# Digital Protection of Power System
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Lecture 18
## Digital Protection of Induction Motors - 3

Hello friends. So, in the previous lecture, we have discussed regarding the inputs required for digital relays for the protection of induction motors and we have seen that after giving several inputs digital relays, digital relays may calculate itself the digital thermal element function that is available in the digital relay.

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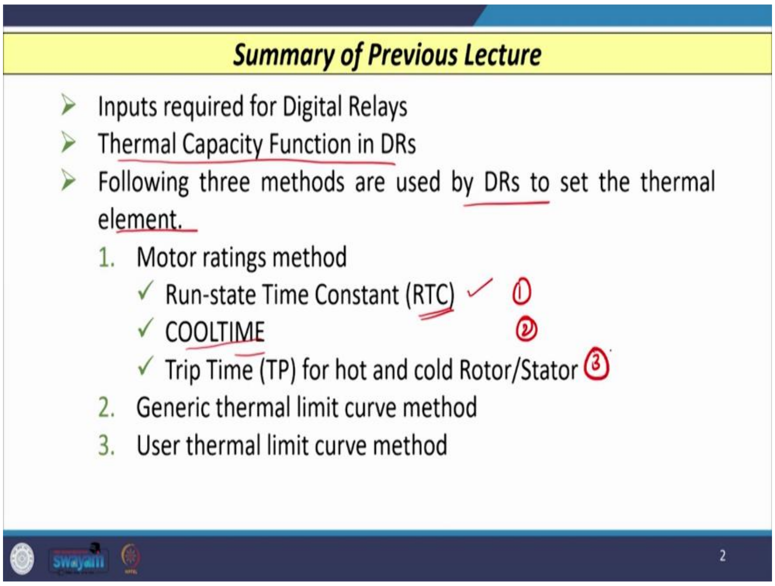

### Summary of Previous Lecture

- Inputs required for Digital Relays
- Thermal Capacity Function in DRs
- Following three methods are used by DRs to set the thermal element.
  1. Motor ratings method
     - ✓ Run-state Time Constant (RTC) ✓ ①
     - ✓ COOLTIME ②
     - ✓ Trip Time (TP) for hot and cold Rotor/Stator ③
  2. Generic thermal limit curve method
  3. User thermal limit curve method

Then we have discussed the thermal capacity function that is available in digital relays. And we have discussed that normally three methods are used by most of the digital relays to set the thermal element and this methods are first is the motor rating methods, second is the generic thermal limit curve method and third is the user thermal limit curve method.

Now, when we use the motor rating methods, we have discussed that we have to calculate three things. First, that is the run state time constant known as RTC. Second, we have to calculate the cool time and third we need to calculate the trip time for hot and cold rotor and stator. So, these three things we need to calculate when we talk about the motor rating methods.

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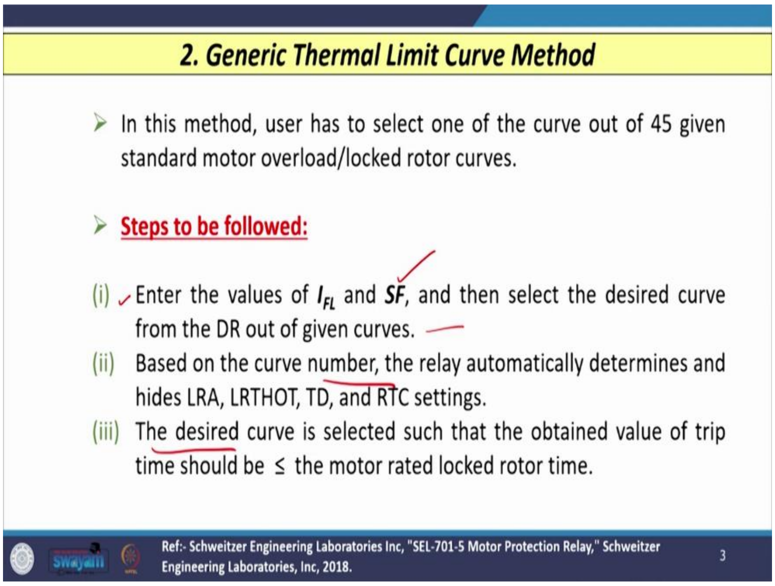

## 2. Generic Thermal Limit Curve Method

- In this method, user has to select one of the curve out of 45 given standard motor overload/locked rotor curves.
- **Steps to be followed:**

(i) Enter the values of $I_{FL}$ and **SF**, and then select the desired curve from the DR out of given curves.

(ii) Based on the curve number, the relay automatically determines and hides LRA, LRTHOT, TD, and RTC settings.

(iii) The desired curve is selected such that the obtained value of trip time should be $\leq$ the motor rated locked rotor time.

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

Now, let us discuss the second method that is known as generic thermal limit curve method. So, in this method user has to select one of the curve out of the several curves given by standard motor manufacturers or overload or locked rotor curves. So, most of the relay manufacturers they will provide several curves normally they provide let us say 40 45 or 50 curves.

So, user has to select one of the curves out of this given or available curves by the manufacturers and then relay will automatically calculate other things. So, what are the steps to be followed when we use generic thermal limit curve method. So, the first step is that we have to enter the values of full load current of the motor and the value of SF that is service factor and then select the desired curve from the available or given curves by the manufacturers.

So, this is the first point we need to consider based on the curve number which we have selected, the relay automatically determines or calculates and again hides the value of LRA, LR hot TD and RTC settings. Then, the desired curve is selected in such a way that the obtained value of trip time should be less than or equal to the motor rated locked rotor time. So, this is very important point we need to consider.

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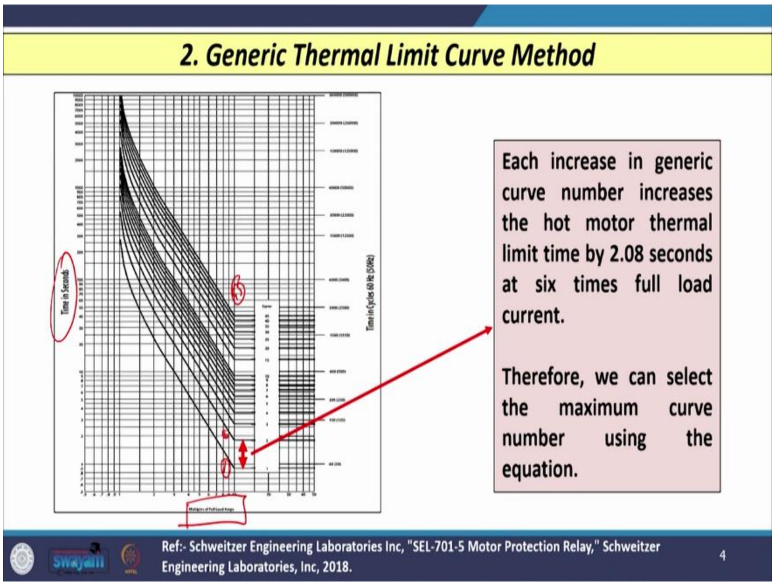

## 2. Generic Thermal Limit Curve Method

Each increase in generic curve number increases the hot motor thermal limit time by 2.08 seconds at six times full load current.

Therefore, we can select the maximum curve number using the equation.

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

Now, let us see what are the different curves given or provided by the relay manufacturer. So, you can see here on the screen (as shown in above slide), the curve that is on x axis we have multiple of full load amps are given and on y axis the time in seconds are given and several curves are given. So, you can see that here several curves starting from here, 1 to 2 to let us say up to maybe 45, this curves are given here (as shown in above slide).

And here one important point is whenever we increase or whenever we move from one curve to the another curve, then each increase in genetic curve number that indicates the 2.08 second particularly at 6 times the full load current. So, when you move from first curve to the second curve, there will be an increase of 2.08 second time and this is at 6 times the full load current. So, therefore, based on this we can select the maximum curve number using the given equation.

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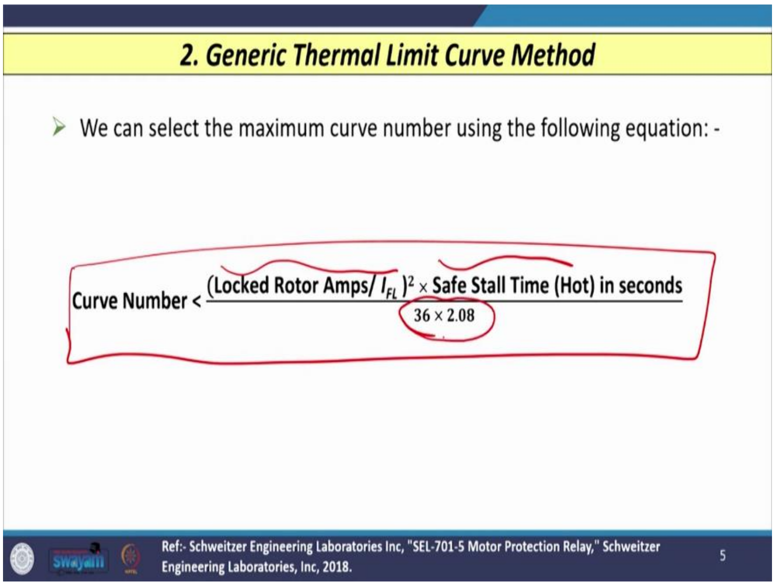

## 2. Generic Thermal Limit Curve Method

- We can select the maximum curve number using the following equation: -

$$\text{Curve Number} < \frac{(\text{Locked Rotor Amps}/\ I_{FL})^2 \times \text{Safe Stall Time (Hot) in seconds}}{36 \times 2.08}$$

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

So, if we wish to select the curve number, then we have to use this equation and in this equation you can see that whatever value you obtained, you have to select that curve or you have to select lower than that value whatever curves are given you can select it according to this equation, for curve number.

$$\textbf{Curve Number} < \frac{\textbf{(Locked Rotor Amps/ } I_{FL}\textbf{ )}^2 \times \textbf{Safe Stall Time (Hot) in seconds}}{\mathbf{36 \times 2.08}}$$

