ECET 4530

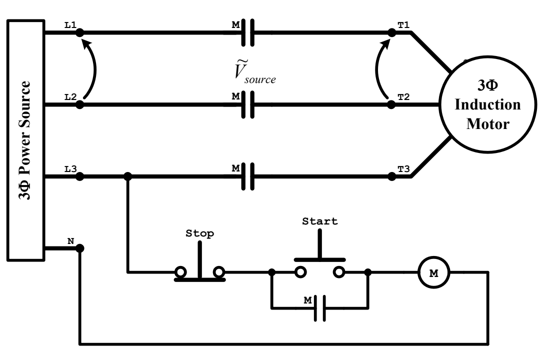
Industrial Motor Control

Starting Induction Motors

1

Across-the-Line Motor Starting

Across-the-Line starting of an induction motor involves starting the motor with full-rated voltage applied across its terminals.



Across-the-Line Motor Starter Circuit

When the main contacts close, the motor's terminals are connected directly to the source terminals, and thus:

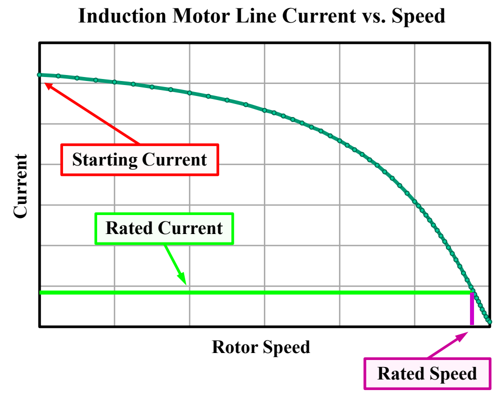
$$\widetilde{V}_{motor} = \widetilde{V}_{source}$$

2

Across-the-Line Motor Starting

Although this is the simplest starting method, starting a motor in this manner can be problematic due to the **current vs. speed characteristics** of an induction motor.

When supplied with **full voltage**, an induction motor typically draws a **starting current** that is **4 –10x larger than rated current**, the magnitude of which then decreases the motor accelerates up to its normal operational speeds.



3

Across-the-Line Motor Starting

Depending on the specific situation, the **large currents** associated with a **full-voltage startup** can adversely affect or damage:

- the motor,
- the motor's mechanical load, and/or
- the distribution system supplying the motor.

And, if the impact of these effects is too severe, an alternate method for starting the motor may be required.

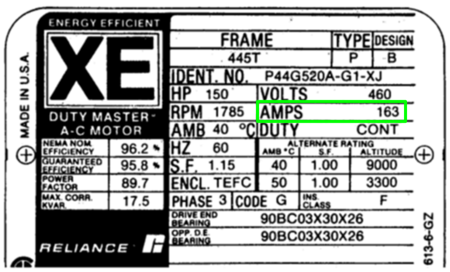
But, before we discuss these adverse effects and some of the manners in which they can be mitigated, let's first take a quick look at how you can determine the starting current for a NEMA-rated induction motor.

4

Predicting the Locked-Rotor Current

Although the actual value will vary by type and size of motor, **locked-rotor current**, which is indicative of **starting current**, can be predicted based on the **NEMA ratings** of a motor.

Consider the following **NEMA-rated**, **3Φ**, **460V**, **150hp**, squirrel-cage induction motor:



The **rated line-current** for this motor is **163A**.

5

Predicting the Locked-Rotor Current

As per **Table 31** of the NEMA **MG-1 Standard**, the nominal **locked-rotor current** for a 3Φ, **230V**, **150hp**, induction motor is **2170A**.

But our motor is rated at **460V**.

The footnote at the bottom of the table specifies how to account for the different voltages.

Table 31
LOCKED-ROTOR CURRENT OF 3-PHASE 60-HERTZ SMALL AND MEDIUM SQUIRREL-CAGE INDUCTION MOTORS RATED AT 230 VOLTS [MG 1-12.35.1]

HP	Locked-Rotor Current, Amperes	Design Letters	HP	Locked-Rotor Current, Amperes	Design Letters
1/2	20	B, D	60	870	B, C, D
3/4					
1	30	B, C, D	100	1450	B, C, D
1-1/2	40	B, C, D	125	1815	B, C, D
2	50	B, C, D	150	2170	B, C, D
3	64	B, C, D	200	2900	B, C,
5	92	B, C, D	250	3650	B
7-1/2	127	B, C, D	300	4400	B
10	162	B, C, D	350	5100	B
15	232	B, C, D	400	5800	B
20	290	B, C, D	450	6500	B
25	365	B, C, D	500	7250	B
30	435	B, C, D			
40	580	B, C, D			
50	725	B, C, D			

NOTE—The locked-rotor current of motors designed for voltages other than 230 volts shall be inversely proportional to the voltages.

