Power System Protection and Switchgear
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Lecture 35
Arc Interruption Theory in Circuit Breaker-II

So let us continue our discussion on Arc Interruption Theory of Circuit Breaker. So we have already discussed the different, important parameters of the Circuit Breaker.

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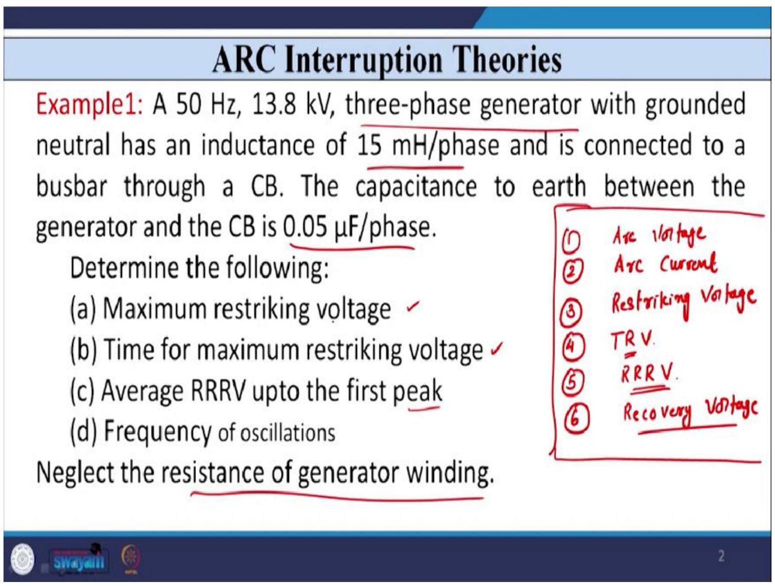

So, the first, we have discussed very important point that is, we started our discussion with the Arc Voltage. Then we have discussed along with the Arc Voltage that is the Arc Current. Then we have discussed the Restriking Voltage. So this term is very important. So, the Restriking Voltage comes after the separation of the contact of Circuit Breaker and before the extinction of arc. Then the fourth term that is known as the TRV, Transient Restriking Voltage, this voltage means the voltage across the contact of Circuit Breaker at the time of extinction of arc.

And the fifth one, that is the Rate of Rise of Restriking Voltage. So, the first peak of the TRV that is known as the Rate of Rise of Restriking Voltage and the sixth one that is the Recovery Voltage. So the steady state voltage after the extinction of arc that is known as the Recovery Voltage. So, whenever the contact of the Circuit Breaker separates, then what are the different voltage that is going to appear across the context of Circuit Breaker.

So, with this background, let us solve one example. So, it is given that the 50 hertz, 13.8 kV, three-phase generator with grounded neutral has an inductance of 15 millihenry per phase and it is connected to a busbar through a Circuit Breaker. The capacitance to earth between the generator and the Circuit Breaker that is 0.05 microfarad per phase. And you need to determine the following:

The first thing that is the maximum Restriking Voltage, that is basically nothing but your RRRV. So, when the value of our RRRV is maximum that you need to find out. The second is the time for the maximum Restriking Voltage. So, at what instant, at what time your RRRV becomes maximum that time you need to find out. The third thing is the average RRRV up to the first peak.

So, this is nothing but the third-parties available from the previous two parts that is the average RRRV up to the first peak that is given by maximum Restriking Voltage divide by the time for maximum Restriking Voltage that is nothing but your average RRRV. And the last D part, that is the frequency of oscillations. And all this you need to find out assuming that the resistance of the generator winding, it is very small or zero.

So, let us find out the first thing that is the maximum Restriking Voltage with the given value. So, let us find out what is the maximum Restriking Voltage in this case.

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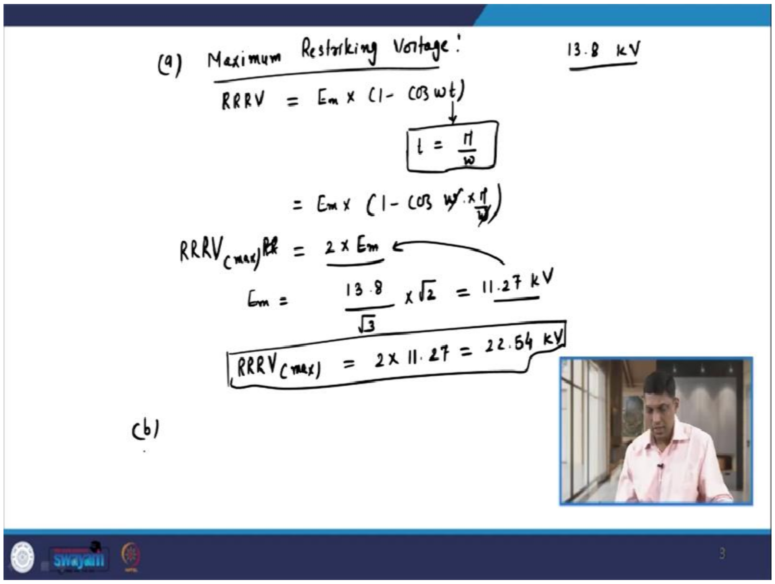

So, the first part you need to find out the maximum Restriking Voltage. So, the maximum Restriking Voltage that is nothing but as I told you, it is your RRRV. So, we have already considered the equation of RRRV. So, the equation of RRRV that is given by the Em, the maximum value of the voltage into 1 minus cos omega t. So this is the equation of RRRV and the value of RRRV that becomes maximum when you have the value t that is t is equal to pi by omega.