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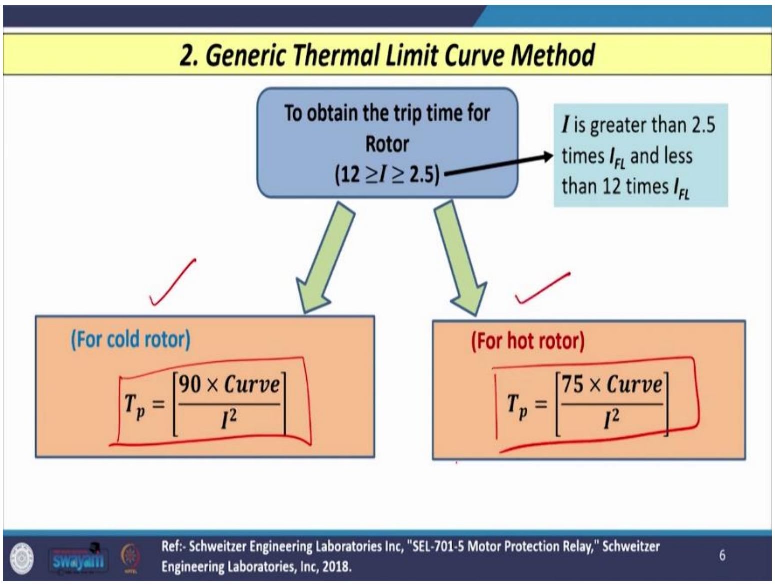

## 2. Generic Thermal Limit Curve Method

To obtain the trip time for Rotor $(12 \geq I \geq 2.5)$

$I$ is greater than 2.5 times $I_{FL}$ and less than 12 times $I_{FL}$

(For cold rotor)

$$T_p = \left[\frac{90 \times Curve}{I^2}\right]$$

(For hot rotor)

$$T_p = \left[\frac{75 \times Curve}{I^2}\right]$$

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

So, if we consider or if we wish to find out about the trip time for rotor and particularly when the current I is greater than 2.5 times the full load current and it is less than that 12 times the full load current when it falls within this range, and if you wish to calculate the trip time or rotor, then when rotor is in cold condition, then you have to use this equation $\boldsymbol{T_p} = \left[\frac{\mathbf{90}\times \boldsymbol{Curve}}{\boldsymbol{I^2}}\right]$

Whereas, when it is in hot condition, you have to use this equation $\boldsymbol{T_p} = \left[\frac{\mathbf{75}\times \boldsymbol{Curve}}{\boldsymbol{I^2}}\right]$

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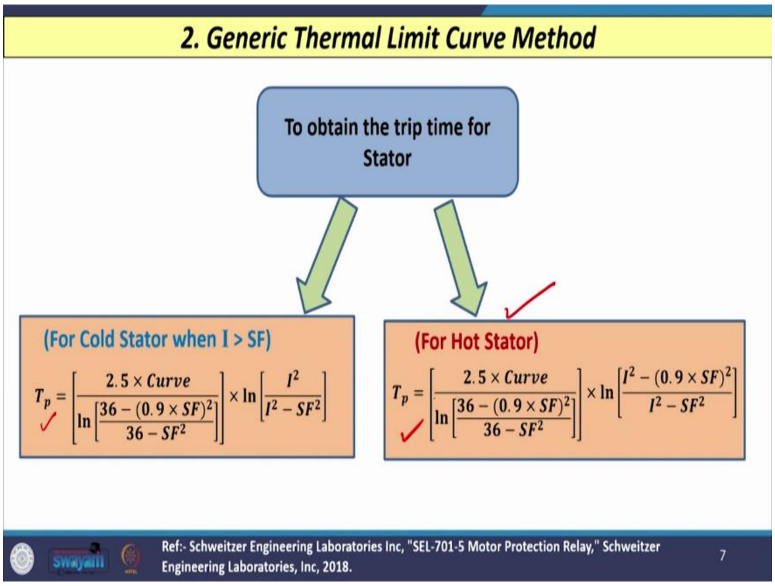

## 2. Generic Thermal Limit Curve Method

To obtain the trip time for Stator

(For Cold Stator when I > SF)

$$T_p = \left[\frac{2.5 \times Curve}{\ln\left[\frac{36-(0.9\times SF)^2}{36-SF^2}\right]}\right] \times \ln\left[\frac{I^2}{I^2-SF^2}\right]$$

(For Hot Stator)

$$T_p = \left[\frac{2.5 \times Curve}{\ln\left[\frac{36-(0.9\times SF)^2}{36-SF^2}\right]}\right] \times \ln\left[\frac{I^2-(0.9\times SF)^2}{I^2-SF^2}\right]$$

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

To obtain the trip time for stator, when cold stator is used particularly when I is greater than the service factor SF, then you have to use this equation $\boldsymbol{T_p} = \left[\frac{\mathbf{2.5}\times \boldsymbol{Curve}}{\mathbf{ln}\left[\frac{\mathbf{36}-(\mathbf{0.9}\times \boldsymbol{SF})^2}{\mathbf{36}-\boldsymbol{SF}^2}\right]}\right] \times \mathbf{ln}\left[\frac{\boldsymbol{I^2}}{\boldsymbol{I^2}-\boldsymbol{SF^2}}\right]$.

And when it is in hot condition, then you have to use the another alternate equation,

$$\boldsymbol{T_p} = \left[\frac{\mathbf{2.5}\times \boldsymbol{Curve}}{\mathbf{ln}\left[\frac{\mathbf{36}-(\mathbf{0.9}\times \boldsymbol{SF})^2}{\mathbf{36}-\boldsymbol{SF}^2}\right]}\right] \times \mathbf{ln}\left[\frac{\boldsymbol{I^2}-(\mathbf{0.9}\times \boldsymbol{SF})^2}{\boldsymbol{I^2}-\boldsymbol{SF^2}}\right]$$

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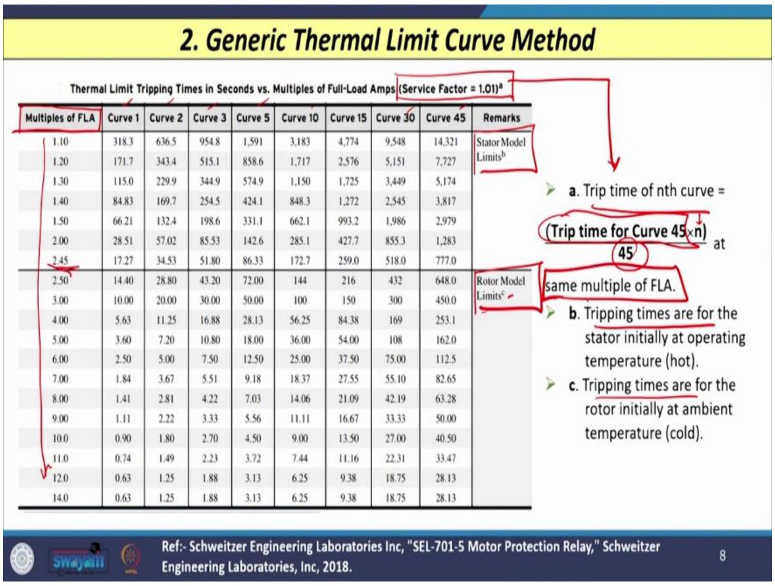

## 2. Generic Thermal Limit Curve Method

Thermal Limit Tripping Times in Seconds vs. Multiples of Full-Load Amps (Service Factor = 1.01)[a]

| Multiples of FLA | Curve 1 | Curve 2 | Curve 3 | Curve 5 | Curve 10 | Curve 15 | Curve 30 | Curve 45 | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 1.10 | 318.3 | 636.5 | 954.8 | 1,591 | 3,183 | 4,774 | 9,548 | 14,321 | Stator Model Limits[b] |
| 1.20 | 171.7 | 343.4 | 515.1 | 858.6 | 1,717 | 2,576 | 5,151 | 7,727 | |
| 1.30 | 115.0 | 229.9 | 344.9 | 574.9 | 1,150 | 1,725 | 3,449 | 5,174 | |
| 1.40 | 84.83 | 169.7 | 254.5 | 424.1 | 848.3 | 1,272 | 2,545 | 3,817 | |
| 1.50 | 66.21 | 132.4 | 198.6 | 331.1 | 662.1 | 993.2 | 1,986 | 2,979 | |
| 2.00 | 28.51 | 57.02 | 85.53 | 142.6 | 285.1 | 427.7 | 855.3 | 1,283 | |
| 2.45 | 17.27 | 34.53 | 51.80 | 86.33 | 172.7 | 259.0 | 518.0 | 777.0 | |
| 2.50 | 14.40 | 28.80 | 43.20 | 72.00 | 144 | 216 | 432 | 648.0 | Rotor Model Limits[c] |
| 3.00 | 10.00 | 20.00 | 30.00 | 50.00 | 100 | 150 | 300 | 450.0 | |
| 4.00 | 5.63 | 11.25 | 16.88 | 28.13 | 56.25 | 84.38 | 169 | 253.1 | |
| 5.00 | 3.60 | 7.20 | 10.80 | 18.00 | 36.00 | 54.00 | 108 | 162.0 | |
| 6.00 | 2.50 | 5.00 | 7.50 | 12.50 | 25.00 | 37.50 | 75.00 | 112.5 | |
| 7.00 | 1.84 | 3.67 | 5.51 | 9.18 | 18.37 | 27.55 | 55.10 | 82.65 | |
| 8.00 | 1.41 | 2.81 | 4.22 | 7.03 | 14.06 | 21.09 | 42.19 | 63.28 | |
| 9.00 | 1.11 | 2.22 | 3.33 | 5.56 | 11.11 | 16.67 | 33.33 | 50.00 | |
| 10.0 | 0.90 | 1.80 | 2.70 | 4.50 | 9.00 | 13.50 | 27.00 | 40.50 | |
| 11.0 | 0.74 | 1.49 | 2.23 | 3.72 | 7.44 | 11.16 | 22.31 | 33.47 | |
| 12.0 | 0.63 | 1.25 | 1.88 | 3.13 | 6.25 | 9.38 | 18.75 | 28.13 | |
| 14.0 | 0.63 | 1.25 | 1.88 | 3.13 | 6.25 | 9.38 | 18.75 | 28.13 | |

- **a**. Trip time of nth curve = $\frac{\text{(Trip time for Curve 45} \times n)}{45}$ at same multiple of FLA.
- **b**. Tripping times are for the stator initially at operating temperature (hot).
- **c**. Tripping times are for the rotor initially at ambient temperature (cold).