6

Predicting the Locked-Rotor Current

Accounting for voltage, the locked-rotor current is calculated as follows:

$$I_{LR(460\text{V})} = I_{LR(230\text{V})} \cdot \frac{230}{460}$$

$$= 2170 \cdot \frac{230}{460}$$

$$= \boxed{1085A}$$

which is equal to **666% rated current**!

Table 31
LOCKED-ROTOR CURRENT OF 3-PHASE 60-HERTZ SMALL AND MEDIUM SQUIRREL-CAGE INDUCTION MOTORS RATED AT 230 VOLTS [MG 1-12.35.1]

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50	725	B, C, D			

NOTE—The locked-rotor current of motors designed for voltages other than 230 volts shall be inversely proportional to the voltages.

7

Adverse Effects of Starting Current

The **adverse effects** associated with the large currents that are drawn into a motor during startup include:

- **Rapid heating of the stator windings** that, if sustained over an extended period of time due to a failed or delayed startup, can damage the motor's windings.

  Note – thermal damage can also result from multiple restarts within a short amount of time.

- **Rapid heating of the branch circuit conductors** that supply the motor.

  Note – the conductors utilized in a branch circuit that supplies a motor are typically sized for 125% of the motor's rated current.

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Adverse Effects of Starting Current

The **adverse effects** associated with the large currents that are drawn into a motor during startup include:

- A **torque surge** developed by the motor that can be damaging to the motor's connected mechanical load.
- A **voltage drop in the supply network** that may affect the operation of other devices.

Whether these currents are short-lived during a successful startup or extended in length during a problematic/failed startup, their effects should be considered in order to determine if they need to be mitigated by the motor control system.

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Induction Motor Starting Methods

A variety of different methods have been developed to mitigate the undesirable effects that are associated with the large currents that are normally drawn when starting an induction motor.

They include:

- **Reduced Voltage Starting**
- **Partial Winding Starting**
- **Reduced Frequency Starting**

Note – reduced frequency starting using Variable Frequency Drives (VFDs) is covered in a later presentation.

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Reduced Voltage Motor Starting

The **starting currents** can be reduced to an “acceptable level” by **limiting the voltage** applied to the motor’s terminals during start-up.

Reduced-Voltage Starter **configurations** include:

- **Series Resistance** (Impedance) **Starters**
  Note – typically utilized for ≤ 200hp motors
- **Auto-Transformer Starters**
- **Wye-Delta (Y–Δ) Starters**
- **Solid-State Starters**

(Auto-Transformer, Wye-Delta and Solid-State Starters:) **not covered within this presentation**

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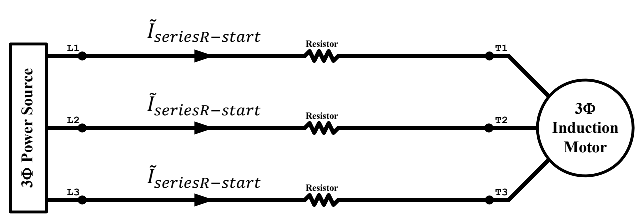
Series-Resistance Motor Starters

In the case of a **Series-Resistance Motor Starter**, the motor is initially started with a set of resistors wired in series with each of the motor’s terminals, thus increasing the overall resistance of the stator circuits and, in-turn, decreasing the magnitude of the currents drawn by the motor.

$$\tilde{I}_{seriesR-start} < \tilde{I}_{across-the-line-start}$$



Larger resistor values will result in greater reductions in current, but they might also impede the motor’s ability to successfully accelerate its load from standstill.

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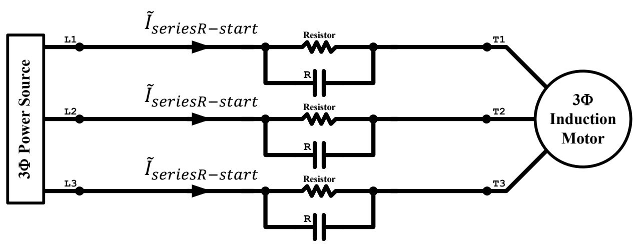
Series-Resistance Motor Starters

Once the motor has had a chance to accelerate to the point at which the currents drawn by the motor would have decreases to an acceptable level if supplied at rated voltage, the **resistors** must then be **electrically removed from the circuit** so as not to impair the motor's operation under normal use.

A **contactor** is typically employed to provide this service.



