

Power Grid Synchronous Detection Based on Voltage and Frequency

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Abstract

The power grid system is a complex electrical network that supply electricity from power generation to consumers. Required the variation of voltage and frequency are maintained within the normative limits. The aim of this research is to design a circuit model that simulate a power grid synchronous system using Proteus 8.17 software. This research had designed and built a model that can detect grid condition based on voltage and frequency variation. Arduino UNO microcontroller had been used in this research to control the overall operation flow. The functionality of the model had been examined through software simulation testing. Six different conditions had been set to test the functionality of the model. The assigned conditions include Normal Voltage (between 207V and 253V), Under Voltage (<207V), Over Voltage (>253V), Normal Frequency (between 49.5Hz and 50.5Hz), Under Frequency (<49.5Hz) and Over Frequency (>50.5Hz). Overall, the developed model in simulation using Proteus 8.17 software had a accuracy when detecting grid based on over/under voltage and over/under frequency variation.

1. Introduction

In the modern world, electricity is a cornerstone of economic development and quality of life. Ensuring the stability and reliability of power supply systems has become increasingly important due to the growing demand for energy and the integration of various energy sources, including renewable ones. The power grid, which is a vast and intricate system of generation, transmission, and distribution components, must operate in perfect synchronization to function effectively. Key parameters such as voltage and frequency must remain within specific normative ranges to prevent disruptions, blackouts, or damage to equipment [1][2].

This research aims to designing and simulating a power grid synchronization detection system with the help of an Arduino UNO microcontroller and Proteus 8.17 software such that they will be accurate when detecting voltage and frequency variations to identify the detection as soon as possible in a single-phase low-voltage grid. The presented study is a simulation of a detection system of the single-phase low-voltage grids that involve testing six conditions including normal, under and over voltage/frequency. The simulation process is realized in Proteus 8.17 software.

The purpose of this research is to detect the variation of voltage and frequency from normative limits based on grid standard. By implementing threshold-based detection voltage (207V–253V) and frequency (49.5Hz–50.5Hz), the system can provide immediate indicators of synchronization failures. This enables early intervention by electricity national utility and homeowner. the earlier action that electricity national utility can take are such as to ensure protection and safety of the system. Anti-islanding devices like relays are also used as a protective measure to automatically de-energize the source of the home (solar PV in this case) to avoid unsynchronized power injected into the grid and lead to grid instability or equipment damage. The utility can observe these

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occurrences with its system and in case the synchronization failure continues, may send technical staff to investigate the interconnection point and make sure that it is meeting the requirements of the grid and regulations. The system might be able to re-synchronize by a simple reset or restart, but the homeowner must not bypass the system in any manual way that may jeopardize safety. In case the issue occurs, they can call their system installer or technician to investigate the equipment, and in case the problem seems to be associated with unstable grid conditions, they can report the matter to the utility.

A comprehensive review of the power grid system is conducted in this report, covering its core components generation, transmission and distribution as well as its vulnerabilities. Emphasis is also placed on the Malaysian power grid framework, including its voltage regulation standards, short circuit ratings, and the challenges faced due to renewable energy integration [5][6]. Previous research studies have been analyzed to identify existing gaps and to form the foundation upon which this project is built. Through simulation and analysis, this project aims to deliver a reliable and effective approach to grid synchronization failure detection, particularly in low-voltage, single-phase applications.

Power grids the successful detection of synchronization failure in power grids is dependent on the use of real-time monitoring systems that allow the early detection of faults. Nevertheless, the drawbacks are presented in the packing order of data processing and analysis as well as response delays, which do not allow instantaneous intervention in case of faults. Such delays may permit serious faults to remain unnoticed or be repaired after it is too late to avoid the possibility of power failures and system cascading failures. The issue is to make monitoring systems with minimal processing delays in order to make fault detection and response fast and effective[7].

