Power System Protection and Switchgear
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Lecture 34
Arc Interruption Theory in Circuit Breaker-I

Okay. So, let us discuss the one important topic that is known as the Circuit Breaker and in that let us see what is the Arc Interruption Theory in the Circuit Breaker.

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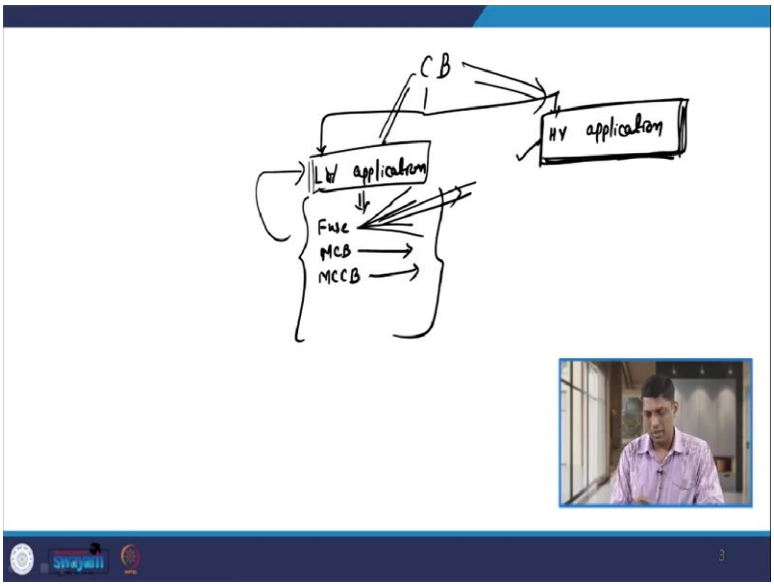

Now, when we consider the Circuit Breaker, then we know that the Circuit Breaker is a device, which can open and close particularly in high voltage applications. So, if I just write down the Circuit Breaker. Then the Circuit Breaker that can be of two type. One, that is you for Low Voltage Application, right, so, I write LV applications and the other that is used for the High Voltage Application.

So, whatever breaker we are discussing in this class, in this lecture that is related to only high voltage application because in low voltage applications the device that is available is fuse. We have the MCB, that is Miniature Circuit Breaker or we do have the Molded Case Circuit Breaker that can be different types of fuse also available. The MCB and the Molded Case Circuit Breaker, so, all that come under the low voltage application.

So, we will discuss here only the breaker related to the high voltage application. There is a fundamental difference between the breaker or the device used for a low voltage application and

the device used for the high voltage application. What is the difference? If I use the fuse MCB or MCCB as the voltage value that is very small. So, the arc quenching medium is not required air itself acts as arc quenching medium. So, the arc can be easily quenched without any medium, unless and until if I use some specific type of fuse then arc quenching medium can be used. Otherwise, arc quenching medium is not required.

Whatever High Voltage Circuit Breaker we are discussing that all the Circuit Breakers applied or the high voltage circuit they need separate arc quenching medium. So, that is the fundamental difference between these two.

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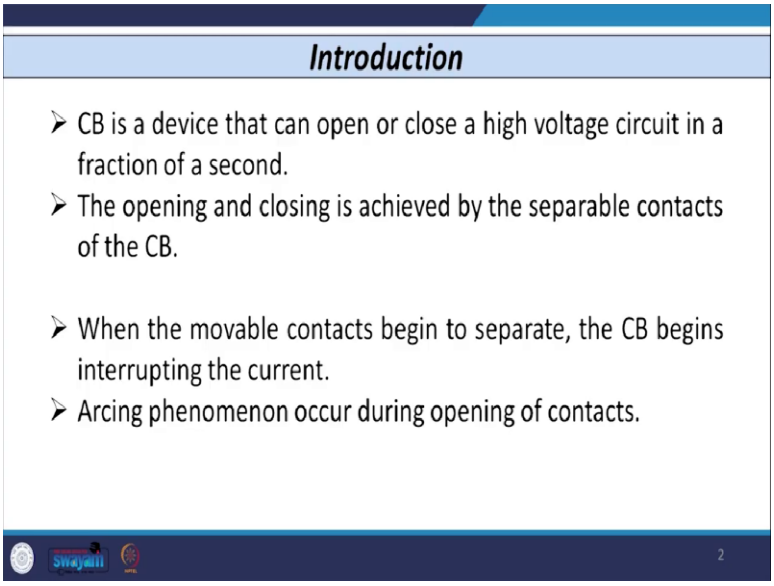

So Circuit Breaker acts as a switch, so you can open it and you can close it, right. So, the opening and closing that is achieved by several contacts. So whatever Circuit Breaker we are talking, it has basically the High Voltage Circuit Breaker.

