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ANALYSIS OF FIVE-PHASE INDUCTION MOTOR WITH DYNAMIC LOAD

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ABSTRACT

The three-phase induction motor with squirrel-cage rotor is the workhorses of industry because of their low cost, rugged construction, low price, and easy to maintain, which employs a clever scheme of electromechanical energy conversion. On top of that, the interest on electric motor with higher number of phases are kept increasing due to certain advantages such as higher torque density and less torque pulsation. In this project, five-phase induction motor is introduced and its performance as compared to three-phase induction motor will be discussed. This five-phase induction motor may replace conventional three-phase induction motor where higher torque density application is required.

Keywords: five-phase, multiphase, induction motor.

INTRODUCTION

An asynchronous motor or known as induction motor is one type of AC electric motor. Through the interaction of the magnetic field from the stator winding with the shorted rotor current, the torque is produced (Hamad, 2004). An induction motor therefore does not required mechanical commutation, separate-excitation or self-excitation for the process of energy transfer from stator to the rotor. When operating directly from supply voltages (50 to 60 Hz utility input at essentially a constant voltage), the induction motor will operate at a nearly constant speed. The induction motor can be categorises into the three-phase and single-phase motors. Both of them are widely used today and can be found in almost every domestic and production equipment (Chapman,2005).

The single-phase motor consist of two sets of winding referred as main winding and start winding. The start winding has a maximum angle of 90° apart from the main winding in order to create high starting torque at the locked-rotor position. This phase angle also determine the direction of the rotation. A capacitor (with the pre-determine value) are commonly connected in series with the start winding in order to create the phase shift. Due to the wide availability of the single-phase supply, the single-phase induction motor are very dominant for domestic usage and low power application such as for home appliances and small machine tool.

The three-phase induction motor are the motors that frequently used in the industry and high power application such as for cranes, lifts and drilling machines. In three-phase motor, there are three sets of winding which are spatially phase-shifted by 120° (Levi, 2008). The rotating magnetic field that having the same phase difference between them allow the rotor to rotates without the need of the capacitor. This kind of motor has higher starting torque and smoother operation as compared to the single-phase motor.

Currently, an electric motor with higher number of phases (known as multiphase motor) has start to gain an interest from the researcher. The construction of the multiphase motor; for example a five-phase induction

motor; is almost similar to the squirrel cage three-phase and single-phase induction motor. The different is the motor requires five-phase ac supply to operate and the stator consists of five sets of winding. In a balance (or symmetrical) five-phase induction motor, the five groups of stator winding are distributed with a spacing of 72° (Apsley, 2006). This lower number of phase difference contribute to a higher power density of the machine.

Among the advantages of five-phase induction motor is the capability of the motor to start and run even when one or two of its stator is opened or short circuited, lower current per phase without an increase in voltage per phase, higher reliability and increased power for the same motor frame (Iqbal,2010), (George, 2013). The limitation of five-phase machine is that it requires a more complex power electronic circuitry or special transformer for phase conversion for supplying the motor since only single-phase or three-phase supply is available from utility (Karim,2015).

MOTOR CONSTRUCTION

Stator and rotor

Both three-phase and five-phase induction motors have been constructed using two identical stator and rotor frame that are available in the laboratory. It has 24 slots on the stator side and 8 shorted bars on the rotor side. The outer radius of stator active material is 72mm and the stack length is 200mm. In this project, the five-phase motor is supplied using three-to-five phase transformer that is readily available in the laboratory.

Winding arrangement

In order to construct the five-phase induction motor, the number of slot per pole and coil span should be properly determined in order to achieve a balance radial force. Figure-1shows the phase sequence of the motor while Figure-2 shows the winding arrangement to suit the slot numbers. The number of winding per slot is set to 50 turns which calculated based on equation (1).