So when your value of t that is equal to pi by omega, you have the value of RRRV that is equal to Em into 1 minus cos omega into t that is pi by omega. So this gets cancelled, so you have 1 minus cos pi, cos pi is minus one, so that is two times the Em. That is your RRRV maximum. That is your RRRV, this is maximum value.

So, now what is Em? So, your Em that is nothing but the value that is the 13.8 kV is the rating of the generator, voltage rating that is given. So, this is line voltage. So let us divide it by root 3 so it becomes phase voltage. And maximum value Em, so we need to multiply it with the root 2 now. So your Em becomes the 11.27 kV.

So, if I put this value here, that is this value here, then I have the RRRV maximum, that is equal to 2 into Em that is 11.27, so that comes out to be 22.54 kV. So that completes your first part, that is the, what is the maximum Restriking Voltage.

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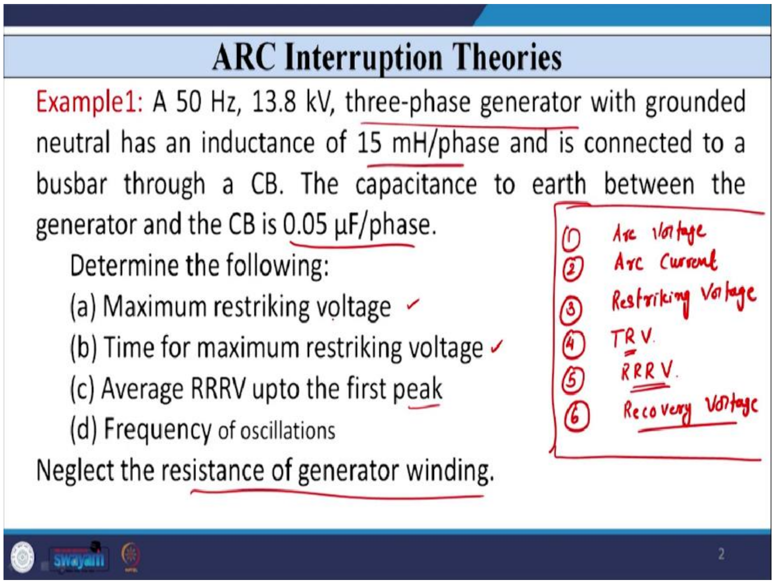

So, let us take the second part. So, what is the second part? The second part is the, this point, time for which the maximum is Restriking Voltage. So what is the time at which the maximum Restriking Voltage occurs.

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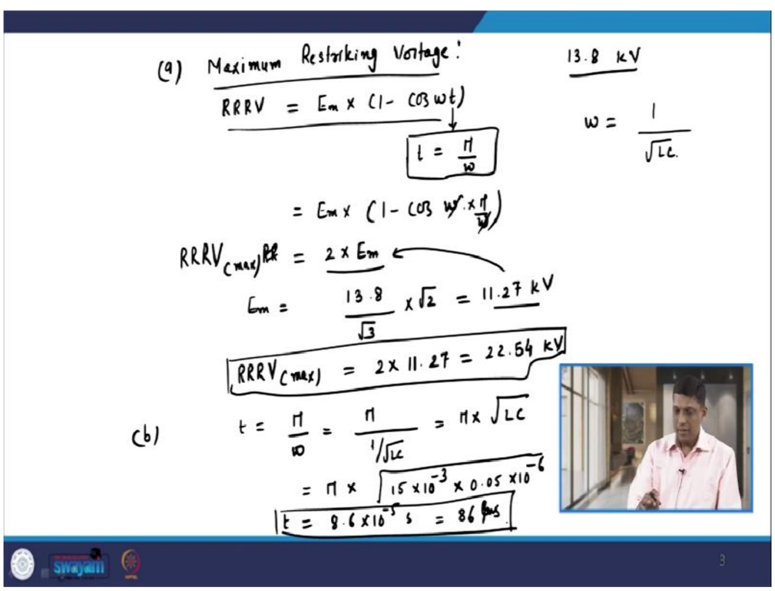

So as I told you earlier, that the, in this equation, the maximum Restriking Voltage occurs at t is equal to pi by omega. So, we have the pi, what is omega? As I told you, omega that is equal to nothing but the 1 upon under root LC. So if I just put this value here, that is 1 upon under root LC, then I have the pi into under root LC.

So if I put the value that is pi into under root, what is the value of L? L that is given as the value that is the 15 millihenry per phase and the C that is 0.05 microfarad per phase. So this is 15 millihenry, so 15 into 10 raise to minus 3 henry into the value of c that is 0.05 microfarad. So it is 0.05 into 10 raise to minus 6.

So if you solve this, you will have the value of t that is equal to 8.6 into 10 raise to minus 5 second or we can say 86 micro second. So this is how we can find out the second part, that is nothing but the time for maximum Restriking Voltage that is this thing.

Now let us solve the third part that is the average RRRV up to the first peak. So average RRRV up to the first peak, we can calculate as we have already calculated the Part A and Part B, first two parts. So the average RRRV that also we can calculate.