Inverter-based renewable energy systems, like solar panels and wind turbines, can become unstable when there are uneven problems in the power grid. This makes it hard to detect and handle synchronization failures. Right now, we don't fully understand how inverters behave during faults. Because of this, some detection models may not catch important problems or may respond too slowly. These current systems are not advanced enough and could miss faults or react too late, which might lead to bigger failures in the grid. This shows the need to create better and more accurate systems that can handle the special behavior of inverters during faults[8].

The study on "Loss of mains detection for small generators" explains a method that checks the flow of reactive power between the generator and the power grid. This power flow only works correctly when the grid is connected. So, if the power flow changes too much, it can be a sign that the grid has failed. However, the downside of this method is that it is slow. Because of this, it is not suitable for systems where small generators need to produce power at a perfect balance [9].

This research looks closely at different methods for detecting power grid synchronization problems, especially focusing on the importance of Phase-Locked Loop (PLL) systems. PLLs help detect and respond to changes in voltage and frequency in the grid. The study reviews several types of PLLs, such as the Synchronous Reference Frame PLL and the Enhanced PLL (EPLL), which are known for being strong and flexible even when the grid is not stable. These methods are useful for your project because they offer a reliable way to monitor the grid and detect problems caused by voltage or frequency changes [10].

Another big problem is the lack of standard rules for how power grids and failure detection systems are set up. Because different grids are designed and operated in different ways, it's hard to use the same detection method everywhere. This causes problems and makes it difficult to fix synchronization issues properly. A method that works for one grid might not work for another. As a result, the detection systems become less efficient and less reliable. To solve this, we need more flexible and standardized solutions that can work well across different types of power grids [11]. In fact, many studies only deal with specific aspects, such as voltage and frequency variations, without considering the integration of renewable energy sources or modern communication technologies[12].

However, some of the methods are based on advanced algorithms or require high computational power and hence are difficult to apply in real world grid systems. Cost, scalability, and ensuring reliable data communication during grid faults are other approaches, such as using IoT and smart sensors, that are challenged[13]. Finally, using advanced methods like data fusion, machine learning, and artificial intelligence can help improve the detection of synchronization failures in the power grid. These methods work by combining information from many sensors and sources. However, processing all this data at the same time is very difficult and requires a lot of computer power. It's also hard to collect and manage large amounts of accurate, real-time data. Because of this, it's challenging to use these high-tech methods in real situations. To fully benefit from data fusion and improve detection accuracy, we need to overcome these technical challenges [14].

2. Methodology

The flowchart in Fig. 1 describes the technical process that was employed in designing and simulating a model of power grid synchronization detection model utilizing Proteus program 8.17. It starts with generating a new project through the establishment of the default schematic layout. Subsequently, component mode is used to add all needed elements out of the library of the software.

The design is then divided into two parallel branches which are the voltage circuit and the frequency circuit. In the case of voltage circuit, transformer with primary and secondary windings ($pri=1$, $sec=1$) and coupling factor 0.3 is utilized. Resistors (10kohm) and capacitors (1nF) are added together with the transformer. The input voltage (V_{sine2}) is put into three different conditions i.e. under voltage (below 207V), normal voltage (207V to 253V), and over voltage (above 253V). In case they are not what a result is supposed to be, the voltage circuit is analyzed and adjusted respectively. Equally in the frequency circuit, we have another photocoupler circuit with the same values (10k and 1nF) of resistors and capacitors. The value of the input voltage of this circuit is 120V and the input frequency (V_{sine1}) is tested at 4 cases i.e. under frequency (less 49.5Hz), normal frequency (49.5Hz to 50.5Hz), and over frequency (more 50.5Hz). This assists in the determination of whether frequency is acceptable or not. Otherwise, the circuit is checked and modified accordingly.

When the two circuits are established, Arduino IDE is utilized to create the control program in C++. Code is compiled and debugged to eliminate any error. Having been compiled successfully, the code is then transferred in HEX format into the Arduino microcontroller. These LCD and LED is hooked to show voltage and frequency values.

