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ARTICLE

Multiple three-phase induction motors connected to a zigzag transformer

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ABSTRACT

Many experiments have been conducted in this research work which is (i) connecting a zigzag transformer with an induction motor, (ii) connecting a zigzag transformer with multiple induction motors, and (iii) connecting multiple zigzag transformers with multiple induction motors. These experiments provide a thorough understanding of the sequence network connections under the single-phasing condition of a three-phase induction motor. Moreover, these experiments protect the three-phase induction motors from unbalancing voltage supply and allow the induction motor to start under unbalance voltage supply. Additionally, they keep the three-phase induction motor running even any one of the three phases disconnected from the power supply without creating excessive heat in the motor winding.

1. Introduction

Induction motor is widely used in industry to convert electrical energy into mechanical energy due to its reliability, affordability, and superior performance (Lyshevski, 2018). These motors can be employed in both low- and high-power applications. However, an induction motor is susceptible to different faulty conditions during operation, which would lead to machine shutdown.

To avoid unexpected shutdowns, the induction motor must be monitored regularly to identify possible early-stage faults. By detecting these faults earlier, maintenance engineers can execute corrective actions. Some standard external faults of induction motor are over-loading, single phasing, unbalanced supply voltage, locked rotor, phase reversal, ground faults, and under/overvoltage (Choudhary et al., 2019).

In a three-phase system, the single-phasing condition can occur for several reasons, such as burning a jumper and snapping a conductor. The failure to develop any starting torque by a three-phase induction motor arises once an open-circuited in one of the three-phase conductors of a three-phase supply. The motor continues to run even though if a single phasing occurs. However, the motor continues to run but at a slower speed. Moreover, it produces a lower torque at a reduced power factor (PF) (Fitzgerald et al., 2003). The negative sequence current results in excessive heating, which indicate that the motor should not be run continuously.

An induction motor is a motor in which alternating current is directly supplied to the stator, while in the case of the rotor, it is supplied by either transformer action from the stator or induction. It produces a magnetic field in the air gap once the induction is excited from a balanced three-phase. This magnetic field rotates at

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synchronous speed, which can be determined by the applied stator frequency and the number of stator poles (Fitzgerald et al., 2003).

An induction motor or three-phase induction motor is an essential part of many manufacturing lines if unbalance voltage of the three-phase induction motor under the single-phase condition create a negative sequence current (Maruthi & Hegde 2015). Thus, the induction motor is unable to start and generate a high level of temperature. Even though the single phase has field while the induction motor is running, it will create excessive heating in the motor winding, which may lead to the induction motor's damage. This research aims to eliminate the effects of unbalanced three-phase induction motors such as high temperature, low speed and low torque by connecting zigzag transformers with multiple three-phase induction motors.

2. Materials and Methods

Different experimental investigations have been conducted for various types of connecting the three-phase induction motor to a zigzag transformer in this research work. The type of connections is as listed below:

1. The standard operating condition of the three-phase induction motor.
2. Operation of the induction motor with opening any one of the three-phase supplies.
3. Open one phase of the three-phase supply while the motor is running.
4. Operation of the induction motor connected to a zigzag transformer.
5. Operation of multiple induction motors connected to a zigzag transformer, and
6. Operation of multiple induction motors connected to multiple zigzag transformers.

2.1. Normal operation condition of three-phase induction motor

The stator of the three-phase induction motor has three-phase windings uniformly distributed around the periphery.

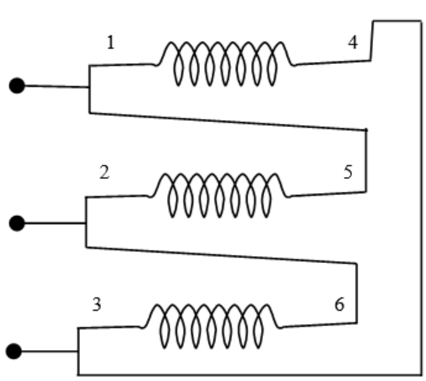

Figure 1 Motor windings connection.

When a balanced three-phase supply is given to the three-phase windings, which are displaced in space by 120 electrical degrees, the rotating magnetic field is produced in the air gap between stator and rotor. Figure 1 shows the connections of the induction motor windings as delta type connections. Figure 2 illustrates the normal operation condition of a three-phase induction motor.

