

Arduino Mega Based System Design for Sequence and Phase Difference Detection of Three-Phase Systems

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Abstract

In a three-phase system, the difference in the angle between the phases and the phase sequence of the system is very important to ensure the system functions normally and does not cause damage to the three-phase equipment connected to the system. Trigonometric formulas in multiphase systems are used to obtain the angle difference between the phases and the sequence of phases in the system. The trigonometric formula was tested in a simulation using MATLAB software, then applied to an Arduino Mega-based system. In the simulation, the data are two voltages vs. time with a certain phase angle difference, then using the trigonometric formula in the MATLAB program, the data is recovered from the phase angle difference and the direction of rotation of the two voltages. Based on the valid MATLAB simulation test results, the program algorithm is embedded in an Arduino Mega-based system equipped with 2 voltage sensors and a 2.4-inch TFT LCD. The Arduino Mega-based system has succeeded in detecting and visualizing in the form of a graph the angle difference between the phases and the direction of rotation of the three-phase system.

Keywords: arduino mega; three-phase system; phase sequence; phase difference;

Introduction

The AC system allows the system to have multiple phases making it more advantageous than a single-phase system. Such a three-phase AC system has several advantages such as: smaller system size for larger power such as three-phase electric motors and power plants; in the operation of a three-phase electric motor, the motor does not require an auxiliary coil to rotate; and the power delivery of a three-phase system is greater than that of a single-phase AC system. In a three-phase power system, the power plant (three-phase generator) is the main component to supply electrical power to the system. As the electrical load increases, additional power is required from other power generating units to enter the system. Other generating units that will enter the system must go through a synchronization process. One of the requirements for the synchronization process is the phase sequence of the generating unit must be the same as the system. The same phase sequence between the power generation unit and the system is very important to avoid the failure of the operation of the power generation unit.

In a balanced three-phase system, the phase angle difference is 120° . Phase balance is very important for the operation of three-phase electrical equipment such as three-phase electric motors. Three-phase power supply imbalance in three-phase electric motors can cause abnormal operation, and even damage the motor. This study aims to design an Arduino Mega-based system to detect differences in the angle between phases and the direction of rotation of a three-phase system. The difference in the phase angle and direction of rotation of a three-phase system can be obtained simply from the two voltage values of a three-phase system. The formulation to obtain the difference in phase angle and direction of rotation of a three-phase system was tested on MATLAB before the algorithm was implanted in an Arduino Mega-based system equipped with two voltage sensors and a 2.4-inch TFT LCD. This article describes the results of system design starting with the introduction in the first part, followed by a literature review in the second part. The methods and materials used for system design in the third, fourth, and fifth sections are the results and discussion of research, and conclusions.

Literature Review

Arduino Mega 2560 is a circuit board with an Atmega 2560 microcontroller chip. This type of Arduino has the most number of pins among all other types of Arduinos. This is the reason why Arduino Mega was widely used for research. Arduino Mega as a microcontroller in smart home design using a local area network (Kusriyanto & Putra, 2016), besides that Arduino Mega is also used as a basis for making smart energy meters to increase efficiency and accuracy in calculating electricity bills (Jaiswal & Chaubisa, 2017), Arduino Mega as a weather station base that uses the IoT platform (Kusriyanto

& Putra, 2018). In the MPP tracking system on the PV system, Arduino Mega is used to drive a boost converter to get optimal power (Nabil et al., 2018), MPP tracking design with P&O and INC methods for stand-alone PV systems using Arduino Mega (Mishra et al., 2019). (Djamel et al., 2019) produced an Arduino Mega based PID digital controller for DC-DC boost converter control. In addition to controlling the DC-DC converter, Arduino Mega has also been successfully used to control a variable frequency converter to drive a BLDC motor (Vlad et al., 2020). The development of electric vehicles requires an electric charging station, where the station requires intelligent energy billing to calculate electricity bills, (Nnartha et al., 2018) succeeded in building an Arduino Mega-based intelligent billing system for this solution. For complex systems such as automatic segmentation of uterine contractions in EHG signals, Arduino Mega collaborates with raspberry pi for hardware implementation (Naaman et al., 2021).