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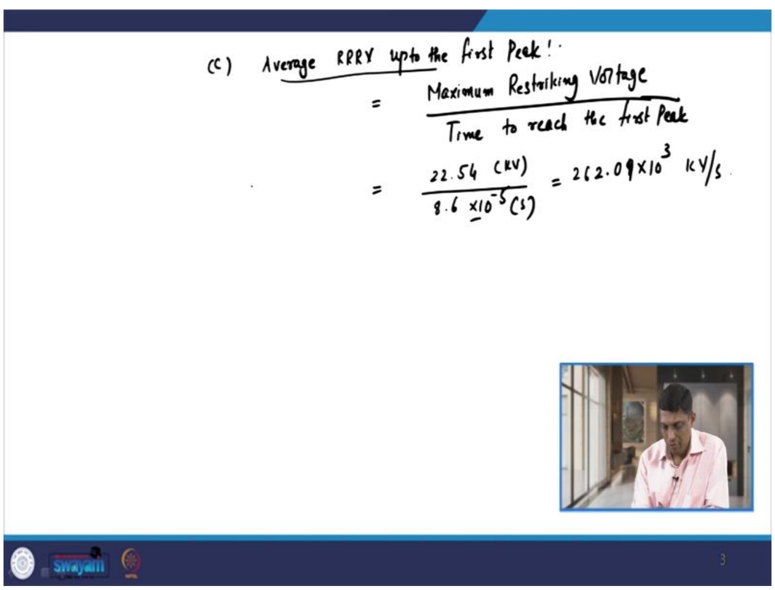

So let us see this third part that is C, that is the average RRRV up to the first peak. So the average RRRV up to the first peak that is given by the maximum Restriking Voltage, which we have already calculated in part A and then divide it by the time to reach the first peak. So, the maximum Restriking Voltage we have already calculated that is the 22.54.

So we have the value 22.54, you can also convert it into voltage also because this is in kV, divide it by time to reach the first peak that is your 86 microsecond or 8.6 into 10 raise to minus 5 second. So if you solve this, you will get the value 262.09 into 10 raise to 3 kilo volt per second. As we have taken this value in denominator in second and this value that is in kV. So, we have the value in kilo volt per second. So, this is all about the average RRRV up to the first peak.

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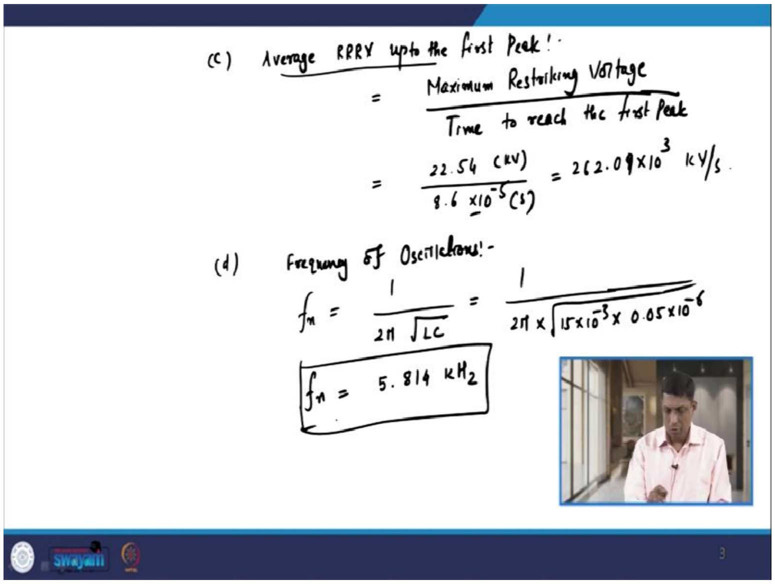

Now let us see the last part, that is what is the frequency of oscillations. So the natural frequency of oscillations, as I have discussed the frequency of oscillations that is given by the equation fn that is equal to 1 upon 2 pi under root L into C. So if you put the value of L into C, then you will get the value that is nothing but let us say it is 2 pi under root L that is your, I think we have the value 15 into 10 raise to 3 henry. So, you have 15 into 10 raise to minus 3 into 0.05 into 10 raise to minus 6. So if you put this value, you will have the value that is given by 5.814 kilohertz. So this is the frequency of oscillations.

So this is, this already we have solved. All the four parts. So you can see that the only four parts that we have calculated. So if you observe, this value, you can see that the frequency of oscillations that is very high that is in terms of kilohertz and you can see the RRRV is also very high 22 kV for 13.8 kV generator, the whatever breaker you have connected the RRRV imposed that is 22.54 kV.

So, with this example, let us further proceed and let us discuss the arc interruption theories. So we have already discussed how the arc is formed. We have discussed that because of the process known as ionization process, whenever the contact of Circuit Breaker separates across the contact of Circuit Breaker, arc is formed and the temperature of the arc that is very high 5000 degree kelvin and this arc that is surrounded by the hot ionized gases. So, if we want to remove or quench the arc, if we wish to extinguish the arc, then we need to use some external medium. So let us see how the external medium if we use then that can be quench the arc.