Last but not least, the result is seen in the LCD screen and the LED lamps. In the event that the outcomes are compatible with the expected conditions, the process will be regarded complete. Otherwise, corrections are done, and the simulation is done until the desired output is produced. Figure 1 is the flowchart of model project in detail and describes a formal design and test a model simulation of a circuit procedure within a Proteus 8.17 software setting.

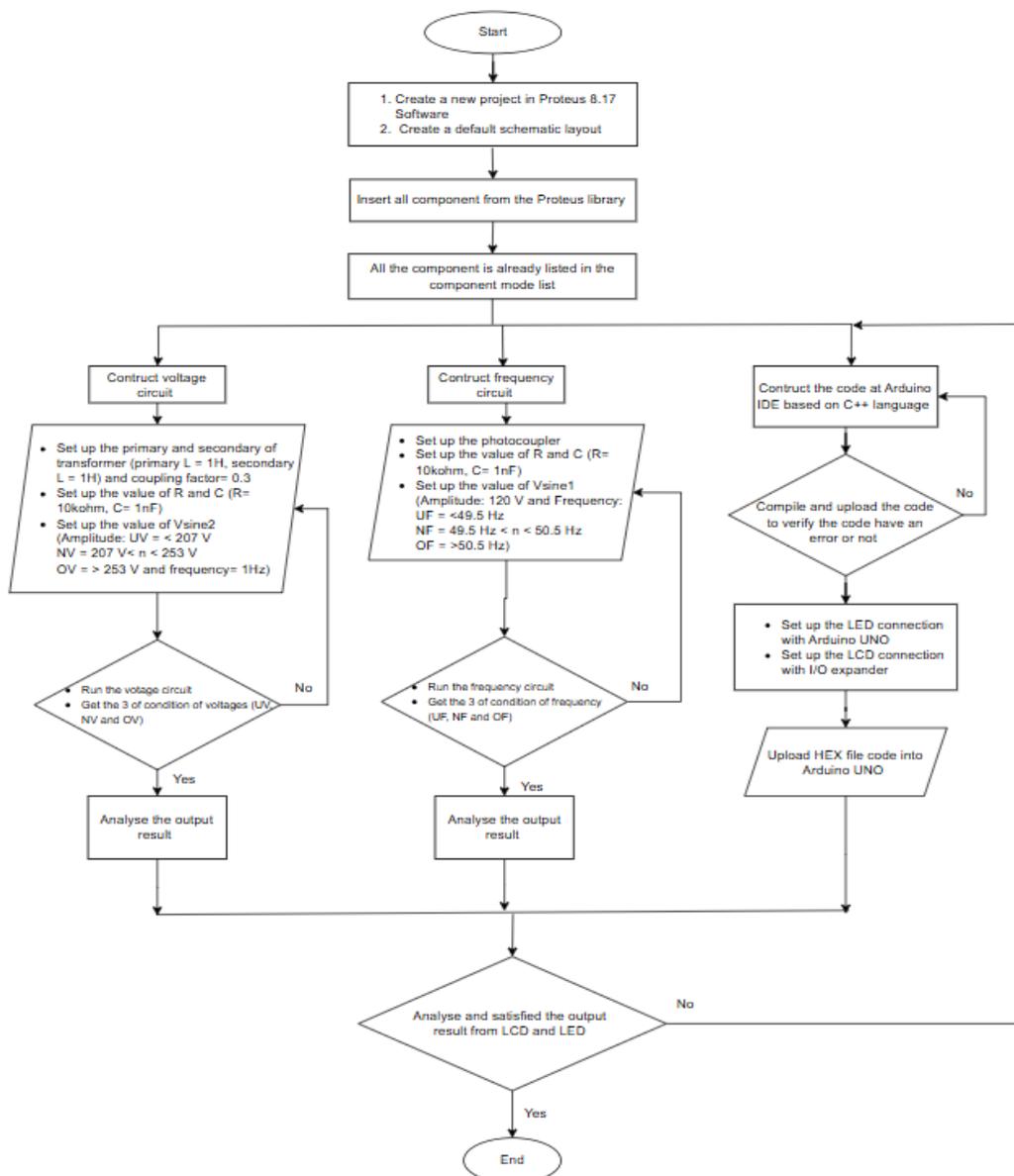


Fig. 1 Flowchart of model project in detail

2.1 Circuit Design

In this section, the designed circuit consists of three integral components, each serving a specific purpose. The first component is the processing and displaying circuit acts as the brain of the system, managing the input from the detection circuits, processing the data, and providing visual feedback or alerts through a display interface.