In an electric power system, components such as generator, transmission, and primary distribution are three-phase systems. In a three-phase system, the angle difference between the phases and the sequence of the phases will produce the direction of rotation in three-phase electrical equipment such as three-phase electric motors. The direction of rotation of a three-phase electric motor can be reversed by swapping the connection of any two phases (Ben, 2020). The electric generator is the main power source in the electric power system. Sometimes the increase in load on the electric power system requires power supply from an electric generator that is not yet operating, because the power from an operating electric generator is not sufficient. An electric generator that will enter the power system requires that the electric generator has the same phase sequence as the electric power system (Teja, 2021). The unequal phase sequence will cause the electric generator unable to enter the electric power system. This is the reason why there is a need for devices to detect phase angle differences and phase sequences of three-phase systems. Figures 1.A, 1.B, 1.C, and 1.D, are the positive sequence voltage waves of a balanced three-phase system, the phasor diagram of the positive sequence, the negative sequence voltage waveform, and the phasor diagram of the negative sequence. A balanced three-phase system has an angle difference between the phases of 120° for the positive and negative sequences. The positive sequence represents the clockwise phase rotation of A-B-C (Figure 1.B), while the negative sequence represents the anticlockwise phase rotation of A-B-C (Figure 1.D).

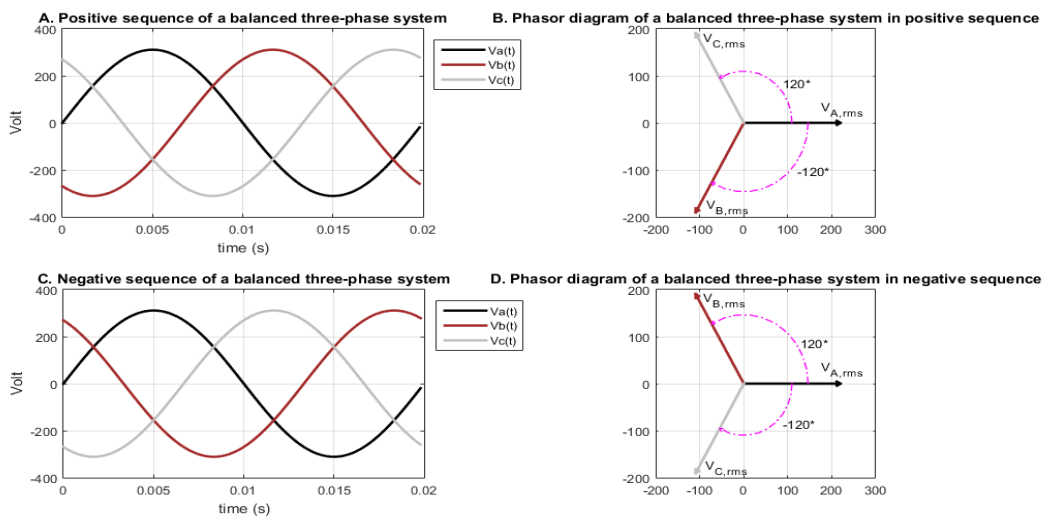


Figure 1. Balanced Three-Phase System

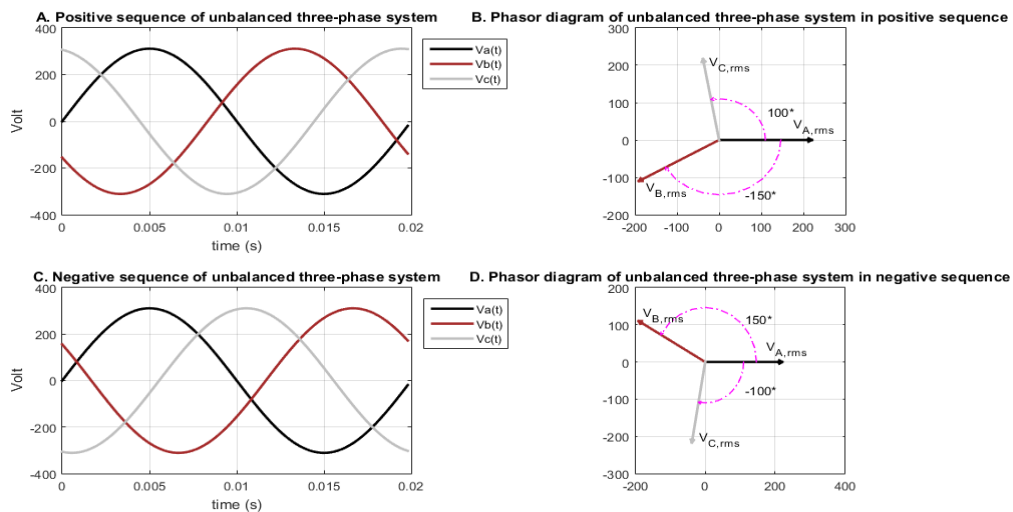


Figure 2. Unbalanced Three-Phase System

Figures 2.A, 2.B, 2.C, and 2.D, are the positive sequence unbalanced voltage waveforms of a three-phase system, the phasor diagram of the positive sequence, the negative sequence voltage waveforms, and the phasor diagram of the negative sequence. In an unbalanced three-phase system, the angle difference between the phases is not the same. Figure 2, the angle difference between the V_A and V_B phases is 150° , while the V_A and V_C phases is 100° so that the angle difference between the V_B and V_C phases is 110° .

The AC voltage equation can be written as follows:

$$v_x(t) = V_{max} \cos(\omega t - \theta_x) \tag{1}$$

