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SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

# External resistors of wound rotor motor

Tesi di Laurea Magistrale in
Electrical Engineering - Ingegneria Elettrica

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Academic Year: 2021-22

# Abstract

The external rotor circuit of a wound-rotor induction motor was studied in this Thesis. The relation between torque, speed, and current shows that it is possible to control the speed of the rotor by including resistor sections in the circuit. Firstly, we have calculated the current of the rotor circuit by analyzing the constructional features of the wound rotor motor. The main focus of the following chapters was the design and calculations for each step of the external resistor on the basis of the relationships between torque-speed and current-speed. The Thesis is divided into two sections: one is a theoretical approach, and the other is a practical approach. In both parts design of external resistors was examined. Despite the fact that the two methods are similar and based on the same theory, in cases where there is less knowledge of data, a practical approach is proposed, by taking into account some prior knowledge of the operation of the motor.

**Keywords:** External rotor, wound rotor induction motor.

# Abstract in lingua italiana

In questa Tesi si studia il circuito esterno collegato all’avvolgimento di rotore di una macchina ad induzione a rotore avvolto. La relazione fra coppia, corrente, velocità mostra che è possibile controllare la velocità del rotore includendo sezioni di resistori nel circuito. In primo luogo, abbiamo calcolato la corrente del circuito del rotore analizzando le caratteristiche costruttive del motore ad anelli. L'obiettivo principale dei capitoli seguenti è la progettazione e il calcolo di ogni fase del resistore esterno sulla base delle relazioni coppia-velocità e corrente-velocità. La tesi è divisa in due sezioni: una è un approccio teorico e l'altra è un approccio pratico. In entrambe le parti è stata esaminato il progetto di resistori esterni. Nonostante i due metodi siano simili e basati sulla stessa teoria, nei casi in cui vi sia una minore conoscenza dei dati, si propone un approccio pratico, tenendo conto di alcune conoscenze pregresse del funzionamento del motore.

**Parole chiave:** rotore esterno, motore ad anelli.

# Contents

# Introduction

The induction motor has two main types: wound rotor and squirrel cage. As the name suggests they vary for the structure of the rotor. A wound rotor induction motor (WRM) is most commonly used in applications where speed control and high starting torque are needed. It is achieved of the special structure of the rotor which is connected with external resistors. The operating speed of the motor is different from than synchronous speed, therefore it is also called the asynchronous motor. The wound-rotor induction motor has the same number of poles in the stator and rotor. There are three insulated windings in the rotor of WRM. Each of those windings is connected to slip rings through brushes. The brushes are connected to the rheostat that is in a three-phase connection. In bellow, the diagram represents the electrical scheme of the wound rotor motor [4].

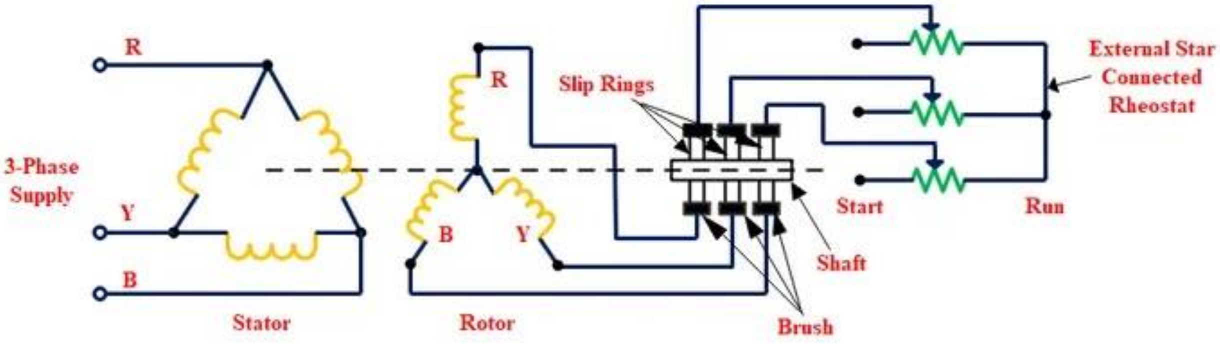


Fig.1: Electrical scheme of WRM

The torque of a slip ring or wound rotor induction motor is increased by using a star-connected rheostat to add external resistance to the rotor circuit. As the motor's speed rises, the rheostat resistance is gradually reduced. This increased resistance lowers the rotor current by increasing the rotor impedance. Full line voltage is almost always applied across the stator terminals when the slip ring induction motor is started. In the rotor circuit, a variable resistance is used to adjust the starting current value. The controlling resistance is in a star-connected rheostat, which gradually loses resistance as the motor speeds up. When the rotor resistance is raised, the rotor current is lowered, resulting in a reduction in stator current, but an increase in torque owing to the enhanced power factor. As previously stated, the higher resistance in the rotor circuit enables the slip-ring motor to provide a high beginning torque with a low starting current. As a consequence, a winding rotor or slip ring motor may be started at any moment when there is some load. While the motor is functioning normally, the slip rings are shorted and the brushes are removed.

The resistance in the rotor circuit can be controlled to adjust the speed of a WRM. It can be achieved only wound rotor type of induction motors. When the motor is running and all steps of resistors in the rotor circuit are connected, the motor's speed drops. When the motor's speed is reduced, more voltage is induced in the rotor circuit to produce the required torque. As a result, torque rises. Similarly, the motor's speed rose as the rotor resistance was reduced.

The torque of a three-phase induction motor is proportional to flux per stator pole, rotor current, and the power factor of the rotor:

$$T = k \cdot \phi \cdot I_2 \cdot cos\phi_2$$

where, $\phi$ = flux per stator pole,

$I_2$ = rotor current at standstill,

$\phi_2$ = angle between rotor E.M.F. and rotor current,

k = a constant.

Now, let $E_2$ = rotor E.M.F. at standstill

we know, rotor E.M.F. is directly proportional to flux per stator pole, therefore:

$$T = k_1 \cdot E_2 \cdot I_2 \cdot cos\phi_2$$

$E_2$ of a WRM is induced E.M.F. in rotor conductors due to rotation of the armature in a magnetic field [3]. The magnitude of $E_2$ can be given by the E.M.F. equation of WRM:

$$E_2 = \frac{P \cdot \emptyset \cdot N \cdot Z}{60 \cdot A}$$

where: P = number of poles,

$\emptyset$ = flux/pole,

N = speed in rpm,

Z = number of rotor conductors,

A = parallel paths.

thus, from the above equations

$$N = \frac{E_2 \cdot 60 \cdot A}{P \cdot \emptyset \cdot Z}$$

$E_2$ can also be given as,

$$E_2 = V - I_2 \cdot R_2$$

That means, when supply voltage V and the rotor resistance R2 are kept constant, then the speed is directly proportional to rotor current I2. Thus, if we add resistance in series with the rotor, I2 decreases and, hence, the speed also decreases. By increasing the resistance of the rotor circuit, we will see a decrease in speed. The slip ring induction motor's speed-torque characteristics are shown in the diagram below.

