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DESIGN AND IMPLEMENTATION OF A FORWARD-REVERSE DOUBLE-SPEED THREE-PHASE INDUCTION MOTOR CONTROL SYSTEM BASED ON A PROGRAMMABLE LOGIC CONTROLLER

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Abstract
The Dahlander motor is an asynchronous AC motor that operates at two or more distinct rotational speeds, making it different from standard three-phase motors, which generally maintain a single speed under the same power conditions. This motor features a squirrel-cage rotor design and is integrated with a programmable logic controller (PLC), which simplifies wiring systems and allows operational adjustments without altering the wiring layout. However, an additional component, the selector switch, is also employed. This switch controls the motor's rotational direction, enabling it to rotate either clockwise or counterclockwise. The study utilizes a quantitative approach with a developmental design to assess the performance of the Dahlander motor control system. The system functioned as expected, with the selector switch responsible for changing rotational direction. In the right position, pressing the ON 1 button activates contactor 1 for slow clockwise rotation, while pressing ON 2 activates contactors 2 and 3 for fast clockwise rotation. In the left position, pressing ON 1 activates contactor 4 for slow counterclockwise rotation, and pressing ON 2 activates contactors 5 and 6 for fast counterclockwise rotation. The measured rotational speeds were as follows: during slow clockwise rotation, the rotor reached 1494 rpm, while for fast clockwise rotation, it hit 3055 rpm. During slow counterclockwise rotation, the rotor speed was 1456 rpm, and for fast counterclockwise rotation, it reached 3050 rpm.

Keywords:
Dahlander motor; PLC; Motor control; Forward reverse

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1. Introduction

The industrial sector in this country has experienced rapid growth, both in large-scale and small-scale sectors. To support efficiency in terms of time and cost, appropriate production equipment is necessary. A significant portion of industrial equipment operates using electric power, particularly induction motors, which are favored for their simple construction, affordability, light weight, efficiency, and ease of maintenance compared to DC motors [1].

The Dahlander motor, also known as a pole-changing or two-speed motor, is a type of multi-speed induction motor where speed is adjusted by altering the number of poles. This is achieved by changing the electrical connections within the motor. Depending on the stator windings, the motor may exhibit either constant or variable torque.

Pole switching in the motor reduces its speed. Robert Dahlander, a Swedish engineer who worked for ASEA, along with his colleague Karl Arvid Lindström, was granted a patent in 1897 for the electrical design that enables pole switching in motors. The Dahlander connection became associated with this new wiring method, and motors utilizing this configuration are commonly referred to as pole-changing motors or three-phase Dahlander induction motors.

In the industrial sector, three-phase motors are widely used to support operations, particularly in large-scale industries. A commonly employed system is the forward-reverse mechanism. Three-phase induction motors are preferred for their numerous advantages, including simple construction, relatively low cost, and high efficiency. These motors require an alternating current (AC) power supply to operate. The forward-reverse system is widely applied in various industries, such as conveyors, elevators, cranes, and more. In particular, this system is suitable for industries requiring clockwise and counterclockwise rotational operations, such as conveyor applications [2].

Motor control can also be achieved using contactors with the star-delta method, which requires additional components such as a timer to regulate the motor connection transitions. This method minimizes current surges, although the downside is that the installation system becomes complex, requiring extensive wiring to construct the control circuit. Due to the large number of cables needed for control circuit design, this complexity can be reduced by utilizing Programmable Logic Controller (PLC) technology. PLC offers advantages in motor control systems, simplifying operations and reducing the time required for designing or troubleshooting the control system.

2. Method

This study focuses on the design of a Dahlander motor control system using a Programmable Logic Controller (PLC). Proper steps are required in conducting this research to achieve its objectives. These steps follow the flowchart shown in Figure 1, starting with a literature review, which involves examining various sources and theories relevant to this research. The next step involves designing the PLC-based forward-reverse control system for the Dahlander motor. After completing the design, the following stage is creating the ladder diagram using the CX-Programmer software. This step is crucial for operating and executing the Dahlander motor control system via PLC. After the system design is completed, the system configuration process is carried out. This involves verifying whether the equipment used functions according to the instructions and checking the PLC ladder diagram using CX-Programmer. Once this step is complete, the process proceeds to data collection and analysis of the test results.

