figures 9 and 10 respectively.

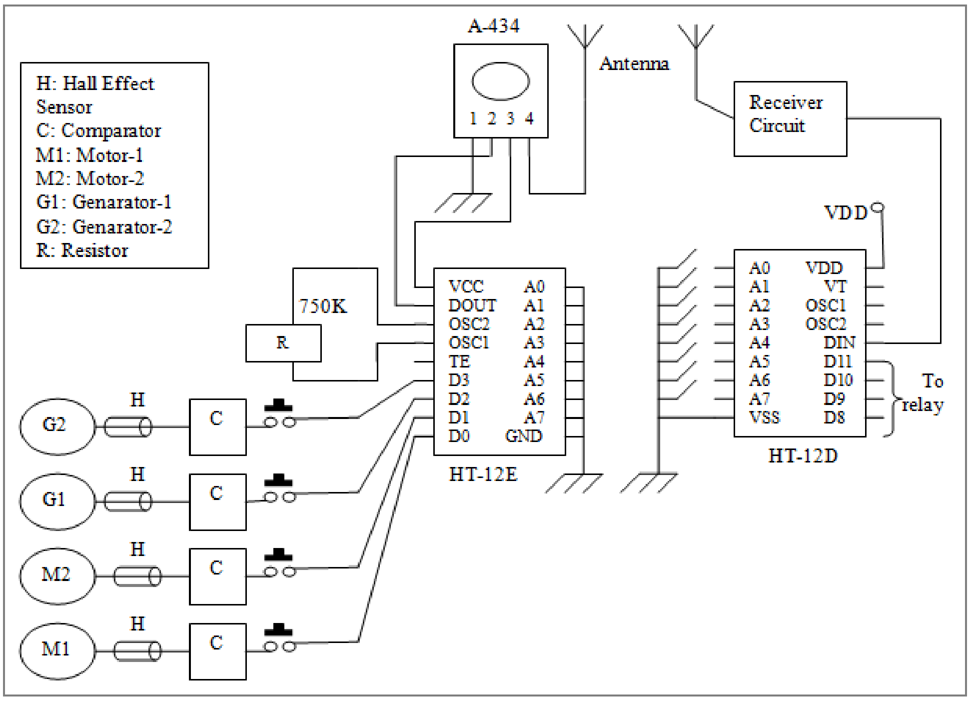

Fig. 8: *Proposed Relay Schematic Using a Digital Circuit for the Protection of Generators and Motors in Industries.*

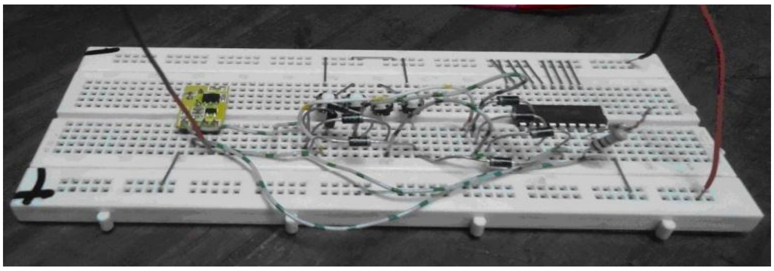

Fig. 9: *Transmitter Circuit of the Digital System.*

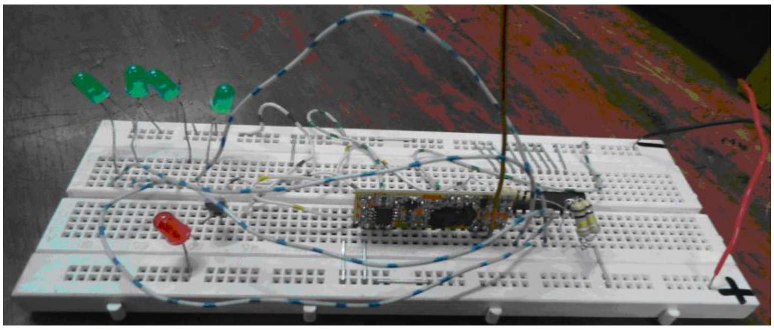

Fig. 10: *Receiver Circuit of the Digital System.*

OBSERVATION AND EVALUATION

For the AM technique, the signal at the receiving end shows significant susceptibility to noise and hence appears distorted. Also, the transmitter and receiver circuits need to be placed quite close to each other to get a reliable signal. For the FM technique, the susceptibility to noise is much improved and the transmitter and receiver can be placed further apart (a few meters). However, both the analog modulation methods (AM and FM) are prone to performance degradation when there are obstacles present between the transmitter and the receiver circuits. For the digital modulation circuit, a much-improved signal is received since the circuit is neither susceptible to noise nor experiences any performance setback due to the presence of obstacles in its pathway. The transmitted signal was easily received despite the transmitter and receiver being isolated from each other. Other advantages include significant improvement in range and the use of cost-effective, low power and high noise immunity ICs for the construction of the system. This makes it suitable for use in industries which are often widespread over a large geographical area.

CONCLUSION

For industries such as oil and gas which are classed as major hazards industry and where the misinterpretation of fault condition can lead to acute danger, using digital system is preferable since it is more reliable than the analog system. The use of our proposed digital system along with the Hall-effect sensor would not only overcome the problem of saturation but would also make the system smarter and more responsive to faults. If the above-mentioned factors are taken into consideration and a large-scale system that is compatible with the smart-grid is built, it could open a new door of opportunity for wireless technologies intended to protect the industrial systems.

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Cite this Article

Nadia Anam, Susmita Ghosh, Tasmia Farihba. Design of a wireless protection scheme for smart-grid-based industrial systems. *Journal of Power Electronics & Power Systems*. 2017; 7(3): 30–37p.