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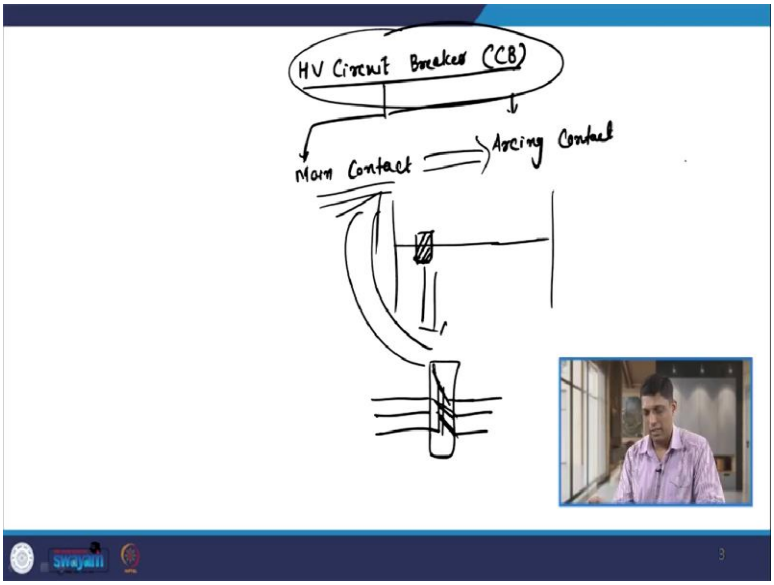

So, High Voltage Circuit Breaker, normally, we denote it with CB, Circuit Breaker. So, this has basically two contacts, one is known as the main contact and the other that is known as the arcing contact.

So, wherever usually the opening of the breaker that is very important, because if I consider a line, right, connected between say two buses and if I use the breaker here. So, if I just draw this circuit, the breaker used here, 3 phase circuit. So, then you have the device here, right. This is your circuit breaker. So whenever you open it, it has to break the very high value of current and for that application, the duty of Circuit Breaker that becomes very important.

So, initially, when the current that is passed, when it is in close condition most of the current that will flow through the main contact. When the contact of the breaker separate or open it, then the current that will be transferred from main contact to the arcing contact.

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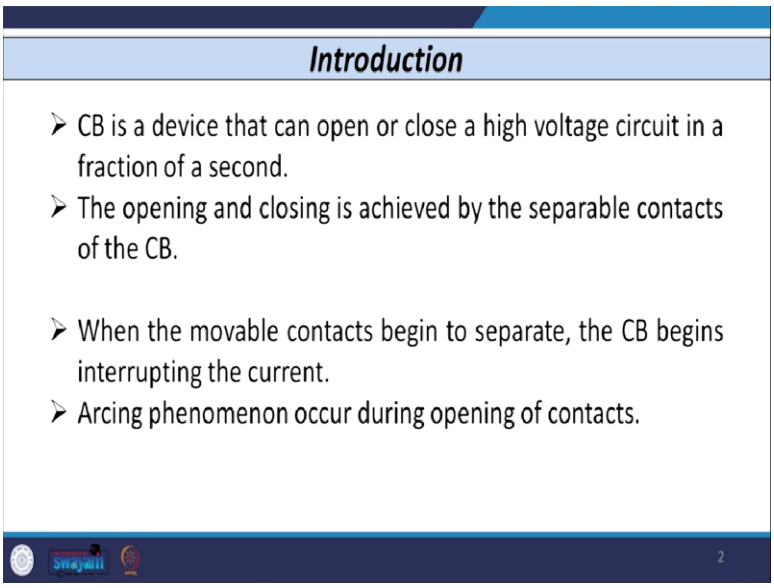

So, when the moveable contact begin to separate the Circuit Breaker starts interrupting the current. So, arcing phenomena occurs and that is very important, how to quench the arc that plays an important role.

