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Design and Construction of Multi-Mode Induction Motor Starter

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ABSTRACT:
This paper is aimed at designing and constructing a portable multi–mode induction motor starter which includes a Direct on Line (DOL), Variable Frequency Drive (VFD), and star–delta starting modes. Several starting and control modes are available. The design is done such that a three-phase induction motor could be started with each of the starting modes independently, depending on the requirement of the user of such induction motor. The selection of each of the starting modes is done with the aid of a button which is automated by an Arduino programmed board. An overload relay is used for system protection to detect an over current in the system. System protection is facilitated by the contactors and the Arduino board output relays and these two components get instruction from the Arduino board. A portable multi–mode induction motor starter has been successfully designed and implemented in the module that is presented. On testing of the module with a 1hp induction motor, it was observed that the DOL mode starting current peaked at 1.61A while that of the VFD peaked at 0.31A. The designed and implemented module provides a simple means of choosing an adequate operational mode to operate an induction motor under full and no-load conditions; view operational conditions (i.e. operational current of the induction motor), as well as, serves as a protective circuitry for the induction motor powered system during operation.
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KEYWORDS: Arduino, Direct on Line, Induction Motor, Star-Delta, Variable Frequency Drive

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1. INTRODUCTION:

An induction motor is a sort of asynchronous AC motor where power is made available to a turning device by induced electromagnetic fields. A wrapped rotor induction motor was invented in 1882 by Nikola Tesla while he was in France, and then in the year 1888, a patent was issued to him when he had already relocated to the US. In cause of Tesla's work, he showed the basics for comprehending the operation of electric motors. (Lemme, 2005)

After some years in Europe, the caged rotor induction motor was invented by Mikhail Dolivo – Dobrovolsky. Sizing was greatly enhanced by technological improvement where a 100hp (74.6kW) motor of 1976 takes about the same volume as a 7.5hp (5.5kW) motor of 1897 (Arnold & Alger, 2017).

Induction motors are currently the most popular alternative for industrial motors thanks to their robust construction, absence of brushes which are present in most DC motors and the ability to control the speed of the motor.

Over the years, researchers have designed and proposed means of starting up three phase induction motor. In industries where variation of loads is present, having a compact portable module which combines several starting methods would be very necessary. This would provide an easy for the operator to be able to select the desired starting method which is required.

In this paper, a compact portable module which houses three different start up methods which includes; Direct – on – line (DOL), Start – Delta (S – D) and Variable Frequency Drives (VFD) methods is to be designed and constructed. The construction would be a compact portable multi – mode three phase motor starter which will be able to start the three-phase motor using the three modes which are Direct on Line, Star – Delta and Variable Frequency Drive. Each of the three-phase induction motor starter methods should be able to start the induction motor independently. The portable multi – mode induction motor starter should provide protection for the induction motor to be started and the operator should be able to view the starting and running current of the induction motor through an ammeter.

2. MATERIALS AND METHODS:

2.1 Direct-On-Line (DOL) Starter

Being the most readily available means of starting an induction motor, components needed for this type of starting mode is mainly a contactor and current overload relay. The short coming of this starting mode is that during start up, it allows very high current. On the average, the starting current of any induction motor using this mode is about six to seven times the capacity of the motor to be started and sometimes in rare occasions, this value of starting current can go up to nine to ten times. When starting with the direct on-line mode, the torque with which the motor starts is usually very high and mostly higher than what is required for the application which it is being used for (Goh *et al.*, 2009).

The investigation by Therib (2014) showed that in this mode, the motor starting torque is around the range of 0.75 to 2 times the rated torque of the load. Small induction motor within the range of 5kW and below are recommended for using this starting mode to prevent too much voltage drop that would be experienced in the supply voltage line due to the high draw current for starting the induction motor

2.2 Star/Delta Starter

To reduce the surge of the starting current of the motor, it is advised that these high capacity motors be started at minimal voltage, when they run to near full speed, the full voltage be connected back to the motor.