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

So, if I just give you the table, so, this table indicates you can see (as shown in above slide) the first column that shows the multiple of the FLA and this FLA are given here, right starting from 1.1 to 14 values, the multiples of FLA that is given and after that from second column the different curves are given let us say curve number 1 to curve number 45. But I have shown only few curves, say curve number 1, 2, 3, 5, 10, 15, 30 and 45. And for each curve the time is given and this time is usually in seconds.

So, you can see (as shown in above slide) that for each curve let us say curve number 1, curve number 2 or curve number number 15, the time is given and you can see that here, if I consider the last column that is the remark column, then you can see that the stator model limits that is given and that is up to the FLA that is up to 2.45. And beyond that when your FLA becomes 2.5 to 14 then the rotor model limits that is given (as shown in above slide).

So, here stator model limits you can see that is nothing but the tripping times. In this case are for the stator initially when the motor is operating in hot condition, whereas, the rotor model limits you can see the constant c that is nothing but the tripping times are for the rotor initially at ambient temperature when it is in cold condition.

And here you can see that one more point I have given that is nothing but the service factor is equal to 1.01 A, where this A is an important parameter which is nothing but the trip time of n$^{th}$ curve. So, you can calculate the trip time of any curve, if the trip time let us say of curve number 45 is available, then you have to multiply with that n and divided by 45.

So, you can calculate the trip time of any particular n$^{th}$ curve with a condition that you have to use the same multiple of FLA while calculating the trip time of n$^{th}$ curve.

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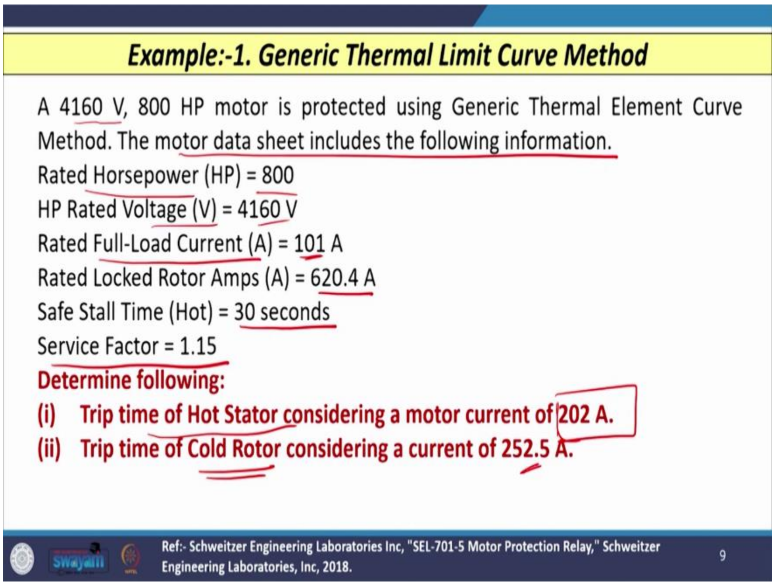

## Example:-1. Generic Thermal Limit Curve Method

A 4160 V, 800 HP motor is protected using Generic Thermal Element Curve Method. The motor data sheet includes the following information.

Rated Horsepower (HP) = 800
HP Rated Voltage (V) = 4160 V
Rated Full-Load Current (A) = 101 A
Rated Locked Rotor Amps (A) = 620.4 A
Safe Stall Time (Hot) = 30 seconds
Service Factor = 1.15

**Determine following:**

**(i) Trip time of Hot Stator considering a motor current of 202 A.**
**(ii) Trip time of Cold Rotor considering a current of 252.5 A.**

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

So, let us consider one example for generic thermal limit curve method. So, let us say that we have 4160 volt, 800 HP induction motor which is protected by generic thermal element curve method. The motor datasheet includes the following information.

So, rated HP is 800, rated voltages 4160 volt, rated full load current of the motor in ampere ratings 101 and rated locked rotor amps that is also given in ampere, that is 620.4 A and safe stalling time when motor is running in hot condition it is given as 30 seconds and service factor is also given that is 1.15.

So, with this available data for the motor, we have to determine two things number one, what is the trip time of hot stator considering a motor current of 202 A and in second case we have to calculate the trip time of cold rotor considering a current of 252.5 A. So, let us calculate the first thing that is trip time of hot stator considering the motor current that is given as 202 A.

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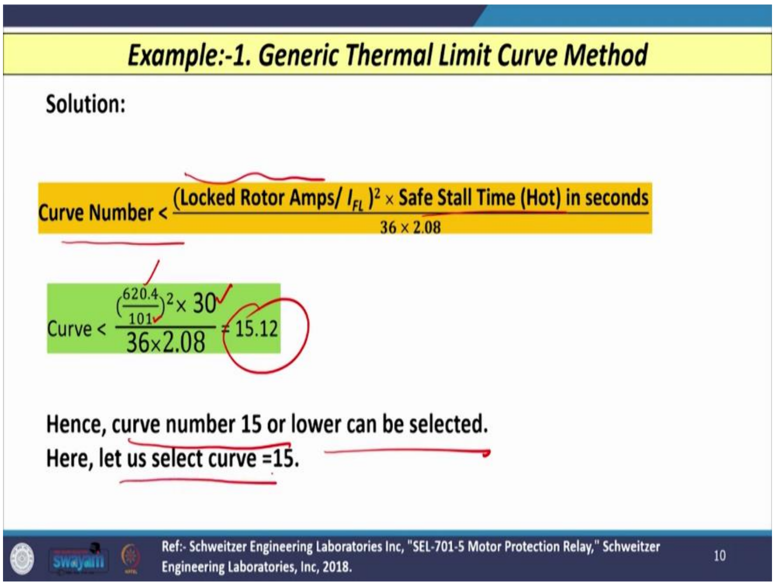


**Example:-1. Generic Thermal Limit Curve Method**

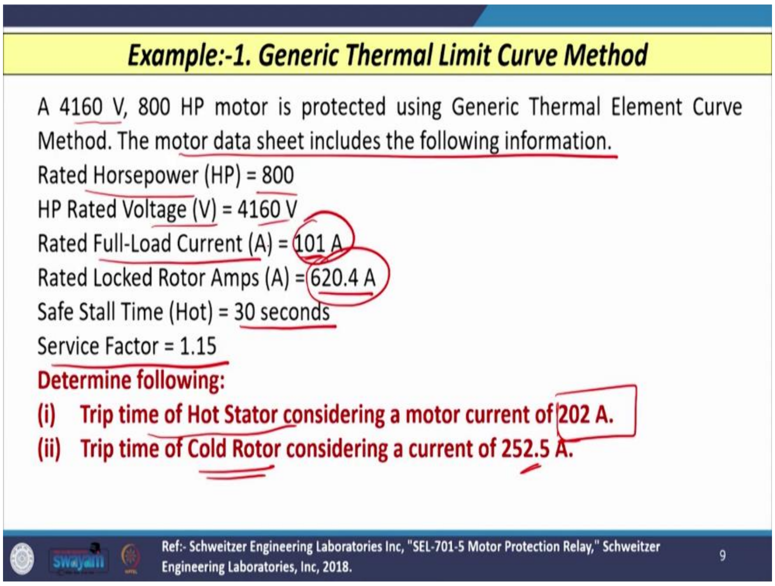
**Solution:**

$$\text{Curve Number} < \frac{(\text{Locked Rotor Amps}/ I_{FL})^2 \times \text{Safe Stall Time (Hot) in seconds}}{36 \times 2.08}$$

$$\text{Curve} < \frac{(\frac{620.4}{101})^2 \times 30}{36 \times 2.08} = 15.12$$

**Hence, curve number 15 or lower can be selected.**
**Here, let us select curve =15.**

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.



**Example:-1. Generic Thermal Limit Curve Method**

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**Determine following:**

**(i) Trip time of Hot Stator considering a motor current of 202 A.**
**(ii) Trip time of Cold Rotor considering a current of 252.5 A.**

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

So, before we start calculating the first thing, let us calculate first the curve number. So, we have already discussed that the curve number equation,

$$\textbf{Curve Number} < \frac{\textbf{(Locked Rotor Amps/ } I_{FL}\textbf{ )}^2 \times \textbf{Safe Stall Time (Hot) in seconds}}{\mathbf{36 \times 2.08}}$$

$$\text{Curve} < \frac{(\frac{620.4}{101})^2 \times 30}{36 \times 2.08} = 15.12$$

By using this we can have the value of curve number that is less than 15.12. Now, my curve number that is always integer, so, we can select the curve number either 15 or any lower value. So, here in this example, I have selected the curve number that is 15.

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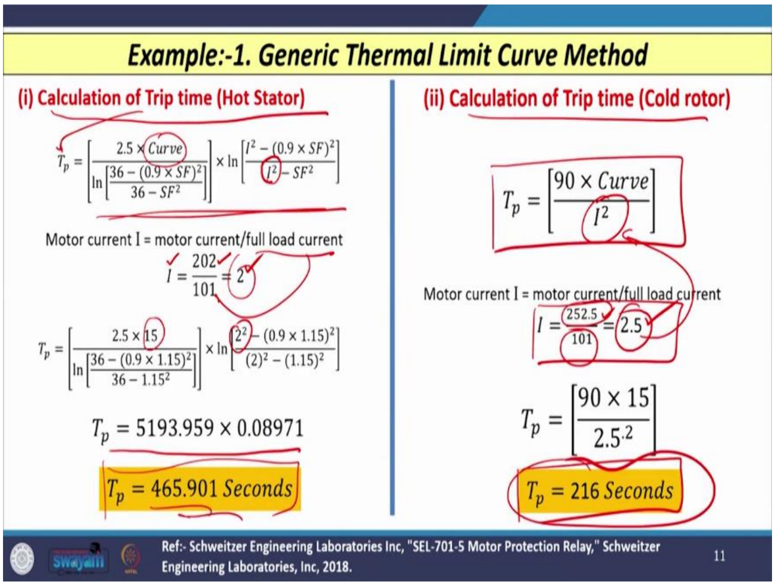

## Example:-1. Generic Thermal Limit Curve Method

**(i) Calculation of Trip time (Hot Stator)**

$$T_p = \left[\frac{2.5 \times Curve}{\ln\left[\frac{36-(0.9\times SF)^2}{36-SF^2}\right]}\right] \times \ln\left[\frac{I^2-(0.9\times SF)^2}{I^2-SF^2}\right]$$