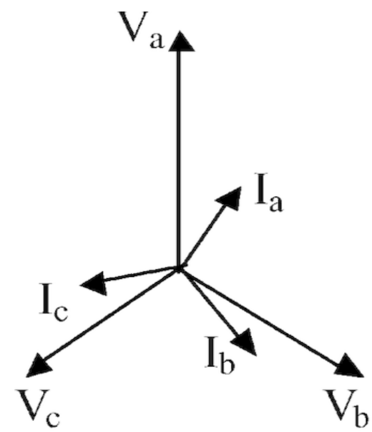

Figure 2 Normal operation condition of three-phase induction motor.

The squirrel cage induction motor used in this project is shown in Figure 3. This induction motor contains four-pole with the rating values of 175 W - 1395 r/min - 415 V - 0.46 A - 3 ~ - 50 Hz.

Figure 3 Squirrel cage induction motor.

2.2. Operation of the induction motor with opening any one of the three-phase supply

The condition of the single phasing in a three-phase system may occur due to several reasons such as a conductor got snapped, a jumper got burnt, a fuse blows up, etc. When one of the three-phase conductors of a three-phase supply is open-circuited, a three-phase induction motor fails to develop any starting torque. Under single phasing conditions, the power system's negative and zero sequence networks are connected in parallel across the point of an open conductor, as shown in Figure 4.

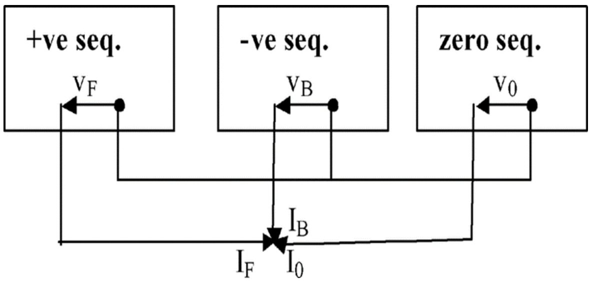

Figure 4 Sequence network connection with one phase open.

The net torque developed at any slip (s) can be stated by Eq. 1;

$$T \ \alpha \ I_F^2 R_F - I_B^2 R_B \qquad (1)$$

The net torque can be calculated based on voltage and current as given by Eq. 2.

$$T \ \alpha \ I_F V_F - I_B V_B \qquad (2)$$

Where; T is the net torque, I_F is the current fault, V_F is the voltage fault, I_B is the current bases, V_B is the voltage bases.

At the point of opening, the sum of positive, negative and zero sequence current equals zero. For an insulated neutral star connected or delta connected induction motor, the zero-sequence current becomes zero when the zero-sequence impedance (Z_0) is infinite. Therefore, the developed torque by positive and negative sequence current magnitudes cancels each other at the starting once they become equal.

At running condition (s<1), due to the motor's higher value of positive sequence resistance, the produced torque by the positive sequence current surpasses that of the negative sequence current. Nonetheless, the heating due to negative sequence current continues

2.3. Open one phase of the three-phase supply while the motor is running

The induction motor continues to run even though one phase of the three-phase supply is open. However, the motor runs at a low speed, producing a lower torque at a reduced power factor. Moreover, the temperature of the induction motor becomes excessive due to the negative sequence current; at this stage, the motor should be switched off (Barusu et al., 2018). Figure 5 illustrates the operation of the induction motor with an open phase.

If the A-phase conductor opens, then $I_a = 0$. This set of three unbalanced currents may be resolved into positive, negative and zero sequence components of current.

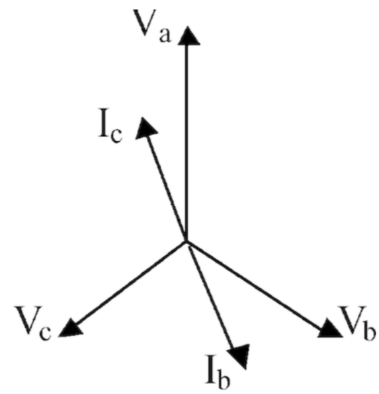

Figure 5 Operation of the induction motor with an open phase.

2.4. Operation of the induction motor connected to a zigzag transformer

Figures 6 and 7 show the windings connection of a zigzag transformer in the delta on the limbs of its core.

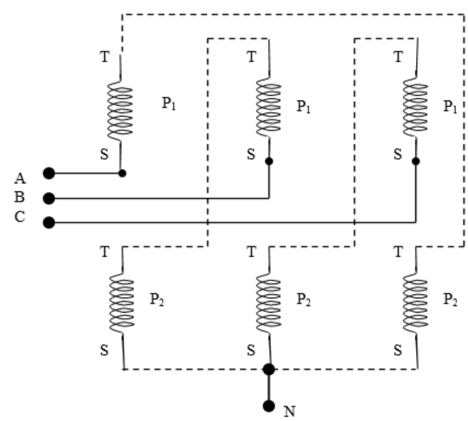

Figure 6 Zigzag transformer windings connection.

