

# Assignment 1 Joseff Jones

*by* Joseff Jones

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HND Electrical and Electronic Engineering

PSDE5027 – Power & Machines  
Assignment 1 - Investigation into Three-Phase  
Induction Motors

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## 1. Research

This assignment involves a practical investigation into the behaviour of three-phase induction motors along with a number of simulations to compare and corroborate with. Prior to the practical investigation and simulations, research was made in a number of topic areas in order to develop a strengthened understanding of the results, this first section of the report discusses the findings of that research.

### 1.1 - Construction and operation of three-phase cage and wound rotor induction motors.

Induction motors (also known as asynchronous motors) are the most common type of AC motor due to their simplicity, cost-efficiency, cheap maintenance costs and load capacity; three-phase cage and wound rotor are two types of induction motor that can be commonly found in industry. All induction motors consist of two major parts - the stator and the rotor. The stator is the stationary part of the motor, it is made of silicon steel rings to reduce hysteresis and is laminated to reduce eddy currents. The rotor is the revolving part of the motor, is often made from copper, and according to Wildi (2013, p. 271) to operate efficiently is separated from the stator by a small air gap, ranging from 0.4mm to 4mm, depending on the power of the motor. The way the rotor is assembled is what determines whether the induction motor is a three-phase cage or wound rotor – three-phase cage rotors have a laminated core which carries rotor conductors, pushed into slots. These rotor conductors have copper end-rings which cause them to short-circuit and due to this external resistance cannot be added, resulting in a constant speed usually dictated by the frequency of the current being injected. Hughes (2016, p. 727) states that motors are commonly three-phase cage when they are below 50kW. Wound rotors have three-phase windings which are connected to three slip rings mounted on the motor shaft, these slip rings in turn are connected to a terminal box which allows the amperage of the current induced in the rotor windings to be controlled using external resistors – this allows the wound rotor induction motor to be used with high starting torque, which is something that generally three-phase cage induction motors cannot do, and instead they have a starting current limit.

With regards to the principle of operation, according to Reeves (1989, p. 317), an induction motor's principle is that a rotating flux is produced by the current in the stator winding which cuts the rotor bars and produces a current in the windings of the rotor, producing its own field. This field then reacts with the rotating flux from the stator and produces the necessary torque to start and run the motor. The speed of induction motors is dependent on the frequency of the current being injected into the stator, running at a speed slightly less than synchronous speed; because of this, standalone induction motors tend to have inflexible speed control, but they also operate at a nearly constant speed from no-load to full-load which makes them ideal for applications such as conveyors, pumps and anything lift-related. Although induction motors are inflexible in RPM relative to other motors, variable frequency drives are devices that can be added to allow the speed of the motor to be controlled. Reeves also states that "The difference between the actual speed and synchronous speed is termed the *slip*, which is usually expressed as a percentage or a fraction of the synchronous speed. For standard machines the maximum slip at full load is usually about 4%." (1989, p. 317)

## 1.2 – Per-phase equivalent circuit of a three-phase wound-rotor induction motor

Induction motors have several parameters and properties that on their own can seem of little value, but with the use of tools such as equivalent circuits can be used to predict the performance and behaviours of the motor. Wound-rotor induction motors in particular convert very well into equivalent circuits because they are very similar to three-phase transformers in design and so can be treated as such, where the stator can be compared to the primary winding of a transformer and the rotor can be compared to the secondary winding - a wound-rotor induction motor's approximate per-phase equivalent circuit is shown in the figure below.

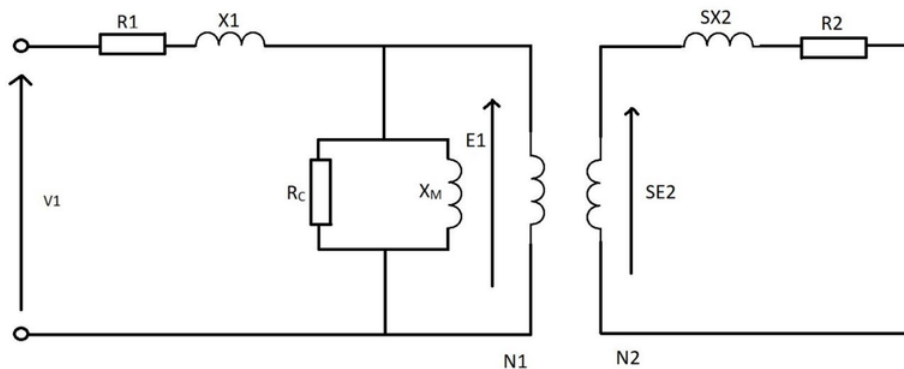


Figure 1 - Wound-Rotor Induction Motor Per-Phase Equivalent Circuit

With regards to the parameters in the figure above:

$R_c$  and  $X_M$  are used to depict the stator laminations

$R_1$  and  $X_1$  are used to depict the stator resistance and leakage reactance (caused by the leakage of flux)

$R_2$  and  $X_2$  are used to depict rotor resistance and leakage reactance

$V_1$  depicts the stator's phase voltage

$E_1$  &  $SE_2$  represent the induced EMF of both the stator and rotor at standstill

$N_1$  &  $N_2$  are the windings of the stator and rotor, respectively.

Hughes (2013, p. 383) makes a good point of stating that typically, simulations would be used in place of equivalent circuits, but developing an understanding of equivalent circuits can result in a greater comprehension of the results from simulations and helps with understanding what each property is useful for, which can prove very useful.

1.3 – Suitable formulae of torque and rotor current that can be used to predict the performance of a three-phase wound-rotor induction motor based upon the approximate per-phase equivalent circuit

In order to calculate the full load torque and ultimately the rotor current of a three-phase wound-rotor induction-motor, values which can be obtained via an approximate per-phase equivalent circuit must be used.

In order to calculate full-load torque, the equation  $T = \frac{1}{2\pi \cdot n_s} * \frac{s|E_2|^2 R_2}{R_2^2 + (sX_2)^2}$  must be used. Before that's possible, E1 must be obtained either from the equivalent circuit or by calculating it by dividing the supply voltage by  $\sqrt{3}$ , as the supply is three phase and single phase is needed.

The stator to rotor winding ratio, or  $\frac{N_1}{N_2}$ , at standstill can be used to calculate E2 using  $E_2 = \left(\frac{N_2}{N_1}\right) E_1$ .

Synchronous speed,  $n_s$ , can be calculated by dividing the frequency by the pole pairs, and that's measured in RPS.

$N_r$  needs to be in seconds for the torque equation and so the  $n_r$  is obtained from the equivalent circuit and divided by 60, alternatively it can be calculated using  $N_s(1-S)$  if the fractional slip is already known.

The fractional slip is calculated using  $S = \frac{N_s - N_r}{N_s}$ .

$X_2$  and  $R_2$  are both found on the equivalent circuit.

With all of these values, it should be possible to calculate the torque using the torque equation; once the torque equation is used, the outcome value will need to be multiplied by three in order to find the total torque. It is also possible to calculate the starting rotor current with these values, as the equation for rotor starting current is  $|I_2| = \frac{s|E_2|}{\sqrt{R_2^2 + s^2 X_2^2}}$  where  $S$  is always equal to 1, since the rotor would be at standstill.

## 1.4 – Methods of speed control and braking for cage and wound rotor induction motors

### Speed Control

Speed control is of paramount importance for some applications, there are a couple of methods that can be used to vary the speed of cage and wound-rotor induction motors, where they fit particular needs. The most efficient methods of speed control focus on varying the synchronous speed of the stator, instead of the rotor's speed; this is because motors operate most efficiently with a relatively small slip. Looking at the equation for synchronous speed,  $N_s = \frac{f_s}{p} * 60$ , it can be seen that the only variable that can alter the synchronous speed is the number of pole pairs, as the frequency is a constant from power supplies (but can be altered using a variable speed drive). The first method of speed control then is pole-changing motors.

Pole-changing motors are motors that can only run at one of two designated speeds at a time, and so this method of speed control is mainly suitable for applications such as pumps and fans. The pole-changing motor works because of the way it is constructed – according to Austin Hughes (2013, p. 196) it is constructed with two separate stator windings, where the appropriate ones are energized.

A method of speed control that is specific to cage motors is voltage control – this method involves simply varying the supply voltage. As to be expected, this has a direct effect on the torque of the motor and is a very inefficient method of speed control, but it is a variable speed control method nonetheless. This method is only really efficient on high-rotor resistance motors, because low-resistance cage motors have a restricted operating speed range.

For wound-rotor motors, it is possible to vary the speed of the motor by varying the rotor resistance on the rotor i.e. via braking. This method is inefficient because it increases the slip, but is cheap and simple to do.

### Braking

Three of the most common methods of braking are plug-braking, DC injection braking, and frequency reduction.