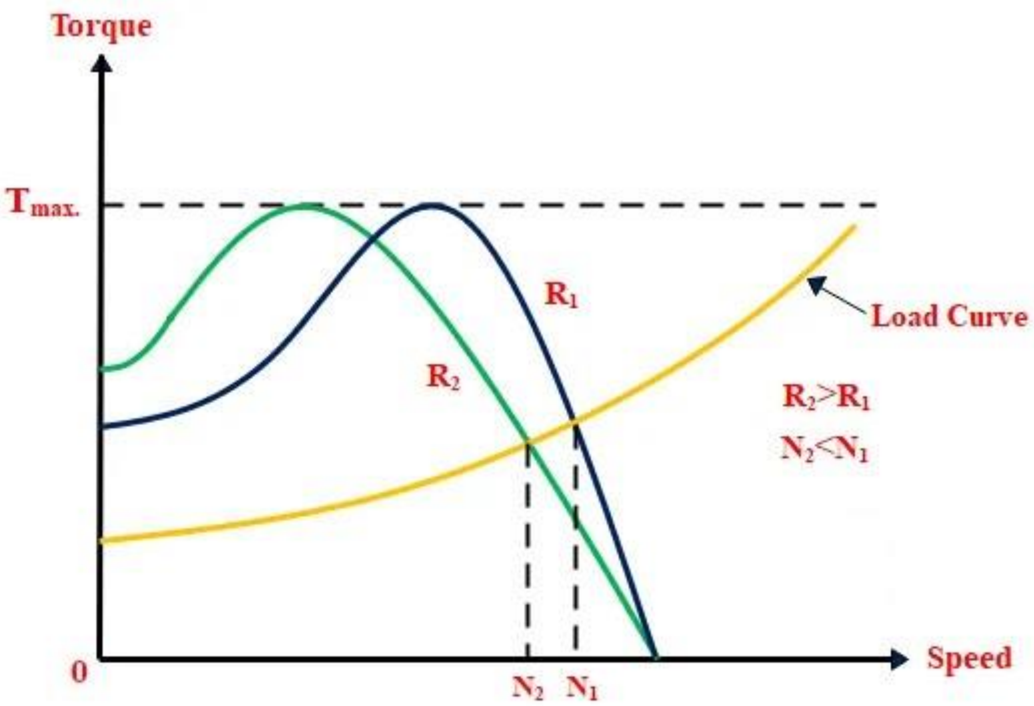


Fig.2: Torque-Speed Characteristics of WRM

When the rotor resistance per phase is R1, the motor's speed becomes N1. A blue line represents the torque-speed characteristics of the motor at R1. The motor's speed is reduced to N2 when the per-phase rotor resistance is changed to R2. The torque-speed characteristics of the motor at R2 are shown by a green line.

The slip rings on a wound rotor motor's rotor shaft are used to connect external resistance in the rotor circuit in the form of a star-connected rheostat. Slip rings are electromechanical devices that transfer power or electrical signals from fixed components to rotating components. Slip rings are also known as electrical rotary couplings, electrical rotary interfaces, and collector rings.

There are some of the benefits of WRM because of which it is still widely used in industry:

- Due to the presence of external resistance in the rotor circuit, slip ring induction motors can generate high beginning torque.
- When compared to squirrel cage motors, slip ring induction motors have a considerable overload capacity and offer smooth acceleration under heavy loads.

- Low starting current — The extra resistance in the rotor circuit lowers the rotor impedance, reducing the starting current.
- Controllable speed – speed can be controlled by switching steps of the rotor circuit resistance.
- Optimization of power factor

In this paper, the main concepts of sizing of external resistors for WRM will be covered along with its constructional features. The calculation will be performed in two methods: precise theoretical calculation and practical calculation. Both methods are essential for many reasons, for example in real-life situations usually not all data is available to perform more precise theoretical calculations so engineers use a practical approach to the case.

# 1| Chapter one

## 1.1 Constructional features.

The following are the primary structural characteristics of IMs:

- The air gap is typically very small (less than 1/100 of the polar pitch) to limit no-load current and thus achieve a high power factor at load; however, the air gap width must be sufficient to avoid rubbing between the rotor and stator caused by, for example, a shaft or a case deformation or bearing wear.
- The rotor winding has few conductors per slot and is made of bars: it is a double layer wave winding with lap end windings; the stator winding has many conductors per slot and is made of wires: it is a single layer spiral winding with concentric end windings on two levels; an important component of wound rotors is the device used to short circuit the winding and lift the brushes during normal operation.
- The case and shaft must be extremely strong, both to allow for a small air gap and to avoid vibrations and noise; the shaft is sized according to its deflection (which should not exceed 1/6 of the air gap), and is typically oversized in terms of torsion and bending resistance.

## 1.2 Equivalent circuit and important parameters.

It is decided to use an equivalent circuit identical to the one used for the transformer to better understand how wound rotor induction motors work. It is shown in Fig.3 with the shunt branch after the primary impedance [1].

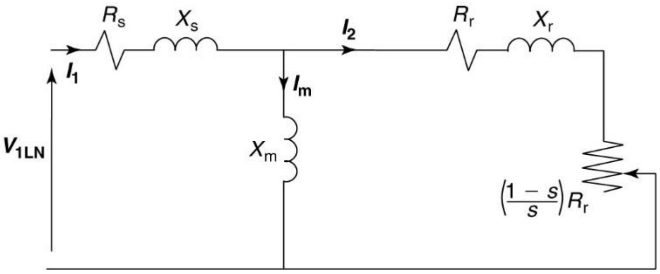


Fig.3: Simplified equivalent circuit

Since the frequency of a secondary circuit is different from that of a primary circuit, the secondary values must be linked to not only primary winding data but also primary frequency to be considered valid.

As for referring the secondary winding data back to the primary winding data, the referred quantities have a definite physical meaning, which is similar to that of the transformer: the secondary quantities referred to the primary are those quantities that would exist in the secondary if the secondary winding (with the same total copper cross-section and overall dimensions, as well as the same winding factor) had the same number of phases and the same number of conductors as the primary winding. Similar to how primary quantities are referred to as secondary quantities in the transformer, secondary quantities that are referred to as primary quantities are very near in magnitude to the corresponding primary values.

Let us evaluate the referring factors for the wound rotor (where one rotor phase is referred to as one stator phase, and the phase numbers are m1 and m2 for the stator and rotor, respectively).

