Design of a smart control and protection system for three-phase generator using Arduino

Ahmed J Ali, Ahmed M T Ibraheem* and Omar Talal Mahmood
Dep. of Electrical Power Engineering Technologies, Technical Engineering College/Mosul, Northern Technical University, Iraq

* ahmed_alnaib85@yahoo.com

Abstract. Proper monitoring of electrical apparatus that has power consumption is a step towards efficient energy and saving management. Parameters of electrical power system have wide variations during operation of electrical devices. These changes in the parameters required to be measured using accrued meter. This paper presents design and implementation of AC multi-meter based on Arduino for three-phase synchronous generator. This meter measures the values of load current, terminal voltage and the frequency. In addition, it used to detect the abnormal operation of three-phase synchronous generator (overload, under and over voltage, and low and high frequencies). The multi-meter displayed the measured parameters and the protection status of each data directly on LCD, and serial print of the Arduino software program in PC via USB cable. A smart monitoring for these operation conditions designed using a Bluetooth module. Two sensors have been used with multi-meter; current sensor type ACS-712, and ac voltage sensor type ZMPT101b. The frequency has been measured utilizing the ac voltage sensor signal, i.e. it measured without using any external zero crossing detector hardware circuit.

1. Introduction
The synchronous generators are considering the main part of the generation system where it supply the customers required power. According to different abnormal conditions, that faces the grid such as faults, unbalance load, and inability to keep the minimum level of power requirements, the generator voltage, current, and frequency will suffer from fluctuations above and lower the safely limits. This undesirable work will affect directly on the performance, efficiency and reduce the reliability of the power system.

Currently, digital electronics energy measurement is continuously replacing existing technology of electro-mechanical meters. A wireless digital power meter will definitely offer greater convenience to the meter-reading task [1]. Arduino is getting more and more attention in this field (i.e. measurement instruments and monitoring systems) due to its flexible features and rich library functions. It is user robust, fast and at the same time user friendly. Many approaches have been used to measure, monitor, and detect faults in the electrical systems based on microcontroller. Khan et al designed a training system that uses both electro-mechanical and microcontroller (Arduino) based relays simultaneously such a way that the electrical system could be switched to either electro-mechanical or microcontroller-based relay setup. This system also displays the current magnitude during the fault and the time required by the relay to clear the fault [2]. In [3], an experimental study had been considered to monitor and measure the electrical quantities using Arduino Uno, this system also
protects the load from voltage variation and over current conditions. The authors in [4], designed a system based on Atmega328P as a microcontroller to measure the voltage of the particular phase and switch to another phase if the measured voltage is over or under the voltage condition with a range from 160 to 220 volt. Arduino-GSM based power system protection have been implemented as an educational test pinch in [5] for different electrical quantities. Shivkumar etal in [6] designed a frequency protection relays and power factor correction system based on Arduino. The authors in [7] have used Arduino Uno to implement over and under current protection for a renewable energy system practically. A monitoring and protection system for distribution transformer has been implemented practically using Arduino, GSM and GPS; this system records the current, voltage, oil pressure and ambient temperature for the transformers [8 - 10]. In this paper, a protection and smart monitoring system for one phase of synchronous generator designed and implemented practically. Over load, under & over voltage, and low & high frequency parameters were detected. Three types of monitoring the data were used (serial monitor in IDE Arduino software, 16*2 LCD, and android app. which reserved the data via Bluetooth module).

2. Proposed Monitoring & Protection System:
Figure 1 shows the proposed system based on Arduino. The system consists of three main parts: sensors, controller (Arduino), and monitoring part. Two sensors have been used; the first one responsible for current and other for voltage. Arduino type Mega 2560, which is built-in ATMega328 microcontroller. It has 54 digital I/P and O/P pins, 16 analog I/P, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, Analog to Digital Converter (ADC) with 10-bit resolution. It encloses everything needed to support the microcontroller; it simply programmed by the Arduino IDE software via USB connection. In this work, three types of monitoring systems are used. The first uses the serial monitor property for monitoring the data on the PC, in which the USB cable of the Arduino must always connected to the PC. The second approach achieved by using 2*16 LCD with I2C interfacing model for directly displaying the data. The last method; is done by using the Bluetooth module for sending all measurement to a mobile for displaying these data via mobile application (serial monitor).

