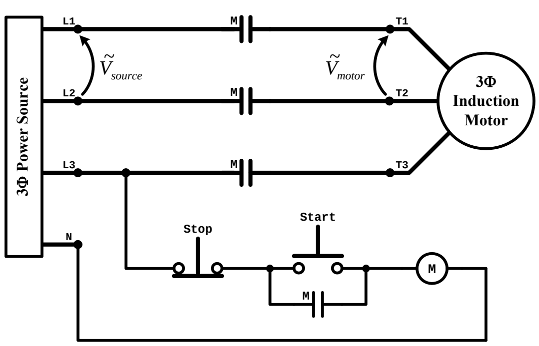
ECET 4530

Industrial Motor Control

Starting Induction Motors

Across-the-Line Motor Starting

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



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

Across-the-Line Motor Starter Circuit

Across-the-Line Motor Starting

Although this is the simplest starting method, starting a motor with full-voltage applied to its terminals can have adverse effects upon:

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

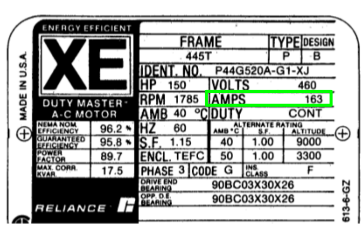
These adverse effects are associated with the large currents, typically ranging from 4x–10x times rated current, that are drawn into a motor during startup.

If the impact of these effects is too severe, a more complex motor control system may be required.

Across-the-Line Motor Starting

Although the actual value will vary by type and size of motor, nominal starting current values can be specified based on the ratings of the machine.

For example, consider the following NEMA-rated, 3Φ, 460V, 150hp, squirrel-cage induction motor:



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

Locked-Rotor Current

According to Table 31 in the NEMA MG-1 standard, the locked-rotor current for a 3Φ, 230V, 150hp, induction motor is 2170A.

Accounting for voltage, this value is scaled as follows:

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

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

$$= 1085A$$

which is 666% of 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]

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.

Induction Motor Starting

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.

Induction Motor Starting

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 whether or not they need to be mitigated by the motor control system.

Induction Motor Starting

A variety of different methods have been developed to minimize the undesirable effects that occur when starting an induction motor.

They include:

- Reduced Voltage Starting
- Partial Winding Starting

  Note – although partial winding starters are presented briefly at the end of this presentation, they will not be covered during the lecture sessions.

- Reduced Frequency Starting

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

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.

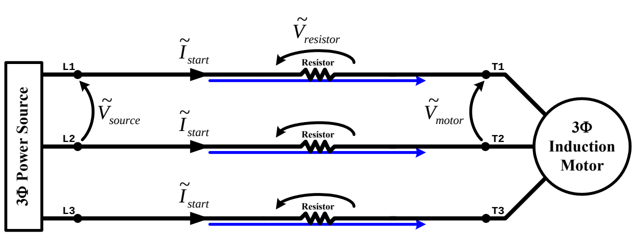
Reduced-Voltage Starter configurations include:

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

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

Series-Resistance Motor Starters

- **Series Resistance Starting**
  - **Resistors are placed in series with the stator windings of the motor.**
  - **When initially energized, a large voltage drop will occur across the resistors, resulting in a reduced voltage being applied across the motor's terminals.**

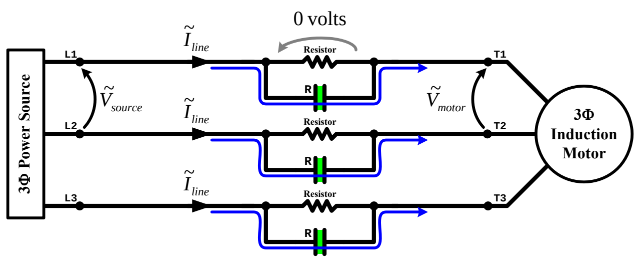


$$\tilde{I}_{start} > \tilde{I}_{rated}$$

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

Series-Resistance Motor Starters

- **Series Resistance Starting**
  - **As the motor accelerates, the line currents will decrease, in-turn causing the terminal voltage 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.**

