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# Experimental Investigation and Analysis of Induction Motors Operation under Single-Phasing Condition

# التحقيق والتحليل التجريبي لتشغيل المحركات الحثية ثلاثية الطور في ظل حالة المرحلة الواحدة

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**Abstract:** A three-phase induction motor will continue to operate when a disturbance of some sort causes the source voltages of the motor to become unbalanced. When an induction motor is operated at unbalanced voltage supply the performance characteristics like efficiency, power factor, input power, output power and losses are affected. The single-phasing occurs when one phase fails as a result of a fuse blowing, protective device opening on one phase of the motor, open phase on one terminal of the motor or other causes. This paper will analyze the operation of a 3-phase induction motor under normal balanced source voltages first, then under single phasing experimentally in order to follow a comparative approach.

**Keywords**: Induction motors, unbalanced Voltages, Positive and Negative Sequences, single-phasing, losses.

**المستخلص**: سيستمر المحرك الحثي ثلاثي الطور في العمل عندما يتسبب اضطراب من نوع ما في أن تصبح الفولتية المصدر للمحرك غير متوازنة. عندما يتم تشغيل المحرك الحثي بجهد غير متوازن ، تتأثر خصائص الأداء مثل الكفاءة ، ومعامل القدرة ، ومدخلات الطاقة ، وطاقة الخرج ، والخسائر. يحدث الطور الأحادي عندما تفشل إحدى الطور نتيجة انفجار الصمامات ، أو فتح جهاز الحماية على مرحلة واحدة من المحرك ، أو المرحلة المفتوحة على أحد طرفي المحرك أو لأسباب أخرى. ستحلل هذه الورقة تشغيل المحرك الحثي ثلاثي الطور في ظل الفولتية الطبيعية المتوازنة للمصدر أولاً، ثم تحت مرحلة واحدة تجريبيًا من أجل اتباع نهج مقارن.

**الكلمات المفتاحية:** المحركات الحثية ، الفولتية غير المتوازنة ، المتواليات الإيجابية والسلبية ، المرحلة الواحدة ، الفقد.

## INTRODUCTION:

Three phase induction motors are widely used in industrial applications. They are preferred due to their high torque to volume ratio, reliable operation, and relatively low maintenance cost (Mutiullah et al., 2017). When this type of motors is powered by a three-phase ac supply, a rotating magnetic field is produced in the stator which in turn induces an electro motive force in the rotor circuit. A magnetic field

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will be induced in the rotor and the interaction between the two magnetic fields will create a torque that run the shaft of the motor .

Three phase induction motors may be subjected to different types of faults. One of these faults is the single phasing fault. It is occurred when any one of the three phases of the supply gets disconnected. This may be caused by a fuse blowing or protective device opening on one of the phases, an open circuited of one of the three phase contacts of the power contactor, a failure in one of motor stator coils, a failure in one of the phases of the supply system, or a fuse blowup in one of phases of the supply feeder or transformer) Sudasinghe et al., 2016.(

Single phasing is one of the unbalanced cases that may affect the operation of the three phase induction motors. When a three-phase induction motor is energized by unbalanced voltage supply, positive and negative sequence components are generated. The negative sequence component generates its own magnetic field in addition to the positive sequence magnetic field that is generated by the positive sequence component. (Mutiullah et al., 2017).

Single phasing problem on a three-phase induction motor will have the following adverse effects:

- If the motor is not running and supplied by a supply with a single phasing fault, it can't start its operation, and the motor should be protected against this type of faults .
- If the single phasing fault occurs while the motor is running, it will continue its operation unless it is provided with a special protection circuit. The two remaining phases can continue producing the torque required by the load (partly loading case).
- The motor will be overheated if the single phasing fault occurs while the motor is running and the two remaining phases continue supplying the same load. This may result in melting the windings .
- The speed of the motor reduces under the case of single phasing condition .
- The torque produced by the two remaining phases may cause abnormal vibration in the shaft. As previously mentioned, a three-phase induction motor running at a steady state mode, it will continue its running under single phasing condition. (Mutiullah et al., 2007) carried out a comparative study to analyze the operation of a three-phase induction motor under case as well as unbalanced case (overvoltage and under voltage unbalanced condition). They found that under unbalanced case, the performance characteristics like current, power, power factor, and efficiency are affected. The case of single phasing was not analyzed in this paper. (Madescu et al., 2007) analyzed a generalized case for a three-phase induction motor under unsymmetrical condition. Their results allow the analysis of the effect of certain unsymmetrical number of windings of the stator of a three-phase induction motor .

(Fortes et al. 2018) analyzed the behavior of the induction motor when subjected to unbalance cases of the power supply. The unbalance was performed by inserting a certain resistance in series with one of the stator windings. The purpose of the analysis is to evaluate the effect of the power factor and the harmonics contents .