Plug braking is a very typical method of braking, it involves switching two phases of the motor, resulting in a reversed field and slowing down the rotor. This method can wear the motor down if there is frequent plugging because as the phases are swapped, four times the stored kinetic energy is dumped as heat in the windings; also, according to Hughes (2013, p. 188), “large cage motors can only be plugged if the supply can withstand the very high currents involved”. Speed sensing relays are also important for plug braking, because without a speed sensing relay the motor would just start rotating in the opposite direction.

DC injection braking involves injecting DC into the stator of the motor which results in a non-moving rotating field, leaving the rotor to spin based on its own inertia and temporarily turning the motor into a generator.

Frequency reduction is self-explanatory, and involves using VFDs (variable frequency drives or variable speed drives) to vary the frequency of the supply, resulting in a slower rotating field.

## 2. Simulation

Task 2 of the assignment involved using simulations to predict the performance of a three-phase wound-rotor induction motor, these simulations were made in a spreadsheet which were used to make two graphs; first, a torque against fractional-slip graph and secondly, a rotor current against fractional-slip graph. The assignment brief states that "data must be generated from values of fractional-slip between -1 and 2, in increments of 0.1" and the following motor information was provided:

- Open circuit EMF between slip-rings = 161.6V
- Rotor Resistance = 4.8  $\Omega$
- Locked rotor Reactance = 39.6  $\Omega$
- Supply Frequency = 50Hz
- Motor poles = 2

### 2.1 – Fractional Slip Against Torque

The first graph to be produced was the fractional-slip against torque graph, which uses the equation

$$T = \frac{1}{2\pi ns} * \frac{s^2 |E_2|^2 R_2}{(R_2^2 + s^2 X_2^2)} \text{ for torque. The graph can be seen in the figure below.}$$

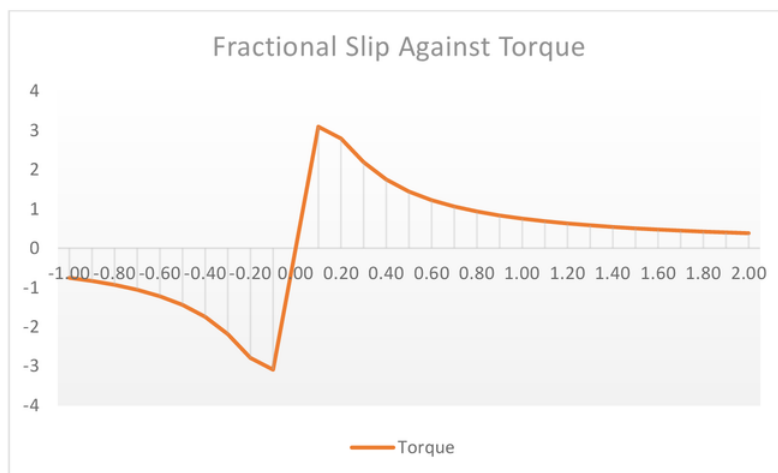


Figure 2 - Fractional Slip Against Torque Graph

The fractional slip is along the x-axis, ranging from -1 to 2 in increments of 0.2. What can be observed from the graph is that as the fractional slip crosses over from negative to positive, the torque rapidly decreases to the negative peak and then linearly increases to the positive. What can

be deduced from the graph is that for small values of fractional slip between -0.1 to 0.1, torque is proportional to fractional slip, this is because in the torque equation  $T = \frac{1}{2\Omega ns} * \frac{s^2 |E_2|^2 R_2}{(R_2^2 + s^2 X_2^2)}$  the numerator would be very close to zero due to the fact that the fractional slip (denoted as S in the torque equation) of 0.1 would be squared, resulting in a negligible value. Also, the further from -0.1 or 0.1 the fractional slip becomes, the less torque is in the system.

Using the fractional slip against torque graph it is possible to determine whether the motor is motoring, generating, or braking by putting a vertical line through a fractional slip value of 1 to create quadrants.