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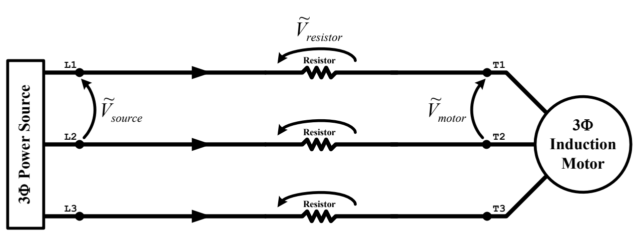
Series-Resistance Motor Starters

Note that the series-resistance motor starter is classified as a **reduced-voltage motor starter** because, as long as the stator currents are forced to flow through the resistors, there will be a voltage drop across the resistors, resulting in a terminal voltage for the motor that is less that the supply voltage.

$$\tilde{V}_{motor} < \tilde{V}_{source}$$



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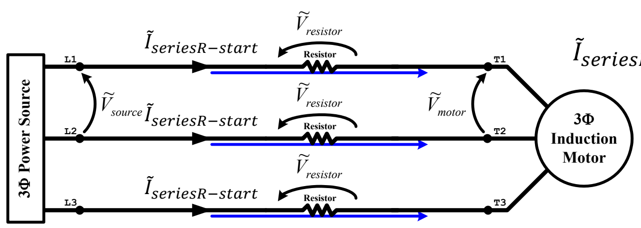
Series-Resistance Starter Operation

Series Resistance Starting Process:

- **Resistors** are placed **in series** with the **stator terminals**.
- When initially energized, a large voltage drop will occur across the resistors, resulting in a **reduced terminal voltage** and a **reduced starting current** (compared to a full-voltage start).



$\tilde{I}_{seriesR-start} < \tilde{I}_{FullV-start}$

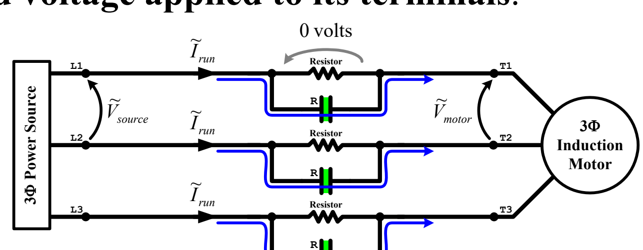
$\tilde{V}_{motor} < \tilde{V}_{source}$

15

Series-Resistance Starter Operation

Series Resistance Starting Process:

- As the **motor accelerates**, the **line currents decrease**, in-turn causing the **terminal voltage** at the motor **to increase**.
- Once the motor has sufficiently sped-up, the **resistors are bypassed**, allowing the motor to operate normally with **rated voltage applied to its terminals**.



$\tilde{I}_{run} \leq \tilde{I}_{rated}$

$\tilde{V}_{motor} = \tilde{V}_{source}$

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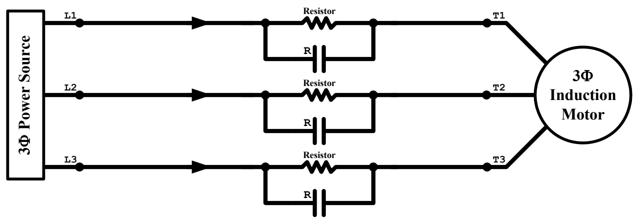
Series-R Starter Control Circuit

Thus, a series-resistance motor starter utilizes a **two-step process**:

- **Start the motor with the resistors in-place**, and then
- **Bypass the resistors** once the motor has accelerated.

Although this process could be controlled manually, an on-delay **timer** is often utilized in order to **automate** this process and to ensure that the resistors are bypassed at the appropriate time.



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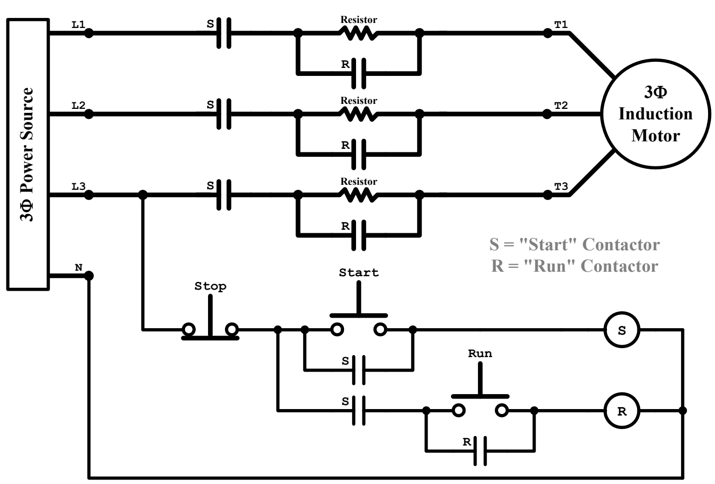
Series-Resistance Starter Operation