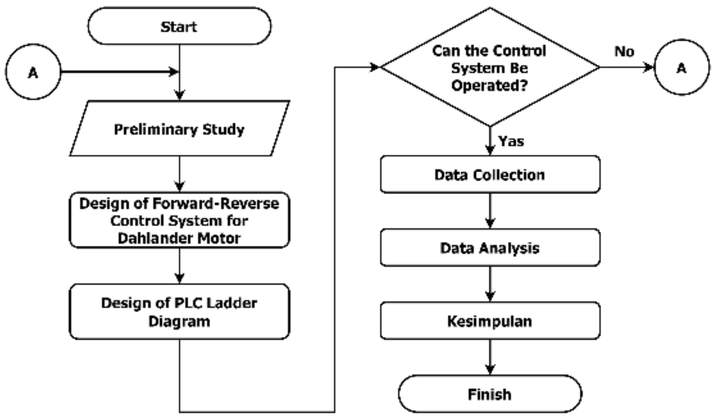

Figure 1. Flowchart of design Dahlander motor control system using PLC

A. Dahlander Motor

The Dahlander motor is a motor with two or more rotational speeds. The presence of two separate windings results in a significantly larger size for three-phase motors designed for two speeds compared to three-phase motors with a single speed at the same power rating. In the Dahlander motor, high speed is achieved using a star (Y) connection, which produces fewer poles, resulting in higher motor speed. For low speed, the motor uses a delta (Δ) connection, which generates more poles, thus leading to slower rotation [6-9]. Each coil in a Dahlander motor has two ends, or in some cases, a center tap for each winding. By altering the connection at the center tap or the ends of the coil, the number of poles changes, allowing speed adjustment due to the variation in the motor's pole ratio.

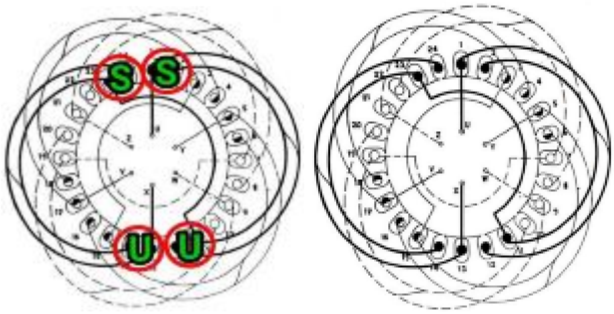

Figure 2. Winding Scheme for 2 Poles

Figure 2 shows a configuration with two poles. The number of poles can be determined using the right-hand rule, where the direction of the current indicates the north pole. In Figure 1, the current starts at slot 1 and moves to slot 11. Slots 1 and 2 form a south pole, while slots 11 and 12 form a north pole. The current then moves from slot 11 to slot 24, continuing to slot 13, where slots 23 and 24 form a south pole, and slots 13 and 14 form a north pole. Figure 2 illustrates that the north poles are located at slots 11, 12, 13, and 14, while the south poles are located at slots 1, 2, 23, and 24. From this, it can be concluded that Figure 2 represents a two-pole configuration.

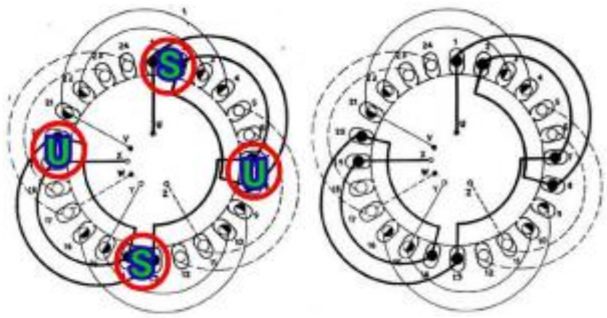

Figure 3. Winding Scheme for 4 Poles

Figure 3 depicts a four-pole configuration. The number of poles is again determined using the right-hand rule. In Figure 3, the winding starts at slot 1 and ends at slot 7. Slots 1 and 2 form a south pole, while slots 7 and 8 form a north pole. The winding then moves from slot 7 to slot 13, ending at slot 19, where slots 13 and 14 form a south pole, and slots 19 and 20 form a north pole. This configuration results in the formation of four poles within the winding.

The equations for calculating the stator rotating field, slip, and rotor speed of the Dahlander motor are presented in Equations (1), (2), and (3), where n_s is the stator speed (rpm), f is the frequency (Hz), p is the number of poles, s is the slip, dan n_r is the rotor speed (rpm):

$$n_s = \frac{120 \times f}{p} \tag{1}$$

$$s = \frac{n_s \times n_r}{n_s} \times 100\% \tag{2}$$

$$n_r = n_s \times (1 - s) \tag{3}$$

B. Programmable Logic Controller

A Programmable Logic Controller (PLC) is a digital electronic device with programmable memory used to store instructions that execute specific functions such as logic, sequencing, timing, counting, and arithmetic operations to control machinery as desired [3]. As its name suggests, PLC incorporates three main concepts: programmable, logic, and controller, which together are used to manage machines or processes.