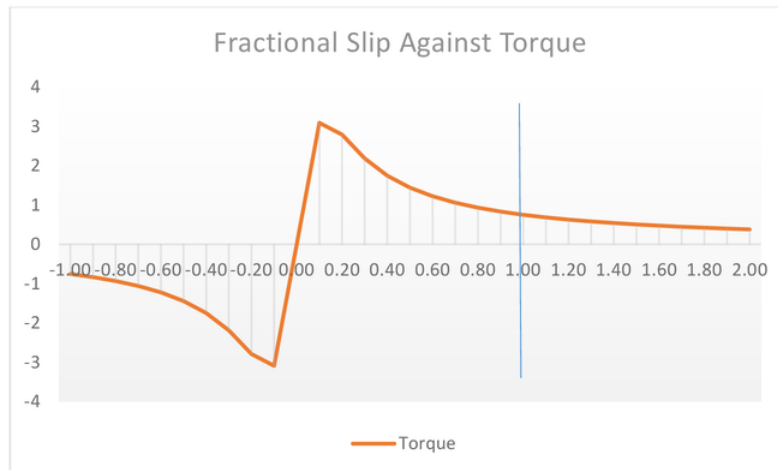


Figure 3 - Fractional Slip Against Torque Graph with Quadrants

When the fractional slip is going from -1 to 2, as the figure above is, the braking part of the motor would be in the top-right part of the quadrant i.e. from 1 to 2, the motoring part would be on the top-left part of the quadrant i.e. from 0 to 1, and the generating part would be on the bottom-left part of the quadrant i.e. from -1 to 0. Definitions of motoring, braking, and generating are:

**Motoring** – When the rotor is rotating slower than the stator field ( $n_R < n_s$ )

**Braking** – The rotor is being driven in the opposite direction to the stator field ( $n_R < n_s$ ), the most common methods of braking are plug braking, frequency reduction and DC injection

**Generating** – The rotor is rotating faster than the stator field ( $n_R > n_s$ ), this is only achieved with a complementary motor known as a 'prime mover' or a load

## 2.2 – Fractional Slip Against Rotor Current

The second graph to be produced was the fractional-slip against rotor-current graph, which uses the equation  $|I_2| = \frac{s|E_2|}{\sqrt{R^2 + s^2 X^2}}$  for rotor-current. The graph can be seen in the figure below.

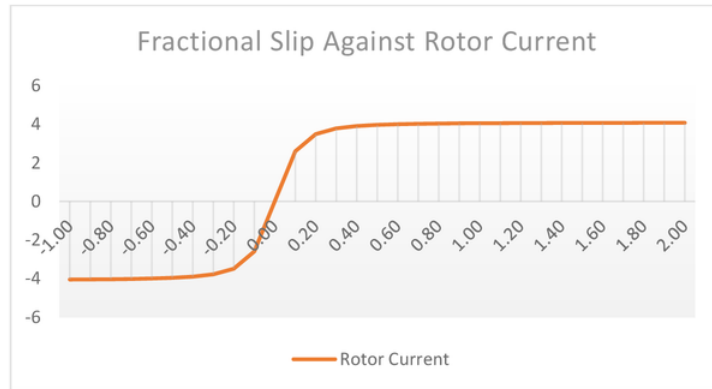


Figure 4 - Fractional Slip Against Rotor Current Graph

The fractional slip is along the x-axis, ranging from -1 to 2 in increments of 0.2. What can be observed from the graph is that until the fractional begins to approach zero, the rotor current is at a steady -4A, and as it approaches 0.4 it begins to crossover to a positive current, to the point where it's linear from -0.1 to 0.1, and finally at a current of ~4A from 0.4 onwards.

Combining both graphs sheds some light on what is happening with the rotor current, below is a graph that shows fractional slip against torque and rotor current.

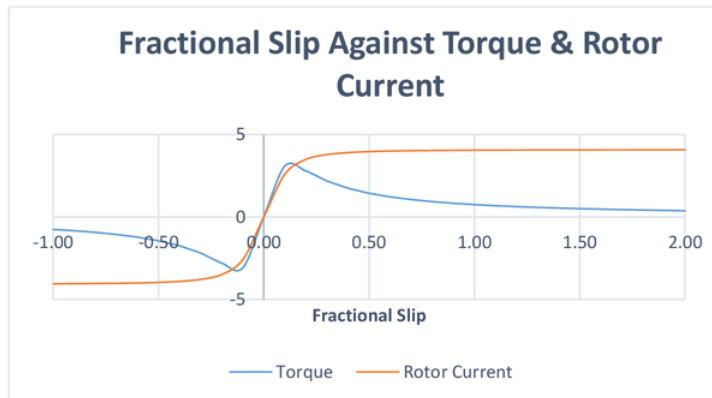


Figure 5 - Fractional Slip against Torque and Rotor Current Graph

What can be deduced from this is that rotor current is negative when the motor is generating, there is a negative rotor current and when the motor is motoring or braking, there is a positive rotor current.