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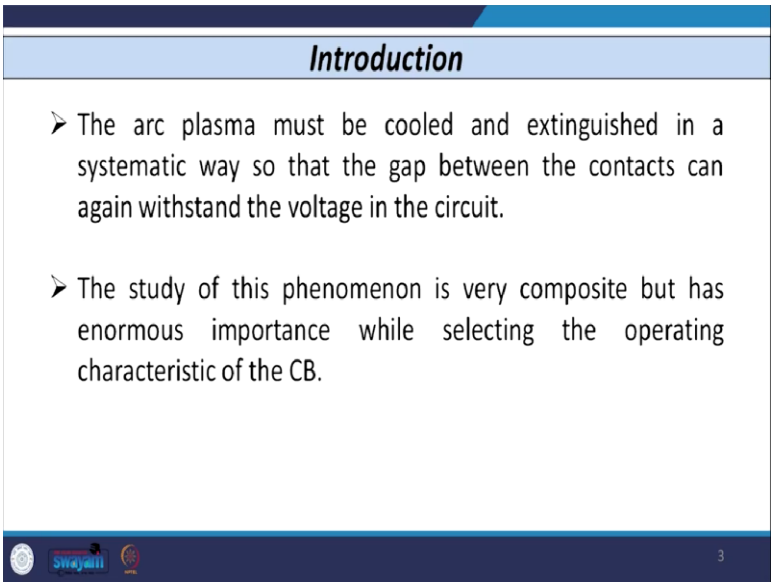

The arc plasma that has to be cooled. So, arc can be extinguished, because earlier in this case, when arc is formed, the medium is ionized. So, you need some deionization technique through which you can easily quench the arc.

So, basically, you need the gap between the contact of Circuit Breaker has to withstand that voltage, right. So, the study of the arcing phenomena that is very important and that we need to study in this class.

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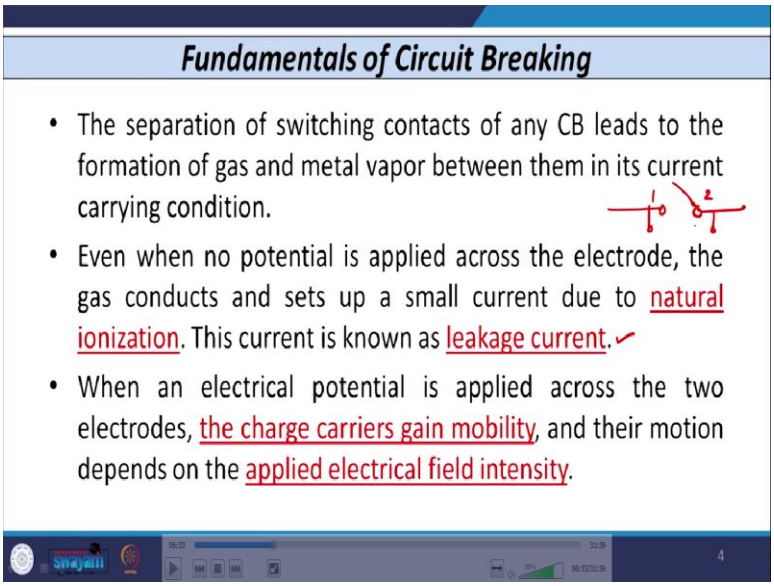

So, let us see what are the fundamentals of Circuit Breaking. So, if I consider the several fundamentals of Circuit Breaking, the separation of switching contacts of any Circuit Breaker. So whenever the contact of the Circuit Breaker become open, then there is a formation of a gas and the metal vapor when the current is interrupted. So, when there is no potential is applied. So, if I consider, let us say, these two are the contact of the breaker, right, since, these two, one and two are the contacts of the breaker or you can say electrode of the breaker.

So, where no potential is applied across this, then also there is a very small magnitude of current flows because of the natural ionization that occurs, right because the holes are going on one side, electrons are going to the other side. So, because of that the natural ionization occurs and this type of current that is known as the leakage current. Its magnitude is very small.

Now, whenever you apply the electric potential across the electrode or across the contact of circuit breaker, then the charge carriers that means the electron hole pairs that gain the mobility and the motion of this charges, that depends on the intensity of the applied electric voltage across the contact of Circuit Breaker or across the electrode.

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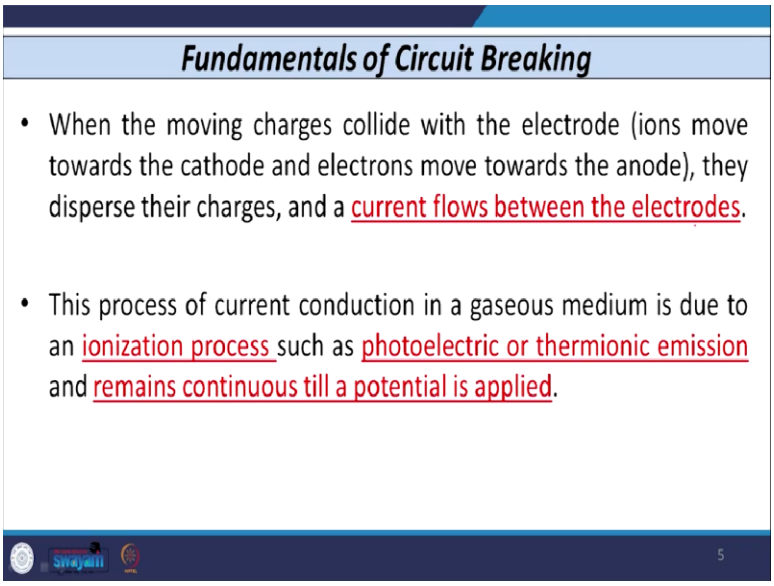