Series Resistance Starter with **Manual (2-Step) Control Circuit**



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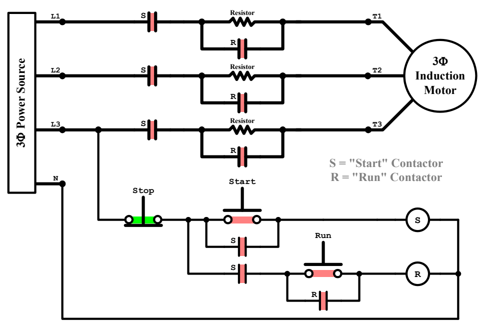
Series-Resistance Starter Operation

Series Resistance Starter with **Manual (2-Step) Control Circuit**

- **Initial Conditions**:



S ≡ "Start" Contactor
R ≡ "Run" Contactor
TR ≡ Time-Delay Relay

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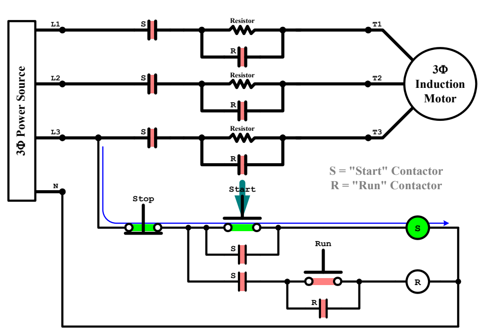
Series-Resistance Starter Operation

Series Resistance Starter with Manual (2-Step) Control Circuit

- When "**Start**" is **pressed**, the "**S**" **coil** is **energized**…



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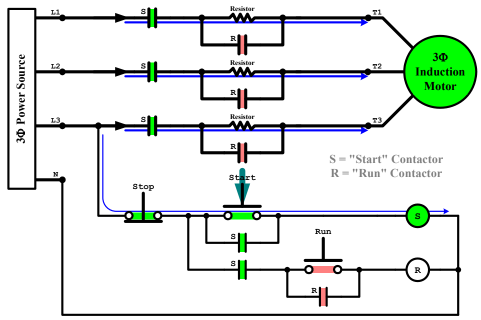
Series-Resistance Starter Operation

Series Resistance Starter with Manual (2-Step) Control Circuit

- When "**Start**" is **pressed**, the "**S**" **coil** is **energized**…
- The energized "S" coil **actuates the "S" contacts**, in-turn **energizing the motor through the resistors**, which **limits the starting current** to a predetermined value.



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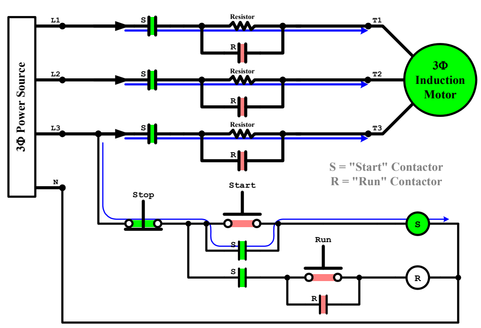
Series-Resistance Starter Operation

Series Resistance Starter with Manual (2-Step) Control Circuit

- When "**Start**" is **released**, the "S" contact in parallel with the Start button allows the **"S" coil to remain energized**, in-turn **holding-in the "S" contacts** and **keeping the motor energized** through the resistors (i.e. – reduced voltage).



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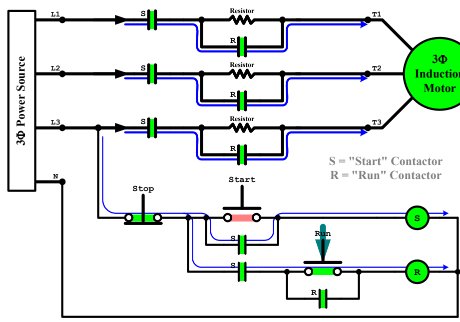
Series-Resistance Starter Operation

Series Resistance Starter with Manual (2-Step) Control Circuit

- When "**Run**" is **pressed**, the "**R**" **coil** is **energized**, in-turn **actuating the "R" contacts** to **bypass the resistors** and **supply the motor at full-voltage**.



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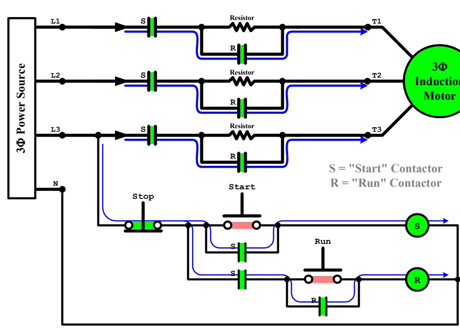
Series-Resistance Starter Operation

Series Resistance Starter with Manual (2-Step) Control Circuit

- When "**Run**" is **released**, the "R" contact in parallel with the Run button allows the **"R" coil to remain energized**, in-turn **holding-in the "R" contacts** and **keeping the motor energized at full-voltage**.