2.1 Current Sensor:
ACS-712 current sensor operates with 5V, its analog output voltage is proportional to the current measured on the sensing terminals. You can simply use an Arduino ADC to read the values [11]. ACS-712 sensor mechanism depends on Hall effect principle, according to this mechanism, when the conductor that carries an electrical current placed in magnetic field a voltage will be induced, which called "Hall voltage". The sensor is used to normalize the required voltage level from the current which is further fed to the Arduino [2]. Then Arduino converts the Hall voltage to the RMS actual current using formula given in equation (1):
The sensitivity value depends on the type of the current sensor, there are three types of current sensors each one used for a specific range to measure the current, sensitivity value for ACS-712 ELCTR-30A-T which is measure until 30A equal to 185mV/A, has used in this work.

\[
\text{current(A)} = \frac{\text{sensor value-512)+5/1024}}{\text{Sensitivity value}+\sqrt{2}}
\]  

2.2 Voltage Sensor:
ZMPT101B sensor unit is an AC type voltage sensor based on built-in voltage transformer. It performs high accurate, good reliability for voltage and power measurement, also, it has a wide range of measurement (0-250 AC voltage) [12]. It is very easy to use and build with a multi turn trim potentiometer for adjusting the ADC output. The module read the signal that will be measured (220V phase voltage) in current work with a peak value 311 V. The built-in voltage transformer reduces it to 2.5 V (peak). Then a 2.5 V offset has been inserted to shift the signal to a positive level where the Arduino ADC can be detected as shown in Figure 2.

![Figure 2. Operation of single-phase ZMPT101B voltage sensor.](image)

2.3 Frequency Measurement:
The frequency measured based on AC voltage signal of the zmpt101B sensor. Whereas the AC voltage signal is compared with zero reference value to convert the sine wave signal into a square wave (if the AC voltage signal > 0 then the square wave signal equals 1, if the AC voltage signal < 0 then the square wave signal equals 0) as shown in Figure 3 (a). The time duration of the square wave will be measured between each rising edges of the square wave signal. The frequency is equal to the inverse value of this time duration value as shown in the code in Figure 3 (b).

![Figure 3. Frequency measurement.](image)
2.4 Protection Process:

After measuring the load current, terminal voltage and frequency of synchronous generator, the values of these parameters will be displayed on the (serial monitor on PC, Mobile application via Bluetooth, and 2x16 characters LCD). Then a comparison between measured and threshold values is made for monitoring and protecting the system as follows:

- Threshold value of the over load current has been set in software code (case study: 3A). In case of exceeding this current a message "Over Load" will appear in the (Serial monitor on PC, and Mobile application via Bluetooth) in addition to possibility of sending an output signal for ignites the trip coil of the circuit breaker that will isolate the load. At the same time: "OL" message will appear on the 2 x 16 LCD as shown below in the over load code.

```cpp
if (AmpsRMS >= 3 ) {Serial.println("Over Load");
  blue.print("Over Load");
  lcd.setCursor(6,1);lcd.print("OL");}
```

Figure 4. Over load message code.

- In the same manner for the current, when the generated voltage exceeds 225V, an "Over Voltage" message will be displayed on the (Serial monitor on PC, and Mobile application via Bluetooth), and "OV" message will appear on the LCD. When the generated voltage reduced below than 200V a "Low Voltage" message will displayed on the (Serial monitor on PC, and Mobile application via Bluetooth), and "LV" message will displayed on the LCD as shown in code below.

```cpp
if (supplyVoltage <= 200 ) {Serial.println("Low Voltage");
  blue.print("Low Voltage");
  lcd.setCursor(6,0);lcd.print("IV");}
if (supplyVoltage >= 225 ) {Serial.println("Over Voltage");
  blue.print("Over Voltage");
  lcd.setCursor(6,0);lcd.print("OV");}
```

Figure 5. Abnormal supply voltage values message code.