Secondly, the over/under voltage circuit, responsible for integrating and detecting voltage anomalies to prevent potential damage to the connected equipment. Finally, is the over/under frequency circuit, which monitors and identifies frequency deviations beyond acceptable limits, ensuring system stability. Together, these components form a comprehensive system for monitoring and maintaining electrical parameters within safe operating conditions.

2.1.1 Processing and Display Circuit

In this simulation, the Arduino UNO microcontroller is used in a model and an important in managing and processing the system. It acts like the brain of the setup, controlling how the system operates. The LCD screen is used to display important information, like the voltage and frequency of the power supply, so users can easily monitor these values. Additionally, LED is to indicate the types of problems in the power source. For example, if there is an issue like under voltage or over frequency issue, the LED will light up to warn the user. This makes the system easy to understand and helps users identify problems quickly. Fig. 2 shows the design of processing and indicator circuits.

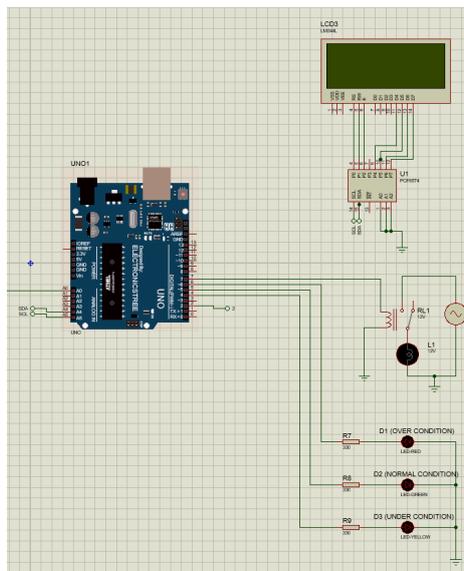


Fig. 2 Processing and indicator circuit

Table 1 shows the connection of pin of the Arduino UNO to be used in this project, which shows the arrangement of the input/output pins of the microcontroller with the other components, such as the voltage circuit, frequency circuit, LCD display, LEDs, and relay module. This table shows the relationship where each pin on the Arduino will be designated to fulfil its specific role on the circuit.

Table 1 Pin connection of Arduino UNO

Port	Description	Application
A0	Input to Voltage circuit	Voltage circuit
A4	Output	Connect to LCD
A5	Output	Connect to LCD
D7	Input to relay	Relay signal
D6	Output to LED	Indicates over condition
D5	Output to LED	Indicates normal condition
D4	Output to LED	Indicates under condition
D2	Input to Frequency circuit	Frequency circuit

2.1.2 Voltage Circuit

The type of circuit depicted in the provided schematic connects an Arduino UNO microcontroller and transformer-based power supply that allows monitoring and controlling voltage levels. Due to an AC voltage generator and a transformer attached to it marked as TRAN2P5S, the input range of voltage is converted to a safer and lower range. The last voltage would pass through these resistors (R1, R2, R3, R4) to allow compatibility with the analog input pins of the Arduino (say A0). Based on the SDA and SCL signals, the Arduino UNO reads the voltage measurements to regulate normal, low or high voltage and shows real time of it.

The voltage at any part of the dividing network can be computed as per the voltage divider formula that will be necessary to calculate the input voltage at the Arduino. The formula in Equation (1):

$$V_{out} = \frac{R_2}{(R_1 + R_2)} \times V_{in} \quad (1)$$

In case V_{out} is the voltage on the Arduino analog input, V_{in} is the voltage after rectification and filtering, and R1, R2 are the resistances in the divider circuit (and R3 and R4 may be stages in addition to this, depending on how it is configured). This will provide a value that stays within 0 and 5V, the analog input range of the Arduino to properly measure and simulate the state of voltage based on the testing sections in the project.