In the 50Hz frequency world, this starter is called star/delta and it is the most readily available voltage reducer starter but in the 60Hz frequency world it is called Wye/Delta. In an attempt to minimize the starting current to the motor which in turn reduces the interference and disturbances to the supply line, this starter mode is used. The star/delta starter is produced using three contactors, a thermal overload relay and a timer. The contactors that are used for the direct on-line starter are larger in capacity compared to the ones used for star/delta starter as the contactors used for the star/delta are only meant to regulate the currents to the windings of the motor only. 1√3 = 0.58 (58%) of the line current is what will go through the windings of the motor that is about 30% of the delta values and this also implies that the starting current to the motor is brought down to one third of the direct starting current (Sairatun & Saidul, 2018)

2.3 Variable Frequency Drive

The speed of an electric motor is controlled by transforming the frequency of the grid to variable values on the machine side thereby giving the electric motor the ease to adjust its speed to any required value. (Enemuoh *et al.*, 2013)

Output frequency control and power conversion between frequencies are the two main functions of a variable speed drive. From the smallest appliances to the largest mine drive and compressors can apply the usage of the variable speed drive.

A variable frequency drive consists of:

i. The Rectifier unit
ii. DC Bus
iii. The Inverter unit

The DC bus consists of a filter section where harmonics generated at the point of AC voltage to DC voltage transformation are filtered out. The last unit has an inverter which comprises of six Insulated Gate Bipolar Transistors (IGBT) where the filtered DC voltage is transformed into quasi-sinusoidal wave of AC voltage which is then applied to the motor connected to it. It is a well-established fact that the synchronous speed of an electric motor depends on the frequency of the supply. Hence, varying the frequency of the supplied power using the Variable Frequency

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Drive (VFD), the motor speed can be controlled. (Abhay *et al.,* 2019).

$$N = \frac{120f}{p} \quad (1)$$

Where;
N = speed of motor
f = Power supply frequency in Hz,
p = Number of poles in the stator of the motor.

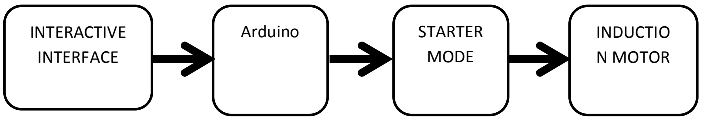

Figure 1: Block Diagram of System to be designed

From the above block diagram, the interactive interface which is mostly made up of push button to select a particular startup mode (Direct on Line, star – delta or Variable Frequency Drive) when selected will be indicated by an LED (Light Emitting Diodes).
The Arduino board does the most of the selection process after a particular mode is to be selected for starting an induction motor.

2.4 Mathematical Analysis of How Components Were Selected for DOL and Star – Delta

a. Fuses

Table 1: Fuse Specification according to NEC 430-52

Types of Motor	Time Delay Fuse	Non – Time Delay Fuse
Single phase	300%	175%
3 phase	300%	175%
Synchronous	300%	175%
Wound Rotor	150%	150%
Direct Current	150%	150%

Source: According to N.E.C 430-52

Time delay fuses maximum size = 300% x full load line current (2)

Full load current for 1Hp motor

$$\text{Motor line Full load current} = \frac{KW\ X\ Motor\ Rating}{\sqrt{3}\ X\ 415} \quad (3)$$

$$\text{Motor line Full load current} = \frac{KW\ X\ 1000}{\sqrt{3}\ X\ 415} = 1.04A$$

$$\text{Motor phase full load current} = \frac{LFLC}{\sqrt{3}} \quad (4)$$

$$\text{Motor phase full load current} = \frac{1.04}{\sqrt{3}} = 0.6A$$

Starting current of motor = 6 to 7 times full load current (5)
Starting current of Motor = 7 x 1.04 = 7.28A
Maximum size of time delay fuses = 300% x 1.04 = 3.12A
Maximum size of time delay fuses = 175% x full load line current (6)
Maximum size of time delay fuses = 1.75 x 1.04 = 1.82A

b. Size of Circuit Breaker

Table 2: Breaker Specification According to NEC 430-52

Types of Motors	Instantaneous Trip	Inverse Time
Single phase	800%	250%
3 phase	800%	250%
Synchronous	800%	250%
Wound Rotor	800%	150%
Direct Current	200%	150%

