Detection of Failures in Alternator of Diesel Generator Based on the Microcontroller Technique

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ABSTRACT

The goal of the present paper is to design and build electronic protection unit for detection of failures in alternator of diesel generator because of the many technical problems and failures or abnormal operating conditions that accompany the work of the generators when it used as a substitute for electrical energy, especially in long working hours.

Some of these problems and failures: increasing the temperature of the stator coils, loss of excitation, over/under frequency, over/under voltage and phase failure.

When any problem occur the proposal protection unit will be displayed the type of error or problem on liquid crystal display (LCD) as well as gives us an audio alarm and also shuts down the generator in critical situations.

The design was adopted mainly on microcontroller PIC16F877A, this design is characterized by low cost, uncomplicated, very high response and flexible to change software in case you need to add another failures without changing hardware if compared with the current protection unit in the original generators.

Keywords: Alternator, Electrical failures, Microcontroller, Protection unit.

الكشف عن حالات الفشل في رأس التوليد الكهربائي لمولدات الديزل بالاعتماد على تقنية المسيطر الدقيق

الخلاصة

الهدف من هذا البحث هو تصميم وبناء وحدة حماية الكترونية لرأس التوليد الكهربائي لمولدات الديزل للكشف عن الاعطال وذلك بسبب المشاكل والاعطال التقنية الكثيرة اوظروف العمل الغير طبيعية التي ترافق عمل المولدات الكهربائية عند استخدامها كبديل عن الطاقة الكهربائية، وخصوصا في ساعات العمل الطويلة.

والبعض من هذه المشاكل والاعطال : زيادة درجة حرارة ملفات الجزء الثابت، فقدان الحث، ارتفاع وانخفاض التردد ، ارتفاع وانخفاض الجهد ، وفشل أحد الاطوار الثلاثية.

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عند حصول اي مشكلة في عمل المولدة فان وحدة الحماية المقترحة سوف تعرض نوع الخطاء او المشكلة على شاشة كرستال (LCD) موجودة في وحدة الحماية بالاضافة الى اصدار تنبيه صوتي وايضا تقوم وحدة الحماية بايقاف المولدة عن العمل عند الحالات الحرجة.

تم بناء هذا التصميم بالاعتماد على المسيطر الدقيق (PIC16F877A)،ويتميز هذا التصميم بكلفته المنخفضة وبكونه غير معقد بالاضافة الى سرعة استجابته والمرونة في تغير البرامجيات في حالة الحاجة الى اضافة اعطال اخرى دون الحاجة الى تغير الكيان المادي عند مقارنته مع وحدة الحماية الموجودة حاليا في المولدات الاصلية المنشأ.

INTRODUCTION

A generator is the heart of an electrical power system, as it converts mechanical energy into its electrical equivalent, which is further distributed at various voltages. It therefore requires a 'prime mover' to develop this mechanical power and this can take the form of steam, gas or water turbines or diesel engines.

Steam turbines are used virtually exclusively by the main power utilities, whereas in industry three main types of prime movers are in use [1]:

1-Steam turbines: Normally found where waste steam is available and used for base load or standby.

2-Gas turbines: Generally used for peak-lopping or mobile applications [1 and 2].

3-Diesel engines: Most popular used in industrial plants, factories, and houses as standby generators.

Larger units are connected to the electrical high voltage (EHV) grid via a transformer whilst Small- and medium-sized generators are normally connected direct to the distribution system.

Many different faults can occur on these generators, for which diverse protection means are required. These can be grouped into two categories [1]:

a-Electrical failures such as stator winding temperature, over/under voltage , over/under frequency, loss of excitation ,and phase failure or line drop.

b-Mechanical failures such as prime mover, low condenser vacuum, lubrication oil failure, over speeding, rotor distortion, and excessive vibration [1 and 2].

The purpose of generator protection is: minimize damage, maintain electrical system stability, maintain equipment operating limits and leave unaffected equipment in-service. Also the protection system requires some specification like speed,reliability,security and sensitivity[3].

In this paper the electrical failures protection of small and medium –sized diesel generator will be discussed while the larger units and mechanical failures out of this paper.

A protection unit for mechanical failures was implemented in research [4 and 5], so it is out of this paper and we will be introduced alternator failures only.