Sudasinghe et al. analyzed the effect of variation of the unbalanced voltages applied to the stator of an induction motor. The purpose was to identify the possible range of variation of the unbalance in voltage with accepted performance .

(Rajashree and Chaudhari. 2015) conducted an analysis of the induction motor performance under the effect of unbalance voltage. The results indicated that unbalanced voltages may cause difference in phase currents in the range from 6 to 10 times the percent of the variation in the voltage unbalance.

Quispe et al. (2018) analyzed the influence of the sequence components on the characteristics of an induction motor running at unbalance voltage supply. The effect of the load variation on both the positive and negative impendences was also analyzed in this study .

Detailed experimental investigation and analysis of a three-phase induction motor running at single phasing condition will be carried out in this study .

## MATERIAL AND METHODS:

The equivalent circuit of the induction motor under single phasing condition, the derived equations that describes its operation and the experimental setup are included in this section.

Single phasing condition applied to a three-phase induction motor is one of the unbalanced cases that may affect the three-phase induction motor, so sequence components are used to represent the voltage supply at the terminals of the induction motor. The voltage at the terminals is resolved into positive, negative and zero sequence components. These components are shown in **Figure (1).**

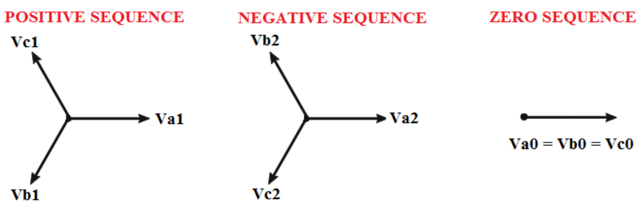


**Figure (1): Decomposition of unbalanced system into sequence components.**

In terms of sequence components, the phase voltages at the terminals of the induction motor are given as presented by **equation (1).**

$$\begin{aligned} V_{an} &= V_{a0} + V_{a1} + V_{a2} \\ V_{bn} &= V_{b0} + V_{b1} + V_{b2} \\ V_{cn} &= V_{c0} + V_{c1} + V_{c2} \end{aligned} \qquad (1)$$

Using the $a$ operator where $a = \cos 120^\circ + j\sin 120^\circ$ and the vectors of positive, negative and zero sequence components shown in figure 1, then **Equation (1)** can be rewritten as given in **Equation (2).**

$$\begin{aligned} V_{an} &= V_{a0} + V_{a1} + V_{a2} \\ V_{bn} &= V_{a0} + a^2 V_{a1} + a V_{a2} \\ V_{cn} &= V_{a0} + a V_{a1} + a^2 V_{a2} \end{aligned} \qquad (2)$$

In matrix form, **Equation (2)** can be rewritten as given in **Equation (3).**

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \times \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} \qquad (3)$$

To calculate the sequence components of phase a if the voltages of the phases a, b, and c are known, then **Equation (3)** should be resolved (by calculating the inverse of the A matrix) and the result is given in **Equation (4).**

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \qquad (4)$$

**Single Phasing Condition:**

The term single phasing condition is used to describe the operation of the motor when one of its supplying phases is open**. Figure (2)** illustrates the currents passing through the three phases and the voltages across its terminals .

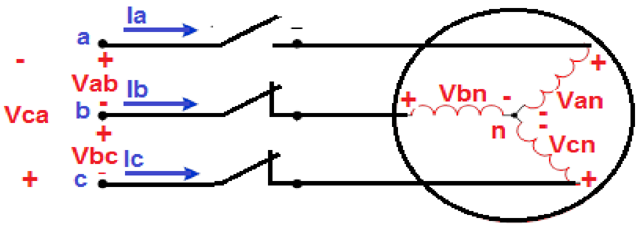


**Figure (2): Single Phasing Condition – open the path of phase a**

The currents passing through the three phases of the three-phase induction motor under the single-phasing condition are as follows (considering the open circuit occurs at phase a (Kersting, 2005)):

$$I_a = 0$$
$$I_c = -I_b \qquad (5)$$

The symmetrical sequence components of the phase a current can be given by **Equation (6).** From the result of this equation, one can notice that the negative sequence component of phase a equal the negative of the positive sequence component of this phase and no zero-sequence current will pass through this phase. This is illustrated in **Equation (7).**

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix}$$

$$=\frac{1}{3}\begin{bmatrix}0\\(a-a^2)\times I_b\\(a^2-a)\times I_b\end{bmatrix}=\begin{bmatrix}0\\j(1/\sqrt{3})\times I_b\\-j(1/\sqrt{3})\times I_b\end{bmatrix} \quad (6)$$

$$I_{a2}=-I_{a1} \quad (7)$$

As negative sequence component equals the negative of the positive sequence component, the positive sequence equivalent circuit can be connected in series opposition with the negative sequence equivalent circuit, and this is shown in **Figure (3).**