The operation of a PLC is fundamentally similar to other control devices. It begins with the activation of field devices connected to both the input and output components, which in turn are linked to the machine or other components. During this process, three key scanning phases occur reading and receiving data/signals, executing the programming stored in memory, and updating the state of field devices through the output interface. Once these processes are complete, an interface system is created, enabling the field devices to interact with the controller. The input receives signals, typically instructions from the field devices, while the output executes those instructions accordingly [12-15].

C. Miniature Circuit Breaker (MCB)

An MCB (Miniature Circuit Breaker) is an electrical component that functions to interrupt the flow of electricity when overloading or a short circuit occurs. This interruption serves as a safety measure to prevent undesirable outcomes such as fires. The function of an MCB is similar to that of a fuse, acting as a protective device.

The operating principle of an MCB in normal conditions is as a manual switch, capable of connecting (ON) or disconnecting (OFF) the electrical current. In cases of overload or a short circuit, the MCB automatically interrupts the flow of electricity. This operation can be visually observed as the knob or switch moves from the ON to the OFF position. According to the PUIL 2011, the MCB rating can be determined using Equation (4).

$$Ratting\ MCB = 250\ \% \times I_n \tag{4}$$

D. Contactor

A contactor is an electronic device used to facilitate the operation of electrical installations or equipment. The contactor operates based on the principle of electromagnetic induction, where an energized coil creates a magnetic field that closes the normally open (NO) contacts and opens the normally closed (NC) contacts [11].

A magnetic contactor is an electromechanical switch capable of connecting and disconnecting a circuit, controlled remotely. The movement of the contacts is driven by electromagnetic force. Magnetic contactors function as switches that rely on magnetism meaning they only operate when magnetism is present. The magnet pulls or releases the contacts. Normal operating current refers to the current that flows when no switching is occurring. The coil of a magnetic contactor is designed specifically for either direct current (DC) or alternating current (AC) [4] and [10]. The formulas used to calculate power and current in a contactor are presented in Equations (5) and (6), where *P* is power (watt), *V* is voltage (volt), and *cosφ* is the power factor.

$$P = \sqrt{3} \times V \times I \times Cos\ \varphi \tag{5}$$

$$I = \frac{P}{\sqrt{3} \times V \times I \times Cos\ \varphi} \tag{6}$$

E. Hardware Design

This stage begins with preparing the tools and materials for the forward-reverse control system of the Dahlander motor. The next step is determining the layout of the components within the Dahlander motor control panel. The

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wiring system is designed and connected to the components in the control panel. Additionally, a full inspection of the completed control system is conducted. The forward-reverse control circuit for the Dahlander motor is shown in Figure 4.

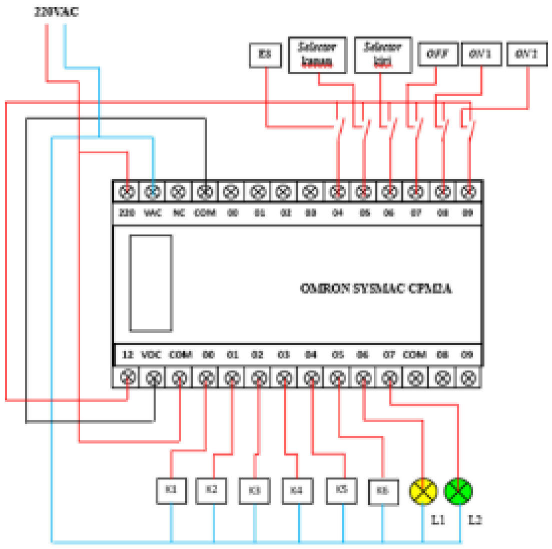

Figure 4. Forward-reverse control circuit for Dahlander motor

C. Software Design

The software design uses a ladder diagram, implemented using the CX-Programmer application. The input and output usage in the PLC system is presented in Table 1.