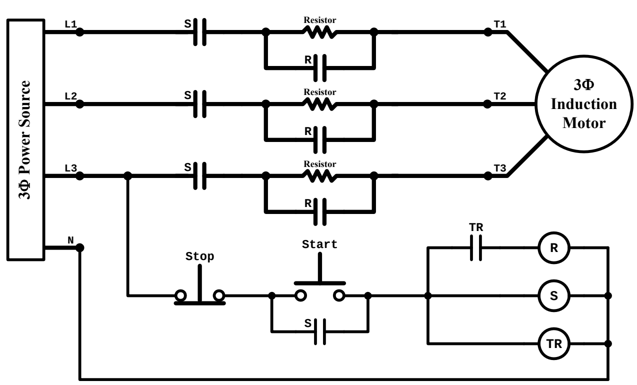


$$\tilde{I}_{line} \le \tilde{I}_{rated}$$

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

Series-Resistance Motor Starters

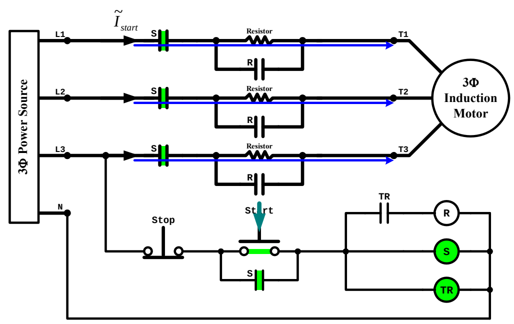
- **Series Resistance Starter with Control Circuit**



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

Series-Resistance Motor Starters

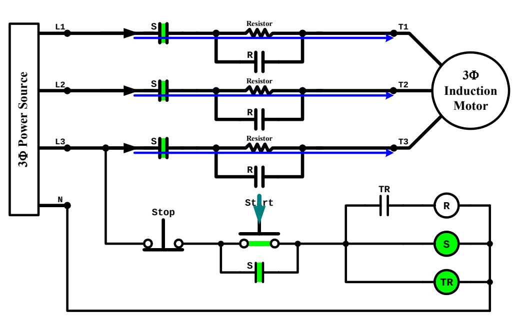
- Series Resistance Starter
  - When the "Start" button is pressed, both the "S" and the "TR" coils are energized.
  - The "S" coil will actuate its contacts immediately, while the "TR" coil will actuate its contact after a preset time delay.



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

Series-Resistance Motor Starters

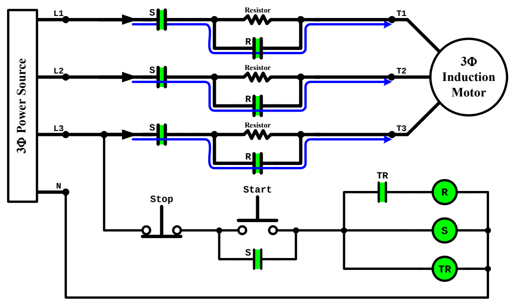
- Series Resistance Starter
  - When the "S" contacts actuate (close), the motor is connected to the supply through the resistors, thus decreasing the terminal voltage and limiting the starting current.



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

Series-Resistance Motor Starters

- 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 to actuate (close), the resistors are bypassed and the motor is supplied with rated voltage.



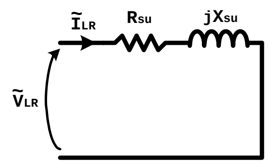
S ≡ “Start” Contactor
R ≡ “Run” Contactor
TR ≡ Time-Delay Relay

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 resistor may be determined by testing the motor under locked-rotor conditions.

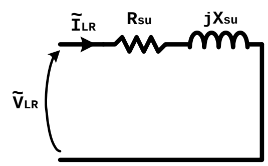
Determining the Series-Resistor Value

- 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.



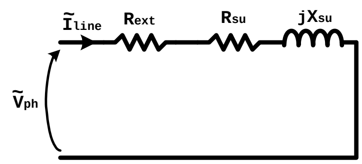
Determining the Series-Resistor Value

- Series Resistance Determination
  - By choosing a locked-rotor test voltage equal to one half of the rated voltage, the locked-rotor test current will be one-half of the full-voltage starting current.
  - The 50% reduction in locked-rotor current will decrease both the heat generated and the torque developed during the test by 75%.