where, x , ω , and θ are the phase of the voltage, the radian frequency, and the phase shift.

The phase angle difference between voltages (δ), for example the voltages of phase $v_a(t)$ and phase $v_b(t)$ can be obtained using equation 4.

$$v_a(t) = V_{max} \cos(\omega t - \theta_a) \tag{2}$$

$$v_b(t) = V_{max} \cos(\omega t - \theta_b) \tag{3}$$

$$\delta = |\theta_a - \theta_b| \tag{4}$$

An alternative way to get the voltage angle difference between phases, if the data of the voltages as a function of time are known. The formula in equations 5 to 8 can be used for this.

$$V_{a,rms} = \sqrt{\frac{1}{T} \int_0^T v_a^2(t) dt} \tag{5}$$

$$V_{b,rms} = \sqrt{\frac{1}{T} \int_0^T v_b^2(t) dt} \tag{6}$$

$$V_{vv,avg} = \frac{1}{T} \int_0^T (v_a(t) * v_b(t)) dt \tag{7}$$

$$\delta = \arccos\left(\frac{V_{vv,avg}}{V_{a,rms} * V_{b,rms}}\right) \tag{8}$$

By using trigonometry, equation 8 can be drawn in Figure 3.

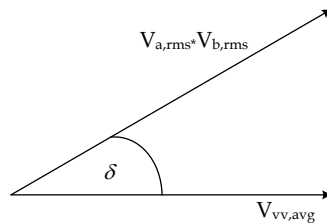


Figure 3. The Trigonometric for The Angle Difference between Phases

The direction of rotation of the three-phase system can be determined from the data of the two phases of the system (eg phases $v_a(t)$ and $v_b(t)$). Visualization of the direction of rotation can be obtained from plotting equations 2 and 3 as follows:

$$\text{plot}(v_b(t), v_a(t)) \tag{9}$$

Visualization of rotation direction using equation 9 can also estimate the angle difference between the voltage phases a ($v_a(t)$) and b ($v_b(t)$) based on the resulting circle shape.

Materials & Methods

The hardware materials for designing this system are one Arduino Mega 2560, one 2.4-inch TFT LCD, and two AC voltage sensors (ZMPT101B module). The software is Arduino IDE 1.8.19 and some of the libraries are UTFTGLUE.h, SPI.h and MCFRIEND_kbv.h. Figure 4 is a block diagram of systems based on Arduino Mega for sequence and phase difference detection of three phase systems.

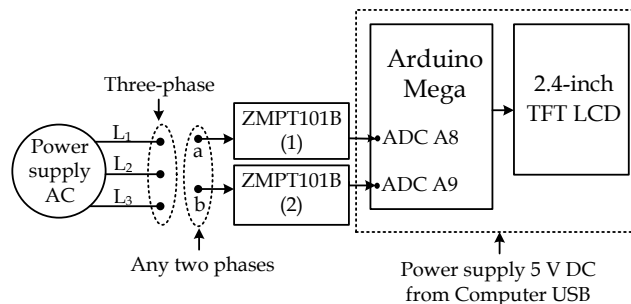


Figure 4. Block Diagram of The System

The study began by testing the direction of rotation of a three-phase electric motor by supplying a three-phase source to an electric motor and exchanging a two-phase connection to indicate a change in the direction of rotation. Based on the results of the direction of rotation of the electric motor and changes in the direction of rotation, the phase sequence of the three-phase source is determined. This determination was to validate the simulation results in MATLAB for the direction