### 3. Practical Investigation

A practical investigation was carried out which involved using a wound-rotor induction motor connected in DELTA coupled with a VSD motor and prony brake; instruments were used to gather readings of the numerous variables of the setup. Following the procedure from the assignment, the data below was obtained.

| Speed | Fractional Slip | Volts | Amps  | Watts | Power Factor | VAr  | VA  | Torque |
|-------|-----------------|-------|-------|-------|--------------|------|-----|--------|
| 2900  | 0.033333333     | 214   | 0.593 | 122   | 0.55         | 184  | 220 | 0      |
| 2850  | 0.05            | 213   | 0.656 | 160   | 0.67         | 177  | 237 | 0.1    |
| 2800  | 0.066666667     | 212   | 0.761 | 220   | 0.78         | 172  | 277 | 0.2    |
| 2750  | 0.083333333     | 212   | 0.839 | 255   | 0.82         | 174  | 302 | 0.4    |
| 2700  | 0.1             | 211   | 0.909 | 282   | 0.85         | 175  | 333 | 0.6    |
| 2650  | 0.116666667     | 211   | 0.985 | 313   | 0.87         | 176  | 356 | 0.65   |
| 2600  | 0.133333333     | 211   | 1     | 337   | 0.88         | 173  | 377 | 0.65   |
| 2550  | 0.15            | 210   | 1.14  | 368   | 0.9          | 181  | 498 | 0.75   |
| 2500  | 0.166666667     | 210   | 1.21  | 416   | 0.91         | 190  | 457 | 0.9    |
| 2450  | 0.183333333     | 209   | 1.19  | 392   | 0.91         | 182  | 433 | 0.95   |
| 2400  | 0.2             | 209   | 1.35  | 445   | 0.92         | 190  | 481 | 1.1    |
|       |                 |       |       |       |              |      |     |        |
|       |                 |       |       |       |              |      |     |        |
| Speed | Fractional Slip | Volts | Amps  | Watts | Power Factor | VAr  | VA  | Torque |
| 3000  | 0               | 215   | 0.53  | 41    | 0.2          | 194  | 198 | 0      |
| 3050  | -0.016666667    | 215   | 0.54  | 21.9  | 0.11         | 198  | 201 | 0      |
| 3100  | -0.033333333    | 215   | 0.56  | 14.5  | 0.07         | 205  | 205 | 0      |
| 3150  | -0.05           | 216   | 0.56  | 41.7  | -0.2         | -209 | 214 | 0      |
| 3200  | -0.066666667    | 215   | 0.57  | 44.5  | -0.21        | -209 | 215 | 0      |
| 3250  | -0.083333333    | 215   | 0.526 | 43.5  | 0.22         | 191  | 196 | 0      |
| 3300  | -0.1            | 215   | 0.53  | 51.7  | 0.27         | 188  | 196 | 0      |
| 3350  | -0.116666667    | 216   | 0.53  | 54.2  | 0.27         | 191  | 198 | 0      |
| 3400  | -0.133333333    | 215   | 0.53  | 55.3  | 0.28         | 190  | 197 | 0      |
| 3450  | -0.15           | 214   | 0.533 | 55.6  | 0.28         | 191  | 199 | 0      |
| 3500  | -0.166666667    | 215   | 0.534 | 57.5  | 0.29         | 191  | 200 | 0      |

Figure 6 – Practical Investigation Data

The first thing to note about the data is that at the no-load speed of 3000RPM, the fractional slip results in zero; this corroborates with the data from simulations and corroborates with the slip calculation  $S = \frac{ns - nr}{nr}$ . The slip also becomes negative above the no load speed (effectively becoming a generator) and positive below the no-load speed, which also corroborates with the simulations and calculations. Due to there being no data for torque above the no-load speed, the generating could not be compared with the simulations, however a graph could be made for the data collected below the no-load speed, showing the motoring part of the graph. That graph is shown in the figure on the next page, labelled "Practical Torque Against Fractional Slip Graph".