Source: According to NEC 430-52

Maximum size of instantaneous trip circuit breaker = 800% x full load current (7)
Maximum size of instantaneous trip circuit breaker = 800% x 1.04 = 8.32A
Maximum size of inverse trip circuit breaker = 250% x full load current (8)
Maximum size of inverse trip circuit breaker = 250% x 1.04 = 2.6A

c. Thermal Overload Relay

Minimum thermal overload relay setting = 70% x full load current (phase) (9)

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Minimum thermal overload relay setting = 70% x full load current (phase) = 0.7 x 0.6 = 0.42A

Maximum thermal overload relay setting = 120% x full load current (phase) (10)

Maximum thermal overload relay setting = 120% x full load current (phase) = 1.2 x 0.6 = 0.72A

d. Main Contactor

Size of main contactor = 100% x full load current (line) (11)

Size of main contactor = 100% x full load current (line) = 100% x 1.04 = 1.04A

These ratings also apply to that of the star – delta configuration.

2.5 Construction

Designing the above system will involve adding a control system to regulate the mode selection. That is determining which mode it will operate at a particular time. The figure below shows a single line diagram of the system to be constructed.

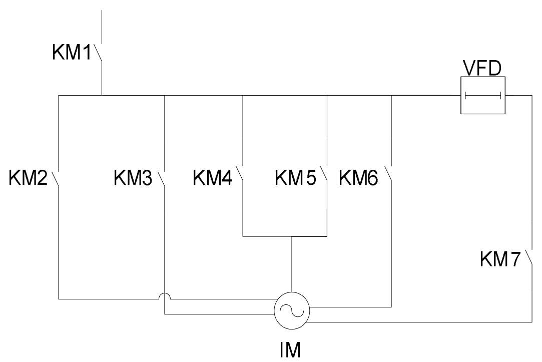

Figure 2: One line diagram of Power Circuit

From the diagram, figure 2;
KM1 = Main input contactor with Over load relay
KM2 = Contactor for DOL forward rotation
KM3 = Contactor for DOL reverse rotation
KM4 = Contactor for Star – Delta Mains
KM5 = Contactor for Star Connection of Star – Delta
KM6 = Contactor for Delta Connection of Star – Delta
KM7 = Contactor for Output of VFD,
IM = Induction Motor
VFD = Variable Frequency Drive

Note: KM7 serves as an Isolating Device to the output of Variable Frequency Drive to avoid reverse current coming into the Variable Frequency Drive when other starting modes are in use.

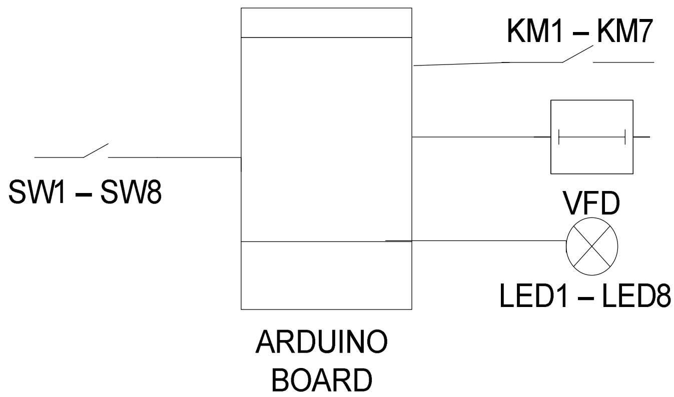

Figure 3: One Line Control Diagram

The diagram, figure 3, shows the control circuit of the entire system. Eight input switches are used to regulate the power output to the motor with the aid of an Arduino board. The Arduino board also controls the on and off of the Variable Frequency drive, with this the Variable Frequency drive is always turned off when not in use.