The voltage transfer factor ($K_v = V_2'/V_2$) is calculated by equating the induced e.m.f.s in a primary active conductor and a secondary active conductor; in both situations, the following holds:

$$K_V = \frac{k_{w1} \times U_1}{k_{w2} \times U_2} \qquad 1.1$$

$k_w$ – winding factor $k_w = k_p \times k_d$

The armature winding for each phase is divided into several slots. The phasor sum of the EMFs created in distinct slots is smaller than their numerical sum due to the phase displacement of the slots. The distribution factor $k_d$ is the name given to this reduction factor. When the slot pitch is less than the pole pitch, the phasor sum of the EMFs created in the go and return conductors of each turn is smaller than their numerical sum. The pitch factor $k_p$ is the name given to this reduction factor.

By equating the secondary and primary total current, the current transfer factor ($K_I = I_2'/I_2$) is obtained; by excluding the common elements, we obtain $m_1 * k_{w1} * U_2 * I_2' = m_2 * k_{w2} * U_2 * I_2$

$$K_I = \frac{m_1 \times k_{w1} \times U_1}{m_2 \times k_{w2} \times U_2} \qquad 1.2$$

The impedance transfer factor (more precisely, the resistance and reactance transfer factors) is equal to the ratio of the two preceding components ($K_Z = Z_2'/Z_2 = K_V/K_I$), and is defined as follows:

$$K_z = \frac{m_1}{m_2} \times \left(\frac{k_{w1} \times U_1}{k_{w2} \times U_2}\right)^2 \qquad 1.3$$

Once we have all of these parameters, we can calculate the actual value of the rotor's resistance. Let N_des denote the desired speed and $I_s$_des denote the desired stator current. From N_des, it is possible to determine the corresponding slip value s_des. By imposing Is = $I_s$_des and s = s_des on the equivalent circuit, we can determine the required value of $R_r'$_des (that is, the value of $R_r'$ that results in s = s_des when $I_s$ = $I_s$_des). We calculate the corresponding value of Rr from Rr'_des using the impedance transfer factor ($K_z$):

$$R_r = R_r'/K_z \qquad 1.4$$

$R_r$ is the physical value of the phase resistance of the rotor windings. External resistor evaluation methods will be discussed in the following subsection.

## 1.3 Selection of external rotor resistance

Two factors will help you choose the external resistance that should be added to the rotor circuit during start-up: how much torque you need and how much current the stator can handle. Because $T_s$ and $I_s$ are linked, any limitations in one will affect the size of the other. With the help of a circle diagram or torque and current curves from the motor manufacturer, it is possible to figure out the value of the stator current that goes with a certain amount of torque and the other way around. These curves can also help you figure out how quickly this torque will slip in its operating range (Fig.4). For this stator current, the corresponding rotor current can be found and the resistance in the rotor circuit can be calculated to get this current [2].

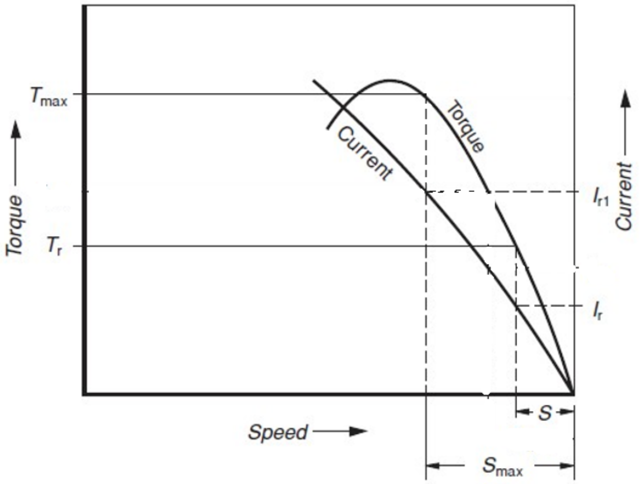


Fig. 4: Torque and current curves operating area

Let us define the following quantities:

Stator full load current = $I_r$

Corresponding rotor current RA = $I_{rr}$

Rotor standstill voltage = ${}_{ss}e_2$

Voltage of the rotor at a specific speed RV = $S \cdot {}_{ss}e_2$

Rotor resistance = $R_2$

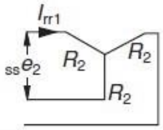
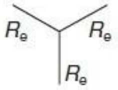
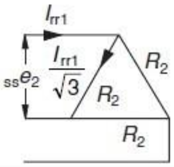
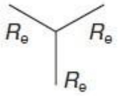
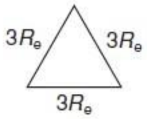
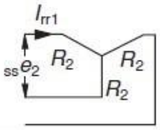
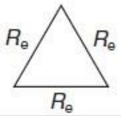
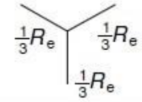
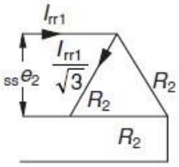
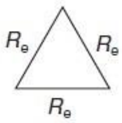
External resistance = $R_e$

Total rotor circuit resistance = $R_{21}$

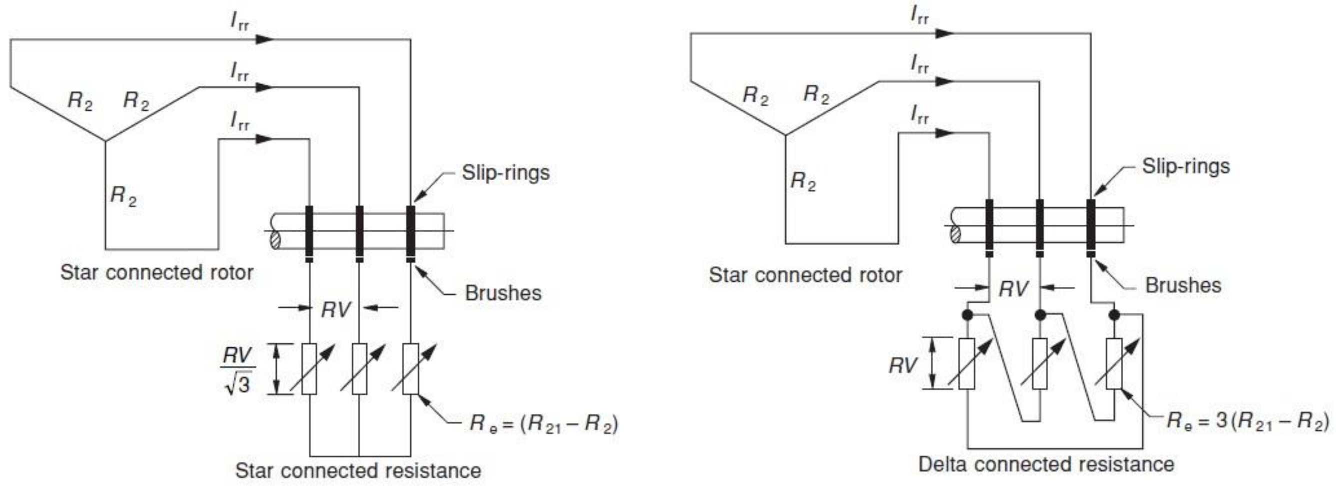
Then, by assuming proportionality between current and torque, for a stator current of $I_{r1}$, corresponding to a starting torque of $T_{max}$, the required rotor current $I_{rr1}$ will be

$$I_{rr1} = \frac{I_{r1}}{I_r} \times I_{rr} \tag{1.5}$$

To produce this rotor current, the desired rotor circuit resistance $R_{21}$ may be calculated as shown in the following table, according to the rotor winding and external resistance configuration:

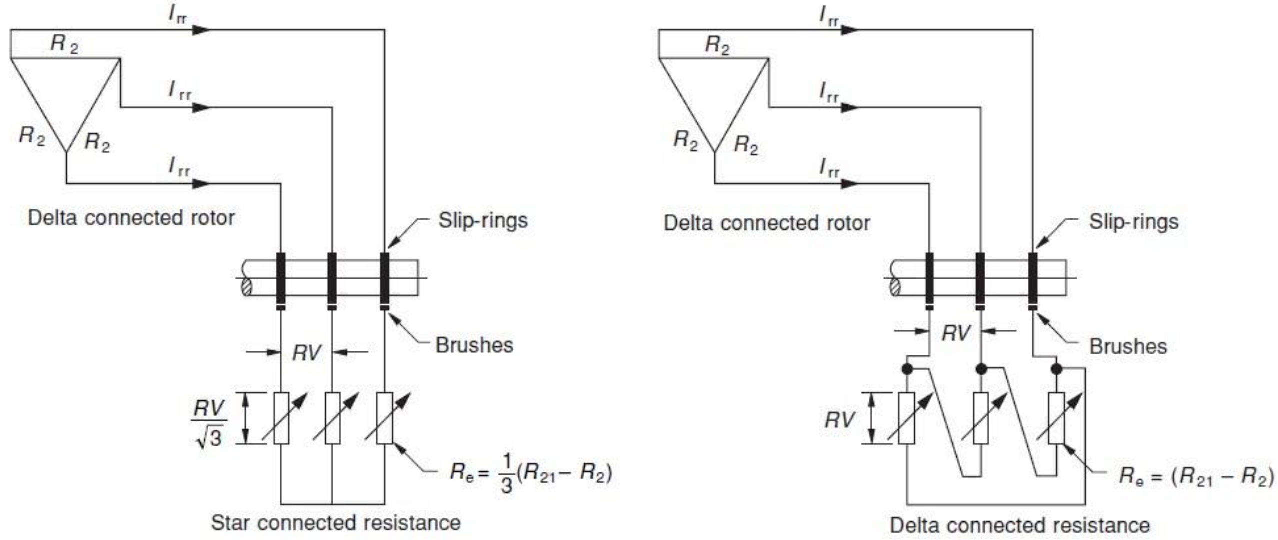
| *Sl. no.* | *Rotor configuration* | *External resistance* | | | *Total rotor circuit resistance* |
|---|---|---|---|---|---|
| | | *Configuration* | *Figure* | *Equivalent configurations of the rotor* | |
| 1 |  |  | 5(a) | — | $R_{21} = R_2 + R_e = \frac{_{ss}e_2}{\sqrt{3}\cdot I_{rr1}}$ |
| 2 |  |  | 5(b) |  | $R_{21} = R_2 + 3R_e = \frac{\sqrt{3}\,{_{ss}e_2}}{I_{rr1}}$ |
| 3 |  |  | 5(c) |  | $R_{21} = R_2 + \frac{1}{3}R_e = \frac{_{ss}e_2}{\sqrt{3}\cdot I_{rr1}}$ |
| 4 |  |  | 5(d) | — | $R_{21} = R_2 + R_e = \frac{\sqrt{3}\cdot {_{ss}e_2}}{I_{rr1}}$ |

It should be noted that when the resistance configuration differs from that of the rotor, the resistance configuration must first be changed to the rotor's equivalent configuration to perform computations. Typically, external resistances are linked in a star configuration. However, for bigger motors that need high resistance grids, they may also be coupled in delta configuration to minimize their current rating and hence cost. Generally, in the case of resistance grids, insulation is not a key barrier.



(a) (b)

Fig. 6: Representation of Star connected rotor connection. (a) – Star-connected External resistors; (b) – Delta-connected External resistors.



(a) (b)

Fig. 7: Representation of Delta connected rotor connection. (a) – Star-connected External resistors; (b) – Delta-connected External resistors.

## 1.4 Method of cutting off the external resistance

Once the entire external resistance is determined, the resistance unit may be constructed with a manually controlled mechanism for cutting off the external resistance. This strategy, however, is appropriate only for situations where the value of torque during the pick-up phase (torque at various speeds) is insignificant. There is no control over the start time or the resistance in the circuit (torque at various speeds) during the start-up phase with these starters. One form is liquid rotor starters, which are only appropriate for mild duty. To take up heavy loads that need precise torque values, appropriate resistances must be injected into the rotor circuit at precise rates. As detailed below, the needed resistances may be computed and fabricated in the shape of a grid. Contactors and timers are then used to regulate these resistance grids. The time interval between each step of the resistance grid is predetermined, the torque demand is known in advance, and the resistance needed at each step is computed in advance. The starter may then be converted to a completely automated touch operation. At each phase, the full resistance is progressively and automatically removed, while preserving the preset torque profile.

Let us consider an example

- P = 125 kW
- V = 415 V
- 3 phases in star configuration
- $I_r$ = 230 A
- $_{ss}e_2$ = 500 V
- $I_{rr}$ = 180 A
- $R_2$ = 0.09 ohm (star configuration)

Figure 8 shows the torque and current curves. Calculate the amount of external resistance needed to provide a 200% initial torque.

The per-unit curves show that the stator current should be 250 % higher for a 200 % torque, or $230 \times 2.5\ A$.