2.1.3 Frequency Circuit

The circuit in the provided schematic is made to measure how frequently an AC signal cycle through at the input using an optocoupler and other related components. There is an AC voltage source (V1 VSINE) that sends a signal to the optocoupler (U2) to prevent noise and any safety issues from the measurement area. An AC signal from the input pairs with a 10kΩ resistor and a 1μF capacitor on the optocoupler side and the output goes through another 1μF capacitor and 10kΩ resistor to ground. With this arrangement, the optocoupler produces pulses when the AC wave reaches a zero and these pulses can be read by a microcontroller or frequency counter to find the frequency of the signal. The calculation regarding the minimum and maximum frequency limits adopted in the project is premised on the nominal system frequency of 50 Hz. The formula is given in Equation (2) and it corresponds to 1 percent difference (deviation) of the nominal frequency. This is calculated to assist in setting the acceptable range of frequency at which under-frequency and over-frequency conditions of the system can be detected.

$$f = \frac{1}{100} \times 50 \quad (2)$$

2.1.4 Complete Circuit

Fig. 3 shows the overall circuit of the system. By combining the frequency circuit, voltage circuit and processing and displaying circuit. The complete circuit of voltage and frequency variation detection had been obtained. It can be used to detect voltage variation and frequency variation of a power supply from the normative limits. In order to test the functionality of the developed system, 6 conditions had been set during testing. The 6 conditions are normal voltage, under voltage, over voltage, normal frequency, under frequency and over frequency. Software simulation and hardware testing were done based on these conditions.

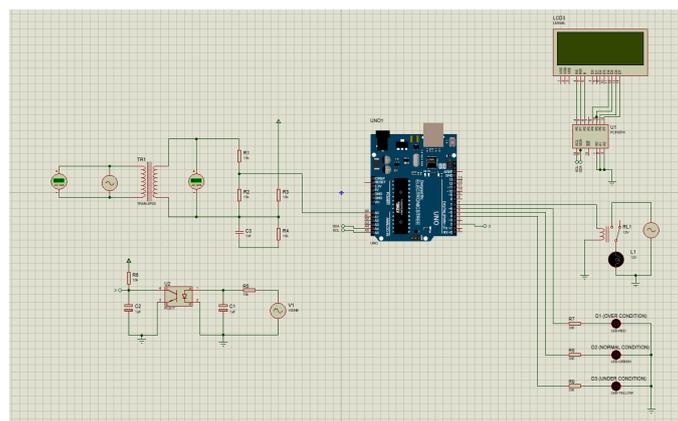


Fig. 3 The complete circuit of voltage and frequency detection

3. Results and Discussion

In this section, the results will be obtained through the usage of Proteus 8.17 software for the simulation of power grid synchronization detection. These simulations will be conducted under six certain conditions which are normal voltage, under-voltage, over voltage, normal frequency, under frequency and over frequency. Each condition will be carried out to confirm the system’s ability to respond to variations in voltage and frequency against the expected results.

In Table 2 display the six conditions that will be conducted in Proteus 8.17 Software. The range of Synchronization Limits.

Table 2 Six conditions of voltage and frequency

Value of Voltage(V) or Frequency (Hz)	Condition
< 207 V	Under Voltage
207 V < Normal < 253 V	Normal Voltage
> 253 V	Over Voltage
< 49.5 Hz	Under Frequency
49.5 Hz < Normal < 50 Hz	Normal Frequency
> 50.5 Hz	Over Frequency

3.1 Simulation Result

This section includes the results obtained from simulation using Proteus 8.17 Software. The simulation had been run through 3 different conditions. Each condition displays a different LED to be lighted up. Besides that, the LCD screen displays the value of voltage (v) and frequency (Hz) based on the conditions. Table 3 shows that the condition of LED during different conditions. During over voltage and frequency, LED D1 will be lighted up while other LED will remain in off condition. During normal voltage and frequency, LED D2 will be lighted up while other LED will remain in off condition. During under voltage and frequency, LED D3 will be lighted up while other LED will remain in off condition.