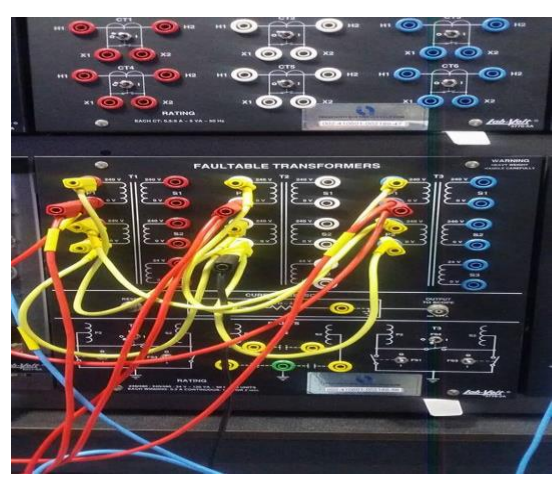

Figure 7 Zigzag transformer connection.

When one phase of a three-phase supply is open, the other two phases are connected across a zigzag transformer while the neutral of the transformer is connected to the supply neutral through a contact R, as shown in Figure 8.

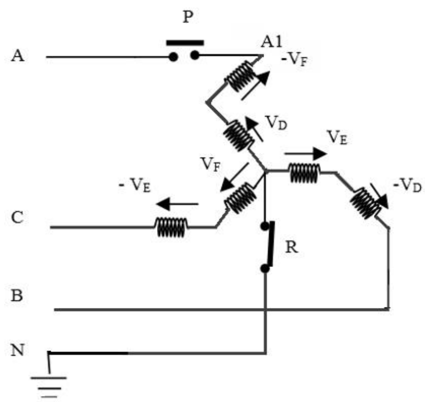

Figure 8 Induced voltages across the windings (A-phase open).

The transformer now gets a two-phase supply from the two healthy phases (B and C and the neutral). The induced voltages across the windings of the zigzag transformer with one phase (A-phase) is open.

The supply voltages across B and C phases are;

$$V_{BN} = V_E - V_D \tag{3}$$

$$V_{CN} = V_F - V_E \tag{4}$$

Where, V_{BN} is the supply voltage across the B phase, V_{CN} is the supply voltage across the C phase, V_D, V_E, V_F are induced voltages across half of the phase windings of the zigzag transformer.

And the voltage across the open phase to neutral is:

$$V_{A1N} = V_D - V_F = -(V_{BN} + V_{CN}) \tag{5}$$

$$V_{A1N} = V_A \tag{6}$$

Therefore, the open phase voltage builds up to the pre-fault A-phase voltage.

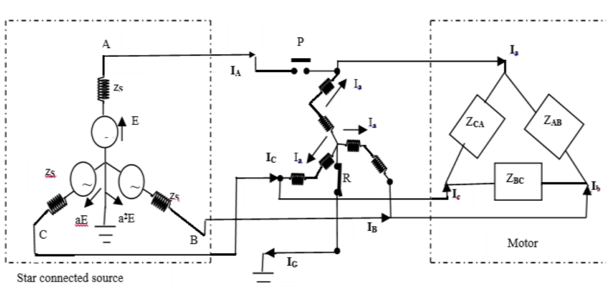

Figure 9 Current distribution in transformer winding and motor with one phase.

A three-phase transformer, having a single zigzag winding, is connected across the motor terminals. The zigzag winding star point is shorted to the power supply neutral, as shown in Figure 9. Figure 10 shows the connection of the zigzag transformer to the induction motor with one open phase from the supply.

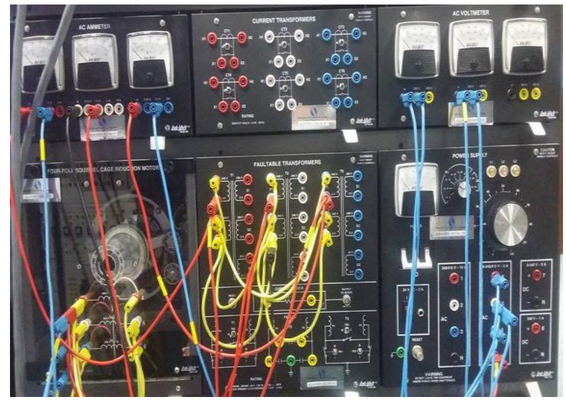

Figure 10 Connection the zigzag transformer to a motor with one phase open.