Table 1. Input and Output Usage on PLC

Component Name	Port	Function
Emergency Stop Button (T. ES)	0.04	Emergency stop button
OFF Button (T. OFF)	0.07	Button to turn off the control system
ON 1 Button (T. ON 1)	0.08	Button to activate slow rotation in both directions
ON 2 Button (T. ON 2)	0.09	Button to activate fast rotation in both directions
Right Selector Switch	0.05	Button to set motor rotation to the right
Left Selector Switch	0.06	Button to set motor rotation to the left
Contactor 1 (K1)	10.00	Output K1 for right-side slow rotation
Contactor 2 (K2)	10.01	Output K2 for right-side fast rotation
Contactor 3 (K3)	10.02	Output K3 for right-side fast rotation
Contactor 4 (K4)	10.03	Output K4 for left-side slow rotation
Contactor 5 (K5)	10.04	Output K5 for left-side fast rotation
Contactor 6 (K6)	10.05	Output K6 for left-side fast rotation
Slow Speed Indicator (L1)	10.06	Indicator light for slow rotation
Fast Speed Indicator (L2)	10.07	Indicator light for fast rotation

C. CX-Programmer

CX-Programmer is a transition software for Omron brand PLCs. To program the PLC, the computer with CX-Programmer must be connected to the PLC processor using a serial cable. Once connected, the PLC parameters must be configured. There are two ways to configure the controller: Auto Online and Manual. The Auto Online method automatically configures the controller by reading the parameters from it. However, if the controller has already been programmed, using Auto Online may produce an error if the controller's module layout differs from the previous setup. In such cases, manual configuration is required. Manual configuration involves creating a new project, selecting the appropriate controller type (Device Type), and entering the module type used by selecting it [5].

3. Result and Discussion

Based on the design and implementation of the forward-reverse control system for a three-phase induction motor with double speed, controlled by a programmable logic controller (PLC), the specifications of the control panel used for the Dahlander motor are shown in Table 2.

Table 2. Specifications of the Dahlander Motor Control Panel

Specifications	Value
Length	60 cm
Width	40 cm
Depth	20 cm
Voltage	380 VAC
Current	1,38,1,18 A
Power	0,8 kW
Frequency	50 Hz

A. Control Panel Design for Dahlander Motor

The control panel design for the Dahlander motor discusses selecting the appropriate tools and components required for the system.

1. Selecting the Miniature Circuit Breaker (MCB)

The MCB specification must be suitable for the load, in this case, a 3-phase Dahlander motor with a running current of 1.38 A at low speed and 1.18 A at high speed (for clockwise rotation). The MCB rating is calculated using Equation (4), and the result is shown in Table 3. The chosen MCB has a safety limit of 4 Amps based on the obtained results.

$$
\begin{aligned}
Ratting\ MCB &= 250\ \% \times I_n \\
&= 250\ \% \times 1{,}38 \\
&= 3{,}45\ A
\end{aligned}
$$

Table 3. MCB Rating Calculation Results for Motor Rotation

Kondisi	Current (A)
Right-side slow speed	3.45
Right-side fast speed	2.95
Left-side slow speed	3.42
Left-side fast speed	2.85

2. Selecting the Contactor

Based on the nameplate, the contactor's current, power, and voltage match the design specifications. During slow clockwise rotation, Contactor 1 operates. During fast clockwise rotation, Contactors 2 and 3 operate. For slow counterclockwise rotation, Contactor 4 works, and for fast counterclockwise rotation, Contactors 5 and 6 are engaged. Power and current in the contactor are calculated using Equations (5) and (6). From the calculations, it is concluded that the minimum contactor capacity required is 2 Amps.

$$P = \sqrt{3} \times V \times I \times Cos\ \varphi$$

$$= \sqrt{3} \times 405{,}1 \times 1{,}1 \times 0{,}92$$

$$= 890{,}819\ Watt$$

$$I = \frac{P}{\sqrt{3} \times V \times I \times Cos\ \varphi}$$

$$= \frac{P}{\sqrt{3} \times 405.1 \times 1{,}1 \times 0{,}92}$$

$$= 1{,}38\ A$$

B. Input and Output System Testing

This phase tests the entire system after design completion. Table 4 presents the test results. When the right selector button is activated, the motor is set to rotate clockwise, but it hasn't started yet. Pressing ON 1 initiates the slow clockwise rotation, indicated by Contactor 1 and a yellow indicator light for slow speed. Pressing ON 2 initiates fast clockwise rotation, signified by Contactors 2 and 3 and a green indicator light for fast speed.

In the forward-reverse control system, when the system is set to clockwise rotation, the counterclockwise system cannot operate. To rotate counterclockwise, press the left selector button, followed by ON 1, which starts the slow counterclockwise rotation, indicated by Contactor 4 and the yellow indicator. Pressing ON 2 initiates fast counterclockwise rotation, indicated by Contactors 5 and 6 and the green indicator. To turn off the system, press the OFF button. In case of an emergency, pressing the emergency stop (ES) button shuts down the entire system.