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$$N_T = \frac{E_{ph}}{4.44\,K_p K_d\, f\phi}$$

(1)

N_T = number of winding turns,
E_{ph} = phase voltage,
K_d = distribution factor,
K_p = coil span factor,
f = frequency,
ϕ = sychronous speed

Winding construction

Based on the determined winding arrangement, the winding process is performed manually using 0.7mm enameled copper wire. The winding is formed with the aid of a suitable jig shown in Figure-3 before being securely fitted into the stator slots.
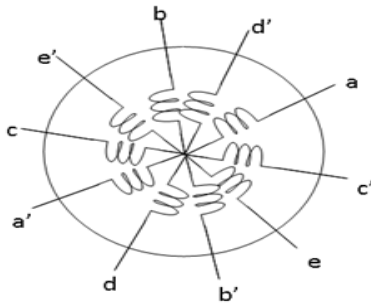
**Figure-1.** Phasor sequence of five-phase motor in star connection.
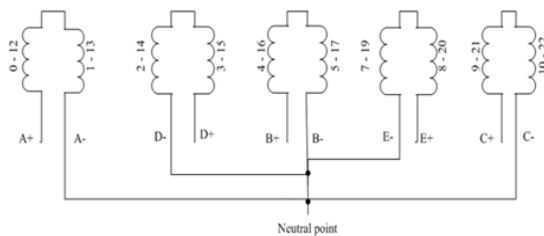
Figure-2. Five-phase winding arrangement on 24 stator slots 2 poles.
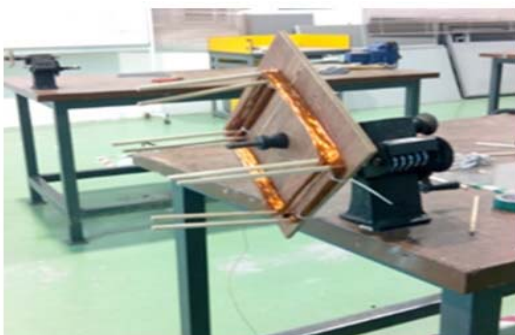
Figure- 3. Winding jig.

The inserting process must be properly executed since the sharp corner can easily damage the thin insulation of enameled wire. The used of insulation paper should help to prevent this from happen. Tears in insulation can cause a faulty condition such as inter-turn short circuit and ground-fault. The completed motor has been tightly screwed and ready for experimental test. The completed motor winding is shown in Figure-4.
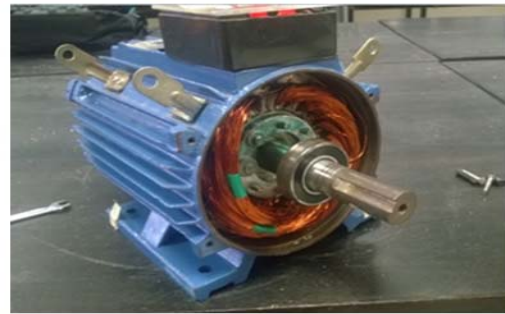

Figure-4. Complete winding of five-phase induction motor.

PERFORMANCE TEST

In order to fairly evaluate the performance of the three-phase and five-phase motors, the motors are constructed using the same frame size and have an equal total number of conductors per stator volume. The number of poles are fixed to two for both motors while the supply frequency is maintained at 50Hz in order to achieve the same synchronous speed. The motor is connected to the power supply through direct online starter configuration. Two tests that has been conducted in order to analyze the performance of the motors, which are no load test and dynamic load test.

No load test

The no load test on an induction motor has been performed to measure the voltage, current and speed of the motor without connected to any load. The arrangement of the test depicted in Figure-5 and a balance five-phase 50 Hz AC voltages is applied to the stator and no load are connected to the rotor. It has to be noted that the slip is close to zero since the motor runs on no-load condition.
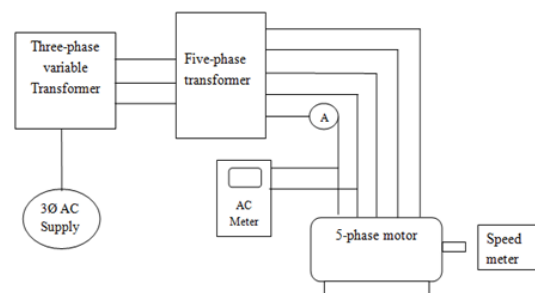
Figure-5. No load test arrangement for five-phase motor.