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.**



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

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:

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

Series-Resistor Value Example

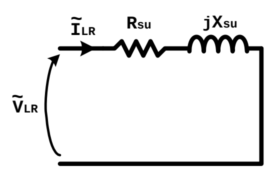
- **Series Resistance Calculation Example**

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

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

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

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



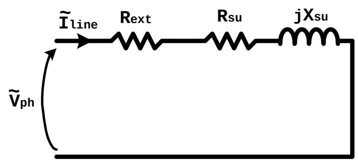
Series-Resistor Value Example

- **Series Resistance Calculation Example**

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

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

2 x 1.2 = 2.4 A



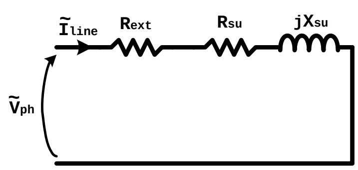
Series-Resistor Value Example

- **Series Resistance Calculation Example**

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

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

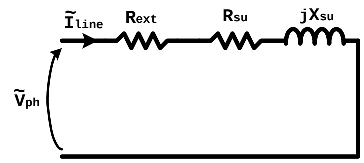
$$\Rightarrow \quad \frac{120}{\sqrt{\left(R_{ext} + 20.4\right)^2 + \left(20\right)^2}} = 2.4\,A$$



Series-Resistor Value Example

- **Series Resistance Calculation Example**

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

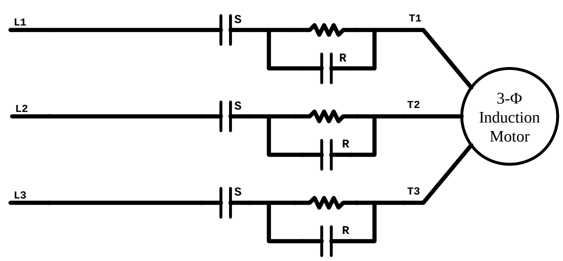


Series-Resistance Motor Starter

- **Series Resistance Calculation Example**

Series Starting Resistance: R_{ext} = 25.4 Ω

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



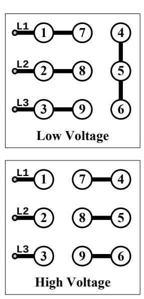
Partial Winding Motor Starting

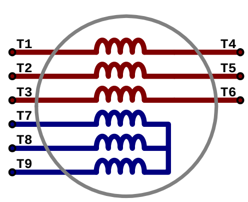
- **Partial Winding Starting**
  - The partial winding starting method is a method that may be used to start a dual-voltage motor.
  - Although full-voltage is applied to the motor's terminals at startup, the starting current is reduced by applying a voltage to only one half of the motor's windings.

Dual-Voltage Motor Nameplate

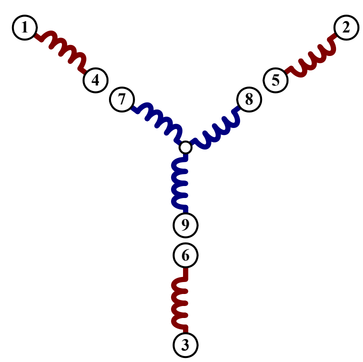
Partial Winding Motor Starting

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





Dual-Voltage Motor

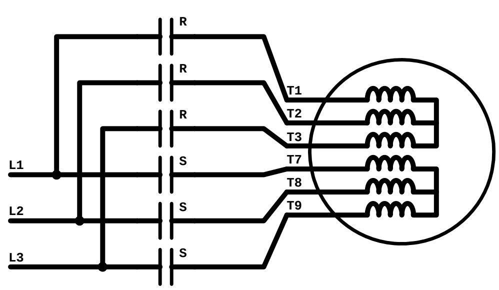


Partial Winding Motor Starting

- **Partial Winding Starting**
  - **For a partial winding starter, the motor must be utilized in its low-voltage configuration.**
  - **The motor is started initially 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.**

Partial Winding Motor Starting

- **Partial Winding Starter**
  - **The start (S) contactor is initially closed, energizing one set of the 3Φ windings.**
  - **After a short time delay, the run (R) contactor is also closed, for normal motor operation.**



Partial Winding Motor Starter