I_A, I_B, I_C are phase currents supplied from the source.

$$I_A + I_B + I_C = I_G \tag{7}$$

$$I_A = 0;\ I_B = I_b - I_a;\ I_C = I_c - I_a \tag{8}$$

For balanced load;

$$|I_B| = |I_C| = \sqrt{3}\,|I_a| \tag{9}$$

I_a, I_b, I_c are the line currents for the delta connected load three-phase induction motor.

$$I_a + I_b + I_c = 0 \tag{10}$$

$$I_G = -3I_a \tag{11}$$

The connection diagram of the motor in parallel with the zigzag transformer is as shown in Figure 11.

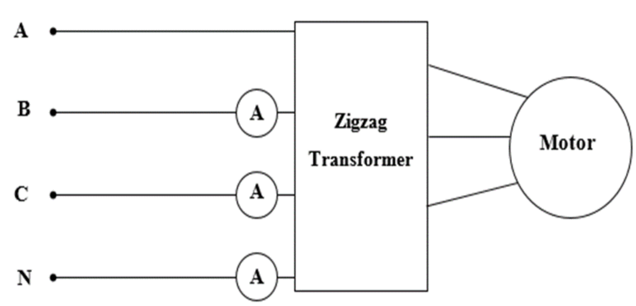

Figure 11 Operation of the motor in parallel with the zigzag.

2.5. Operation of multiple induction motors connected to a zigzag transformer

It is the actual operation of the induction motor connected to the zigzag transformer, but with an additional motor in parallel with the zigzag transformer, as showing in Figure 12.

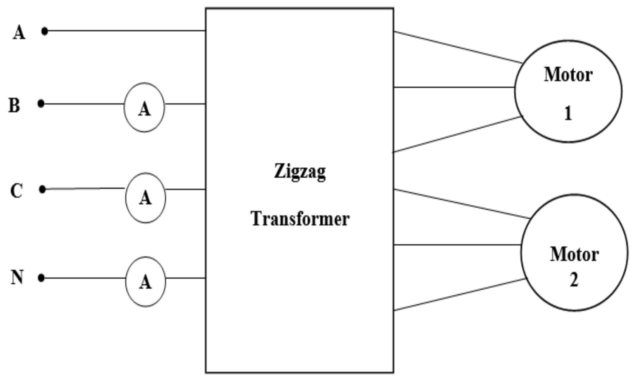

Figure 12 Zigzag transformer connected to two motors.

2.6. Operation of multiple induction motors connected to multiple zigzag transformers

Figure 13 illustrates the connection of two induction motors connected in parallel with two zigzag transformers. Considering that the supply voltage must be connected from one side to avoid any short circuit, the line of neutral of zigzag transformer must be connected to the neutral of supply voltage, while another neutral of the second zigzag transformer is not essential if it is connected or not.

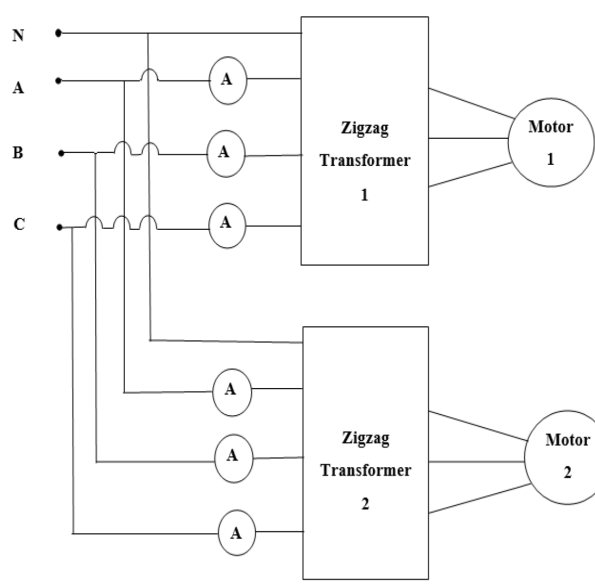

Figure 13 Multiple zigzag transformers connected to multiple induction motors.

3. Results and Discussion

3.1. Normal operation condition of three-phase induction motor

Connecting the motor windings in delta and the three-phase induction motor to a slowly increasing three-phase power supply via a meter yield the results shown in Table 1. Figure 14 shows Ac Ammeter used during the test.