Table 4. Input and Output Testing Results

Address	***Device***	**Function**	**Note**
0.04	Emergency Stop Button	Shuts down the control system in an emergency	Active
0.05	Right Selector Button	Directs motor rotation to the right	Active
0.06	Left Selector Button	Directs motor rotation to the left	Active
0.07	OFF Button	Turns off the control system	Active
0.08	ON 1 Button (Right & Left, Slow)	Activates slow rotation control for both directions	Active
0.09	ON 2 Button (Right & Left, Fast)	Activates fast rotation control for both directions	Active
10.00	Contactor 1	Controls right-side slow rotation	Active
10.01	Contactor 2	Controls right-side fast rotation	Active

10.02	Contactor 3	Controls right-side fast rotation	Active
10.03	Contactor 4	Controls left-side slow rotation	Active
10.04	Contactor 5	Controls left-side fast rotation	Active
10.05	Contactor 6	Controls left-side fast rotation	Active
10.06	Slow Indicator Light	Indicates slow rotation	Active
10.07	Fast Indicator Light	Indicates fast rotation	Active

C. Testing the Dahlander Motor Control Panel

The purpose of testing the Dahlander motor control panel is to verify that the control system operates correctly. During testing, pressing the right selector button and ON 1 engages Contactor 1, corresponding to a delta (Δ) connection for slow speed. Pressing ON 2 switches to fast speed, activating Contactors 2 and 3, which have a star (Y) connection. Similarly, pressing the left selector button initiates counterclockwise rotation. Contactor 4 is engaged for slow speed with a delta connection, and Contactors 5 and 6 work for fast speed with a star connection. Table 5 displays the test results for both clockwise and counterclockwise rotations.

Table 5. Testing Results of the Dahlander Motor Control Panel for Right and Left Rotation Directions

Input	***Output***	**Status**
Right Selector Button, ON 1 (Slow)	Contactor 1	Active
	Contactor 2	Inactive
	Contactor 3	Inactive
	Contactor 4	Inactive
	Contactor 5	Inactive
	Contactor 6	Inactive
	Slow Indicator Light	Active
	Fast Indicator Light	Inactive
Right Selector Button, ON 2 (Fast)	Contactor 1	Inactive
	Contactor 2	Active
	Contactor 3	Active
	Contactor 4	Inactive
	Contactor 5	Inactive
	Contactor 6	Inactive
	Slow Indicator Light	Inactive
	Fast Indicator Light	Active
Left Selector Button, ON 1 (Slow)	Contactor 1	Inactive
	Contactor 2	Inactive
	Contactor 3	Inactive
	Contactor 4	Active
	Contactor 5	Inactive
	Contactor 6	Inactive
	Slow Indicator Light	Active
	Fast Indicator Light	Inactive
Left Selector Button, ON 2 (Fast)	Contactor 1	Inactive
	Contactor 2	Inactive
	Contactor 3	Inactive
	Contactor 4	Inactive
	Contactor 5	Active
	Contactor 6	Active
	Slow Indicator Light	Inactive

Input	*Output*	Status
	Fast Indicator Light	Active

C. Comparison of Forward-Reverse Circuits Using PLC and Manual Systems

The comparison between PLC-based and manual forward-reverse circuits is based on two variables: installation and timer. The results are presented in Table 6.

Table 6. Comparison Between PLC and Manual Circuits

Variable	PLC	Manual
Circuit Installation	Easier to diagnose issues in case of input or output errors. The cause of malfunction can be identified by simply reading the ladder diagram program.	Difficult to identify malfunctions. If input or output errors occur, manual inspection is required.
Timer	Incorporated in the ladder diagram, functioning as a safeguard during speed changes of the Dahlander motor.	Operates through switches or relays based on preset time intervals, with the timer represented as a physical component in the circuit.

4. Conclusion

From the design and implementation of the 3-phase double-speed induction motor control system using a PLC, it can be concluded that the Dahlander motor control system functions as intended. During the slow clockwise rotation, the nominal current is 1.33 A, and during fast clockwise rotation, it is 1.12 A. For counterclockwise rotation, the current is 1.12 A at slow speed and 1.08 A at fast speed. The manual forward-reverse circuit has a simpler installation compared to the PLC-based system, as the latter requires input-output systems to operate the circuit. However, in practical use, the PLC-based system is superior because it simplifies the operation process, and in case of issues, the PLC is easier to troubleshoot without needing to check the wiring installation. In a manual circuit, a wiring diagram is the primary reference, whereas in the PLC system, a ladder diagram is required to operate the forward-reverse control. The PLC-based system also simplifies troubleshooting since it does not require checking the entire wiring, unlike the manual system.

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