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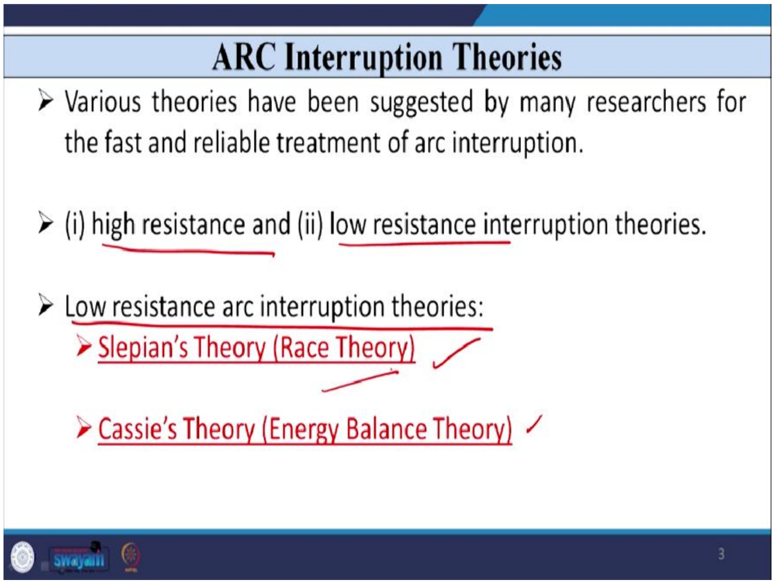

So different types of medium that can be used to quench or extinguish the arc. So if you just go through the literature then the different theories that has been suggested by various researcher for the fast and reliable extinguishing of the arc. So when you want to interrupt an arc then you need several theories. So most of the theory is that is classified or divided in two parts. The first theory that is known as based on high resistance interruption theory and the second part that is known as the low resistance interruption theory.

Normally out of these two theory, for the quenching of the arc at the time of separation of the contact of Circuit Breaker, normally they prefer a low resistance interruption theories. So if I just consider the low resistance interruption theories, arc interruption theories, then that is again classified or divided in two parts, one that is known as the Slepian Theory and another that is known as the Cassie’s Theory.

So, let us start our discussion with the first part, that is the Slepian's Theory, which acts or based on the low resistance arc interruption principle.

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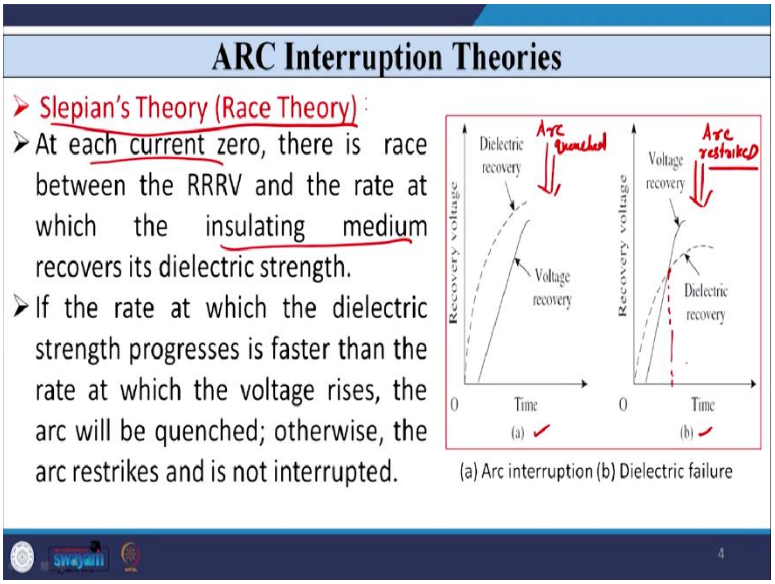

If I just consider this Slepian's Theory, it is also known as the Race Theory. Why it is known as Race Theory? Because whenever the arc is formed across the contact of Circuit Breaker, then there is always a race between the Rate of Rise of Restriking Voltage that is the voltage appears across the contact of Circuit Breaker and the dielectrics or recovery of the dielectric medium that is used in that Circuit Breaker to quench the arc. So there is always a race between this two.

As I also told you, that if we use AC circuit, then for AC circuit arc that are current to be interrupted always at natural current zero. So whenever you have the current zero, there is a race between the Rate of Rise of Restriking Voltage and the rate at which the insulating medium recovers its dielectric strength. This insulating medium that can be air, it can be pressurized air, it can be all or it can be say SF6 gas or it can be some vacuum. So it depends on what type of insulating medium you use.

The dielectric strength of that insulating medium varies according to the type of insulation medium used. So, there is always a race, whenever the current is interrupted at natural current zero in AC circuit. Then there is a race between the RRRV that is Rate of Rise of Restriking Voltage and the rate at which the insulating medium recovers its dielectric strength. If the rate at which the dielectric strength progresses that is faster than the RRRV that is Rate of Rise of Restriking Voltage, then the arc that is definitely quenched.

So, you can see on the right-hand side, the one figure is shown and in there are two parts, Part A and Part B. So you can see in Part A, the rate at which the dielectric strength of the insulating medium that is recovered that is greater than the rate at which the Rate of Rise of Restriking Voltage changes with reference to time. So this value dielectric recovery is greater than the voltage recovery hence, the arc that is definitely quenched. So, in this case, we can say that the arc that is quenched.

On the other side, the other figure B Part, you can see that the rate at which the Rate of Rise of Restriking Voltage or recovery voltage varies with reference to time that is higher than the rate at which the insulating medium recovers its dielectric strength. So, you can see that the voltage recovery is greater than the dielectric recovery at this point of time. So, definitely the arc is not going to quenched.

So here we can say that for this instance, we can say the arc restrikes. Restrikes means, at natural current zero arc is interrupted, current is interrupted, there is a formation of an arc insulating median comes, the arc that is quenched partially, and after, immediately after that point of instant, that is this instant the arc, again that is restrike or that is again formed.

So your medium that is going to become earlier it was ionized then it become deionized and again it becomes ionized when the arc restrikes is. So this is very important as far as this arc interruption theory based on the low resistance arc interruption principle is concerned.