Table 1 Readings of line currents at voltage supply V_{AN}, of 70 V.

V_{AN}	I_a	I_b	I_c
70	0.2	0.2	0.2

Figure 14 Ac Ammeter.

3.2. Operation of the induction motor with opening any one of the three-phase supply

Table 2 shows the ammeter readings when switched on the supply and gradually increased the supply voltage for over 70V, the motor failed to start. However, the current became significantly higher than the standard conditions due to the voltage supply increase.

Table 2 Readings of line currents at voltage supply V_{AN}, of 70 V &100 V.

V_{AN}	I_a	I_b	I_c
70	0.4	0.4	0.4
100	0.5	0.5	0.5

Additionally, the temperature of the motor winding increased and eventually may lead to the damage of the motor.

3.3. Open one phase of the three-phase supply while the motor is running

The induction motor continued to run when one phase of the three-phase supply was being opened. However, the motor continued to run at a slower speed, which might lead to the damage of the motor windings (Bonnett et al., 1992).

3.4. Normal operation condition of three-phase induction motor

With a voltage supply V_{AN} of 200 V, the induction motor started to run normally without any failures due to the connection of the zigzag transformer. The readings of the line currents are shown in Table 3.

Table 3 Readings of line currents at voltage supply V_{AN}, of 200 V.

V_{AN}	I_a	I_b	I_c	I_N
200	0.25	0.25	0.25	0

On the other hand, during opening one phase of the three-phase supply in the same operational conditions, the induction motor continued to run at the same speed. However, the line current (I_a) became zero, and the neutral line current of the zigzag transformer (I_N) changed from (0 to 0.25). The Readings of line currents at voltage supply V_{AN} of 200 V are shown in Table 4.

Table 4 Readings of line currents at voltage supply V_{AN}, of 200 V.

V_{AN}	I_a	I_b	I_c	I_N
200	0	0.25	0.25	0.25

3.5. Operation of multiple induction motors connected to a zigzag transformer

With a voltage supply V_{AN} of 200 V, the induction motors started to run normally without any failures due to the connected zigzag transformer. The readings of the line currents are shown in Table 5.

Table 5 Readings of line currents at voltage supply V_{AN}, of 200 V.

V_{AN}	I_a	I_b	I_c	I_N
200	0.25	0.25	0.25	0

Alternatively, switching off the supply until the two induction motors stopped and then switching on the supply again, it was found that the two induction motors started to run without any failures.

3.6. Operation of multiple induction motors connected to multiple zigzag transformers

After connecting the two induction motors in parallel with two zigzag transformers and the supply voltage was then gradually increased, it was observed that the two induction motors started to run at 70V, and the measured line current was 0.2A. The readings of line currents at voltage supply V_{AN} of 70 V & 0 V are shown in Table 6.

Table 6 Readings of line currents at voltage supply V_{AN}, of 70 V & 0 V.

V_{AN}	I_a	I_b	I_c	I_N
0	0.2	0.2	0.2	0
70	0.2	0.2	0.2	0

Repeating the same operation conditions while the two induction motors are running and one phase of the three-phase supply is opened, the two motors kept running without any failures, mainly due to the neutral line of the zigzag transformers connected to the neutral line of the supply voltage. The readings of I_a for both motors became zero, and I_N became 0.2 A. The readings of line currents at voltage supply V_{AN} of 70 V & 0 V are shown in Table 7.

Table 7 Readings of line currents at voltage supply V_{AN}, of 70 V & 0 V.

V_{AN}	I_a	I_b	I_c	I_N
0	0	0.2	0.2	0.2
70	0	0.2	0.2	0.2

4. Conclusion

This research focused on the effects of unbalanced voltage supply for three-phase induction motors or multiple three-phase induction motors. To avoid the unbalance voltage from the supply, a connection of zigzag transformer in parallel with a three-phase induction motor was used. The system is very cheap as compared to the current available protective devices. The neutral line of the zigzag can also keep the three-phase induction motor running under two-phase supplies.

A three-phase induction motor may be started and operated at full load under a single phasing condition by connecting a transformer, having a single three-phase zigzag winding in parallel with the motor, while the transformer winding star point shorted to power supply neutral. The low value of the zero-sequence impedance of the transformer provides a shunt path to the positive-sequence current, and the negative-sequence current becomes negligible. The kVA rating of the transformer is equal to that of the motor.

A simple laboratory experiment has demonstrated how the two healthy phases of a three-phase system combined with the neutral can be used and identify the idea of sequence network connections with the relative values of sequence impedances.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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