DISEL GENERATOR

A diesel generator may be used independently or in conjunction with a utility in a variety of ways. The four most common modes of operation are described below:

a-Prime Power

The diesel generator is the sole provider of power, such as on a construction site or in a remote location.

b-Automatic Standby and Changeover

In the event of utility supply failure the diesel generator starts automatically and operates an interlocked break-before-make changeover arrangement.

c-Short Term Paralleling

On receipt of a start signal the diesel generator is automatically started, synchronized with the utility supply and operated in parallel for a short time (typically less than 1 second for step load action or up to 10 seconds for soft load transfer). The use of soft load transfer ensures voltage and frequency excursions are minimized.

d-Long Term Paralleling

On receipt of a start signal the diesel generator is automatically started, synchronized with the utility supply and operated continuously in parallel, with the load shared between the generator and the utility. Restrictions on the size of the generator, the site load and the permission ‘to export excess power to the grid will determine the operating regime e.g. base load or import/export control.

The first two operating modes cover applications where there is no permanent or reliable utility supply. Indeed automatic standby system is often referred to in the same terms as an insurance policy. The last two modes are considered “embedded generation”. They have, in the recent past, required large floor standing control panels, relay protection schemes, special engine governing systems and up rated alternators and Automatic Voltage Regulators (AVRs). For smaller diesel generators the extra costs of these can be prohibitive. Where the capital costs can be justified, and the appropriate utility requirements met, embedded generation offers the possibility of both increasing system security and the potential for saving in the overall cost of electricity consumed by responding to the utility tariff structure[6].

PROTECTION REQUIREMENTS

This section briefly describes the damaging effects of faults and abnormal operating conditions and the type of device and their settings commonly used to detect these conditions. A clear understanding of the effects of abnormalities on generators will assist the reader in evaluating the need for and the means of obtaining adequate generator protection in specific situation [7]. The following electrical protection of alternator will be introduced in this paper as follow:

Stator Winding Temperature Protection

Most generators are supplied with a number of temperature sensors to monitor the stator windings. These sensors are usually resistance temperature detectors (RTDs),thermocouples (TCs) and PN junction sensor. As the name implies, the RTD detects temperature by the change in resistance of the sensor, a TC detects temperature by the change in thermoelectric voltage induced at the TC junction and PN junction changes in temperature for every 1℃, in voltage for about 2mV [8].

These sensors are used to continuously monitor the stator winding. In attended generating stations, the sensors may be connected to a data acquisition system [9].

In unattended stations, the sensors may be used with a relay to alarm, to initiate corrective action, or to trip the unit if preset temperature limits are exceeded, the temperature of stator is usually less than 120℃ ,and the space around generator stator is limited [10].

For generators with conventional (indirectly cooled) stator windings, RTDs embedded between the top and bottom bars are used to monitor winding temperatures. For generators with inner-cooled (directly cooled) stator windings, the stator bar coolant discharge temperature is used along with the embedded RTDs (if equipped) to monitor the winding temperature.
The generator manufacturer should be consulted for specific recommendations on the preferred method of monitoring these sensors and temperature limits for alarm and trip purposes [9].
Thermal protection for the generator stator core and windings may be provided for the following contingencies [8]:
1. Generator overload.
2. Failure of cooling systems.
3. Localized hot spots caused by core lamination insulation failures or by localized or rapidly developing winding failures.
In this paper the microcontroller will be used for recording and alarm stator temperature increasing.

Excitation Protection

The excitation system has many similarities to the generator it supplies, and hence requires much of the same type of protection. Although the consequences from equipment damage are less serious, adequate protection of the excitation system is important for reasons of continuity of service.
When generator becomes saturated beyond rating, stray fluxes will be induced into nonlaminated components. These components are not designed to carry flux and therefore thermal or dielectric damage can occur rapidly.
In dynamic magnetic circuits, voltages are generated by the Lenz's Law [11]:

$$V = K\frac{d\phi}{dt} \qquad \text{….(1)}$$

Where:
$\emptyset$: flux and K: constant depending upon the generator design and size.
Measured voltage can be integrated in order to get an estimate of the flux. Assuming a sinusoidal voltage of magnitude V_P and frequency f, and integrating over a positive or negative half-cycle interval [11]:

$$\phi = \frac{1}{K}\int_0^{T/2} V_P \sin(\omega t + \theta)\, dt$$

$$= \frac{V_P}{2\pi f K}(-cos\omega t)\Big|_0^{T/2} \qquad \text{…(2)}$$

One derives an estimate of the flux that is proportional to the value of peak voltage over the frequency. This type of protection is then called volts per hertz [11]:

$$\phi \approx \frac{V_P}{f} \qquad \text{...(3)}$$

The estimated value of the flux can then be compared to a maximum value threshold. With static technology, volts per hertz relays would practically integrate the monitored voltage over a positive or negative (or both) half-cycle period of time and develop a value that would be proportional to the flux.

Excitation system protection may be provided for the following [8]:

1-Exciter phase unbalance: Symptomatic of a serious problem, such as a phase-to-phase or turn-to-turn fault, this condition may lead to winding damage. Detection may be accomplished by comparing three-phase voltages with their average or by differential relaying.

2- Exciter ground fault: This condition may be detected by generator field ground protection.

3- Over current: Detection is provided by generator field protection.

4- Loss of rectifier cooling: To prevent rectifier thermal damage, some form of loss-off low detector should be present, backed up by an over temperature alarm.

5- Alternator armature winding over temperature: This condition may indicate stator winding damage due to failure of the stator cooling system. Detection is provided by imbedded thermocouples or resistance temperature detectors.

6- Alternator air cooler loss-of-water flow: Thermal damage is prevented by a flow detector alarm.

7-Bearing vibration: Severe mechanical damage may be prevented by using vibration detectors/recorders.

Over/Under Frequency Protection

In an alternator, there exists a definite relationship between the rotational speed (N) of the rotor, the frequency (f) of the generated e.m.f. and the number of poles P as follow [12]:

$$f = \frac{PN}{120} \qquad \text{....(4)}$$

Where:

P : total number of magnetic poles , N : rotative speed of the rotor in r.p.m , f : frequency of generated e.m.f. in Hz.

According to Faraday's Laws of electromagnetic induction ,the e.m.f. induced in the coil is given by the rate of change of flux-linkages of the coil. Hence, the value of the induced e.m.f. at this instant (*i.e.* when θ = ω *t*) or the instantaneous value of the induced e.m.f. is[12]:

$$e = -\frac{d}{dt}(N\Phi) \qquad volt$$

$$= -\frac{d}{dt}(\Phi_m \cos\omega t) \qquad volt$$

$$= -N\Phi_m \omega(-\sin\omega t) \qquad volt$$

$$= \omega N\Phi_m \sin\omega t \qquad volt$$

$$e = \omega N\Phi_m \sin\theta \quad volt \qquad \text{...(5)}$$

When the coil has turned through 90º i.e. when θ = 90º, then sin θ = 1, hence e has maximum value,say E_m . Therefore, from Eq. (5) we get[12]:

$$E_m = \omega N \Phi_m = \omega N B_m A$$

$$= 2\pi f N B_m A \quad volt \qquad \dots.(6)$$

Where:
Bm : maximum flux density in Wb/m^2 , A : area of the coil in m^2 , f : frequency of rotation of the coil in Hz.
From equation (6) above the frequency of the generator also is direct proportional to induced e.m.f.

Two separate frequency elements can each be configured to operate in either under, over, or the combination of under and over frequency mode. This will allow protection for not only under frequency operations but also for the similarly damaging over frequency operating conditions [13].
The frequency operation can be described as follows:

a-Over frequency operation

Over frequency results from the excess generation and it can easily be corrected by reduction in the power outputs with the help of the governor or manual control [14].

b- Under frequency operation

Under frequency occurs due to the excess during an overload, generation capability of the generator increases and reduction in frequency occurs. The power system survives only if we drop the load so that the generator output becomes equal or greater than the connected load. If the load increases the generation, then frequency will drop and load need to shed down to create the balance between the generator and the connected load. The rate at which frequency drops depend on the time, amount of overload and also on the load and generator variations as the frequency changes. Frequency decay occurs within the seconds so we cannot correct it manually. Therefore automatic load shedding facility needs to be applied. These schemes drops load in steps as the frequency decays.