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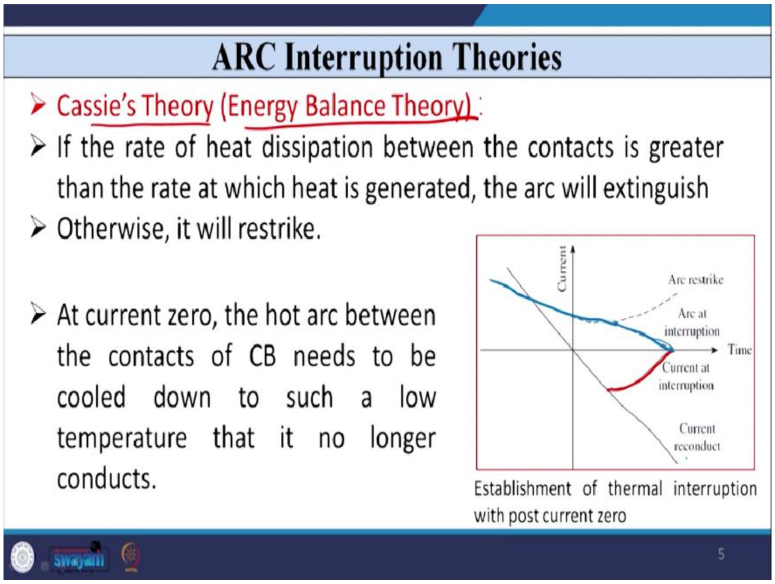

So now let us consider the second type of theory that is given by Cassie's. So, this theory is also known as the Energy Balance Theory. So, in this case, if the rate at which the heat dissipation across the contact of circuit breaker that occurs if that is greater than the rate at which the heat generated, then the arc that is going to be extinguished, otherwise the arc restrikes.

So you can see that here, on this figure, I have shown how the thermal interruption with post current zero that is going to occur. You can see on Y axis I have taken the current and on X axis there is a time and I have shown the waveform of the current as well as the arc. So, you can see that, as this is the waveform of the current as soon as it comes here, then it directly moves from here and at the same time you can see here also for the waveform of the arc, you can see this is the waveform of arc, as soon as it comes here there are two possibilities, either it comes like this or it comes like this.

Whenever the arc voltage comes here and the current that is to be interrupted here, we can say that the arc is quenched because in this case, the rate of heat dissipation across the contact of Circuit Breaker that is greater than the heat generated. So, basically heat dissipated across the contact of Circuit Breaker that is greater than the heat generated. So, at this instant arc is fully quenched.

If reverse is the case, heat generated that is greater than the heat dissipated across the contact of Circuit Breaker then arc that is not going to quenched and it may divert like this. So, there are fair chances of the restriking of the arc. So, this is very important this theory also as far as the arc interruption of the Circuit Breaker is concerned.

Now one more thing is you can see that as I told you, arc or current that is always interrupted at natural current zero for AC circuit. So at current zero, the hot arc between the contacts of Circuit Breaker needs to be cool down. So, basically we can say that whenever we want to deionize the medium or arc which is already ionized, we need to cool down it. So, one of the principle of this type of quenching of an art that is just to cool down the arc, reduce its temperature or intensity, so that the arc that can be easily quenched. Now, this is all about the Low Resistance Arc Interruption Theory.

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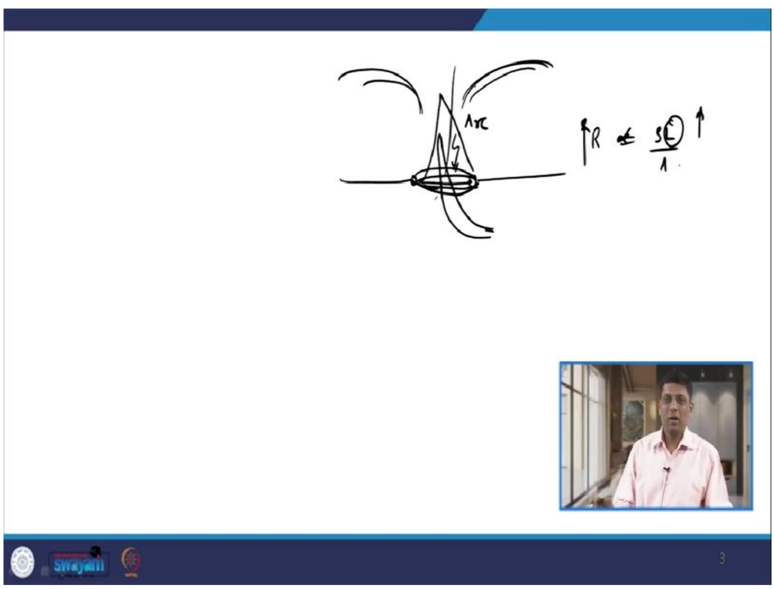

The other type of theory which is not very prominent, but we can say that it is also High Resistance Arc Interruption Theory. So, in certain cases what they are doing, when there is an arc across the contact of Circuit Breaker, let us consider that this is the one contact of the circuit Circuit Breaker and whenever there is an arc across the contact of Circuit Breaker here, this is arc.

Now what you do is, you just with some mechanism, you arrange such type of mechanism, so that this arc that is forced and you just take arrange the arrangement like this, like horn shape. So what will happen that the arc that becomes like this, so it is lengthening of the arc. So, if arc is lengthen and we know that the resistance of the arc that is nothing but are proportional to or equal to ruel by a area. So if you lengthen the arc that means, the L increases then R also increases so resistance of the arc increases and there are fair chances of the quenching or extinguishing of the arc.