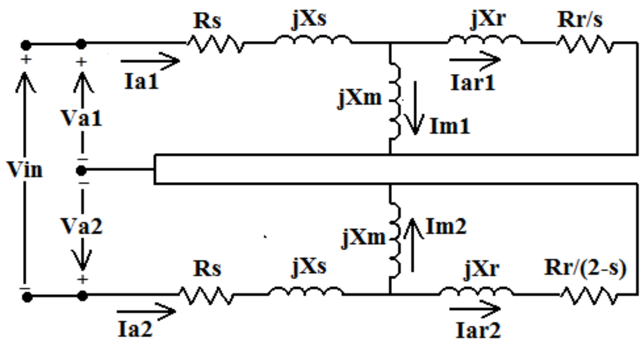


**Figure (3): The sequence network equivalent circuit**.

The first part of the equivalent circuit shown in figure 3 represents the equivalent circuit of an induction motor at steady state operation where Rs and Xs represent the stator resistance and the stator leakage reactance respectively, Xm represents the magnetizing reactance, Rr/s and Xr represent the rotor resistance and the rotor reactance respectively, and s represents the slip (Dubey, 2002). The slip is defined as:

$$s=\frac{n_{sync}-n_m}{n_{sync}} \quad (8)$$

where $n_{sync}$ and $n_m$ represent the synchronous speed and the mechanical speed of the induction motor (Chapman 2011). This equivalent circuit also represents the positive sequence equivalent circuit since the $n_{sync}$ and nm are in the same direction.

The second part of the equivalent circuit shown in **Figure (3)** represents the negative sequence equivalent circuit. It is the same as the positive sequence equivalent circuit except the rotor resistance Rr/(2-s) which appears in this form due to the fact that the slip of the negative sequence is given by:

$$s=\frac{-n_{sync}-n_m}{-n_{sync}} \quad (9)$$

as the synchronous speed is in the opposite direction for the negative sequence mode.

In **Figure (3)**, the input voltage Vin is the difference between the positive sequence voltage and the negative sequence voltage and can be expressed as follows:

$$V_{in}=V_{a1}-V_{a2} \quad (10)$$

Using **Equation (4)** to calculate Va1 and Va2 in terms of phase voltages will end up with the following:

$$V_{a1}=\frac{1}{3}(V_{an}+aV_{bn}+a^2V_{cn})$$
$$V_{a2}=\frac{1}{3}(V_{an}+a^2V_{bn}+aV_{cn}) \qquad (11)$$

So,

$$Vin = Va1 - Va2 = 1/3\ [\ (a-a^2)\ Vbn + (a^2-a)\ Vcn]$$

And after substituting with the value of the operator a, the input voltage.

$$V_{in}=j\frac{\sqrt{3}}{3}(V_{bn}-V_{cn})=\frac{j}{\sqrt{3}}Vbc \qquad (12)$$

The result of **Equation (12)** indicates that the input voltage of the sequence network equivalent circuit of the motor under single phasing condition is a function of the line-to-line voltage $V_{bc}$ and the value of this voltage is known. To simplify the derivation for the formula to calculate the current driven by the motor at a single phasing condition and then to calculate the torque of the motor, a modified approximate equivalent circuit that is shown in **Figure (3)** will be used. This modified approximate equivalent circuit is shown in **Figure (4).**

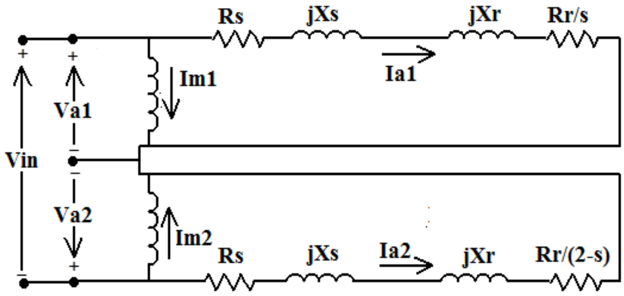


**Figure (4): A simplified approximate sequence network equivalent circuit.**

From this simplified equivalent circuit, the current Ia1 can be calculated using **Equation (13):**

$$I_{a1}=\frac{V_{a1}}{\left(R_s+\frac{R_r}{s}\right)+j\left(X_s+X_r\right)} \qquad (13)$$

The electrical power converted into mechanical power $P_{mp}$ due to positive sequence network can be calculated using **Equation (14)** (Sudasinghe , Upuli, Darshana and Sarath 2016)

$$P_{mp}=3I_{a1}{}^2R_r\left(\frac{1-s}{s}\right) \qquad (14)$$

So, the developed torque by the motor due to positive sequence network can be calculated using the following equation:

$$T_p=\frac{P_{mp}}{\omega_m} \qquad (15)$$

Substituting **Equation (13)** in **Equation (14)** and then in **Equation (15)** gives:

$$T_p = \frac{3}{\omega_{ms}} \left[ \frac{V_{a1}^{2} (R_r / s)}{\left( R_s + \frac{R_r}{s} \right)^2 + j\left(X_s + X_r\right)^2} \right] \qquad (16)$$