Generally load shedding drops 20 to 50% of load in four to six frequency steps. Load shedding scheme works by tripping the substation feeders to decrease the system load. Generally automatic load shedding schemes are designed to maintain the balance between the load connected and the generator. The present practice is to use the under frequency relays at various load points so as to drop the load in steps until they declined frequency return to normal. Non essential load is removed first when decline in frequency occurs.

The setting of the under frequency relays based on the most probable condition occurs and also depend upon the worst case possibilities. During the overload conditions, load shedding must occur before the operation of the under frequency relays. In other words load must be shed before the generators are tripped [14].

Over/Under Voltage Protection

Three-phase generators are the most common, although, for certain special jobs, greater number of phases is also used. For example, almost all mercury-arc rectifiers for power purposes are either six-phase or twelve-phase and most of the rotary converters in use are six-phase. All modern generators are practically three-

phase. For transmitting large amounts of power, three-phase is invariably used. The reasons for the immense popularity of three-phase apparatus are that ***(i)*** it is more efficient ***(ii)*** it uses less material for a given capacity and ***(iii)*** it costs less than single-phase apparatus etc[12].
The instantaneous values of the three e.m.fs. will be given by the equations are[12]:

$$e_a = E_m sin\omega t \quad \ldots.(7)$$

$$e_b = E_m \sin(\omega t - 120^0) \quad \ldots.(8)$$

$$e_c = E_m \sin(\omega t - 240^0) \quad \ldots (9)$$

Where:
$e_a, e_b\ and\ e_c$ the r.m.s. voltages of the three phases. The voltage induced in each winding is called the phase voltage and current in each winding is likewise known as phase current. However, the voltage available between any pair of terminals (or outers) is called line voltage (*VL*) and the current flowing in each line is called line current (*IL*). Hence, in star connection the relationship between phase voltage and line voltage is [12]:

$$V_L = \sqrt{3}\ E_{Ph} \quad \ldots. (10)$$

The voltage operation can be divided into two types over and under voltage protection as follows:

a- Over voltage protection

Over voltage occurs because of the increase in the speed of the prime mover due to sudden loss in the load on the generator. Generator over voltage does not occur in the turbo generator because the control governors of the turbo generators are very sensitive to the speed variation. But the over voltage protection is required for the hydro generator or gas turbine generators. The over voltage protection is provided by two over voltage relays have two units – one is the instantaneous relays which is set to pick up at 130 to 150% of the rated voltage and another unit is inverse definite minimum time (IDMT) which is set to pick up at 110% of rated voltage. Over voltage may occur due to the defective voltage regulator and also due to manual control errors [14].

b- Under voltage protection

Generators are usually designed to operate continuously at a minimum voltage of 95% of its rated voltage, while delivering rated power at rated frequency. Operating a generator with terminal voltage lower than 95% of its rated voltage may result in undesirable effects such as reduction in stability limit, import of excessive reactive power from the grid to which it is connected, and malfunctioning of voltage sensitive devices and equipment. This effect however is a function of time. If applied, the under voltage protection is generally connected to alarm and not trip the unit, so that the operator can take appropriate action to remedy the under voltage condition (if possible)[15].

Phase Failure Protection

Phase faults in a generator stator winding can cause thermal damage to insulation, windings, and the core, and mechanical torsion shock to shafts and couplings. Trapped flux within the machine can cause fault current to flow for many seconds after the generator is tripped and the field is disconnected [16 and 17].

HARDWARE AND SOFTWARE DESIGN

The capability for a single unit to perform the multiple protection functions discussed in this paper is derived from the advanced hardware and software products using digital technology like microcontroller which are available today,digital technology offers several additional features which could not be obtained in one package with earlier technology. These features include: metering of voltages, currents,power, and other measurements

The ability to perform seven separate protection functions simultaneously, and provide response to control relay which shut down the generator or gives alarm[18].

Following is a full description of design the hardware and software protection unit.

Hardware Design

In hardware design, the 8-bit microcontroller PIC16F877A was used this microcontroller is programmed to take an input signals from the generators via various electronic circuits and temperature sensor as shown in block diagram in Figure (1).