So, this type of theory also exists and nowadays in the recent Circuit Breaker lengthening of arc, cooling of arc that is simultaneously done by the same or single equipment.

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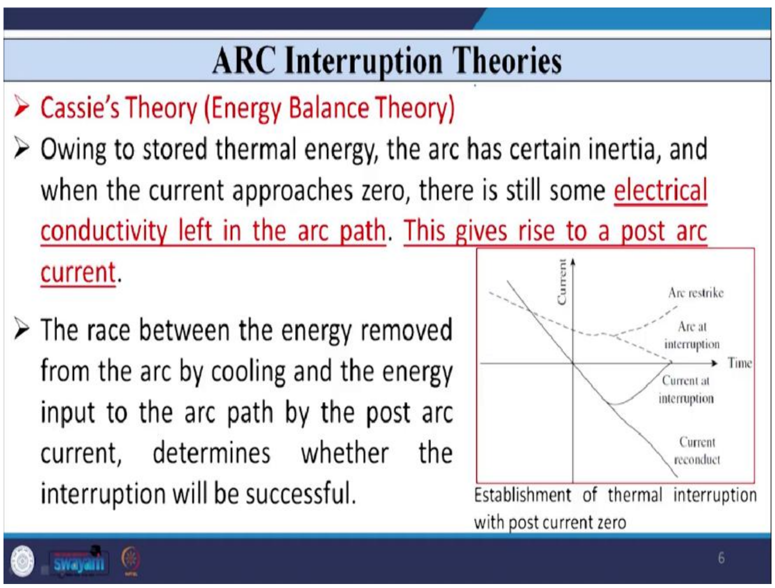

So this is all about the Cassie's Theory. Now, as I told you, owing to the stored thermal energy, the arc has certain inertia and when the current approaches to the natural current zero, there is still some electrical conductivity left in the arc paths which give rise to the arc current. So, the race is between the energy removed from the arc by cooling medium or maybe by lengthening of arc and the energy input to the arc path by the post arc current, that determines whether the arc interruption that is successful or there are chances of restriking of an arc. So this is all about the Cassie's Theory.

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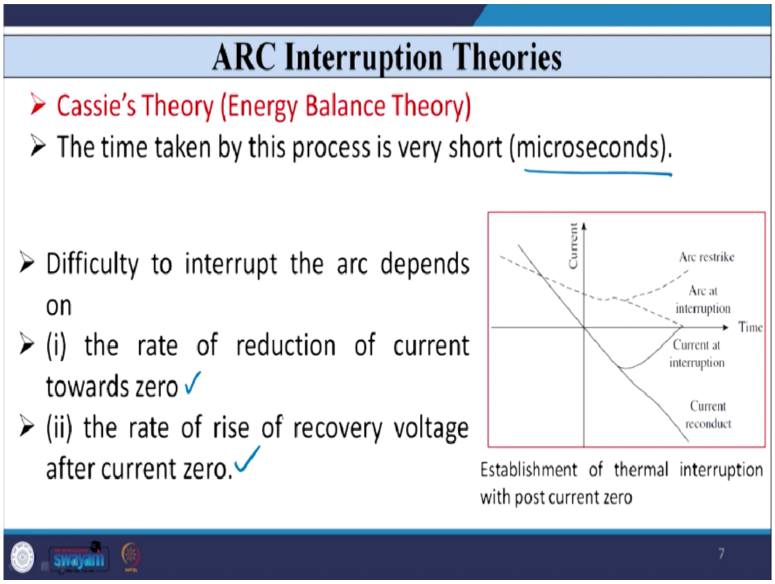

One more important point is the time taken by this process that is very short, that is in microseconds. It may possible that whenever arc restrikes, then the difficulty to interrupt the arc whether arc restrikes it or what are the difficulties faced by the insulating medium effectively quench the arc that depends on many parameters. The first parameter is the rate of reduction of current towards the zero and the second is the rate of Rate of Rise of Restriking Voltage after the current zero. So this two are the important parameters which play a key role, whether the arc is extinguished or arc that is fully quenched.

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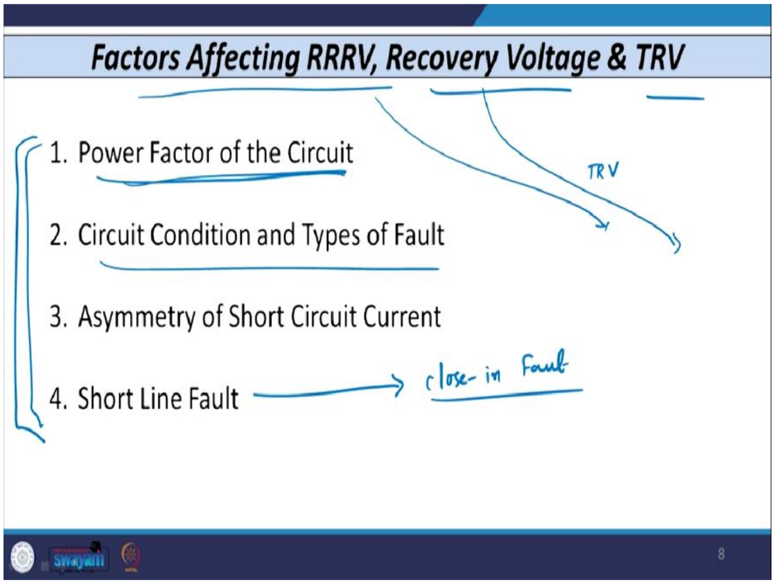

Now, with this two theory that is Slepian's Theory and the Cassie's Theory, both theories are different. In one theory, as I told you, there is a race between RRRV and the recur dielectric strength recovery of the insulating medium and in other case, it act on the, it is based on the energy balance principle.