<u>*Rotor current:*</u>

$$I_{rr1} = \frac{180}{230} \times 230 \times 2.5$$

<u>*Resistance of rotor in a star configuration referring to Fig.5(a):*</u>

$$R_{21} = \frac{500}{\sqrt{3} \times 180 \times 2.5} = 0.641\ Ohm$$

<u>*External resistance:*</u>

$R_e\ =\ 0.641 - 0.09\ =\ 0.551$ Ohm per phase

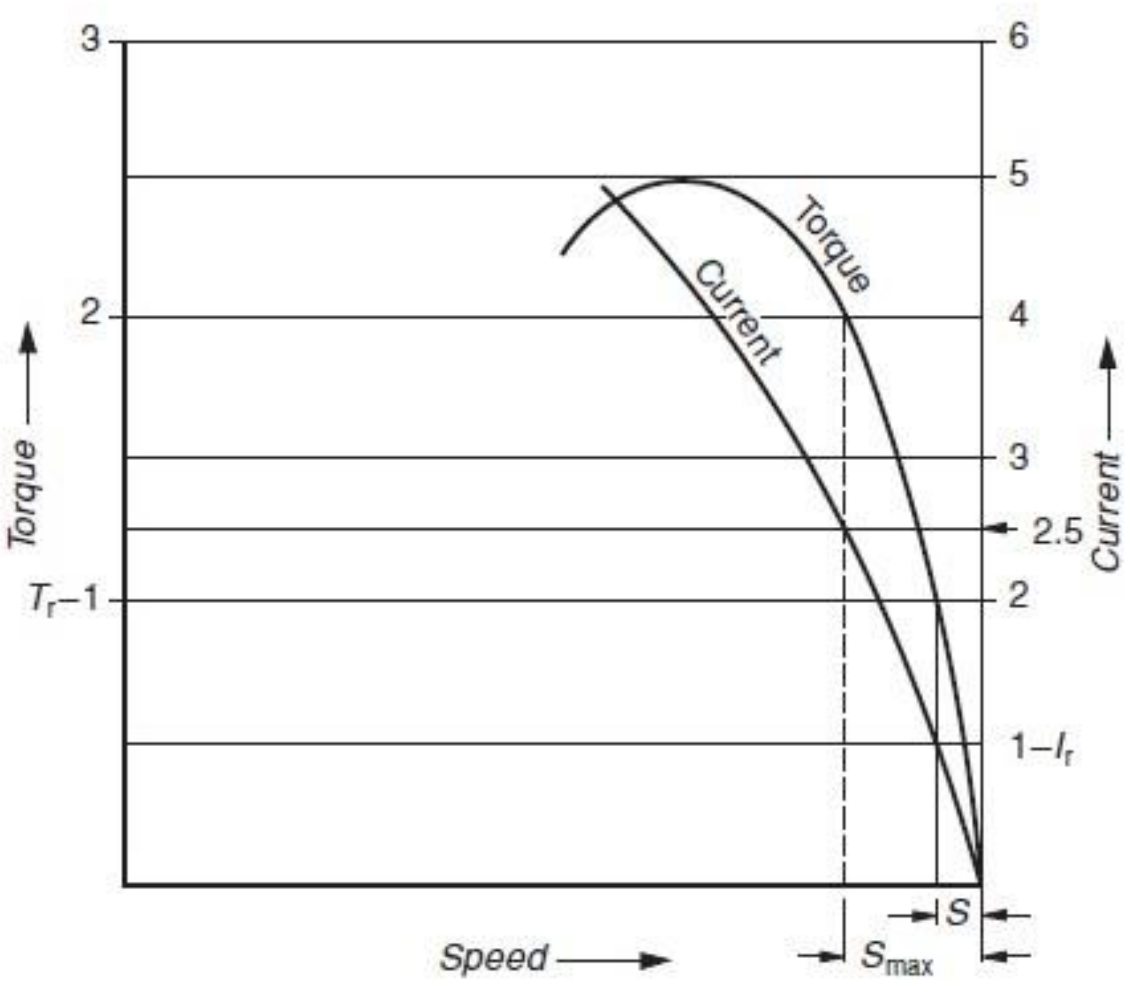


Fig.8: Dependence curve of torque and current from speed;
quantities are expressed in p.u. for rated current $I_r$ and rated torque $T_r$.

## 1.5 Calculating the steps of external resistance and the starting time

Let us consider a resistance unit with five steps (Fig. 9), where $R_{21}$, $R_{22}$, ..., $R_{25}$, and so on are the total rotor resistances per phase after the external resistances have been introduced. Let $S_{max}$ be the slip at the operating point when the torque $T_{max}$ or current $I_{max}$ occurs. The torque and current curves provided by the motor manufacturer may be used to determine this (Figure 8). Let us assume that the maximum and minimum torques are $T_{max}$ and $T_{min}$ between each stage to fit a certain load requirement (Figure 10). Let's call the rotor currents $I_{max}$ and $I_{min}$ their appropriate values.