of rotation using equation 9. Then made a program in MATLAB to calculate the phase angle difference between voltages using equations 5 to 8. The phase voltage data was made according to equations 2, and 3 for phases $v_a(t)$, and $v_b(t)$ with frequency 50 Hz and $V_{max} = 220 \cdot \sqrt{2}$. For one period, the voltage data for each phase was enumerated as much as 100 data. The program code with these equations in MATLAB was tested by changing the data of the phase angle difference and the phase sequence of each phase voltage and seeing whether the results of the phase angle differences between the voltages were the same. After equal or valid, the phase difference between the voltages and the altered phase sequence, the visual form was checked to determine the circular shape and direction of the resulting rotation. The next step was to create the same program code for Arduino Mega on Arduino Ide. The phase voltage data was obtained from the measurement results of two voltage sensors connected to the ADC of Arduino Mega as showed on Figure 4. Each voltage sensor was set to have 100 data for each period. On ATmega-based boards (UNO, Nano, Mini, Mega), it takes approximately 100 microseconds (0.0001 s) to read analog input, resulting in a maximum read speed of about 10,000 times per second. So, for a system that uses a frequency of 50 Hz, two voltage sensors for one period will get 100 sample data of voltage. Phase difference between the voltages could be calculated using equations 5 to 8 on the Arduino Ide using these data. Equation 9 on Arduino Ide with its library to display the rotation direction of a three-phase system and a certain circle shape depending on the phase angle difference on the 2.4-inch TFT LCD. These design steps are shown in Figure 5.