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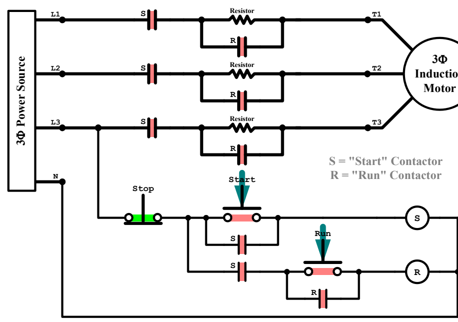
Series-Resistance Starter Operation

Series Resistance Starter with **Manual** (**2-Step**) **Control Circuit**

What if "**Start**" and "**Run**" are pressed at the <u>**same time**</u>?



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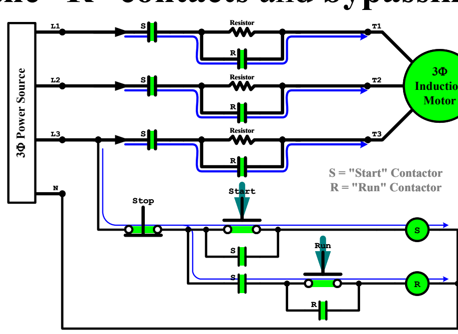
Series-Resistance Starter Operation

Series Resistance Starter with **Manual** (**2-Step**) **Control Circuit**

What if "**Start**" and "**Run**" are pressed at the <u>**same time**</u>?

- The "**S**" **coil** will be **energized**, **actuating the** "**S**" **contacts** and immediately **energizing the** "**R**" **coil**, in-turn **actuating the** "**R**" **contacts** and **bypassing the resistors**.

The small time-delay between the "R" coil being energized and the "R" contacts closing to bypass the resistors will not be long enough for the motor to begin accelerating, and thus the motor will still effectively be at standstill when the resistors are bypassed, in-turn causing the motor to draw the large starting current that we are trying to mitigate.



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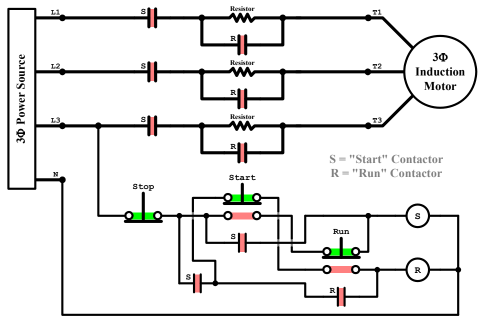
Series-Resistance Starter Operation

Series Resistance Starter with **Manual (2-Step) Control Circuit**

What if "**Start**" **and** "**Run**" **are pressed at the <u>same time</u>?**

To prevent this problem, **combination pushbuttons** could be used for both **Start** and **Run**, with the **NC contact** of each button **wired in-series** with the **opposing button's NO contact**.



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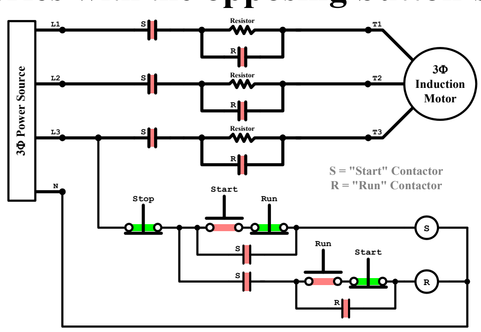
Series-Resistance Starter Operation

Series Resistance Starter with **Manual (2-Step) Control Circuit**

What if "**Start**" **and** "**Run**" **are pressed at the <u>same time</u>?**

To prevent this problem, **combination pushbuttons** could be used for both **Start** and **Run**, with the **NC contact** of each button **wired in-series** with the **opposing button's NO contact**.

Note – electrically this is the same circuit as that shown on the previous slide, except that in this figure, the NO and NC contacts in the Start and Run buttons have been separated and placed at the logical positions within the figure that best depict the overall function of the circuit.