So, when the moving charges collide with the electrode, that means, ions will go to the cathode and electrons will move towards the anode, they disperse their charges and the current flows between the electrodes. This type of current that is known as discharge current and the whole process of the conduction, in gaseous medium, there the current flow starts flowing that is known as the ionization process and this type of ionization that will occur maybe because of photoelectric effect or it may occur because of the thermionic emission. And this type of ionization will remain continue till the applied voltage that is available across the electrode or across the contact of Circuit Breaker.

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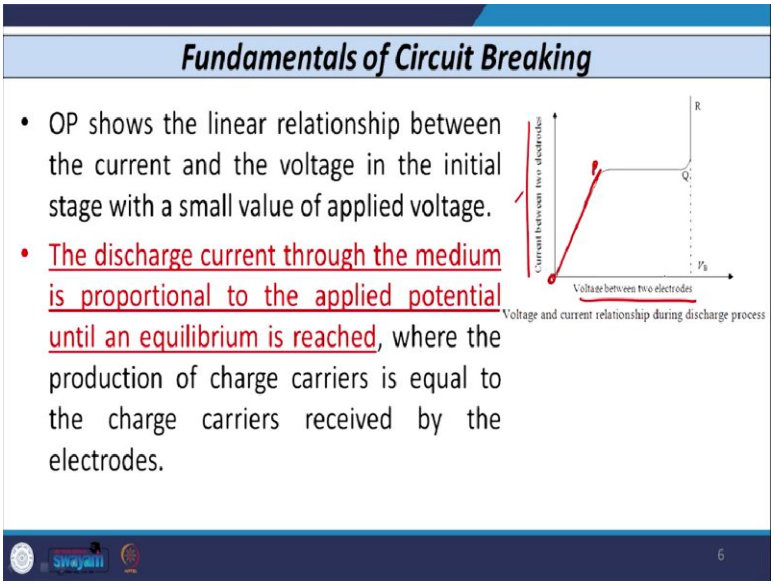

So, if I consider graph, where on X axis we have the voltage between the two electrodes as I told you one and two. And on Y axis, I consider the current between the two electrodes. Then initially, you can see this curve from O to P, this point, the linear relationship that is followed, particularly when you apply a very small voltage across the electrode or across the contact of Circuit Breaker, the current also increasing and it is directly proportional to the applied voltage.

The discharge current that is this current or Y axis, that this current through the medium that is proportional to the applied voltage and this proportionality is maintained until the equilibrium is reached. Equilibrium means, when the production of charge carriers that is equal to the charge received by the electrodes. So, till, you will have the linear relationship between the applied voltage and the discharge current.

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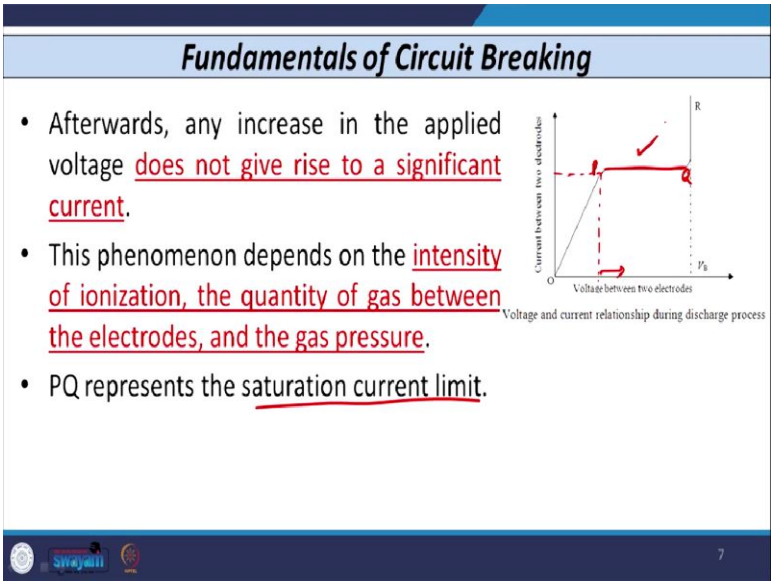

After this, any increase in applied voltage that is from this point, if I extend it here, right, or both the axises then you can see on X axis, after this point, if I increase the applied voltage then there is no significant decrease in the discharge current.