Table 3 Condition of LED based on different conditions

LED	Conditions
D1 (Red)	Over Voltage and frequency
D2 (Green)	Normal Voltage and frequency
D3 (Yellow)	Under Voltage and frequency

3.2 Over Condition

During the over voltage and over frequency condition, the simulated result shows that the voltage exceeds 253 V AC, while the frequency rises above 50.5 Hz. These values are outside the acceptable range defined for normal grid operation, indicating a critical synchronization issue. Under this condition, both normal and under-voltage scenarios are not present.

Fig. 4(a) illustrates the actual voltage and frequency values during the over condition, confirming the deviation from the standard limits. Meanwhile, Fig. 4(b) shows the system's visual indication through the LED setup. Specifically, LED D1 (Red) lights up to signal the detection of an over-voltage and over-frequency condition. This LED indicator serves as a clear alert for users to identify that the system is experiencing parameters beyond the safe operational range.

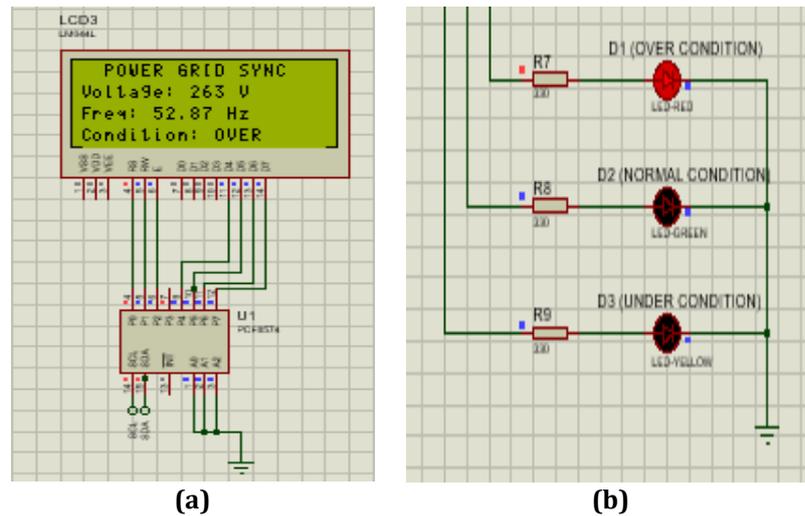


Fig. 4 (a) Result from the model during over condition; (b) LED D1 is light up

3.3 Normal Condition

During the normal voltage and frequency condition, the simulation results show that the voltage is within the acceptable range of 207 V to 253 V AC, and the frequency remains between 49.5 Hz and 50.5 Hz. These values fall within the standard operating limits for a stable and synchronized power grid. In this state, there are no signs of over-voltage or under-voltage, indicating that the system is functioning as intended.

Fig. 5(a) displays the recorded values of voltage and frequency during the normal condition, confirming that both parameters are within safe thresholds. Correspondingly, Fig. 5(b) illustrates the status of the LED indicators. Specifically, LED D2 (Green) is illuminated, signalling that the system is operating under normal voltage and frequency conditions. This visual indicator provides a clear and immediate confirmation that the grid is stable and synchronized.