So with this background, let us discuss what are the factors that affects the Rate of Rise of Restriking Voltage, the Recovery Voltage and the Transient Restriking Voltage. So there are three voltages very important. Again, I told you the Transient Restriking Voltage that is the voltage that appears after the immediately at the point of interruption of arc, so that is TRV, what is the voltage appear across the contact of Circuit Breaker.

RRRV is the first peak of TRV, that is your RRRV and recovery voltage that is a steady state power frequency, fundamental power frequency voltage after the fully extinguishing of the arc that is the recovery voltage. So, let us discuss what are the factors that is going to affect the RRRV, Recovery Voltage and TRV, because if TRV is high, that means, if the voltage across the contact of Circuit Breaker that is higher or higher and higher, then there are a fair chance that the restriking of arc that is going to occur. So arc is not going to be fully quenched.

If arc is not going to be fully quenched, then the time at which the recovery voltage will be achieved that is also so large. So that is why these three voltages are very important and what factors that is going to affect this three voltages that also very important.

So basically there are four factors that is going to affect this three voltages RRRV, Recovery Voltage and TRV. So the first factor that is the power factor of the circuit. The second is the circuit condition and types of fault. The third is the asymmetry exist in the short circuit current and the fourth one is the short line fault, this is basically nothing but the close-in fault. That means if fault occurs very near to the Circuit Breaker then that fault is known as a short line fault or close-in fault.

So, let us start discussing how the power factor that is going to affect the three voltages, three terms, RRRV, Recovery Voltage and TRV.

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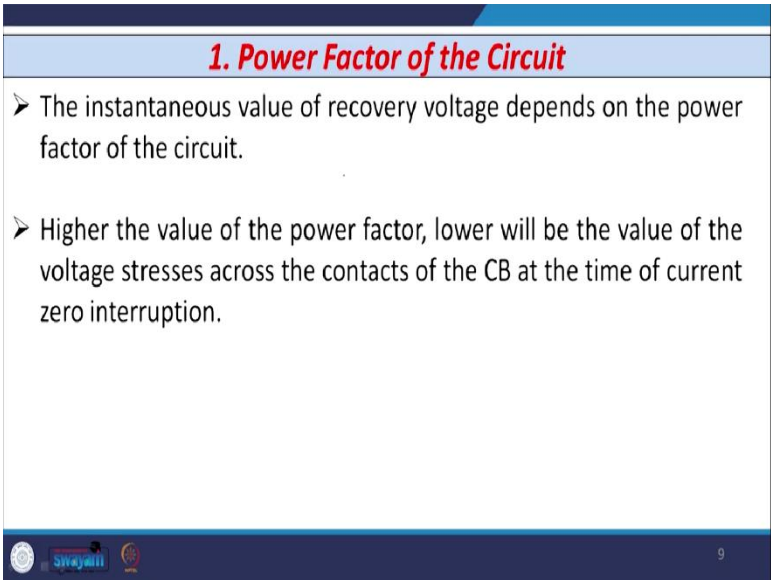

So if I just consider the power factor, then we know that the instantaneous value of Recovery Voltage depends on the power factor of the circuit, higher the value of power factor, lower is the voltage as trace appear or existing on the across the contact of the Circuit Breaker at the time of interruption of current at natural current zero.

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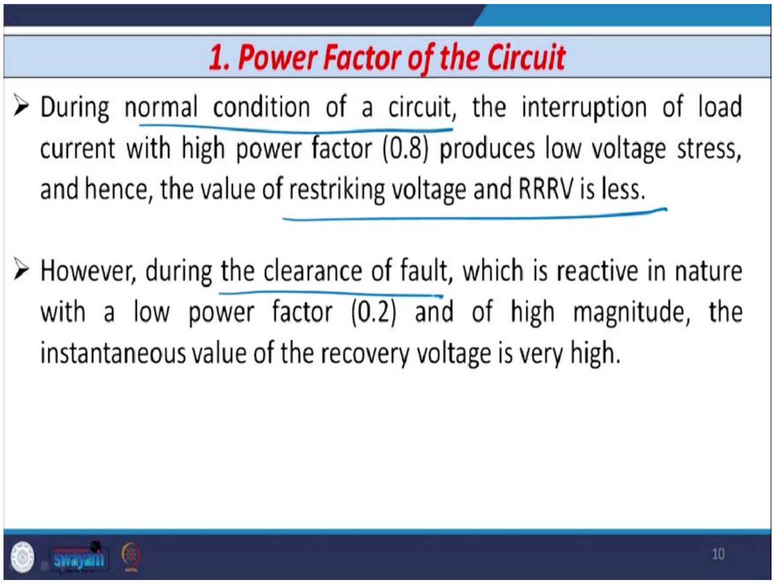

So, if I can consider prefault condition or normal condition, then during normal condition of the circuit, the interruption of load current, obviously, the load power factor is very high, they have to maintain a very high power factor beyond 0.8. So, the interruption of load current with very high power factor that produces low voltage stress across the contact of Circuit Breaker and as the voltage appear across the contact of Circuit Breaker voltage stress is low. So, the restriking voltage and RRRV with that is also less.