Where:

$$\omega_{ms} = \frac{\omega_m}{1-s} \qquad (17)$$

Proceeding as in calculating the positive sequence current and the positive sequence torque in calculating the negative sequence current and torque except replacing s by (2-s) gives:

$$I_{a2} = \frac{V_{a2}}{\left( R_s + \frac{R_r}{(2-s)} \right) + j\left( X_s + X_r \right)} \qquad (18)$$

$$T_n = -\frac{3}{\omega_{ms}} \left[ \frac{V_{a1}^{2} (R_r /(2-s))}{\left( R_s + \frac{R_r}{(2-s)} \right)^2 + j\left(X_s + X_r\right)^2} \right] \qquad (19)$$

In **Equation (19),** the torque has a negative sign since for negative sequence the synchronous speed is negative.

The overall value for the root means square motor current under single phasing condition can be given by:

$$I_m = \sqrt{I_{a1}^{2} + I_{a2}^{2}} \qquad (20)$$

$$T_m = T_p + T_n \qquad (21)$$

By referring to **Equations (20) and (21),** one can conclude that under single phasing condition, the motor draws more current but with less overall torque. This result actually can be utilized in order to break a motor by opening one of its phases. But one should take care about the increase in drawn current. This may burn the motor coils if it persists for prolonged times. In wound rotor motors, this breaking method can be effectively utilized by inserting – during breaking – a three phase star connected resistance in rotor circuit through the three slip ring terminals. This resistance - as given by **Equation (19)**- increases the negative sequence torque as the equivalent rotor resistance increases at a reduced value of the drawn current in comparison with the case of without inserting resistance through the rotor circuit. This in turn will decrease the overall torque that helps in breaking the motor (Dubey, 2002).

## RESULTS AND DISCUSSION:

A number of experiments has been taken in lab. Figure 5 shows the equipment used for experimentation. It consists of a 3-phase squirrel cage induction motor with a braking load. Power supply and data acquisition unit, ammeters, voltmeters and torque meter.

**Figure (5): Equipment used in lab**

**Table (1): No torque measured values**

| torque, kg.cm | speed, rpm | voltage, V | Ia | Ib | Ic |
|---|---|---|---|---|---|
| **8.5** | 2988 | 400 | 0.55 | 0.6 | 0.6 |

In **Table (2)** are shown the measured values when the motor is operating normally with different loads.

**Table (2): Different torque measured values**

| torque, kg.cm | speed, rpm | voltage, V | Ia | Ib | Ic |
|---|---|---|---|---|---|
| **18.2** | 2988 | 400 | 0.6 | 0.6 | 0.65 |
| **163.2** | 2988 | 400 | 1 | 1.05 | 1.15 |
| **200** | 2988 | 400 | 1.2 | 1.156 | 1.25 |

In **Table (3)** are shown the measured values in case of single phasing on phase C with different loads. From this table we can see that the value of $I_c$ is zero and we can see the increasing value of the currents $I_a$ and $I_b$ in case of single phasing compared to those with normal operation. The speed is decreasing in single phasing much more than normal operation with the increasing in load torque.

**Table. (3): Different torque measured values at phase C failure**

| torque, kg.cm | speed, rpm | voltage, V | Ia | Ib | Ic |
|---|---|---|---|---|---|
| **8.5** | 2988 | 400 | 0.95 | 1 | 0 |
| **18.2** | 2981 | 400 | 0.95 | 0.95 | 0 |
| **163.2** | 2828 | 400 | 1.7 | 1.75 | 0 |
| **200** | 2771 | 400 | 2 | 2.1 | 0 |

In **Figure (6)** are shown the three currents in normal and single phasing operation.

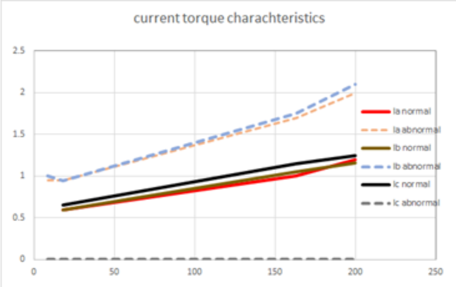


**Figure (6): three phase currents in normal and single phasing operation vs torque**

It is preferred to add units of the two axes.

## CONCLUSION:

A theoretical analysis has been done for the operation of three phase induction motor under single phasing. A number of experiments has been done to verify the validity of theoretical analysis. Experiments showed the increase of current, decrease in speed of the motor in single phasing as expected .

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