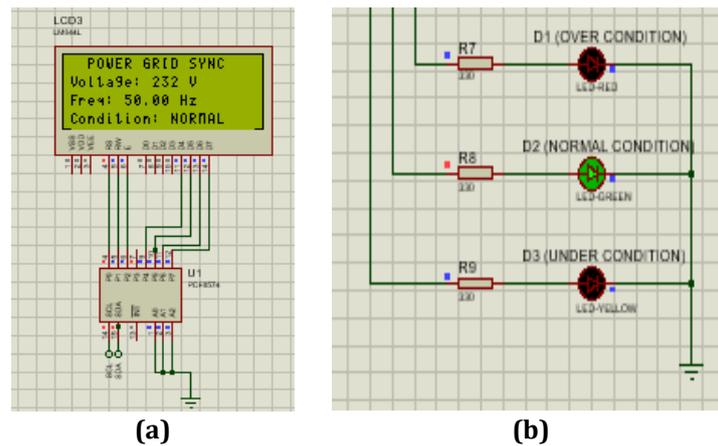


Fig. 5 (a) Result from the model during normal condition; (b) LED D2 is light up

3.4 Over Condition

During the under voltage and under frequency condition, the simulation results indicate that the voltage drops below 207 V AC, while the frequency falls below 49.5 Hz. These readings are outside the lower bounds of the acceptable operational range, signifying a deviation from normal grid performance. In this scenario, neither over-voltage nor normal voltage conditions are present, highlighting a potential instability in the power supply.

Fig. 6(a) presents the measured values during the under condition, clearly showing that both voltage and frequency are below the required thresholds. Meanwhile, Fig. 6(b) displays the response of the LED indicators. Specifically, LED D3 (Yellow) is illuminated, serving as a visual cue that the system has detected an under-voltage and under-frequency condition. This indication helps users quickly identify low power quality issues that may affect grid performance and reliability.

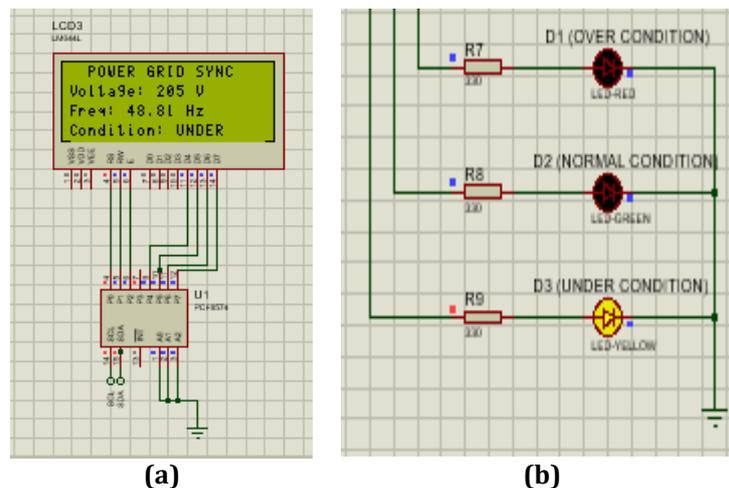


Fig. 6 (a) Result from the model during under condition; (b) LED D3 is light up

4. Conclusion

In conclusion, the successful model and simulation of the power grid synchronous detection system on Proteus 8, that mean the objectives of the research had been achieved. Three conditions that is under, normal and over voltage and frequency are displayed correctly. The exact settings on the circuit made it work well. For example, the transformer's coupling factor was fixed from 1.5 to 0.98 with a 1H primary and a 0.9H secondary, the voltage divider was adjusted, and the zero-crossing detector been improved. Thanks to the modifications, measuring voltage and frequency became correct as shown on the LCD, indicating the system's ability to replicate real grid synchronization in the lab.

The model has precision when it comes to detecting power grid of single-phase system. Since generation units moving to the renewable energy sources like solar and wind energy have gaining its popularity around the world, thus more generation units will be integrated with power grid systems. As a result, the significance of grid failure will increase if the generation units and power grid did not synchronize properly. Thus, by having this model, A person in charged can be notified to team in a timely manner when power grid has fluctuation issue occur.

Going ahead, this project provides a dependable base for more advancements in grid monitoring. With real-time data logging, we could follow voltage and frequency trends, get hints about what to expect and prepare accordingly or use the relay to let the system shut off in response to dangerous settings. Modelling using conditions that make energy production and consumption rise and fall like the real world would help to keep up with new technology. At this point, the project shows how design and technology can be connected, encouraging researchers to learn more about reducing noise and aligning small power grids

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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