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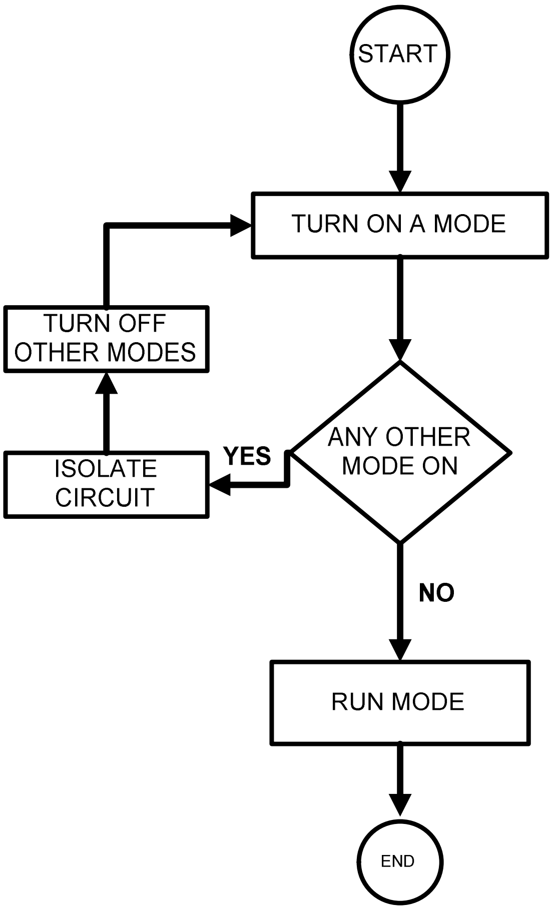

Figure 4: Flow chart of Control program

The flow chat of the Arduino program that controls the entire system is shown in figure 4. Turning on two start up modes simultaneously will isolate the output to the induction motor from power supply. This is to protection feature of the design to safeguard the designed system and the load. However, when one of the startup modes is turned off, the system resets and the remaining start up mode remains on for operation. From the start point, when a mode is turned on for operating the 3-phase induction motor, the system first checks if another mode has been previously left on. Where two different start up modes are chosen or turned on, the system shuts down until only one mode start up mode is turned off.

Figure 5: Interface for operating the system

The operational user interface is shown in figure 5. The operational user interface contains the ammeter, the Direct on Line (DOL) operation buttons, the Star/Delta operation buttons, the Variable Frequency Drive (VFD) operation button and output terminals. The terminals of the induction motor to be operated are connected to the output terminal of the module, the buttons for each mode are used for the operation of the induction motor while the ammeter is used to view the operational characteristics of the induction motor.