However, in case of fault condition, as I told you whenever fault occurs the power factor reduces from point 0.8 and it becomes almost 0.3 - 0.4. So, this is purely reactive or inductive circuit in nature and the power factor is very low magnitude of current is very high. So, in this condition the instantaneous value of recovery voltage that is high because the voltage appear across the contact of Circuit Breaker that is also very high.

So, we can say that the interruption of small value of fault currents particularly reactive short circuit current that is more difficult than the interruption of resistance short circuit current. So, that means if I take first case that the interruption of reactive short circuit current whose magnitude is lower than say some value X. And on the other side case B, consider the interruption of the resistive shot circuit current whose magnitude is higher than the previous one, then also it is very difficult to interrupt the such type of small magnitude of reactive or inductive short circuit current that is more severe.

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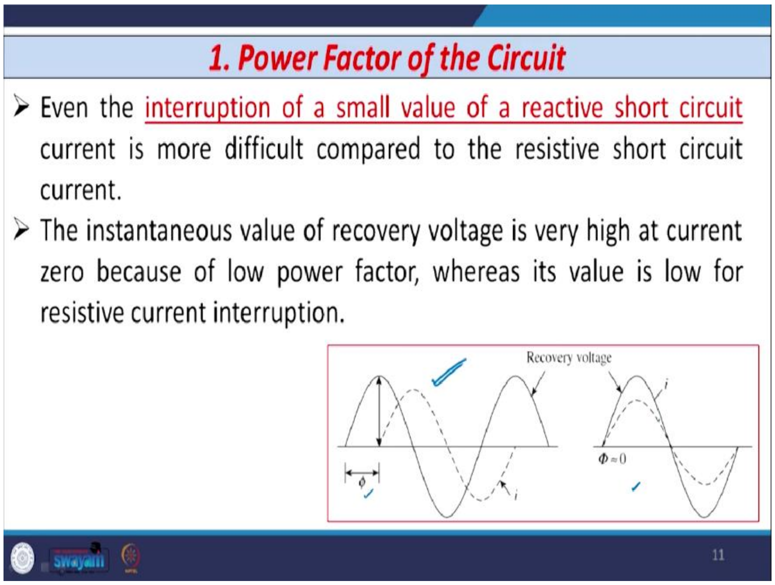

So, the instantaneous value of recovery voltage is a very high at current zero because of low power factor whereas, its value is low for the resistive current interruption. So, you can see that I have shown the two important waveforms. The first waveform you can see that the value of phi that is very high. So, the angle between recovery voltage and the current to be interrupted that is very high. So, power factor is very low because of course phi is very high so, cos phi is very low.

So, this whatever voltage appear across this voltage contacts of the Circuit Breaker that is Recovery Voltage that is high. Whereas on this side, other case you can see the value of phi is almost zero near to zero, because both Recovery Voltage and the current to be interrupted both are in phase. So, power factor is very high. So, we can say that the recovery voltage or voltage appear across the contact of Circuit Breaker that is also lower than the previous case.

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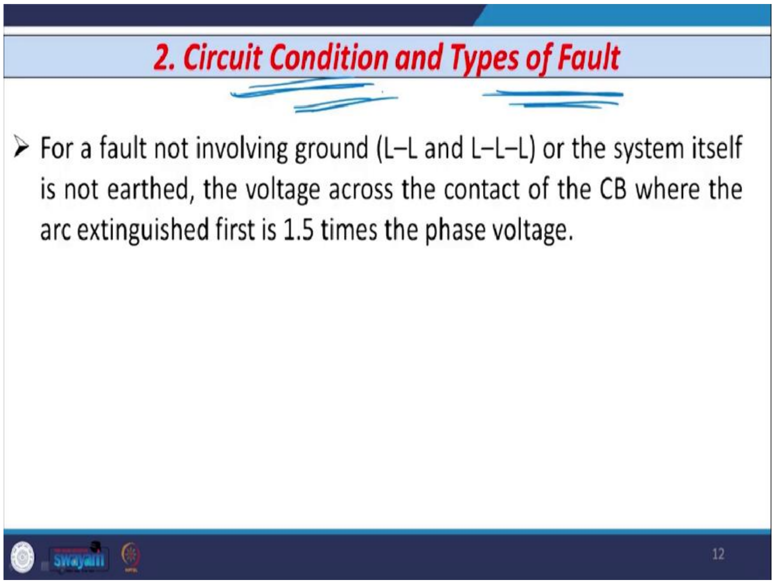

So, let us now consider the second factor that is going to affect the RRRV, Recovery Voltage and Transient Restriking Voltage. So, the second point that is the circuit condition and the type of fault So, okay this is also very important point that is the type of fault and what is the circuit condition means, what is the condition of the parameters whether the system is earth or system is not earth that type.

Till now, we have discussed the important arc interruption theories that is the Slepian Theory theory and Cassie's Theory. We also solved one example that is based on the Recovery Voltage, RRRV, Transient Restriking Voltage and the natural frequency of oscillations.

And then we started our discussion with the factors affecting the three important terms that is the RRRV, Recovery Voltage and the Transient Restriking Voltage. And we have discussed the first two factor that is the power factor of the circuit at the time of interruption of current, that is at the time of fault. So, I stop here and we will continue our discussion in the next class. Thank you