- In general; there are two main levels for acceptable frequency limits; the first one is the "Operational limit", at which the frequency tolerance is equal to ±0.2 Hz (i.e. 49.8 Hz to 50.2 Hz), and the second one, is the "Statutory limit", at which the frequency tolerance equals to ±0.5 Hz (i.e. 49.5 Hz and 50.5 Hz) as shown in Figure 6 [13, 14].

![Figure 6. The statutory and operational frequency limits.](image)

In the current work, the second frequency criteria limit (statutory limit) has been consider. If the frequency value is greater than 50.5 Hz, a "High Frequency" message will be displayed on the (Serial monitor on PC, and Mobile application via Bluetooth) and "HF" message will appear on the LCD. Also in the case of a frequency lower than 49.5 Hz, a "Low Frequency"
message will be displayed on the (Serial monitor on PC, and Mobile application via Bluetooth) and "LF" message will appear on the LCD, as shown below.

```c
if(freq <= 49.500){Serial.println("Low Frequency");
    blue.println("Low Frequency");
    lcd.setCursor(14,0);lcd.print("LF");}
if(freq >= 50.500){Serial.println("High Frequency");
    blue.println("High Frequency");
    lcd.setCursor(14,0);lcd.print("HF");}
```

Figure 7. Abnormal frequency values message code.

3. Experimental Results and Discussion:

Figures 8, and 9 show the experimental setup of the proposed monitoring and protection system for one phase of three-phase alternator based on Arduino.

![Figure 8. Experimental implementation.](image1)

![Figure 9. Arduino board with sensors.](image2)

The performance of the system has been tested under different load conditions, then the measured parameters of the system (current, voltage, and frequency) and the faults cases are directly displayed on the serial monitor on PC. Figure 10.a shows the over load case when the load current exceed 3 A (threshold current/case study: 0.75HP single-phase induction motor as load) the "Over Load" message directly displayed.

Figure 10.b shows the low voltage case, when the generated terminal voltage is lower than 200 V (threshold voltage/case study) the "Low Voltage" message directly displayed. Figure (10.a) shows the over voltage case; when the generated terminal voltage is greater than 225V (threshold voltage/case study) the "Over Voltage" message directly displayed. Figure 10.d and 10.e show a high and low frequency cases, respectively.

At the same time, Bluetooth module has been used to send the same data to be displayed on the android app as shown in Figure 11 with the same sequence of serial monitor displaying, this property adds the flexibility for monitoring the system. At the same time, 2*16 LCD character used for directly mentoring these data and protection message as shown in Figure 12.
Figure 10. Serial monitor screen—shoot of measuring data at various normal and abnormal cases.
Figure 11. Serial Monitor (Mobile application) screen – shoot of measuring data at various normal and abnormal cases.

Figure 12. Data shown in LCD.
4. Conclusions:
The proposed system based on Arduino can monitor many parameters and detect all the abnormally operations of the synchronous generator. Terminal voltage, load current, and frequency are continuously monitoring with high accuracy. If these parameters exceeded the threshold value, which are previously set in the proposed software, an alarm message about the abnormal operation, in addition to a protection scheme can operate and trip the load. Arduino Mega has a wide application in control applications of power system due to its low price with simple circuitry compared to other controller, in addition to its reliability, flexibility in use. In this work, the use of only two sensors (voltage and current sensors); three parameters measured without using an external circuit (i.e. zero crossing detectors) to measure the frequency. In future work; power factor, power consumption, and energy measurement in addition to abnormal states (as unbalance load, phase failure) can be developed for the proposed system (i.e. with two used sensors only).

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