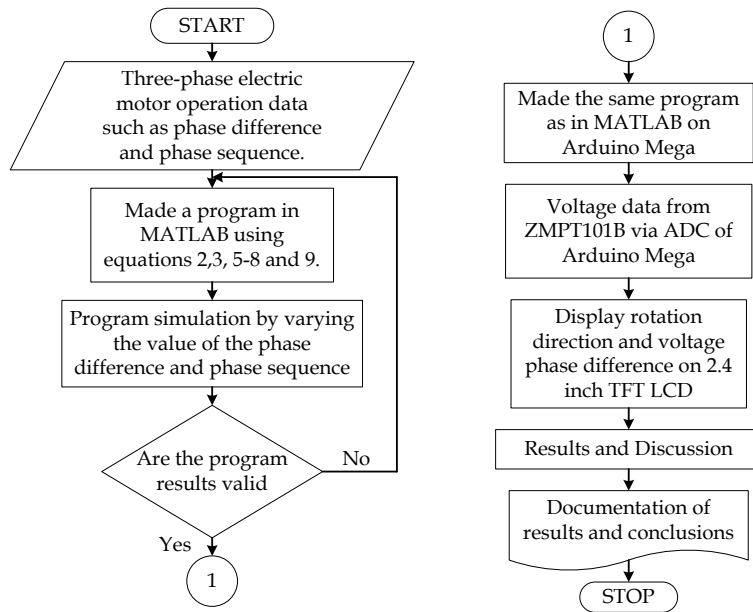


Figure 5. Flowchart for Design of System

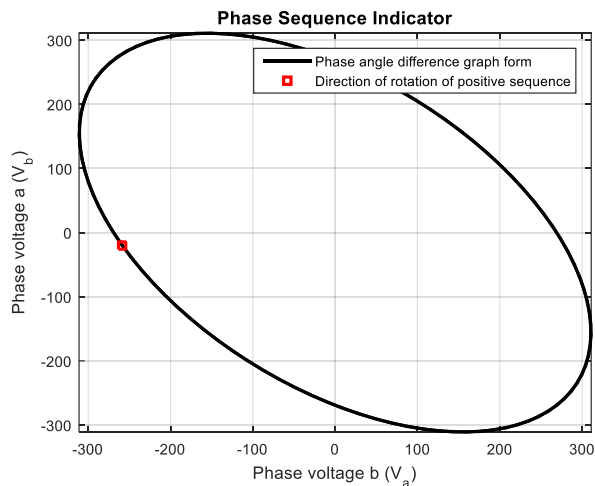
Results and Discussion

The direction of rotation of the rotor in a three-phase induction motor is clockwise when a three-phase power supply is supplied with a positive phase sequence. Based on these results, the MATLAB program was created using equation 9. The program code in Figure 6.A, and 6.B is the result of the program code Figure 6.A.

```

% Direction of rotation of two
% voltages with different phases
% -----
clear
clc
f=50; % frequency
T=1/f; % periode
data = 100; % amount of data in one period
t=linspace(0,2*T,data);
Vrms=220;
Vmax=sqrt(2)*Vrms;
% for positif sequence
va=Vmax*sin(2*pi*f*t-0);
vb=Vmax*sin(2*pi*f*t-120/180*pi);
figure(1)
for i=1:data,
    plot(vb,va,'k-', 'LineWidth', 2)
    hold on
    plot(vb(i),va(i),'rs', 'LineWidth', 2);
    axis([-Vmax Vmax -Vmax Vmax]);
    grid on
    title('Phase Sequence Indicator','FontSize', ...
        12,'FontWeight', 'bold');
    xlabel ('Phase voltage b (V_b)');
    ylabel ('Phase voltage a (V_a)');
    legend ('Phase angle difference graph form',...
        'Direction of rotation of positive sequence',1);
    pause(0.001);
    hold off
end
    
```

A. The program code of rotation direction



B. The result of the program code of rotation direction

Figure 6. MATLAB Program for Phase Sequence

The results of the program code as shown in Figure 6.B, the shape of the graph is oval for the 120° angle difference between phases. The direction of rotation is clockwise according to the data in the program that the phase of voltage a (V_a) leads 120° from b (V_b). Another phase difference between voltages can be tested by changing the angle difference between the phases of voltage a and b, which can be shown in Figure 7.