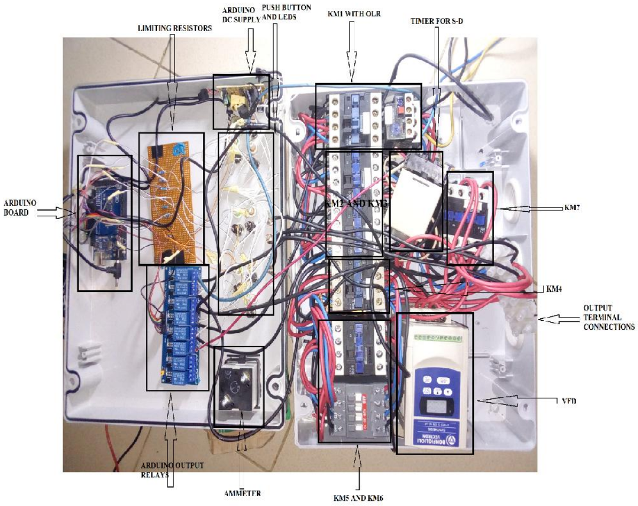

Figure 6: Physical connections of the start method

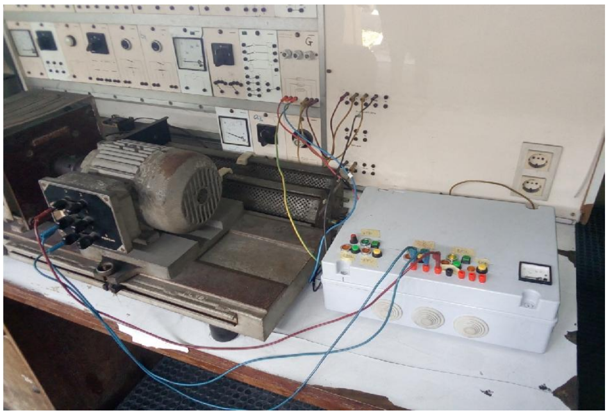

Figure 7: Connection of the Starter during Testing

Figure 7 above shows the physical connections o various start methods, how they are inter connected and linked to a single output. When th motor is connected to the output of the starte module, only one mode can be running or operate at a time.

3. RESULTS AND DISCUSSION:

On testing of the module, starting and runnin current of the electric motor (3Phase inductio motor) were compared for the three startin methods.

The size of the induction motor was limited to 0.5hp motor because of the size of the Variable Frequency Drive (VFD). Without using the Variable Frequency Drive (VFD), a much higher rated motor can be operated from the module as larger current carrying capacity contactors were used for the construction.

When the module was turned on, the Variable Frequency Drive (VFD) was set to operate from 0 – 100Hz frequency that means motor will run for twice its rated speed at the maximum frequency set to the Variable Frequency Drive (VFD). It was discovered that the starting current on Direct on Line (DOL) and Star-Delta was about the same, but the Variable Frequency Drive (VFD) maintained a constant current consumption almost throughout the speed variation.

Below is a table of value to illustrate about the value of current consumed by the Variable Frequency Drive (VFD), Star –Delta and the Direct on Line (DOL).

Table 3: VFD operations

FREQUENCY OF VFD (Hz)	SPEED (RPM)	CURRENT OF VFD (A)
10	300	0.31
20	600	0.29
40	1200	0.28
50	1500	0.29
60	1800	0.28
80	2400	0.26

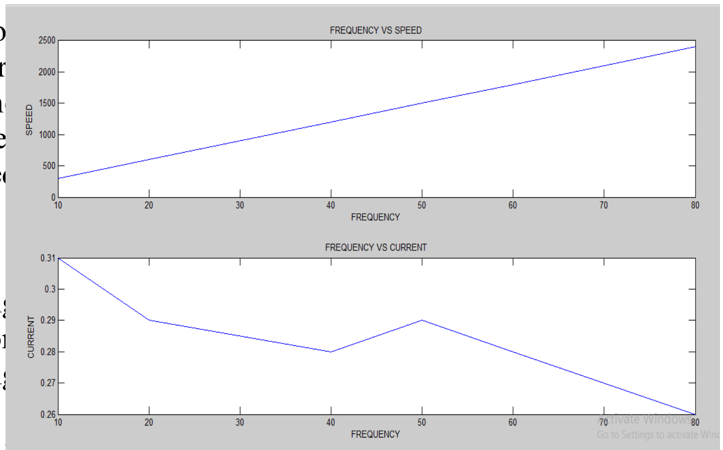

Figure 8: A graph of VFD operation

The above graph in figure 8 depicts the speed and current consumed for the Variable frequency drive (VFD). The first graph shows that there is a rise in speed with a relational increase in the frequency of the variable frequency drive. This is to imply that the frequency at which the variable frequency drive outputs is directly proportional to the speed at which the induction motor is running.

It is also seen that the current consumed by the induction motor at start up and normal operation is almost the same. Very little variation was found for a proportional increase in speed. The current variation was between 0.26A to 0.31A. The induction motor has its highest current consumption during startup which is about 0.31A.

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Below is the table that show the Direct on Line (DOL) testing during operations. The Direct on Line (DOL) had the about the same values during testing when compared with the star – delta.