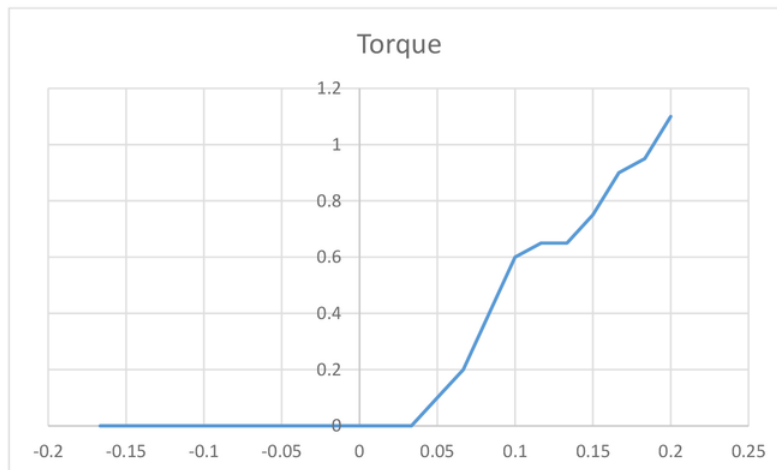


Figure 7 - Practical Torque Against Fractional Slip Graph

There was no torque above the no-load speed during the practical because the rotor was effectively being driven by an external force. The torque against fractional slip isn't very smooth, but using a line of best fit it seems to be very similar to the same graph that was simulated; the ruggedness of the practical graph could be accounted for by the lack of calibration of or misuse of tools.

The data also shows that as the speed is decreased from 3000RPM to 2400RPM, the current is gradually increasing. This is because the speed was reduced using a brake, which acts as a load – and the motor is trying to overcome this “load”, resulting in more drawn current; this also results in a higher apparent power (VA).

The power factor of the system decreases with the speed of the motor – when the speed is 2400RPM, the power factor is at a peak of 0.92, but when the speed is 2900RPM, the power factor is as low as 0.55. When the speed goes to 3000RPM and above, the power factor drops drastically to the point where there is even a negative power factor – this is a resultant of the motor effectively becoming a generator due to the rotor travelling faster than the stator field. A negative power factor results in negative reactive power (VAR), which throughout the data remains within the range 175-198VAR, except when the power factor is negative, at which point the values of VAR become negative too (seen at 3150-3200RPM), this is because the equation for reactive power is  $Q = VI \sin(\theta)$  where  $\sin \theta$  is power factor.

## 4. Conclusions and Recommendations

The calculations carried out for the simulations and the simulations themselves that were carried out in section 2 of this report proved useful moving forward as they provided a strong understanding of what was to be expected in the practical. The torque against fractional slip simulation graph that was produced proved particularly useful because it could later be compared to a torque against fractional slip graph that was developed using readings obtained using tools on a practical build. The comparison that was drawn showed that they were similar if a line of best fit was drawn, but the results obtained from the practical build were somewhat inconsistent, and this could have been due to misuse of tools or poor calibration on measuring tools.

Simple observations about the operation of induction motors from the practical are that as the speed of the rotor reaches an RPM higher than the no-load speed, the fractional slip becomes negative, which can be an indicator that the motor is essentially a generator at that point – this corroborates with findings in the research section of the report. Another observation that was made was that the current was increasing as the speed was decreasing, this is because of the method of speed control that was used, which was essentially a brake that was being tightened, making the motor draw more current in order to compensate for the loss of speed.

## 5. Citation List

Hughes, A. (2013). *Electric Motors and Drives*. Newnes.

Hughes, E. (2016). *Hughes Electrical and Electronic Technology*. Pearson Education.

Reeves, E. A. (1989). *Newnes Electrical Pocket Book*. Oxford: Heinemann Professional Publishing LTD.

Wildi, T. (2013). *Electrical Machines, Drives and Power Systems: Pearson New International Edition*.  
Pearson Education M.U.A.

# Assignment 1 Joseff Jones

## GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

57 /100

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GRADING FORM: CSG-RUBIC

JOSEFF JONES

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## RESEARCH-INFORMED LITERATURE

-  Section 1: Your research - Good evidence of reading covering many aspects of induction motors. Further marks were available for more detail and one important method of speed control namely the use of an inverter. (16/25) Correct method of citation used (though page numbers should have been suppressed in most cases) from a small range of sources listed. (2/5) **18**

## KNOWLEDGE AND UNDERSTANDING

-  Generally good with one misconception noted. (6/10) Brief explanation given. Further marks were available for a full description of the setup which could have included a schematic diagram and photo. (4/10) **10**

## ANALYSIS

-  Good evidence of analysis with further marks were available for identifying optimum regions of operation. (7/10) Some analysis carried out but results could have been explained with reference theory, rather than simply described. (5/10) A few conclusions offered but no recommendations. (4/10) **16**

## PRACTICAL APPLICATION AND DEP.

-  Results were well presented as graphs but tables of data should also have been included. (3/5) Results were well presented as tables with one graph plotted. (3/5) **6**

## SKILLS FOR PROFESSIONAL PRAC.



Very good structure and presentation with a useful list of figures. (7/10)

**7**