Motor current I = motor current/full load current

$$I = \frac{202}{101} = 2$$

$$T_p = \left[\frac{2.5 \times 15}{\ln\left[\frac{36-(0.9\times 1.15)^2}{36-1.15^2}\right]}\right] \times \ln\left[\frac{2^2-(0.9\times 1.15)^2}{(2)^2-(1.15)^2}\right]$$

$$T_p = 5193.959 \times 0.08971$$

$$T_p = 465.901\ Seconds$$

**(ii) Calculation of Trip time (Cold rotor)**

$$T_p = \left[\frac{90 \times Curve}{I^2}\right]$$

Motor current I = motor current/full load current

$$I = \frac{252.5}{101} = 2.5$$

$$T_p = \left[\frac{90 \times 15}{2.5^2}\right]$$

$$T_p = 216\ Seconds$$

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

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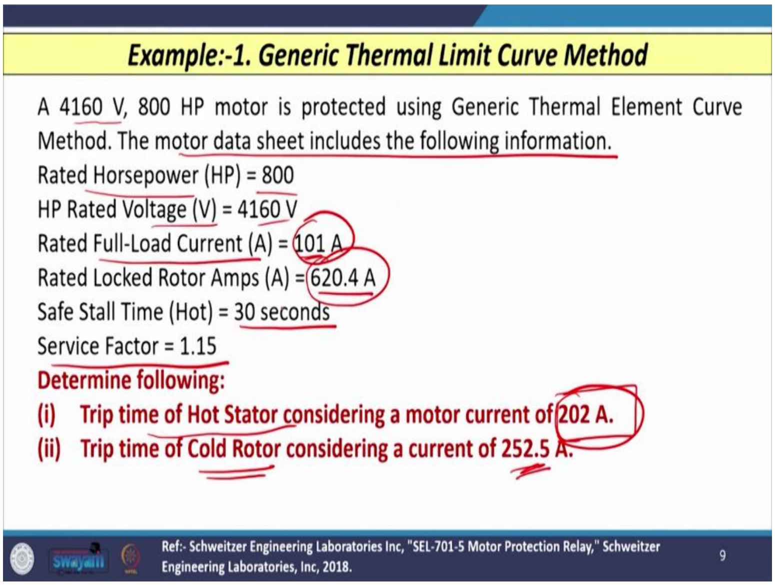

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Rated Full-Load Current (A) = 101 A
Rated Locked Rotor Amps (A) = 620.4 A
Safe Stall Time (Hot) = 30 seconds
Service Factor = 1.15

**Determine following:**

**(i) Trip time of Hot Stator considering a motor current of 202 A.**

**(ii) Trip time of Cold Rotor considering a current of 252.5 A.**

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

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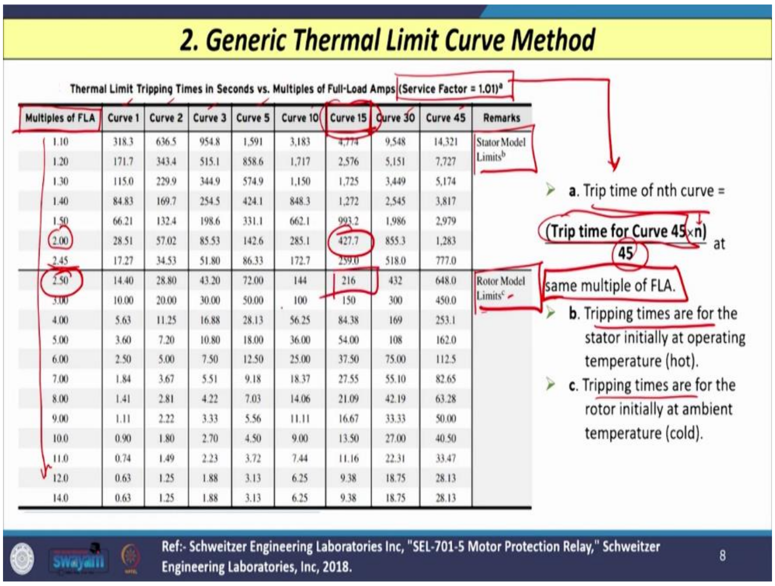

## 2. Generic Thermal Limit Curve Method

**Thermal Limit Tripping Times in Seconds vs. Multiples of Full-Load Amps (Service Factor = 1.01)[a]**

| Multiples of FLA | Curve 1 | Curve 2 | Curve 3 | Curve 5 | Curve 10 | Curve 15 | Curve 30 | Curve 45 | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 1.10 | 318.3 | 636.5 | 954.8 | 1,591 | 3,183 | ~~4,774~~ | 9,548 | 14,321 | Stator Model Limits[b] |
| 1.20 | 171.7 | 343.4 | 515.1 | 858.6 | 1,717 | 2,576 | 5,151 | 7,727 | |
| 1.30 | 115.0 | 229.9 | 344.9 | 574.9 | 1,150 | 1,725 | 3,449 | 5,174 | |
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| 2.00 | 28.51 | 57.02 | 85.53 | 142.6 | 285.1 | 427.7 | 855.3 | 1,283 | |
| 2.45 | 17.27 | 34.53 | 51.80 | 86.33 | 172.7 | 259.0 | 518.0 | 777.0 | |
| 2.50 | 14.40 | 28.80 | 43.20 | 72.00 | 144 | 216 | 432 | 648.0 | Rotor Model Limits[c] |
| 3.00 | 10.00 | 20.00 | 30.00 | 50.00 | 100 | 150 | 300 | 450.0 | |
| 4.00 | 5.63 | 11.25 | 16.88 | 28.13 | 56.25 | 84.38 | 169 | 253.1 | |
| 5.00 | 3.60 | 7.20 | 10.80 | 18.00 | 36.00 | 54.00 | 108 | 162.0 | |
| 6.00 | 2.50 | 5.00 | 7.50 | 12.50 | 25.00 | 37.50 | 75.00 | 112.5 | |
| 7.00 | 1.84 | 3.67 | 5.51 | 9.18 | 18.37 | 27.55 | 55.10 | 82.65 | |
| 8.00 | 1.41 | 2.81 | 4.22 | 7.03 | 14.06 | 21.09 | 42.19 | 63.28 | |
| 9.00 | 1.11 | 2.22 | 3.33 | 5.56 | 11.11 | 16.67 | 33.33 | 50.00 | |
| 10.0 | 0.90 | 1.80 | 2.70 | 4.50 | 9.00 | 13.50 | 27.00 | 40.50 | |
| 11.0 | 0.74 | 1.49 | 2.23 | 3.72 | 7.44 | 11.16 | 22.31 | 33.47 | |
| 12.0 | 0.63 | 1.25 | 1.88 | 3.13 | 6.25 | 9.38 | 18.75 | 28.13 | |
| 14.0 | 0.63 | 1.25 | 1.88 | 3.13 | 6.25 | 9.38 | 18.75 | 28.13 | |

- **a**. Trip time of nth curve = $\frac{(\text{Trip time for Curve } 45 \times n)}{45}$ at same multiple of FLA.
- **b**. Tripping times are for the stator initially at operating temperature (hot).
- **c**. Tripping times are for the rotor initially at ambient temperature (cold).

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

Now, let us calculate the first thing that is the calculation of trip time when stator is used and it is in hot condition. So, in that case, we have already seen the equation to calculate the trip time that is $T_p = \left[\frac{2.5\times Curve}{\ln\left[\frac{36-(0.9\times SF)^2}{36-SF^2}\right]}\right] \times \ln\left[\frac{I^2-(0.9\times SF)^2}{I^2-SF^2}\right]$.

Motor current I = motor current/full load current, so, motor current it is already given as 202 A in first case, the motor current is given us this value and we need to calculate the trip time of hot stator. So, if I consider this 202 A and full load current is given as 101 A, then we will have the value of I that is 2.

$$I = \frac{202}{101} = 2$$

So, with this calculated value of I, we can put the value in this equation, you will have the value of $T_P$ that is 465.901 seconds. So, this is for stator and the dist time is 465.

$$T_p = \left[\frac{2.5 \times 15}{\ln\left[\frac{36-(0.9\times 1.15)^2}{36-1.15^2}\right]}\right] \times \ln\left[\frac{2^2-(0.9\times 1.15)^2}{(2)^2-(1.15)^2}\right]$$

$$T_p = 5193.959 \times 0.08971$$

$$T_p = 465.901\,Seconds$$

So, if I look at this table, then you can see (as shown in above slide) we are interested in curve number 15. Because we have consider the curve as the curve number 15 and we have already calculated for stator and the time comes out to be $T_P$ is equal to 465 for the value that is 2. So, you can say that when we consider the value that is 2 for curve number. Let us say here 15, then value comes out to be close to 427 and here whatever we have calculated there comes out to be 465 seconds, so, which is very close to the value given in the table.

Similarly, if we calculate the value of trip time for cold rotor, then TP is given by this equation,

$$T_p = \left[\frac{90 \times Curve}{I^2}\right]$$

$$I = \frac{252.5}{101} = 2.5$$

$$T_p = \left[\frac{90 \times 15}{2.5^{.2}}\right]$$

$$T_p = 216\ Seconds$$

So, motor current is this 252.5. The full load current is 101 A value of I that comes out to be 2.5. So, with this value if I put it here, then we can have the value of $T_P$ that is 216 second, so, with I 2.5 for curve that is equal to 15, the value of $T_P$ comes out to be 216. So, you can see that when I consider the 2.5 that is equal to I and when I consider the curve number 15 for rotor case, the value comes out to be 216. Whereas whatever value we calculated that is also coming 216 seconds. So, both are exactly matched.

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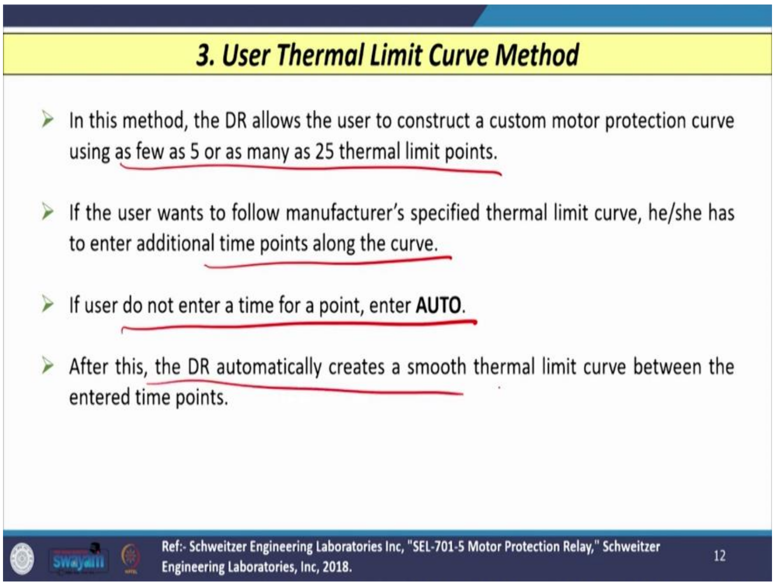

## 3. User Thermal Limit Curve Method

- In this method, the DR allows the user to construct a custom motor protection curve using as few as 5 or as many as 25 thermal limit points.
- If the user wants to follow manufacturer's specified thermal limit curve, he/she has to enter additional time points along the curve.
- If user do not enter a time for a point, enter **AUTO**.
- After this, the DR automatically creates a smooth thermal limit curve between the entered time points.