The output port of the microcontrollers is connected to solenoid valve via relay the relay circuit is responsible for performing the switching action that energizes the generator starting circuit for operation.The relay circuit transforms the electrical signal from the PIC into mechanical movement that performs a switching mechanism via solenoid valve to allow the generator to stop[19 and 20] at any failure occur at the same time the type of failure will be shown in liquid crystal display LCD with sound alarm.

The microcontroller is programmed in BASIC language by using PROTON BASIC program [21].The schematic diagram of the proposal protection unit shown in Figure (2) was drawn by using PROTEUS ISIS (version 7.1) microcontroller simulation software [22].

Microcontroller PIC16F877A have five ports [23,24 and 25] , in this design four ports is used, PORT A and PORT B as input ports and PORT C and PORT D as output ports and PORT E is not used.

The next steps show the operation of the protection unit as follow:-

a-The stator temperature

Stator temperature sensor is connected to PORTA to RA3 pin, when the temperature of stator rises up more than 95 ℃ for any reason, the microcontroller will be sent a signal to the relay circuit in order to shutdown the generator via solenoid valve, also sound alarm will be activated, at the same time alarm case "STATOR WARMED UP" and the temperature value will be displayed on LCD as shown in Figure (3).

b-Over and under three phase voltage circuit

Sample of each phase voltage will be taken as input to the PORT A to RB1, RB2 and RB3 respective to L1, L2 and L3 if the phases voltage increasing or decreasing for any reason, the microcontroller will be sent a signal to the relay circuit in order to shut-down the generator via solenoid valve, also sound alarm will be activated, at the same time the value of each phase voltage and alarm case will be displayed on LCD as shown in Figure (4).

c-Over and under frequency circuit

Sample of single phase voltage will be taken to measure the frequency as input to the PORT B to RB0 if the line frequency decreasing or increasing (less than 45Hz and more than 55HZ) for any reason, the microcontroller will be sent a signal to the relay circuit in order to shut-down the generator via solenoid valve, also sound alarm will be activated, at the same time the value of the frequency and alarm case will be displayed on LCD as shown in Figure (5).

d-Phase failure

Three phase voltage sample will be taken as input to the PORT A to RA0, RA1 and RA2 respective to L1, L2 and L3 if phase voltage failure for any reason the microcontroller will be sent a signal to relay circuit in order to shut-down the generator via solenoid valve, also sound alarm will be activated, at the same time the cases of the phases will be displayed on LCD as shown in Figure (6).

e-Loss of excitation

Three phase voltage sample will be taken as input to the NOR gate then the output of NOR gate go to the PORT A to RA4 if there is no output voltage for all phases this means no excitation, the microcontroller will be sent a signal to relay circuit in order to shut-down the generator via solenoid valve, also sound alarm will be activated, at the same time the message of this case will be displayed on LCD as shown in Figure (7).

The microcontroller was programmed and tested by using EasyPIC6 development tools [26]as shown in Figure (8) and the protection unit was simulated by using PROTEUS ISIS program release 7.1 [22] and was tested by using EasyPIC6 development tools.

Software Design

The software of protection unit was implemented by using BASIC language (PROTON BASIC) program version IDE 1.0.0.1 and loader version 1.1.2.8.The flow chart of the protection unit program shown in Figure (9).

CONCLUSIONS

This paper focus on alternator protection unit based on microcontroller PIC16F877A, there are several conclusions can be summarized as follows:

1-The memory size of this microcontroller is 8Kbyte in this design all memory size was used therefore if the another failures will be added the microcontroller must replace by another one which has larger memory size like microcontroller PIC18F2420 which has 16 Kbyte.

2- PORT A, PORT B, PORT C and PORT D some of these ports pins were used in this design, also PORTE was not used so these pins can be used to detect other failures in future developments like (overload current , phase sequence etc…) only by changing the program of microcontroller with simple addition to the hardware design especially when we change microcontroller by another one has same numbers of ports with larger memory size.

3-The using of PROTON BASIC program in programming microcontroller was very efficient because of the ease of dealing with this program and also gives us speed in the implementation of the program.

The program also can be simulated easily by using PROTEUS ISIS program.

4-This protection unit was designed to work with small generator (10KVA to 1MVA), also this design can be used for medium generator with some modification.

5- The use of microcontroller makes the implementation time faster and low cost when compared with current protection unit in the commercial markets.