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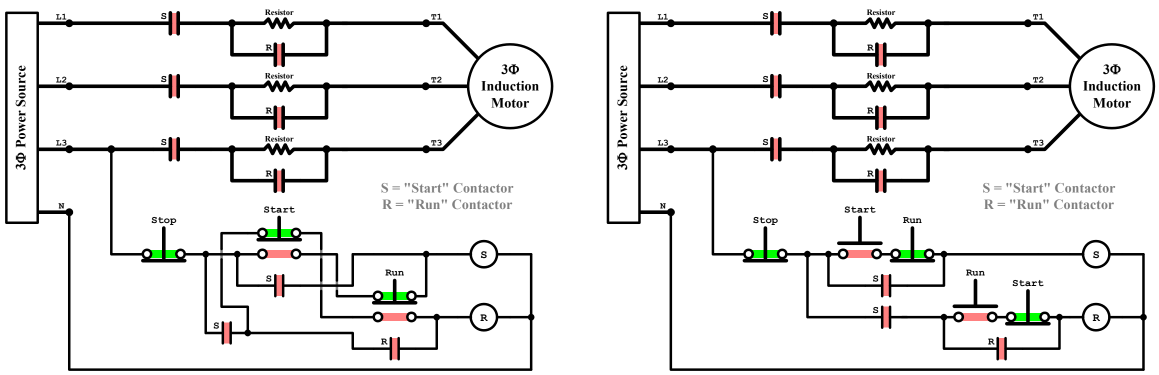
Series-Resistance Starter Operation

Series Resistance Starter with **Manual (2-Step) Control Circuit**

What if "**Start**" and "**Run**" are pressed at the <u>**same time**</u>?



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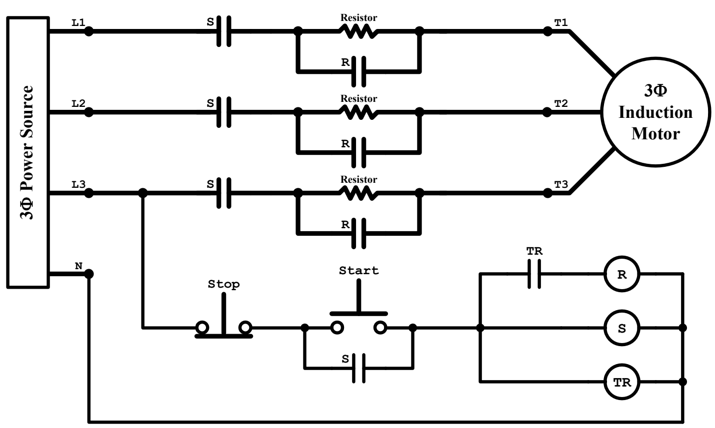
Series-Resistance Starter Operation

Series Resistance Starter with Control Circuit



S = "Start" Contactor   R = "Run" Contactor   TR = Time-Delay Relay

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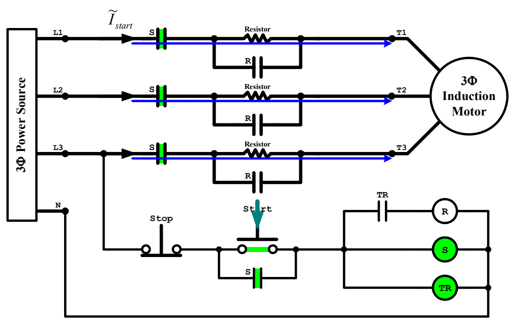
Series-Resistance Starter Operation

Series Resistance Starter

- When the "**Start**" button is **pressed**, both the "**S**" **coil** and the "**TR**" **coil** are **energized**.
- The "S" **coil actuates its contacts immediately**, while the "**TR**" **coil actuates its contact after a preset time delay**.



S ≡ "Start" Contactor
R ≡ "Run" Contactor
TR ≡ Time-Delay Relay

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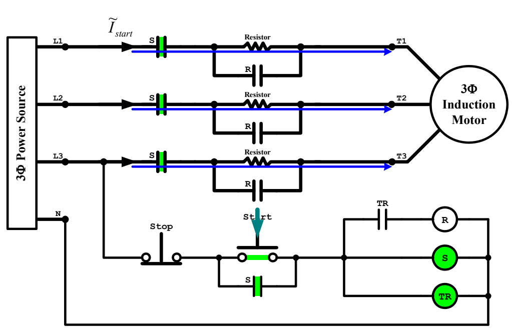
Series-Resistance Starter Operation

Series Resistance Starter

- When the "S" **contacts actuate closed**, the motor is connected to the supply **through the resistors**, thus decreasing the terminal voltage and **limiting the starting current**.



S ≡ "Start" Contactor
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TR ≡ Time-Delay Relay

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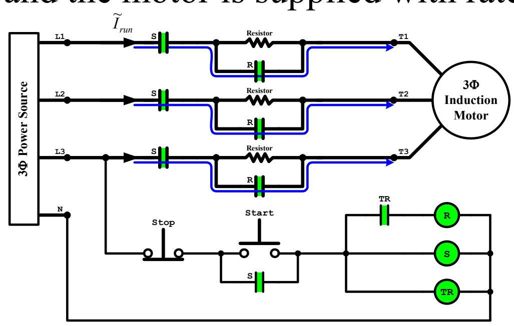
Series-Resistance Starter Operation

Series Resistance Starter

- Once the "**TR**" relay's time delay has passed, the "**TR**" **contact closes**, in-turn **energizing** the "**R**" field coil.
- When the "**R**" **contacts actuate closed**, the **resistors are bypassed** and the motor is supplied with rated voltage.