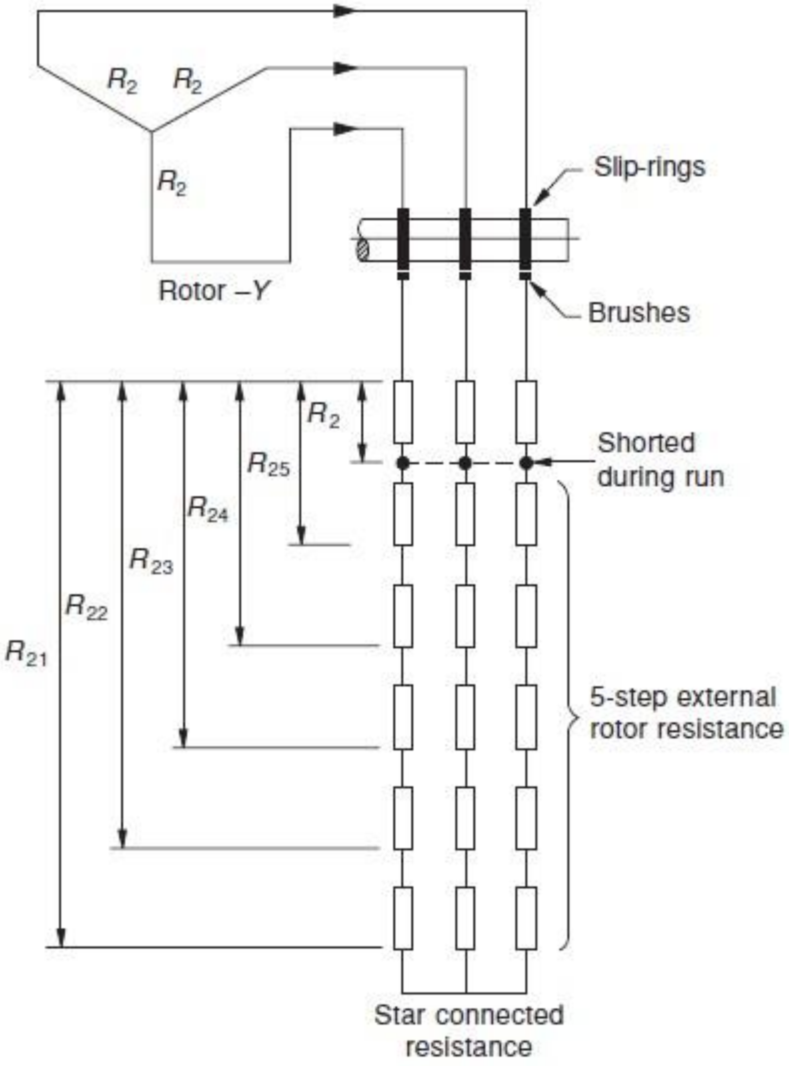


Fig. 9: External resistance divided into 5 steps

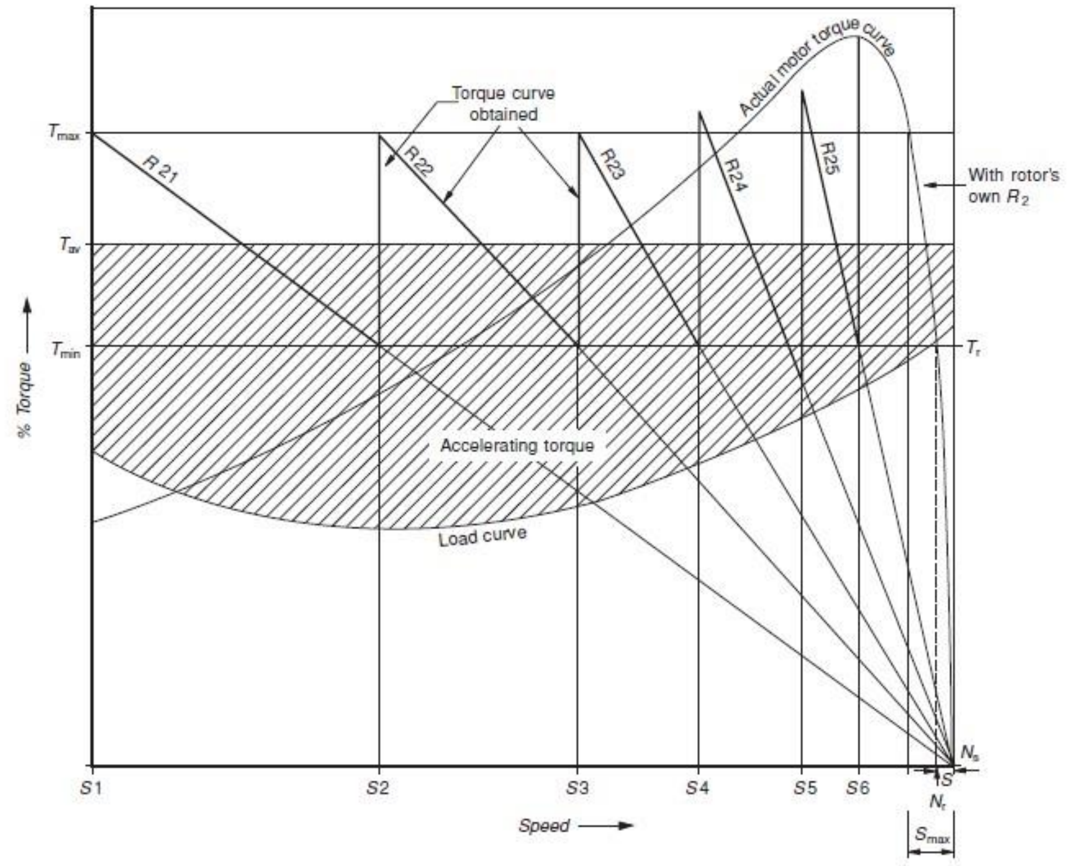


Fig.10: Curve of torque for each step external resistance

Let us impose that all the Imax are equal:

$$I_{max} = \frac{sse_2}{\sqrt{(R_{21}/S_1)^2+ssX_2{}^2}} = \frac{sse_2}{\sqrt{(R_{22}/S_2)^2+ssX_2{}^2}} \ldots \qquad 1.6$$

$$\frac{R_{21}}{S_1} = \frac{R_{22}}{S_2} = \ldots = \frac{R_2}{S_{max}} \qquad 1.7$$

$$R_{21} = S_1 \times \frac{R_2}{S_{max}} \qquad 1.8$$

When $S_1$=1 at the start of the operation,

$$R_{21} = \frac{R_2}{S_{max}} \qquad 1.9$$

Now, let us impose that all the $I_{min}$ are equal:

$$I_{min} = \frac{sse_2}{\sqrt{\left(\frac{R_{21}}{S_2}\right)^2 + ssX_2^2}} = \frac{sse_2}{\sqrt{\left(\frac{R_{22}}{S_3}\right)^2 + ssX_2^2}} = \cdots \tag{1.10}$$

$$\frac{R_{21}}{S_2} = \frac{R_{22}}{S_3} = \ldots = \frac{R_{25}}{S_{max}} \tag{1.11}$$

From eq. 1.7 and 1.11

$$\frac{I_{min}}{I_{max}} = \frac{S_2}{S_1} = \frac{S_3}{S_2} = \cdots = \frac{R_{22}}{R_{21}} = \frac{R_{23}}{R_{22}} = \cdots = \frac{R_2}{R_{25}} = \beta \tag{1.12}$$

$$R_{22} = \beta \times R_{21} \tag{1.13}$$

$$R_{23} = \beta \times R_{22} = \beta^2 \times R_{21} \ldots \tag{1.14}$$

$$R_2 = \beta \times R_{25} = \beta^5 \times R_{21} \tag{1.15}$$

then

$$R_2 = \beta^5 \times \frac{R_2}{S_{max}} \ or\ \beta^5 = S_{max} \tag{1.16}$$

$$\beta = \sqrt[5]{S_{max}} \tag{1.17}$$

This may be used to a variety of resistance levels α:

$$\beta = \sqrt[\alpha]{S_{max}} \tag{1.18}$$

The resistance value for each level may be evaluated once β is known.

Let us apply this procedure to the previous motor. Consider the case of a rotor resistance unit with five distinct portions (with a total of six steps of control).

Then, in the preceding example (Figure 8), assuming $T_{st}$ is 200 % and the related slip $S_{max}$ is around 14 percent, the following results are obtained:

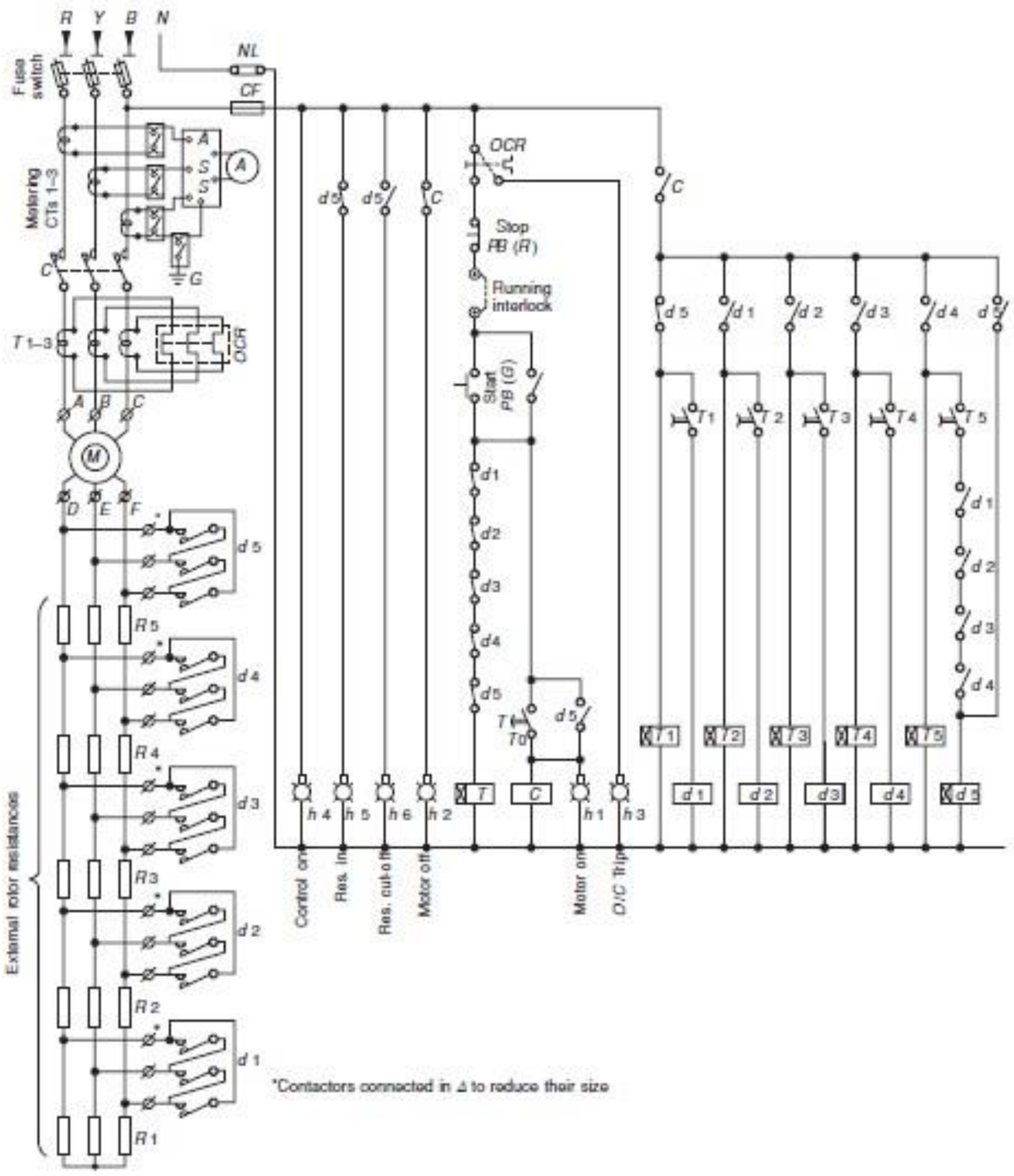
$$R_{21} = \frac{0.09}{0.14} = 0.643\ Ohm$$

and $\frac{I_{min}}{I_{max}}$, i.e. $\beta = \sqrt[5]{0.14} \approx 0.676$

The resistance for each step is calculated using this value of β, which is shown in table 1. A schematic illustration of this design of the resistance unit, as well as its power and voltage ratings, are shown in Figure 11.

| Step no. | Total rotor circuit resistance $R$<br>Ω | External resistance $R_e$<br>Ω | Resistance between steps<br>Ω |
|---|---|---|---|
| 1 | $R_{21} = 0.643$ | $0.643 - 0.09 = 0.553$ | $0.643 - 0.435 = 0.208$ |
| 2 | $R_{22} = \beta \cdot R_{21} = 0.676 \times 0.643 = 0.435$ | $0.435 - 0.09 = 0.345$ | $0.435 - 0.294 = 0.141$ |
| 3 | $R_{23} = \beta \cdot R_{22} = 0.676 \times 0.435 = 0.294$ | $0.294 - 0.09 = 0.204$ | $0.294 - 0.199 = 0.095$ |
| 4 | $R_{24} = \beta \cdot R_{23} = 0.676 \times 0.294 = 0.199$ | $0.199 - 0.09 = 0.109$ | $0.199 - 0.135 = 0.064$ |
| 5 | $R_{25} = \beta \cdot R_{24} = 0.676 \times 0.199 = 0.135$ | $0.135 - 0.09 = 0.045$ | $0.135 - 0.09 = 0.045$ |
| 6 | $R_2 = 0.09 = 0.09$ | $0.09 - 0.09 = 0$ | $0.09 - 0 = 0.090$ |

Table 1: Calculations of resistances for each step.



*Contactors connected in Δ to reduce their size

Fig. 11: A five-step stator-rotor starter's power and schematic diagram

# 2| Chapter two

## 2.1 Practical approach for the calculation of external resistors.

We can compute the required resistance values if we know the rotor voltages and currents. To completely comprehend the resistance calculation, two key factors must be understood: the connection between speed and rotor volts, and the link between rotor current and motor torque. With increasing speed, rotor voltage decays linearly. The rotor voltage would be 0 if the rotor could spin at the same rate as the stator's magnetic field. Because a tiny voltage is constantly required to sustain motor torque, the rotor can never rotate as quickly as the synchronous speed. The secondary voltages are 50% of the nameplate amount at 50% of speed. The rotor voltage is 75% at 25% of rpm.

The slip is defined as the difference between the synchronous and rotor speeds. At a complete stop, for example, the slip is 100%. At 90% of synchronous speed, the slip equals 10%. The slip may (but will never) approach zero. When there is no resistance in the circuit, a WRM will have roughly 3 to 10%, which is called "internal motor slip." In other words, the motor's full-load speed is 90 to 97 percent of its synchronous rpm. As the size of the motor becomes larger, the internal slip reduces. The efficiency of a motor rises with its size. With 3% internal slip, a 300 HP motor can be 96% efficient, but a 3 HP motor can only be 83% efficient with 10% internal slip.

Another crucial point to understand about wound rotor motors is that rotor current and rotor torque are inextricably linked. When the rotor current is doubled, the rotor torque is also doubled. If you want 50% initial torque, you'll need resistors that can handle 50% rotor current. We can compute the torque and consequently the rotor current under specific situations if we know the power of the load at a certain speed.

$$P = k \cdot \phi \cdot I \cdot cos(\varphi_2) \cdot \omega_m = T \cdot \omega_m \qquad 2.1$$

$$T = k \cdot \phi \cdot I_2 \cdot cos(\varphi_2) \qquad 2.2$$

In a practical approach, we calculate the resistance of the rotor by applying Ohm’s law:

$$R = \frac{V}{I} \qquad 2.3$$

Ohm's law is used to determine the size of external resistors in WRM. Each leg of the rotor circuit requires a resistor. Almost without exception, the rotor side of WRM is connected in a star configuration so we need three identical resistors for each phase. The rotor voltage (measured or taken from the nameplate) is a line-to-line value. The voltage across star-connected resistors is equal to the voltage from line to neutral. To find this voltage we divide the line-to-line value by the square root of three.

$$V_{ph} = \frac{V_{LL}}{\sqrt{3}} \qquad 2.4$$

Let's take 5 HP WRM as an example. The rotor voltage and current are 140 V and 19 A, respectively. We need to design a resistor so that the starting torque is limited to 50% of the total load value shown in the nameplate. What is the resistance of the three star-connected resistors that are connected?