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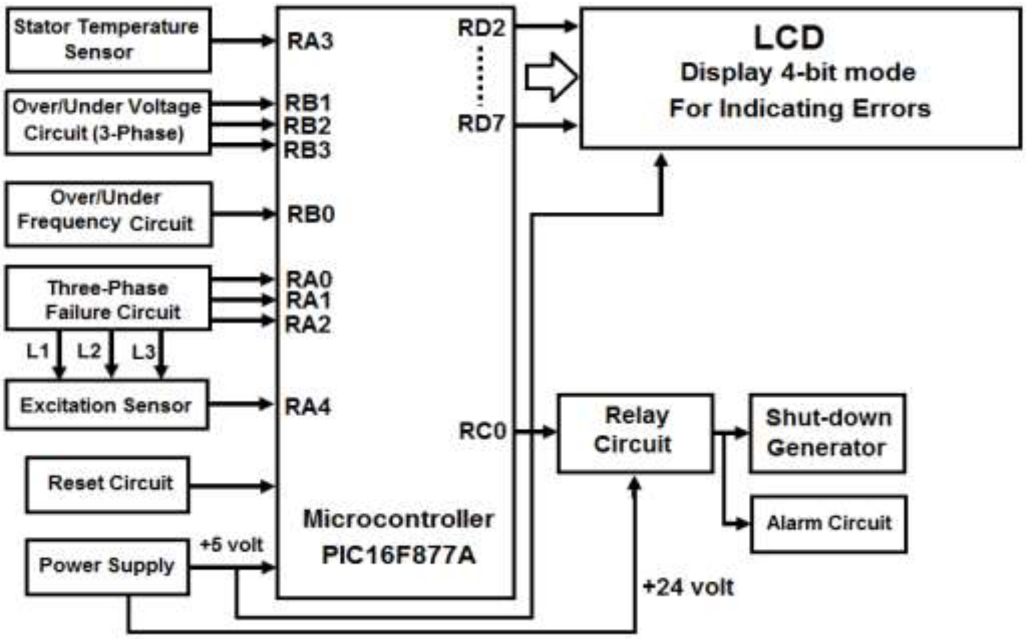
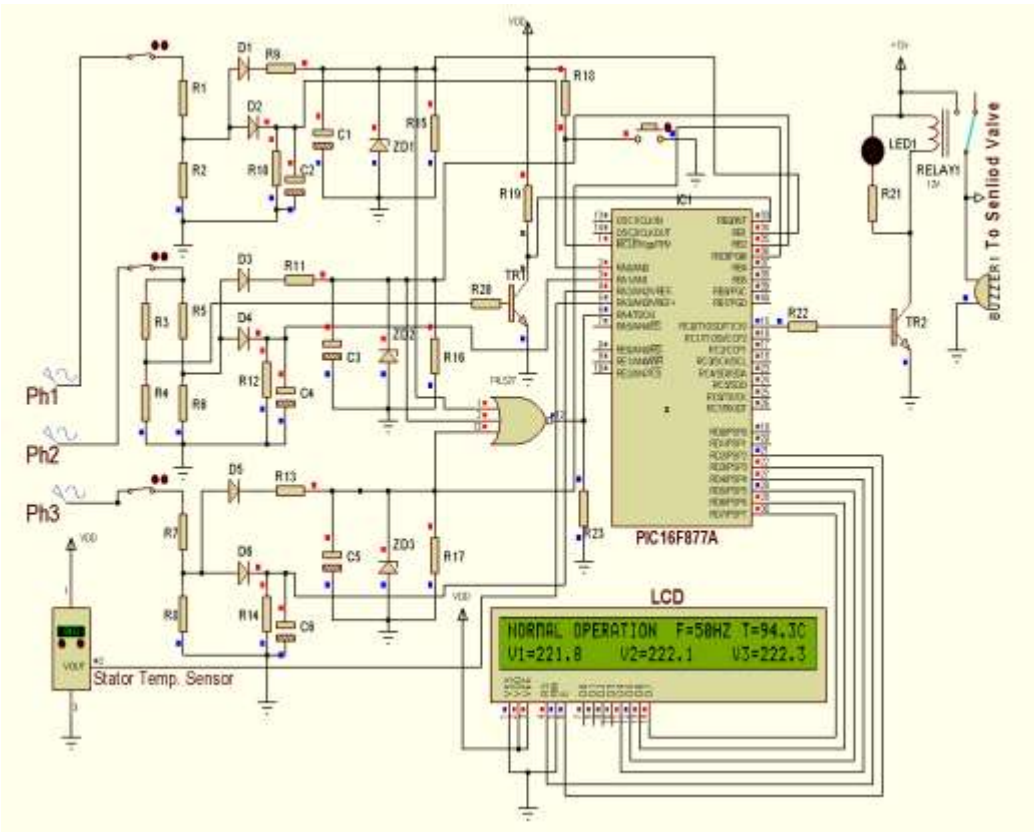