S ≡ "Start" Contactor
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Series-Resistance Starter Use/Design

Series Resistance Starter Applications

- On "**low voltage**" (<600V) **systems**
- For **low current reduction** requirements
- When **load torque is minimal at startup**

Series Resistance Starter Design

- A practical series resistance starter is often designed to **limit** a motor's **starting current** to a specific **percentage** of the motor's full-load **rated current**.
- The value of the series resistance may be determined by **testing the motor** under **locked-rotor conditions**.

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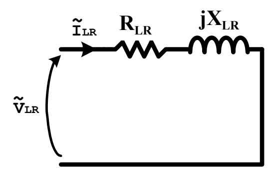
Determining the Series-Resistor Value

Series Resistance Determination

- All that is truly needed to determine the value of the series resistance is the overall **input impedance** of the motor **under locked-rotor conditions**.
- Since the circuit model is independent of the applied phase voltage, the locked-rotor parameters may be determined by applying **less-than-rated phase voltage**.



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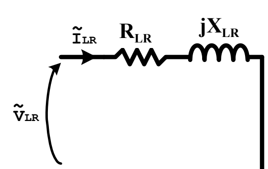
Determining the Series-Resistor Value

Series Resistance Determination

- By setting the **locked-rotor test voltage** to **½ rated voltage**, the locked-rotor test will draw half of the current that would be drawn if full-voltage was applied.
- The **50% reduction** in locked-rotor current will **decrease** both the **heat generated** and the **torque developed** during the test **by 75%**.



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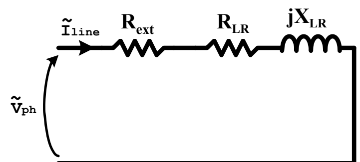
Determining the Series-Resistor Value

Series Resistance Determination

- Once the motor's locked-rotor impedance is determined, the value of the required **external resistance** may be calculated based on the desired starting parameters.



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Series-Resistor Value Example

Series Resistance Calculation Example

Given a **3Φ**, **208V**, **1.2A**, **60Hz**, **¼hp**, **1640rpm** squirrel cage induction motor:

Determine the value of a set of **external resistors** required for a series resistance starter such that the **starting current** is **limited to 200% of the full-load (rated) current**.

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Series-Resistor Value Example

Series Resistance Calculation Example

A **locked-rotor test** is performed on the motor with **½-rated voltage applied per phase** during the test.

The **per-phase test results** are as follows:

$$\mathbf{V_{LR} = 60V,\ I_{LR} = 2.1A,\ P_{1\Phi} = 90W}$$

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Series-Resistor Value Example

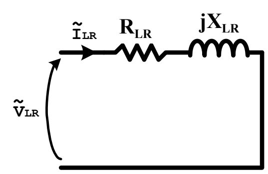
Series Resistance Calculation Example

Test Results: $\mathbf{V_{LR} = 60V,\ I_{LR} = 2.1A,\ P_{1\Phi} = 90W}$

$$R_{LR} = \frac{P_{1\Phi}}{I_{LR}^2} = \frac{90}{(2.1)^2} = 20.4\Omega$$

$$Q_{1\Phi} = \sqrt{|S_{1\Phi}|^2 - P_{1\Phi}^2} = \sqrt{(60x2.1)^2 - (90)^2} = 88.2\ Vars$$

$$X_{LR} = \frac{Q_{1\Phi}}{I_{LR}^2} = \frac{88.2}{(2.1)^2} = 20\Omega$$



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Series-Resistor Value Example

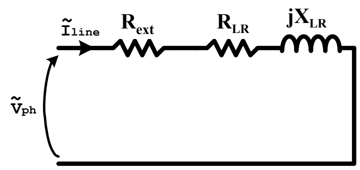
Series Resistance Calculation Example

Motor's LR Impedance: $\mathbf{Z_{su} = 20.4 + j20\ \Omega}$

Desired starting current: **200%** x $\mathbf{I_{rated}}$

2 x 1.2 = 2.4 A

$$\tilde{I}_{line} = \frac{\tilde{V}_{ph}}{Z_{eq}} = \frac{\tilde{V}_{ph}}{R_{ext} + R_{LR} + jX_{LR}}$$



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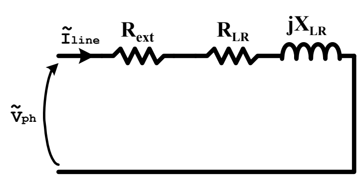
Series-Resistor Value Example