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

Now, let us see the third method that is nothing but the user thermal limit curve method. So in this method, the digital relay allows the user to construct the custom motor protection curve. So, whatever curve we want to construct based on whatever input we give you that is to be constructed. And that we can construct the curves as few as let us say 5 or as many as 25 thermal limit points we can have and based on that the relay can construct the custom motor protection curve.

If user wants to follow manufacturer's specified thermal limit curve, then user that is free to follow that the user has to enter additional time points along the curve. However, if user does not want this, and let us say this is given in auto mode, then after this the digital relay automatically calculates a smooth thermal limit curve between the entered time points.

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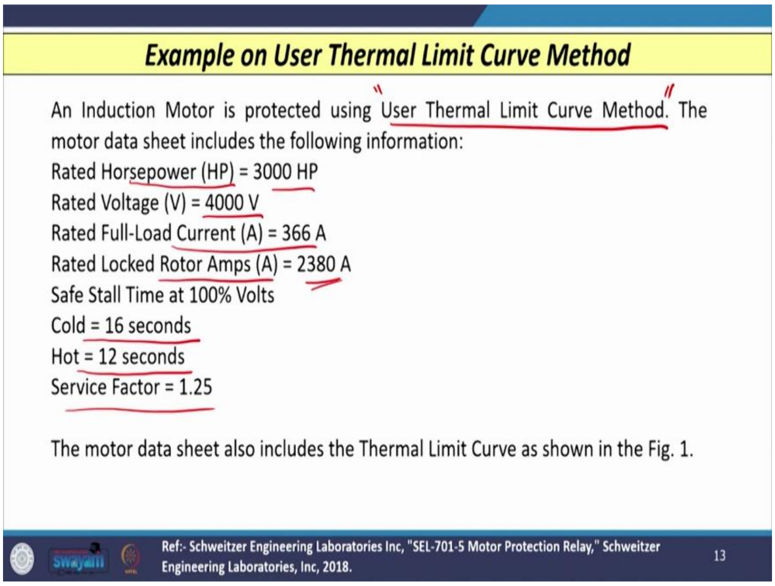

## Example on User Thermal Limit Curve Method

An Induction Motor is protected using "User Thermal Limit Curve Method." The motor data sheet includes the following information:

Rated Horsepower (HP) = 3000 HP
Rated Voltage (V) = 4000 V
Rated Full-Load Current (A) = 366 A
Rated Locked Rotor Amps (A) = 2380 A
Safe Stall Time at 100% Volts
Cold = 16 seconds
Hot = 12 seconds
Service Factor = 1.25

The motor data sheet also includes the Thermal Limit Curve as shown in the Fig. 1.

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

So, let us see how this can be achieved. So, let us understand this thing with one of the example. So, let us consider an induction motor which is protected using user thermal limit curve method. So, we will use this method, the motor datasheet has the following information rated HP that is 3000, rated voltage is 4000 volt, rated full load current is 366 ampere and rated locked rotor amps that is 2380 ampere.

Safe stalling time at 100 percent voltage available at terminal of the motor, when motor is in cold condition it is 16 second and when motor is in hot condition it is 12 seconds. The service factor is given as 1.25. So, the motor datasheet also includes because along with this data, the

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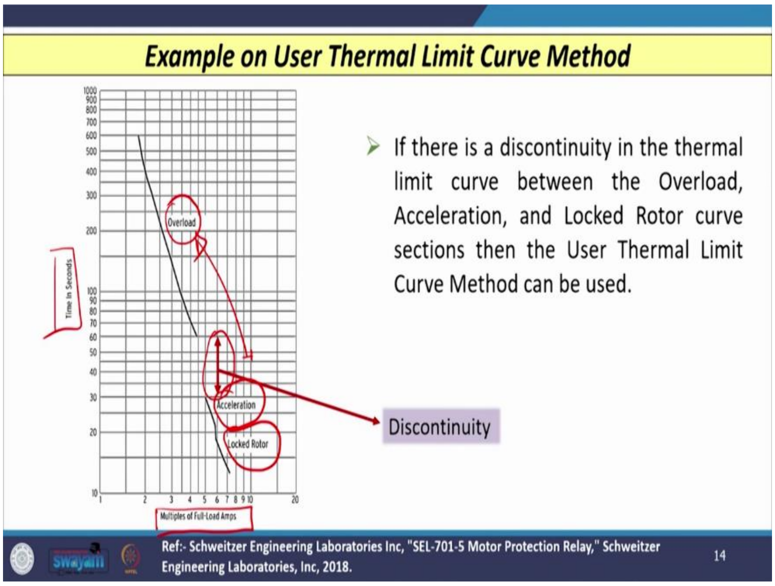

## Example on User Thermal Limit Curve Method

- If there is a discontinuity in the thermal limit curve between the Overload, Acceleration, and Locked Rotor curve sections then the User Thermal Limit Curve Method can be used.

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

thermal limit curve is also given as shown here in this screen. So, you can see (as shown in above slide) that again in this curve or x axis we have multiples of full load amps and on y axis we have the time in seconds and in this curve three regions are clearly marked, one is the overload, another is the acceleration and another is the locked rotor.

However, you can see that there is a discontinuity in this curve between the overload and acceleration and locked rotor, these two. So, that means you can see that discontinuity I have marked with this arrow. So, with this discontinuity, let us see how we can have or how the calculations are to be carried out if we go for user thermal limit curve method.

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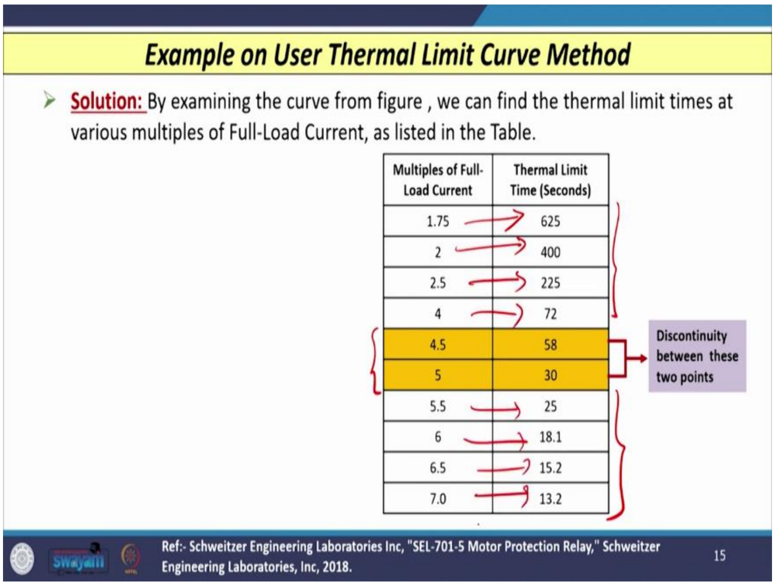


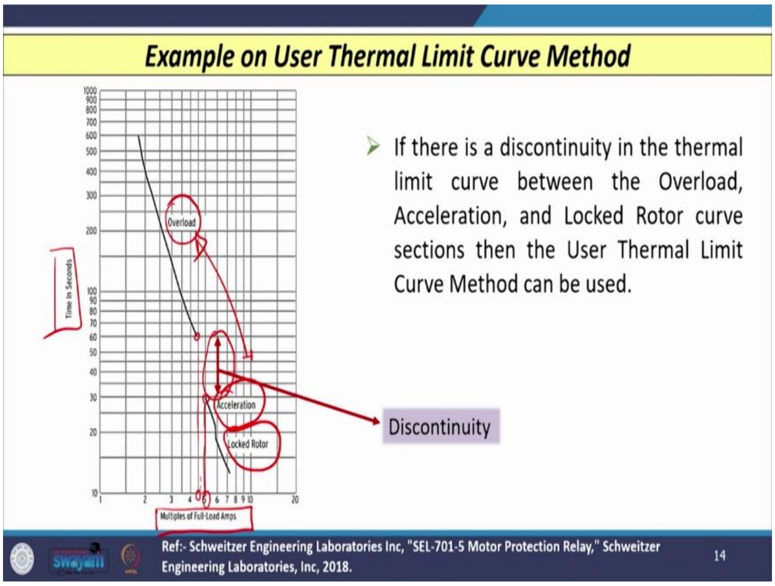
**Example on User Thermal Limit Curve Method**

- **Solution:** By examining the curve from figure , we can find the thermal limit times at various multiples of Full-Load Current, as listed in the Table.

| Multiples of Full-Load Current | Thermal Limit Time (Seconds) |
|---|---|
| 1.75 | 625 |
| 2 | 400 |
| 2.5 | 225 |
| 4 | 72 |
| 4.5 | 58 |
| 5 | 30 |
| 5.5 | 25 |
| 6 | 18.1 |
| 6.5 | 15.2 |
| 7.0 | 13.2 |

Discontinuity between these two points

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.



**Example on User Thermal Limit Curve Method**

- If there is a discontinuity in the thermal limit curve between the Overload, Acceleration, and Locked Rotor curve sections then the User Thermal Limit Curve Method can be used.