Table 4: DOL Testing

TIME (s)	CURRENT (A)
1	0.51
2	1.63
3	0.62
4	0.31
5	0.29
6	0.28
7	0.29
8	0.28

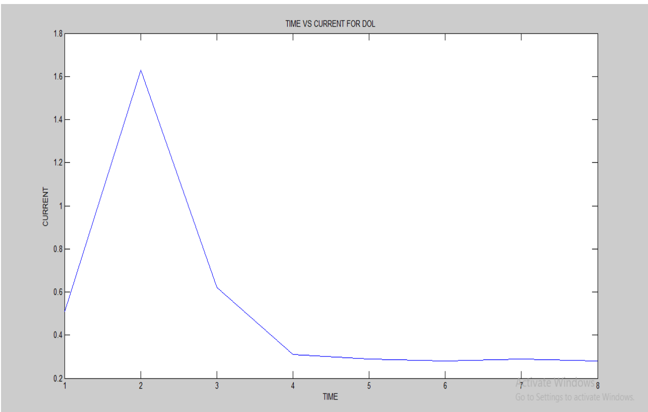

Figure 9: DOL Graph

The above graph in figure 9 shows the graph and table when starting the same induction motor using the Direct on Line (DOL) starting mode. From the above graph, it is observed that as the induction motor is started, just at start up the current consumed peaks to about 1.6A and later stabilizes at a particular value when the induction motor has attained almost full speed.

A comparison on starting conditions was done on the induction motor consumed current between the Variable Frequency drive (VFD) and Direct on Line (DOL). The Direct on line and the Star – Delta consumes almost the same amount of current during start up.

It is seen that the Variable Frequency drive (VFD) consumes fairly about the same current on startup and on running conditions. This implies that for larger induction motors, the Variable Frequency drive (VFD) is a preferred starting option compared to the Direct on Line (DOL).

Table 5: Comparing DOL and VFD Current

TIME (S)	CURRENT (A)	FREQUENCY (F)	CURRENT (A)
1	0.51	10	0.31
2	1.63	20	0.29
3	0.62	40	0.28
4	0.31	50	0.29
5	0.29	60	0.28
6	0.28	80	0.26

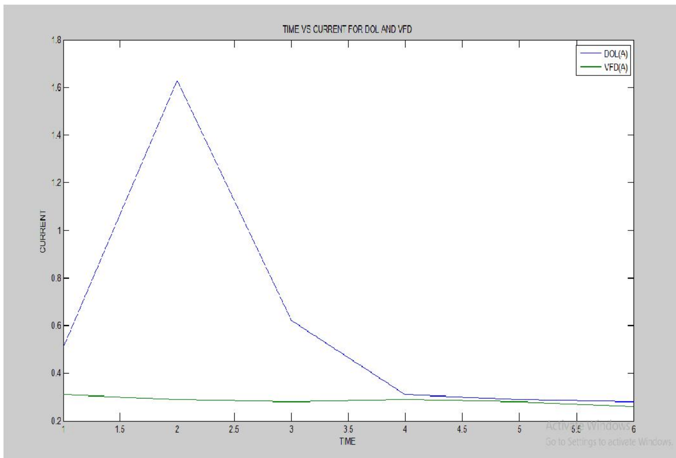

Figure 10: Comparing DOL and VFD Current

The green graph in figure 10 depicts the Variable Frequency drive (VFD) consumed current and the blue graph depicts that consumed by the Direct on Line (DOL). From figure4.4 above, the variation of the green graph is clearly shown. A combination of both the Variable Frequency drive (VFD) and Direct on Line (DOL) graph is shown in figure 10.

4. CONCLUSION:

The hardware which comprises of the Programmable Arduino Controller which makes the protection part of the circuit more prompt with respect to the response time of the user interface makes it very safe and convenient for operation of the induction motor whether in no load or loaded conditions.

A comparison between each of the designed start up methods was also carried out to determine the startup method which will be appropriate for a particular size of induction motor. It was discovered that the Variable Frequency drive (VFD) was a suitable mode for induction motor operation especially where large induction motor is to be operated and speed variation was of the essence. Finally, each of the startup mode can be operated independently.

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