Series Resistance Calculation Example

Desired starting current: $\mathbf{I_{line} = 2.4\ A}$

$$\left|\tilde{I}_{line}\right| = I_{line} = \frac{\left|\tilde{V}_{ph}\right|}{\left|Z_{eq}\right|} = \frac{V_{ph}}{\sqrt{(R_{ext} + R_{LR})^2 + (X_{LR})^2}} = 2.4\ A$$

$$\Rightarrow \quad \frac{120}{\sqrt{(R_{ext} + 20.4)^2 + (20)^2}} = 2.4\ A$$



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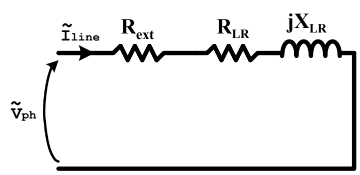
Series-Resistor Value Example

Series Resistance Calculation Example

$$\sqrt{(R_{ext} + 20.4)^2 + (20)^2} = \frac{120}{2.4} = 50$$
$$(R_{ext} + 20.4)^2 + (20)^2 = 2500$$
$$(R_{ext} + 20.4)^2 = 2100$$
$$R_{ext} + 20.4 = 45.8$$
$$R_{ext} = 25.4\,\Omega$$



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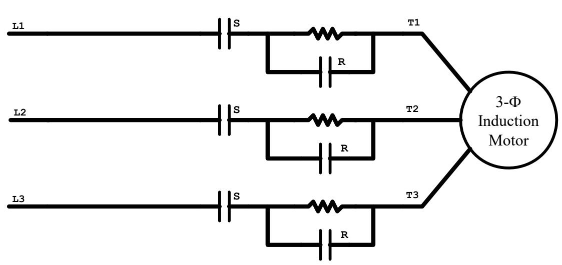
Series-Resistance Motor Starter

Series Resistance Calculation Example

Series Starting Resistance: $\mathbf{R_{ext} = 25.4\ \Omega}$

A series resistance starter utilizing a set of 25.4Ω resistors should **limit the starting current to 200% of the full-load rated current**.



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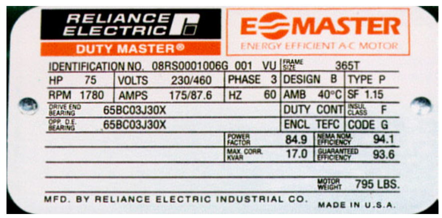
Partial Winding Motor Starting

Partial Winding Starting

- The partial winding starting method may be used to start a **dual-voltage motor**.
- Although full-voltage is applied to the motor's terminals at startup, the **starting current is reduced by initially applying a voltage to only one half of the motor's windings**.



Dual-Voltage Motor Nameplate

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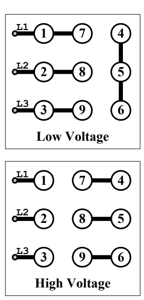
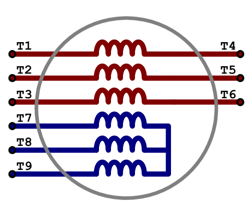
Partial Winding Motor Starting

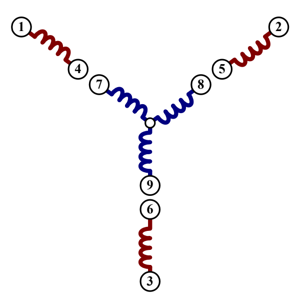
Dual-Voltage Motors

- A **dual-voltage motor** has **two identical sets of 3Φ windings**, each phase of which are wired:
  - in **series** for **high-voltage** (low-current) **operation**, or
  - in **parallel** for **low-voltage** (high-current) **operation**.





Dual-Voltage Motor



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Partial Winding Motor Starting

Partial Winding Starting

- For a partial winding starter, the motor must be utilized in its **low-voltage configuration**.
- The motor is **initially started** with **full-voltage applied to** only **one set of the motor's windings**.
- **Once the motor has accelerated** and its line current has sufficiently decreased, **the second set of windings are then energized for normal operation**.

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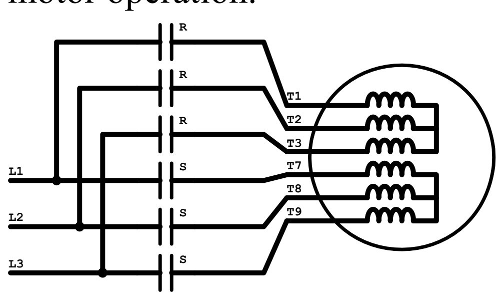
Partial Winding Motor Starting

Partial Winding Starter

- The **start** (**S**) **contacts are initially closed**, energizing one set of the 3Φ windings.
- The **run** (**R**) **contacts are closed after a short time delay** for normal motor operation.



Partial Winding Motor Starter

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