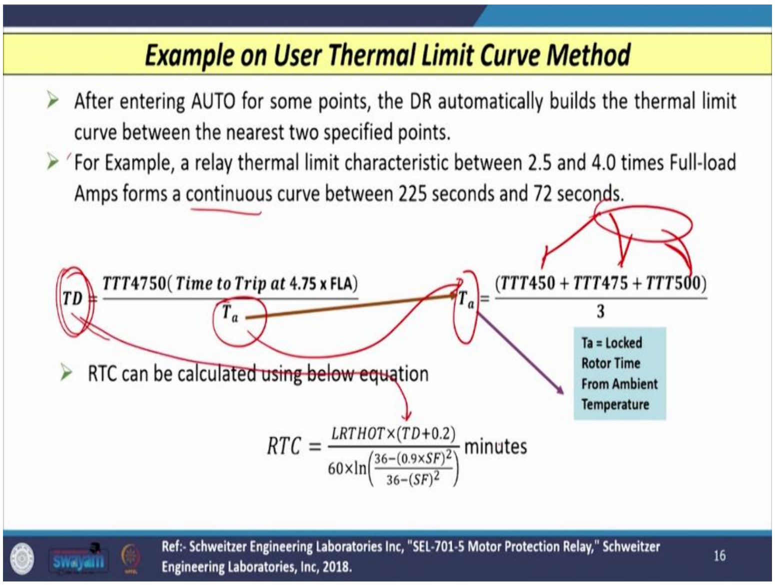
Discontinuity

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

So, if we examine this curve, then we can find that the thermal limit times at various multiples of full load currents are listed in this table (as shown in above slide). So, what I have done, you can see that there is a discontinuity from this point and if I extend it, this value comes out to be 4.5 and when this curve of acceleration start if I extend this point, this value comes out to be five. So, there is a discontinuity between the multiple of full load amps from 4.5 to 5 (as shown in above slide).

So, you can see (as shown in above slide) this two points 4.5 multiples of FL full load amps and 5 that I have marked and the thermal limit time in seconds are also given here. Because there is a discontinuity between these two points other points are easily available. So, for respective value of multiple or full load current you can have the thermal time in seconds for each this value, so this are available.

(Refer Slide Time: 18:19)



## Example on User Thermal Limit Curve Method

- After entering AUTO for some points, the DR automatically builds the thermal limit curve between the nearest two specified points.
- For Example, a relay thermal limit characteristic between 2.5 and 4.0 times Full-load Amps forms a continuous curve between 225 seconds and 72 seconds.

$$TD = \frac{TTT4750(\,Time\ to\ Trip\ at\ 4.75\ \text{x FLA})}{T_a} \qquad T_a = \frac{(TTT450 + TTT475 + TTT500)}{3}$$

Ta = Locked Rotor Time From Ambient Temperature

- RTC can be calculated using below equation

$$RTC = \frac{LRTHOT \times (TD+0.2)}{60 \times \ln\left(\frac{36-(0.9\times SF)^2}{36-(SF)^2}\right)} \text{ minutes}$$

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

Now, after entering AUTO for some points, the digital relay will automatically builds the thermal limit curve between the two nearest points. For example, if a relay thermal limit characteristics that is between 2.5 to 4 times the full load amps from continuous curve between 225 second and 72 seconds, then the value of TD that can be calculated using equation,

$$\boldsymbol{TD} = \frac{\boldsymbol{TTT4750(\,Time\ to\ Trip\ at\ }\mathbf{4.75\ x\ FLA)}}{\boldsymbol{T_a}}\ .$$

And $T_a$ can be calculated using this equation, where you are just calculating the value of Ta by averaging the time to trip at three different value of FLA.

$$\boldsymbol{T_a} = \frac{(\boldsymbol{TTT450} + \boldsymbol{TTT475} + \boldsymbol{TTT500})}{\mathbf{3}}$$

So, these are the three different values of FLA and you are just averaging it and by this way you are calculating the $T_a$ once $T_a$ is available, you can help the value of TD and that TD you can use it here for the calculation of the value of RTC, in this way we can easily calculate the value of RTC using user thermal limit curve method.

$$RTC = \frac{LRTHOT \times (TD+0.2)}{60 \times \ln\left(\frac{36-(0.9\times SF)^2}{36-(SF)^2}\right)} \text{ minutes}$$

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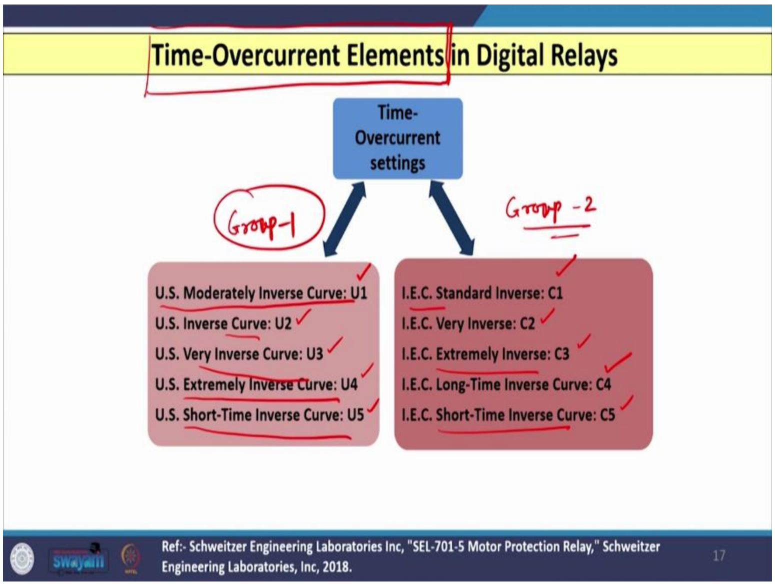

Time-Overcurrent Elements in Digital Relays

Time-Overcurrent settings

Group-1

- U.S. Moderately Inverse Curve: U1
- U.S. Inverse Curve: U2
- U.S. Very Inverse Curve: U3
- U.S. Extremely Inverse Curve: U4
- U.S. Short-Time Inverse Curve: U5

Group -2

- I.E.C. Standard Inverse: C1
- I.E.C. Very Inverse: C2
- I.E.C. Extremely Inverse: C3
- I.E.C. Long-Time Inverse Curve: C4
- I.E.C. Short-Time Inverse Curve: C5

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

Now with this background, let us see what are the other features of digital relays if we consider the induction motor. So another important feature that is provided or given by digital relays when we use it for the protection of induction motor that is in terms of time over current elements. So let us see how time over current elements feature or logic that is given in digital relays.

So time overcurrent logic or elements are given in digital relays to achieve the protection against short circuits. So, if any short circuit occurs, then that can be protected using time over current elements. So, here protection can be in terms of instantaneous or it can be in terms of time delayed. So, let us see how this can be done.

So, in digital relay time over current element settings are normally given in two groups. So, group one that contains different curves, five curves let us say and this curves are starting from U.S. moderately inverse curve given U1, U.S. inverse curve given as U2, U.S. very inverse curve specified as U3, U.S. extremely inverse curve specified as U4 and U.S. short time inverse curves specified at U5.

The second group, group 2 that contains again another five curves, but that is based on I.E.C. standard inverse characteristic that is C1, I.E.C. very inverse characteristic specified as C2, I.E.C. extremely inverse characteristics specified at C3, and I.E.C. long time inverse curve specified as C4 and I.E.C. short time inverse curve denoted as C5. So, two different groups are available, it is up to the user that what group you want to select and in particular group what type of characteristic you want to use or whatever depending upon application.

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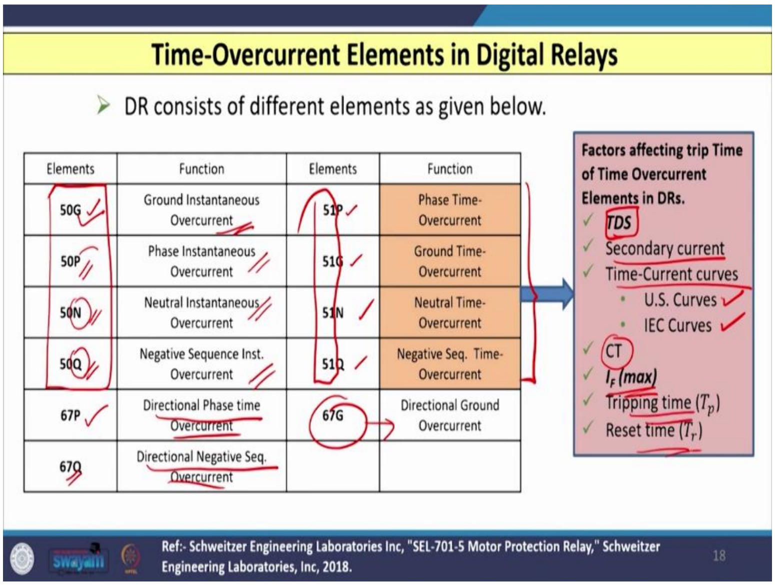

## Time-Overcurrent Elements in Digital Relays

- DR consists of different elements as given below.

| Elements | Function | Elements | Function |
|---|---|---|---|
| 50G | Ground Instantaneous Overcurrent | 51P | Phase Time-Overcurrent |
| 50P | Phase Instantaneous Overcurrent | 51G | Ground Time-Overcurrent |
| 50N | Neutral Instantaneous Overcurrent | 51N | Neutral Time-Overcurrent |
| 50Q | Negative Sequence Inst. Overcurrent | 51Q | Negative Seq. Time-Overcurrent |
| 67P | Directional Phase time Overcurrent | 67G | Directional Ground Overcurrent |
| 67Q | Directional Negative Seq. Overcurrent | | |

**Factors affecting trip Time of Time Overcurrent Elements in DRs.**

- ✓ *TDS*
- ✓ Secondary current
- ✓ Time-Current curves
  - U.S. Curves
  - IEC Curves
- ✓ CT
- ✓ $I_F$ *(max)*
- ✓ Tripping time ($T_p$)
- ✓ Reset time ($T_r$)

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

Now, if I consider these two groups (as shown in above slide) in digital relays, then let us see what is the fundamental difference between these two groups. So, in all these two groups the function or element given as name as 50G which is known as ground instantaneous over current element, 50P that is phase instantaneous over current element, 50N that is neutral instantaneous over current element and 50Q that is negative sequence instantaneous over current element.

So, here in all these four elements, it starts with the number 50, and then for ground the notation is G, for phase the notation is P, for neutral the notation is N, for negative sequence the notation is Q, where 50 number remains common in all these four elements. This indicates that if we wish to achieve instantaneous protection, maybe for ground phase, neutral or negative sequence, then we have to select this elements.

On the other hand, if we want some time delayed protection against particular short circuit, let us say 51P is divided which means that it is phase time over current element 51G is ground time over current element, 51N is neutral time over current element and 51Q is negative sequence time over current element. So, here again you can see the 51 number is common, which indicates this is a time delayed protection.