Figure (1): The block diagram of the proposal protection unit.



Figure(2): The schematic diagram of the proposal protection unit.

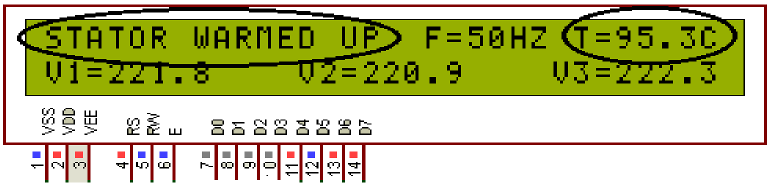
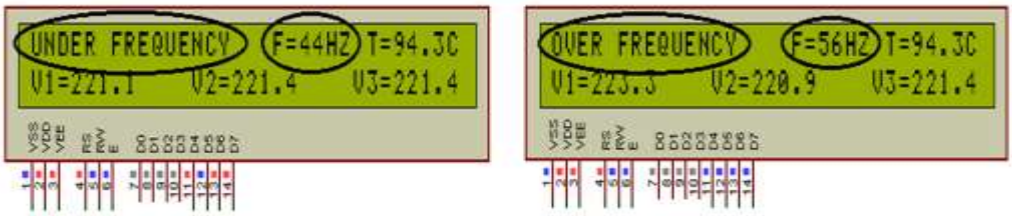


Figure (3): LCD in case of stator temperature alarm.

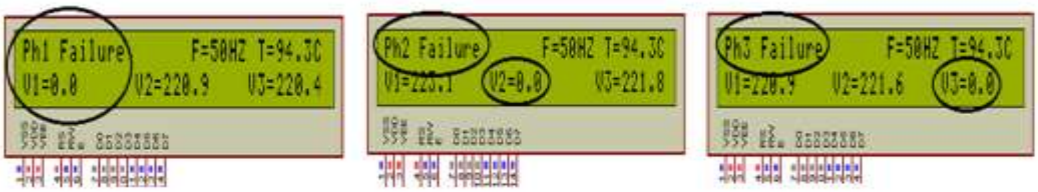
(a)Ph 2 Under voltage. (b)Ph3 Over voltage.

Figure (4): LCD in case of over and under phase's voltage: Under and over voltage.



(a)Under frequency. (b) Over frequency.

Figure (5): LCD in case of over and under frequency: Under and over frequency.

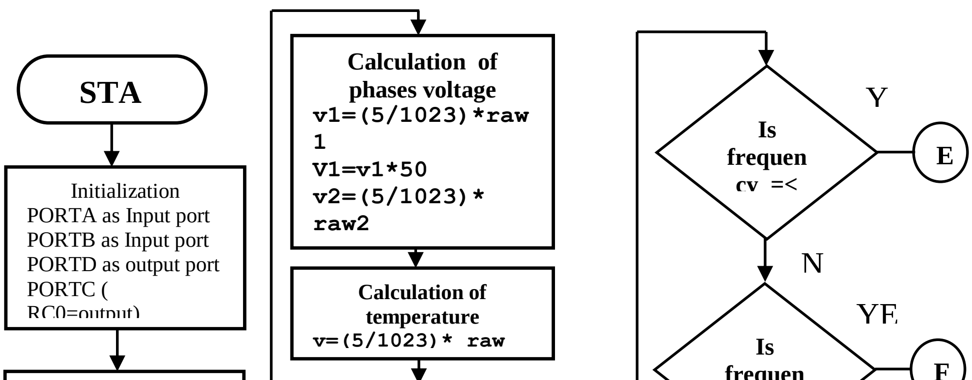


(a) Ph1 failure (b) Ph2 failure (c) Ph3 failure

Figure (6): LCD in case of Phase failure.