The voltage between these resistors by equation 2.4 will be:

$$V_{ph} = \frac{V_{LL}}{\sqrt{3}} = \frac{140}{\sqrt{3}} \approx 81[V]$$

By considering the relationship in equation 2.3, we can state that 50 % rated current is 9.5 A is needed to provide 50% torque. Then to provide 50% starting torque, the resistance of each phase of the rotor circuit will be:

$$R = \frac{V_{ph}}{I_r} = \frac{81}{9.5} \approx 8.5\ [Ohm]$$

When we connect one side of each resistor to the slip rings and attach the other sides of the resistors to establish a common point, we will generate the requisite 50% starting torque when we power the stator. In fact, in terms of motor specifications, we can now build a universal formula to compute the needed resistance per phase for star-connected resistors for any WRM:

$$R = \frac{V_{LL} \cdot (Slip\%)}{I_r \cdot \sqrt{3} \cdot (Torque\%)} \tag{2.5}$$

## 2.2 Multiple steps of control

So far, we've only spoken about resistors that have one step of resistance in each phase to restrict beginning torque or for a single speed point. To smoothly accelerate the load or offer the different speed points needed by the application, most controllers require numerous levels of resistance. The most typical controllers have five-speed points. These controllers typically start the motor with all resistance in the rotor circuit then gradually short out segments of the resistor until all resistance is shorted out and the motor reaches maximum speed. To show how these multi-step resistors are linked, see figure 12. To short out sections of the total resistance, the contactors $K_1$, $K_2$, $K_3$, and $K_4$ are employed. The neutral connection is effectively moved closer and closer to the "no resistance" or ring short state by these contactors.

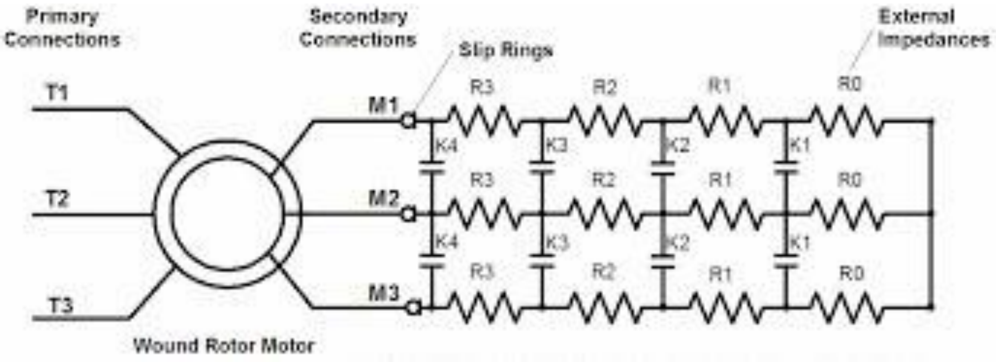


Fig. 12: Equivalent scheme of 5 steps of speed-controlled WRM

There are four resistance levels for a five-speed control. All resistance is removed at the fifth speed. As a result, there is always one more speed point than resistance steps. This rule does have one exception. Permanent resistance is used in certain setups. A permanent resistor stays in the circuit all of the time, as the name indicates. Permanent slip resistors are sometimes employed with particular motor designs to decrease the motor's internal heating. They are often linked to solid-state variable frequency controllers in WRMs

We know how to use the general formula to compute single-step resistors. The resistance values for each step of a multi-step controller may be determined in a few different methods. Tables are created by manufacturers for use with their controls. If these tables aren't available, how should the various levels of control be proportioned? One method is to apply the general formula and enter the required slips and torques at various speed points. The crucial thing to remember is that the general formula determines the rotor circuit's needed resistance value. You must deduct the estimated resistance from the overall resistance to get the value of resistance in a certain phase. Let's say the total ohms necessary for 50% starting torque is calculated to be 10 ohms. Then, at the following controlling step, we determine that 4 ohms are required to get the desired performance. The first step of resistance would have a resistance of 10 - 4 = 6 ohms. It's critical to understand the distinction between per-step and circuit values. The circuit values are determined using the formula. To acquire the per-step values, we must subtract these numbers from each other. The resistance left in the circuit of the rotor is important, but the resistor designer must deal with per-step values. This is particularly important since the current ratings for these steps are often different.

I took an example of how to calculate the different steps of a six-speed controller using this approach. A 125 kW power, $U_2$=500 V, $I_2$=180A motor will be used as an example. I refer to equation 2.6 for calculating the total resistance of the rotor circuit for a given percentage of torque and speed:

| Steps | %Speed | %Slip | %Torque | The total resistance of the rotor circuit for each phase | Step values of external resistor for each phase |
|---|---|---|---|---|---|
| 1 | 0 | 100 | 25% | 6.415 Ohm | 4.124 Ohm |
| 2 | 0 | 100 | 70% | 2.291 Ohm | 1.008 Ohm |
| 3 | 0 | 100 | 125% | 1.283 Ohm | 0.642 Ohm |
| 4 | 60 | 40 | 100% | 0.641 Ohm | 0.16 Ohm |
| 5 | 70 | 30 | 100% | 0.481 Ohm | 0.321 Ohm |
| 6 | 97% (Full) | 3% (internal motor slip) | 100% | 0.16 Ohm (The total resistance of rotor per phase) | all steps are dispatched |

Each step of the external resistor will be dispatched for increasing speed or connected to reduce the speed.

# Conclusions

After analyzing the two methods, we can conclude that the theoretical approach is the more precise and appropriate method for designing external resistors for wound rotor motors. This method makes use of rotor data including the desired limits of $T_{max}$ and $T_{min}$ as determined from the available load curve provided by the manufacturer, and it is more accurate and appropriate. In an actual scenario, we may not have the same level of data knowledge; but, we do have access to data such as motor power, rotor current, and voltage. Therefore, we can figure out how much resistance the rotor has. It is necessary to know at least the application of the motor, such as a conveyer or a crane, etc. in order to estimate the number of steps and resistance of each step of the resistance, before calculating steps of resistance. This provides us with information about the load. Conveyors, for example, do not require a high value of torque in order to reduce the size and expense of the belt. If this is not the case, a larger safety factor for the belts must be considered, resulting in a wider or thicker belt at an additional expense.

After everything is said and done, we can claim that if we project external resistors for a wound rotor motor for particular operating loads in circumstances where there are fewer data available or when the application of a motor changes, a practical method may be beneficial.

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