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The purpose of the test is to determine the minimum supply voltage that is required to start the rotation of the motor. The relationship between the voltage, synchronous speed and developed torque can be expressed as:

$$T_d = \frac{3R_rV_s^2}{S\omega_s\left[(R_s + R_r/S)^2 + (X_s + X_r)^2\right]}$$
(2)

T_s = developed torque,
V_s = supply voltage,

R_r = rotor resistance

R_s = stator resistance,

x_s = stator reactance
x_r = rotor reactance
ω_s = sychronous speed

S = slip

The synchronous speed is directly proportional to the supply frequency and inversely proportional to the number of poles as follow:

$$N_s = \frac{120f}{P}$$
(3)

f = supply line frequency,

P = number of poles,

N_s = synchronous speed in rpm

From equation (2) and (3), if the frequency is fixed to 50Hz and other parameters are maintained constant throughout the experiment, the slip is equal to 1 as the rotor is not moving. In order to start rotating the rotor, the supply voltage has to be increased in ramp manner in order to overcome the friction torque.

Dynamic load test

The arrangement of the dynamic load test is shown in Figure-6. In order to evaluate the loading effect on the five-phase induction motor, the rotor shaft has been coupled to an eddy current brake. In this test, the supply voltage is maintained constant while the load is gradually increased by increasing the voltage supplied to the eddy current brake (known later on as braking voltage) until the motor is stop rotating. During the test, the braking voltage, line voltage, and speed of the motor are recorded.
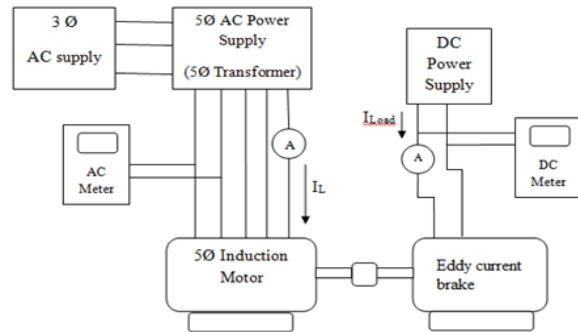
Figure-6. Dynamic load test arrangement of five-phase motor.

For the three-phase motor, it has to be noted that the no load and dynamic load tests for the three-phase motor have been performed using the similar test arrangement as the five-phase motor.

EXPERIMENTAL RESULT

The objective of performing the no load test on both five-phase and three-phase motors is to identify the minimum voltage that required to start rotating the rotor without any load. As the voltage supply is being increased, the speed and phase A current are recorded such as in tabulated in Table-1 and 2. The motor needs supply voltage that able to produce mechanical torque that is higher than the friction torque in order to start to spin.

Table-1. Experimental data of no load test for five-phase induction motor.

Line Voltage, V_L (V)	Phase A current, I_A (A)	Speed, (Rpm)
29	1.03	171
30	1.06	270
40	0.43	2805
50	0.31	2907
60	0.27	2937
70	0.25	2955
80	0.25	2963
90	0.25	2970
100	0.26	2975
110	0.26	2980

Table-2. Experimental data of no load test for three-phase induction motor.

Line Voltage, V_L (V)	Phase A current, I_A (A)	Speed, (Rpm)
55	1.13	149
60	1.25	710
70	0.36	2873
80	0.30	2912
90	0.29	2937
100	0.28	2947
110	0.27	2963

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Figure-7 and 8 show the plotting of supply voltage versus speed for the five-phase and three-phase motors. As can be seen from the figures, the five-phase motor starts to rotate when the supplied voltage is around 29V while the three-phase motor required a voltage around 55V to start rotating. Both motors reach a steady state speed of nearly 3000rpm, limited by the number of poles and the supply frequency. The results indicate that the five-phase motor has a higher starting torque compared to the three-phase motor since a lower starting voltage is required to initiate the rotation.
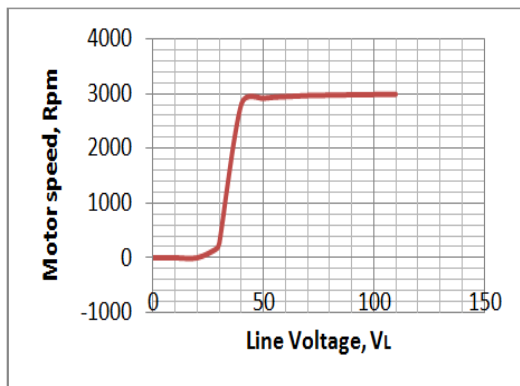

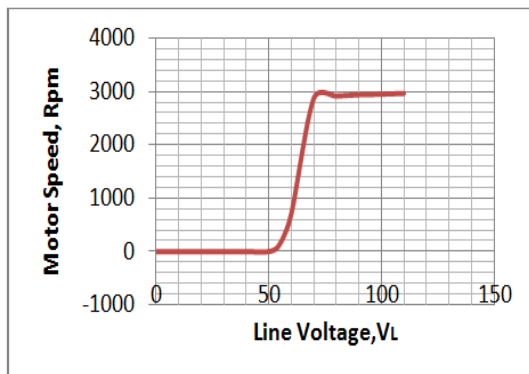**Figure-7.** No load test profile of five-phase motor.