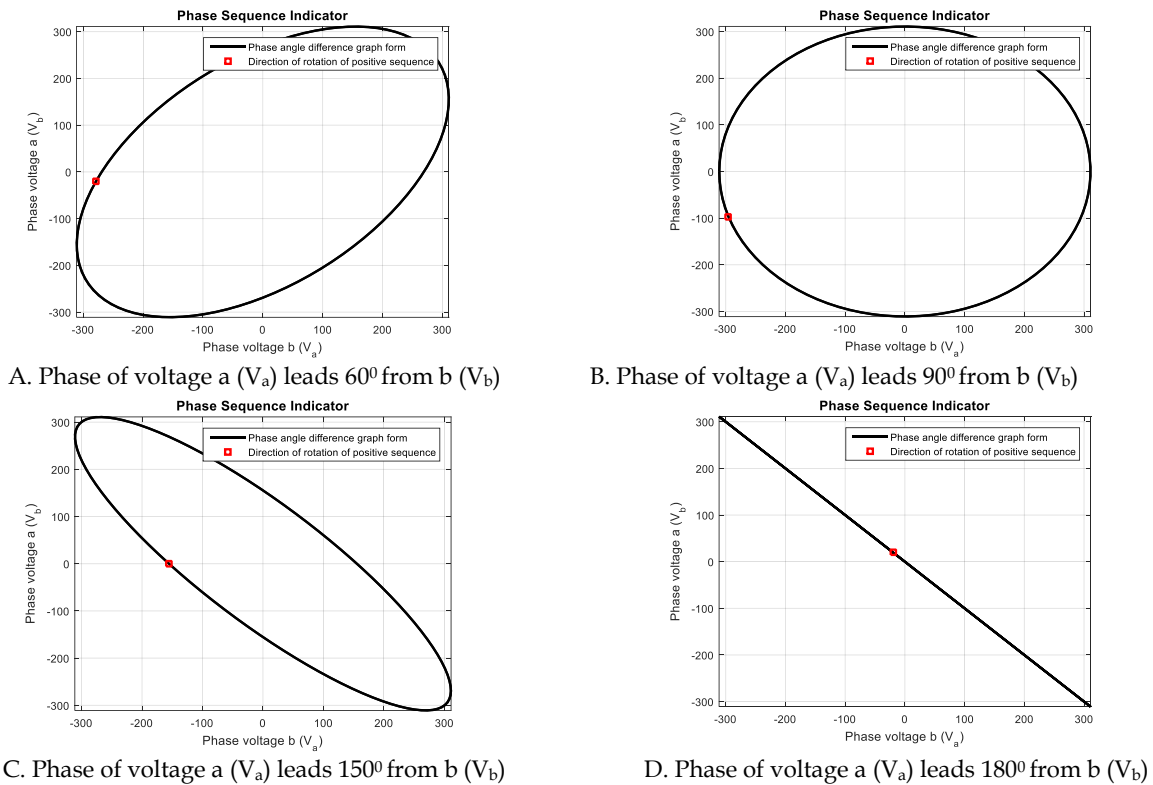


Figure 7. Positive Sequence Rotation Direction or Clockwise

For the direction of rotation for the negative sequence or counterclockwise, the phase difference between the voltages can be shown in Figure 8 for the various phase differences of the phase of voltage a and b.

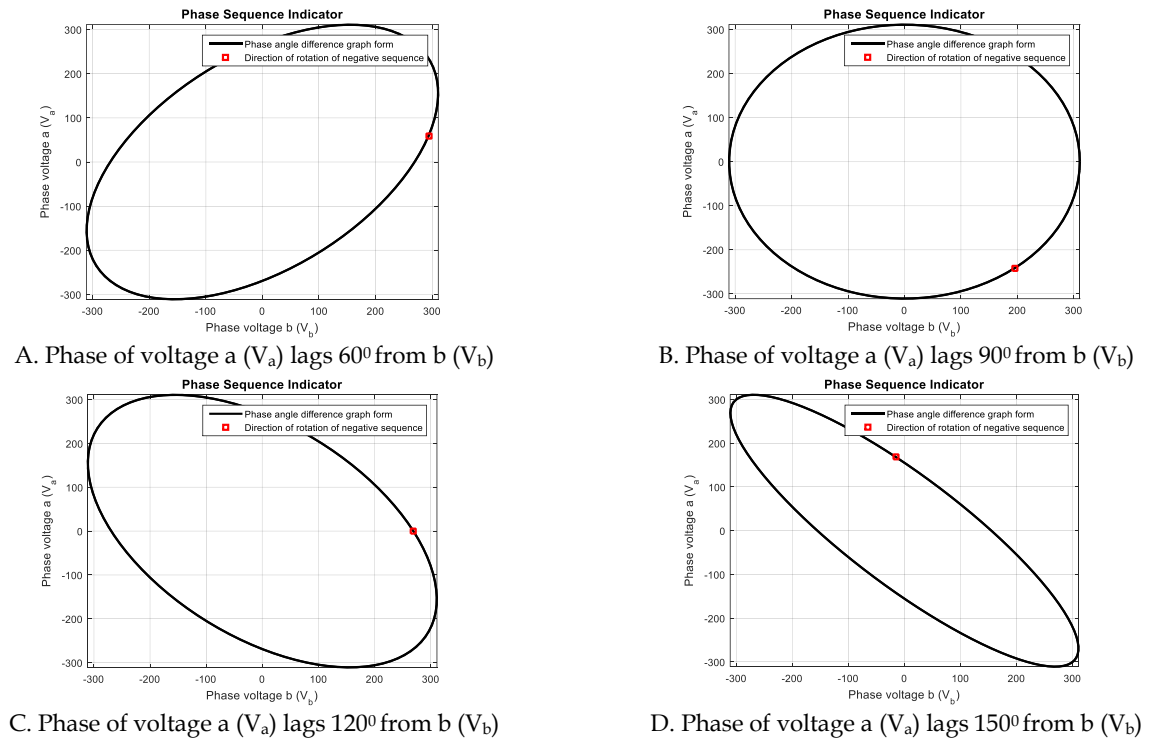


Figure 8. Negative Sequence Rotation Direction or Counterclockwise

Figures 7 and 8 show that for both positive and negative sequences, the same phase angle difference between phase of voltage a and b will produce the same circular shape. The phase angle difference between the phase voltages can be

obtained based on equations 5 to 8. The MATLAB program for this program code is shown in Figure 9. Several variations of the phase angle difference were tested and the results are shown in Table 1.

```

% Phase angle difference (PAD)
% -----
clear; clc;
f=50; % frequency
T=1/f; % periode
data = 100; % amount of data in one period
t=linspace(0,2*T,data);
Vrms=220;
DeltaA=0; DeltaB=30;
DeltaD = (DeltaB- DeltaA);
Vmax=sqrt(2)*Vrms;
% for positif sequence
va=Vmax*sin(2*pi*f*t - DeltaA/180*pi);
vb=Vmax*sin(2*pi*f*t - DeltaB/180*pi);
Varms=sqrt(1/length(va)*sum(va.^2));
Vbrms=sqrt(1/length(vb)*sum(vb.^2));
Vvvavg=1/length(va)*sum(va.*vb);
delta = acos(Vvvavg/(Varms*Vbrms))*180/pi % PAD
    
```