So, if we want to achieve time delayed protection, maybe for phase ground neutral or maybe in case of negative sequence component generation, then we have to go for this four elements. Other than this eight elements, we have 67P elements which is meant for directional phase time over current and 67Q element which is meant for directional negative sequence over current element and 67G is also there for directional ground over current element.

Whenever we select time delayed operation for let us say this four groups then the tripping time what is given by this four elements which are time delayed in nature that depends on many factors, let us say depends on time dial setting what you are going to do in here, it also depends on secondary current, it also depends on time current curves, maybe you can go for U.S. curve or I.E.C. curve, it also depends on CT, it also depends on maximum fault current that is referred on CT secondary side along with tripping time and reset time Tr.

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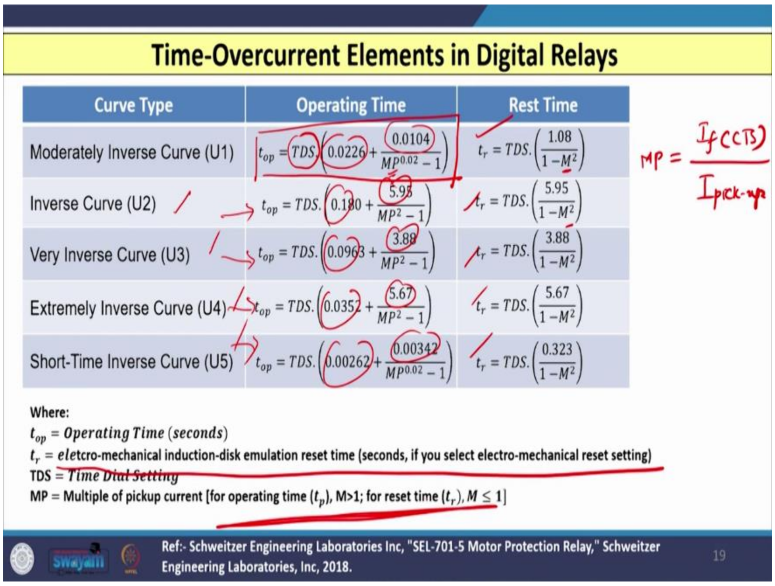

## Time-Overcurrent Elements in Digital Relays

| Curve Type | Operating Time | Rest Time |
|---|---|---|
| Moderately Inverse Curve (U1) | $t_{op} = TDS.\left(0.0226 + \frac{0.0104}{MP^{0.02} - 1}\right)$ | $t_r = TDS.\left(\frac{1.08}{1 - M^2}\right)$ |
| Inverse Curve (U2) | $t_{op} = TDS.\left(0.180 + \frac{5.95}{MP^2 - 1}\right)$ | $t_r = TDS.\left(\frac{5.95}{1 - M^2}\right)$ |
| Very Inverse Curve (U3) | $t_{op} = TDS.\left(0.0963 + \frac{3.88}{MP^2 - 1}\right)$ | $t_r = TDS.\left(\frac{3.88}{1 - M^2}\right)$ |
| Extremely Inverse Curve (U4) | $t_{op} = TDS.\left(0.0352 + \frac{5.67}{MP^2 - 1}\right)$ | $t_r = TDS.\left(\frac{5.67}{1 - M^2}\right)$ |
| Short-Time Inverse Curve (U5) | $t_{op} = TDS.\left(0.00262 + \frac{0.00342}{MP^{0.02} - 1}\right)$ | $t_r = TDS.\left(\frac{0.323}{1 - M^2}\right)$ |

$MP = \frac{I_f(CTS)}{I_{pick\text{-}up}}$

**Where:**

$t_{op}$ = *Operating Time* (*seconds*)

$t_r$ = eletcro-mechanical induction-disk emulation reset time (seconds, if you select electro-mechanical reset setting)

TDS = *Time Dial Setting*

MP = Multiple of pickup current [for operating time ($t_p$), M>1; for reset time ($t_r$), $M \leq 1$]

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

So, let us see if I wish to achieve this curve or this characteristic, then what are the different equations we can use in digital relays. So, if I use moderately inverse curve, then for that to calculate the time of operation of relay this equation is used $t_{op} = TDS.\left(0.0226 + \frac{0.0104}{MP^{0.02} - 1}\right)$

and in this equation TDS indicates time dial setting whereas MP indicates multiple of pickup current.

Similarly, for other curves let us say U.S. curve U2, U3, U4, U5, the respective equations for calculation of time of operation of relays that is given you can see in this equations the time constants this are different for each equations (as shown in above table). Now, one important point is in actual field, it may possible that let us say I have three relays out of which two relays are electromechanical in nature and one relay is a digital relay and I want to coordinate these three relays, then obviously, it is very practical that one digital relay, I want that that should be function as an electromechanical relay, so, that proper coordination can be achieved.

So, if I want to activate the electromechanical logic or unit in digital relay, that that is also available in terms of $t_r$ which is nothing but the electromechanical induction emulation reset time particularly we know that when the disk of the electromechanical relay comes to the original position from its fully operated state, then that time is known as reset time. And that for each curve there is equation of reset time that is different and that you can easily calculate where in this case equation of $t_r$, the value of M you can select based on this (as shown in above table).

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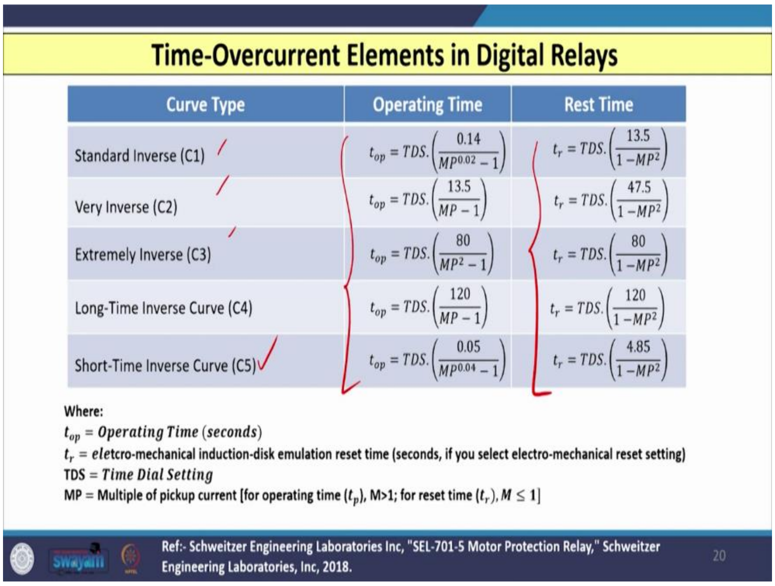

## Time-Overcurrent Elements in Digital Relays

| Curve Type | Operating Time | Rest Time |
|---|---|---|
| Standard Inverse (C1) | $t_{op} = TDS.\left(\frac{0.14}{MP^{0.02}-1}\right)$ | $t_r = TDS.\left(\frac{13.5}{1-MP^2}\right)$ |
| Very Inverse (C2) | $t_{op} = TDS.\left(\frac{13.5}{MP-1}\right)$ | $t_r = TDS.\left(\frac{47.5}{1-MP^2}\right)$ |
| Extremely Inverse (C3) | $t_{op} = TDS.\left(\frac{80}{MP^2-1}\right)$ | $t_r = TDS.\left(\frac{80}{1-MP^2}\right)$ |
| Long-Time Inverse Curve (C4) | $t_{op} = TDS.\left(\frac{120}{MP-1}\right)$ | $t_r = TDS.\left(\frac{120}{1-MP^2}\right)$ |
| Short-Time Inverse Curve (C5) ✓ | $t_{op} = TDS.\left(\frac{0.05}{MP^{0.04}-1}\right)$ | $t_r = TDS.\left(\frac{4.85}{1-MP^2}\right)$ |

**Where:**

$t_{op}$ = *Operating Time (seconds)*

$t_r$ = *eletcro*-mechanical induction-disk emulation reset time (seconds, if you select electro-mechanical reset setting)

TDS = *Time Dial Setting*

MP = Multiple of pickup current [for operating time ($t_p$), M>1; for reset time ($t_r$), $M \leq 1$]

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

Similarly, for the I.E.C curves also from C1 to C5 the different equations of the time of operation of the relays are given in terms of TDS and multiple of pickup current and similarly equation of $t_r$ for reference respective curve that is also given if I wish to use digital relay as an electromechanical relay (as shown in above table).

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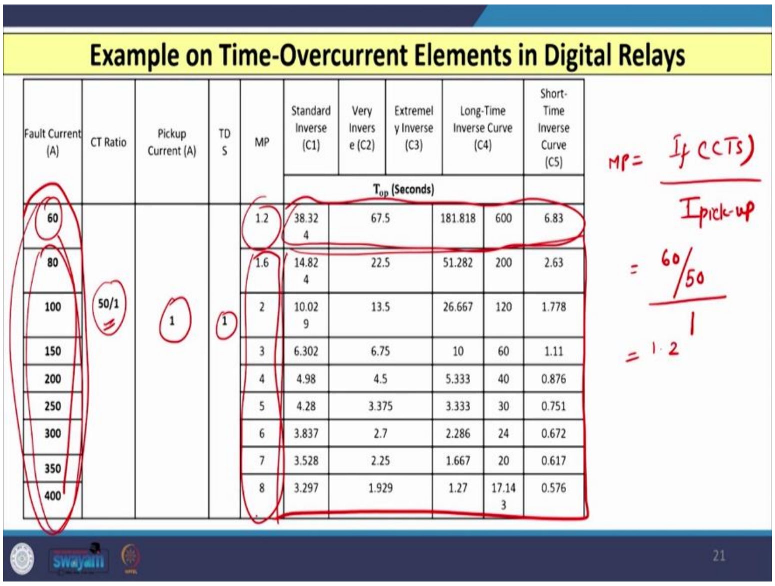
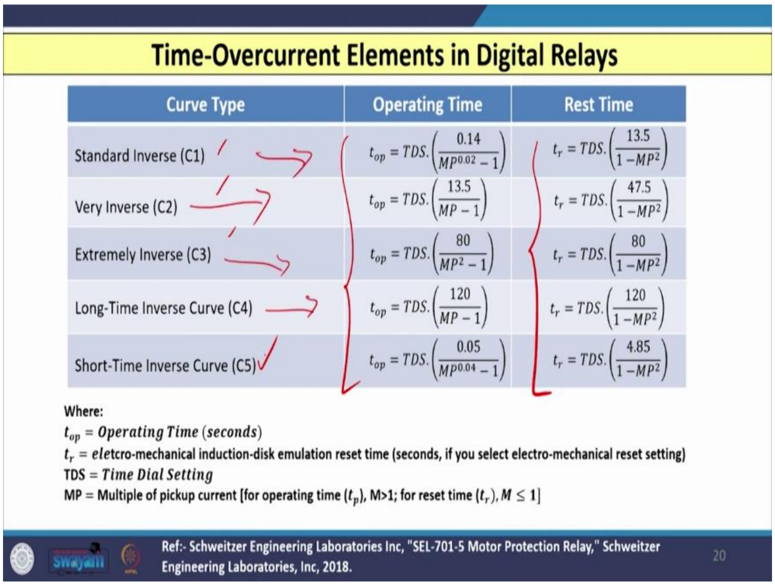