Figure-8. No load test profile of three-phase motor.

For the dynamic load test, the rotor is coupled with an eddy current brake in order to evaluate the power produced by the motor. The braking DC voltage (V_{DC}) supplied to the eddy current brake is steadily being increased in order to imitate the increases of load until the motor is stop running and the rotor is locked. The supply voltage is fixed to 100V throughout the test. The recorded line current for phase A and rotor speed for both three-phase and five-phase motors are tabulated in Table-3 and 4. The plotting of motor speed versus the braking voltage for the three-phase and five-phase motors are shown in Figure-9 and 10 respectively.

Table-3. Experimental data of dynamic load test for three-phase motor.

| Line voltage, V_L (V)	DC voltage, V_{DC} (V)	Phase A Line current, I_L (A),	Speed, (rpm)
100	0	0.36	2922
	10	0.37	2915
	20	0.42	2895
	30	0.51	2860
	40	0.71	2790
	50	0.99	2647
	60	2.37	353.5
	70	2.39	0

Table-4. Experimental data of dynamic load test for five-phase motor.

| Line voltage, V_L (V)	DC voltage, V_{DC} (V)	Phase A Line current, I_L (A),	Speed, (rpm)
100	0	0.38	2972
	10	0.38	2969
	20	0.40	2963
	30	0.43	2954
	40	0.49	2939
	50	0.58	2921
	60	0.70	2898
	70	0.88	2862
	80	1.11	2809
	90	1.51	2708
	100	3.55	332.6
	110	3.56	0

From the figures, it can be clearly seen that the speed of the three-phase motor start to rapidly decreases when the braking voltage reach $50V_{DC}$ and come to a halt at $70V_{DC}$. On the other hand, the speed of five-phase motor only start to decrease sharply at braking voltage around $90V_{DC}$ and completely stop at $110V_{DC}$. The value of braking voltages basically reflects the power level attached to the motor shaft and this clearly shows that for the same frame size, the five-phase motor has a higher torque density than the three-phase motor.

CONCLUSIONS

Based on the no load and dynamic load tests that have been performed using the same frame size and similar test arrangement, the five-phase motor has produce a superior performance when compared to the three-phase motor. The five-phase motor has a higher starting torque to start the rotation which requires a lower starting voltage. It also has a higher running torque whereas it required higher load power to completely stop the rotation. Through this investigation, it can be concluded that for the same physical size and volume, motor with a higher of phases can provide a higher torque density.

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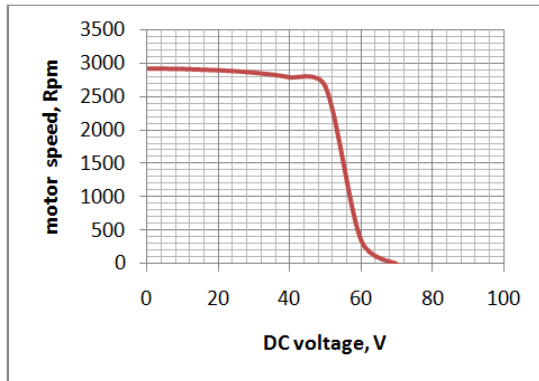
Figure-9. Dynamic load test profile of three-phase motor.
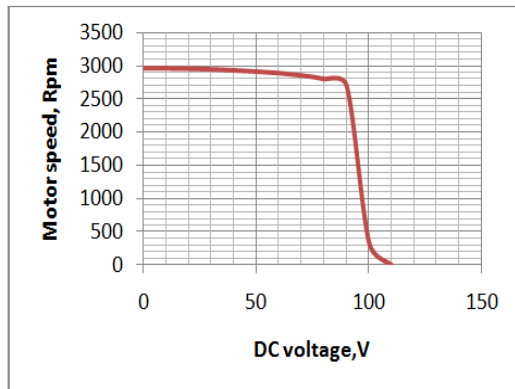
Figure-10. Dynamic load test profile of five-phase motor.

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