Figure 9. The program code of phase angle difference

Table 1. Phase angle difference data versus program code results

DeltaD (°)	Program code results / delta (°)	Different (%)
+/-30	30,2487/30,2487	0,8291
+/-60	60,2475/60,2475	0,4125
+/-90	90,0000/90,0000	0,0000
+/-120	119,7525/119,7525	0,2062
+/-150	149,7513/149,7513	0,1658
+/-180	180,0000/180,0000	0,0000
Average		0,2689

Table 1 shows that the Program code results cannot produce positive or negative values. Positive and negative values can be obtained from the program of rotation direction. Positive phase angle difference means the rotation direction is clockwise, while the opposite for the negative phase angle difference. The difference of DeltaD and Program code results is an average of 0,2689%. The next step was embedded the program code to the Arduino Mega by using Arduino Ide software. Figure 10 shows an Arduino Mega based system for detecting phase angle differences and phase sequences from a three-phase source. The results of phase sequence detection and the difference between phases are shown in Figure 11.

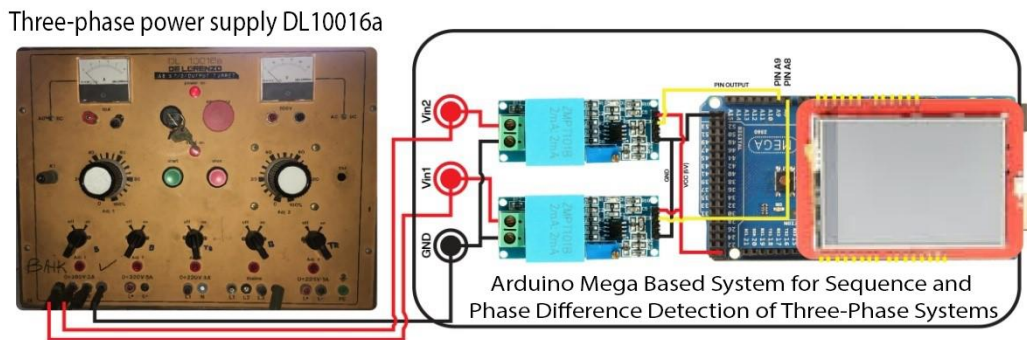


Figure 10. Arduino Mega Based System and Three-Phase Power Supply



A. Positive sequence or clockwise rotation

B. Negative sequence or counterclockwise rotation

Figure 11. Results shown on the 2.4-inch TFT LCD for connection of V_{in1} to Line 1 and V_{in2} to Line 2, and vice versa

Figure 11 A shows the clockwise rotation if V_{in1} is connected to line 1 and V_{in2} to line 2. The phase angle difference between line 1 and 2 is $142,47^\circ$. For the reverse connection, V_{in1} is connected to line 2 and V_{in2} to line 1, the rotation direction is counterclockwise with a phase angle difference $139,24^\circ$. This is shown in Figure 11.B. Difference results for both positive and negative sequences were due to the fluctuating voltage sensor measurement. Because of that, rms voltage also fluctuates. The value of V_{rms} line 1 are 220,41 and 221,90 Volts for positive and negative sequence, respectively. Likewise, the value of V_{rms} line 2 are 225,53 and 222.50 Volts for positive and the negative sequence, respectively. The rated voltage on line 2 is higher than line 1 in both conditions.

Conclusions

The Arduino Mega-based system has been successfully designed to detect the phase angle difference and phase sequence of a three-phase system. The system design starts from observing the direction of rotation of the three-phase electric motor which is supplied by a three-phase source, then by swapping the connection of any two phases to produce reverse rotation. Then made a trigonometric formula to get the phase angle difference and phase sequence of the multiphase system. Two phases of the three-phase system were used, then to be tested in the MATLAB program. Based on the valid output, the program code on MATLAB was embedded in the Arduino Mega using Arduino Ide software and several libraries to display the results on a 2.4-inch TFT LCD.

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