Figure (7): LCD in case of NO Excitation.

Figure(8): EasyPIC6 development system.



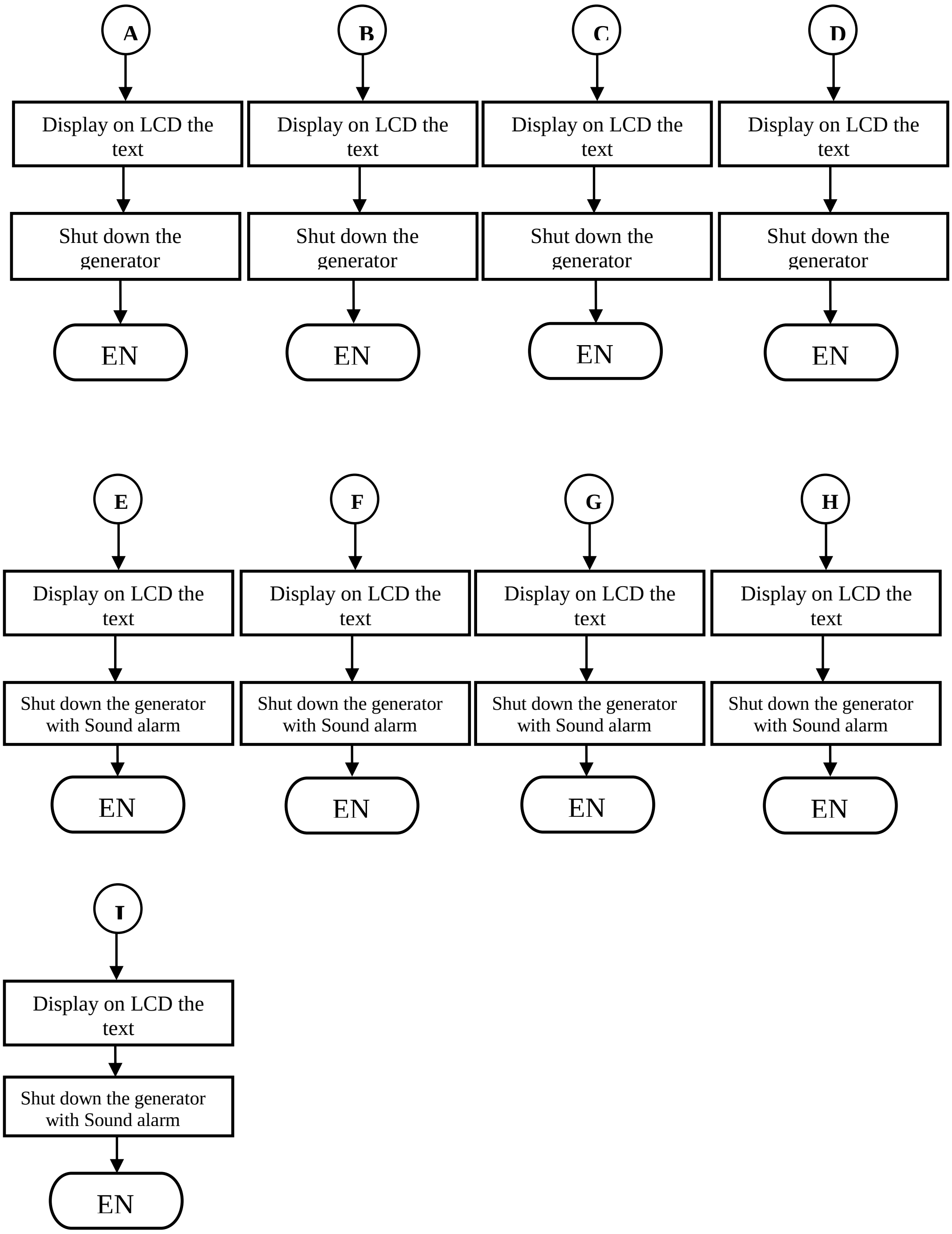


Figure (9): Flow chart of the microcontroller program.