## Example on Time-Overcurrent Elements in Digital Relays

| Fault Current (A) | CT Ratio | Pickup Current (A) | TDS | MP | Standard Inverse (C1) | Very Inverse (C2) | Extremely Inverse (C3) | Long-Time Inverse Curve (C4) | Short-Time Inverse Curve (C5) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | $T_{op}$ (Seconds) | | | | |
| 60 | 50/1 | 1 | 1 | 1.2 | 38.324 | 67.5 | 181.818 | 600 | 6.83 |
| 80 | | | | 1.6 | 14.824 | 22.5 | 51.282 | 200 | 2.63 |
| 100 | | | | 2 | 10.029 | 13.5 | 26.667 | 120 | 1.778 |
| 150 | | | | 3 | 6.302 | 6.75 | 10 | 60 | 1.11 |
| 200 | | | | 4 | 4.98 | 4.5 | 5.333 | 40 | 0.876 |
| 250 | | | | 5 | 4.28 | 3.375 | 3.333 | 30 | 0.751 |
| 300 | | | | 6 | 3.837 | 2.7 | 2.286 | 24 | 0.672 |
| 350 | | | | 7 | 3.528 | 2.25 | 1.667 | 20 | 0.617 |
| 400 | | | | 8 | 3.297 | 1.929 | 1.27 | 17.143 | 0.576 |

$$MP = \frac{I_f\,(CTS)}{I_{pick\text{-}up}} = \frac{60/50}{1} = 1.2$$



## Time-Overcurrent Elements in Digital Relays

| Curve Type | Operating Time | Rest Time |
|---|---|---|
| Standard Inverse (C1) | $t_{op} = TDS.\left(\frac{0.14}{MP^{0.02}-1}\right)$ | $t_r = TDS.\left(\frac{13.5}{1-MP^2}\right)$ |
| Very Inverse (C2) | $t_{op} = TDS.\left(\frac{13.5}{MP-1}\right)$ | $t_r = TDS.\left(\frac{47.5}{1-MP^2}\right)$ |
| Extremely Inverse (C3) | $t_{op} = TDS.\left(\frac{80}{MP^2-1}\right)$ | $t_r = TDS.\left(\frac{80}{1-MP^2}\right)$ |
| Long-Time Inverse Curve (C4) | $t_{op} = TDS.\left(\frac{120}{MP-1}\right)$ | $t_r = TDS.\left(\frac{120}{1-MP^2}\right)$ |
| Short-Time Inverse Curve (C5) ✓ | $t_{op} = TDS.\left(\frac{0.05}{MP^{0.04}-1}\right)$ | $t_r = TDS.\left(\frac{4.85}{1-MP^2}\right)$ |

**Where:**

$t_{op}$ = *Operating Time* (*seconds*)

$t_r$ = *ele*tcro-mechanical induction-disk emulation reset time (seconds, if you select electro-mechanical reset setting)

TDS = *Time Dial Setting*

MP = Multiple of pickup current [for operating time ($t_p$), M>1; for reset time ($t_r$), $M \leq 1$]

Ref:- Schweitzer Engineering Laboratories Inc, "SEL-701-5 Motor Protection Relay," Schweitzer Engineering Laboratories, Inc, 2018.

Now, with this background, let us see one example. So, here in this example, I have considered different value of fault currents in ampere starting from 60 to 400 A, I have considered CT ratio as 50 by 1, pick up current I have considered as 1 and TDS value is also I have considered or I have taken as 1. So, the first thing is I wish to calculate the value of MP. So, MP is nothing but my fault current refer to CT secondary / I pick up current.

So, if I just consider the first fault current which is 60 A, so 60 A I have to refer on CT secondary, so, that is to be divided by CT ratio. So, that is 50 and that is again divided by pickup current that is 1. So, this value comes out to be 1.2 and using this value that is MP is equal to 1.2 and TDS is equal to 1 you can use the standard inverse curve that is this curve, very inverse curve, extremely inverse curve, long time and short time inverse curve that is C4, C5.

And you can calculate the time for each curve. And you can see this are the times which I have calculated (as shown in above slide). So, similarly, for other value or fault current you can calculate the value of multiple of pickup currents and then you can also calculate the time of operation of relays for each curve starting from C1 to C5.

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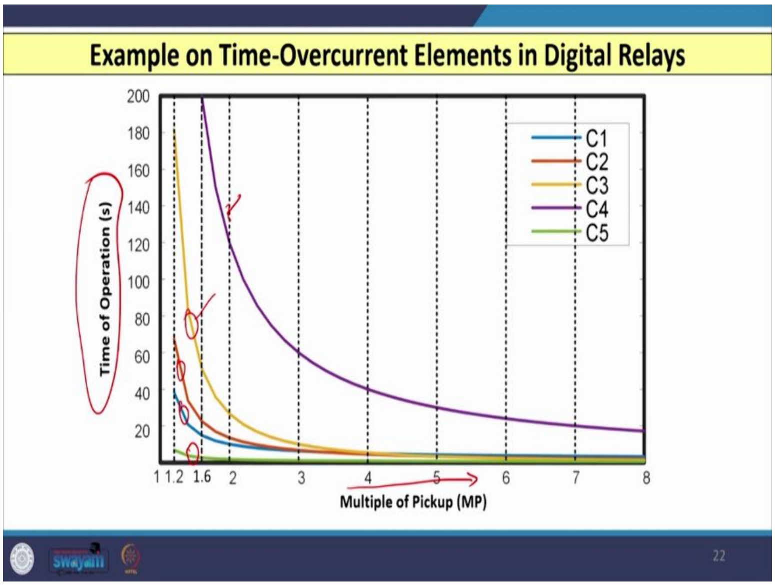
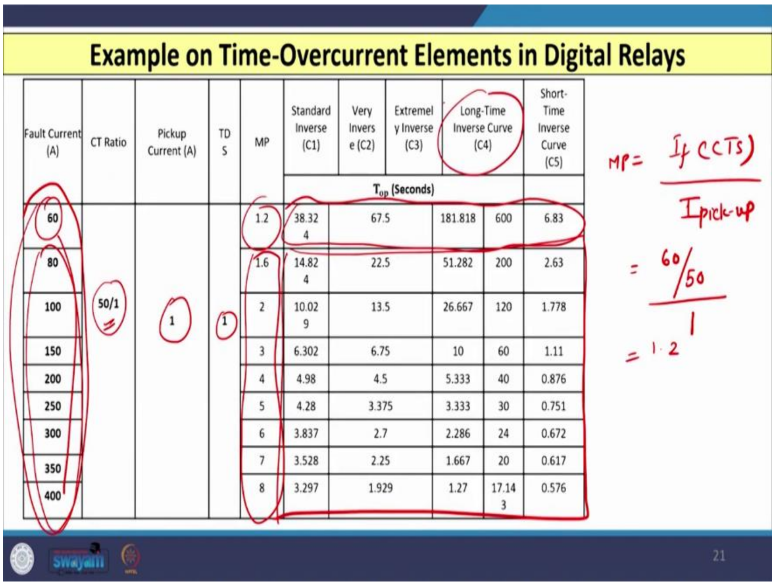
**Example on Time-Overcurrent Elements in Digital Relays**



**Example on Time-Overcurrent Elements in Digital Relays**



| Fault Current (A) | CT Ratio | Pickup Current (A) | TDS | MP | Standard Inverse (C1) | Very Inverse (C2) | Extremely Inverse (C3) | Long-Time Inverse Curve (C4) | Short-Time Inverse Curve (C5) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | $T_{op}$ (Seconds) | | | | |
| 60 | 50/1 | 1 | 1 | 1.2 | 38.324 | 67.5 | 181.818 | 600 | 6.83 |
| 80 | | | | 1.6 | 14.824 | 22.5 | 51.282 | 200 | 2.63 |
| 100 | | | | 2 | 10.029 | 13.5 | 26.667 | 120 | 1.778 |
| 150 | | | | 3 | 6.302 | 6.75 | 10 | 60 | 1.11 |
| 200 | | | | 4 | 4.98 | 4.5 | 5.333 | 40 | 0.876 |
| 250 | | | | 5 | 4.28 | 3.375 | 3.333 | 30 | 0.751 |
| 300 | | | | 6 | 3.837 | 2.7 | 2.286 | 24 | 0.672 |
| 350 | | | | 7 | 3.528 | 2.25 | 1.667 | 20 | 0.617 |
| 400 | | | | 8 | 3.297 | 1.929 | 1.27 | 17.143 | 0.576 |

$$MP = \frac{I_f (CTs)}{I_{pick\text{-}up}} = \frac{60/50}{1} = 1.2$$

And if I plot the graph of this five curves, assuming on x axis I am taking multiple are pickup currents and on y axis I am taking time of operation in seconds, then you can see (as shown in above graph) that this are the characteristic of different curves starting from this is the characteristic of C4 curve. So, this C4 curve is nothing but your long time inverse curve.

Similarly, you have the characteristic for the other curves, which I have shown depending upon what type of equation you have used, you can select the curve and you can have the characteristic like this, which follows inverse relationship.

So, in this lecture, we started our discussion with the second method that is generic method. And then we have discussed the user method, and in both the methods we have seen one example also using which we found that, if we select a particular settings, then using the equations, we can calculate the value of trip time.

And then finally, at the end we have discussed about the time overcurrent elements available in digital relays, we discuss that two groups are available, one is based on U.S. curve and another is based on I.E.C. curve and for each group different five characteristics are also available. And for each characteristic we have separate equations available, so we can utilize those equations. Thank you.