So, this phenomena depends on the intensity of ionization many parameters, what is the intensity what is the quantity of gas, that is available between the two electrodes and what is the pressure of the gas. So, this P, Q, you can see from here, this P and this Q this curve represent that phenomena that even though the applied voltage increases, there is a marginal increase in the discharge current. So, this PQ that is known as the saturation currently limit, right that is represented by this curve.

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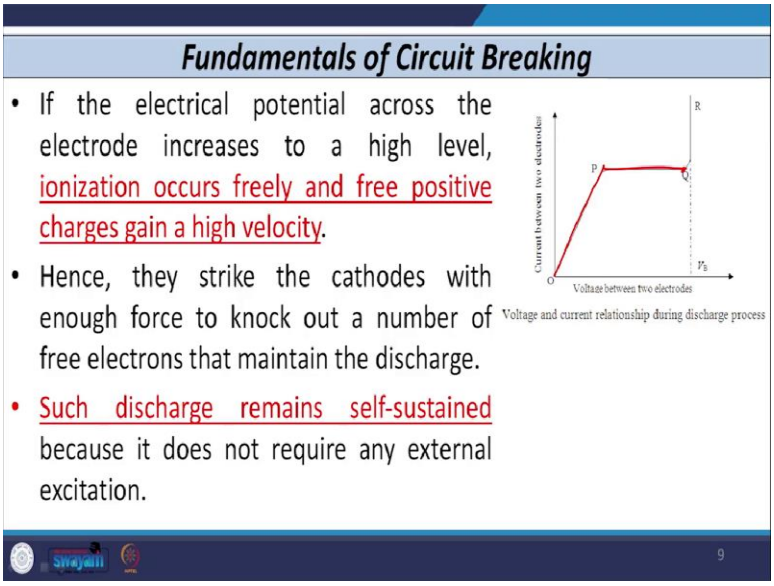

Now, if the electrical potential across the electrode or across the contact of Circuit Breaker increases very high. So, that ionization occurs very freely, free positive charges, they gain a very high velocity. So, they strike with a very high force.

So, they are going to knock out the number of free electrons, which is finally going to maintain the discharge current. So, such discharge remains self-sustained that means say this type of discharge current does not require any external excitation.

So, till now, up to this point, you can see from OP and PQ, they need external excitation if you want to sustain the discharge current. But from this point onwards after Q, no external excitation is required whatever discharge current is that, that is self sustained in nature. So this process rises exponentially and the current continues to increase between the two electrodes even when the applied voltage that remains.

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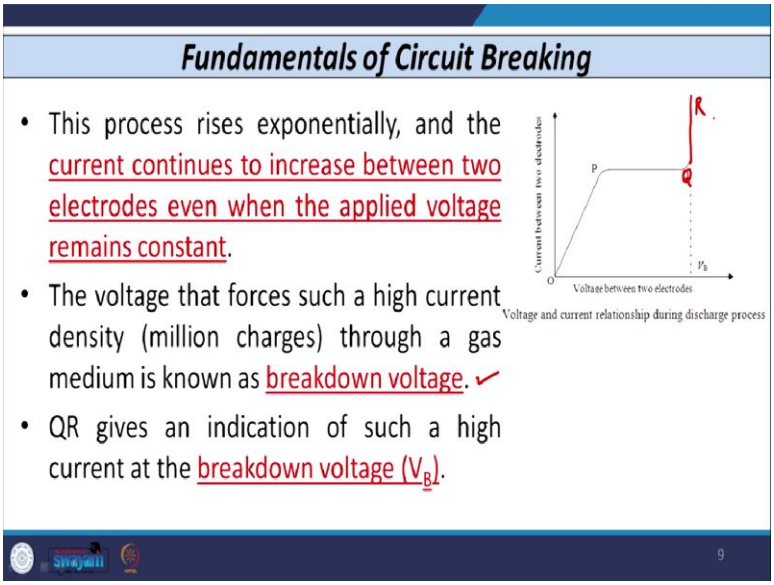

So, even though the applied voltage that is constant and also the current increases very rapidly. The voltage that forces such a high value of current in a gaseous medium, this type of voltage that is known as the breakdown voltage. So, this point, this voltage that is known as the VB or breakdown voltage.

So, this QR curve from here in this graph, you can see this is Q and this is R that indicates this phenomena and if you extend this Q point on the X axis, then you will get the value of breakdown voltage.

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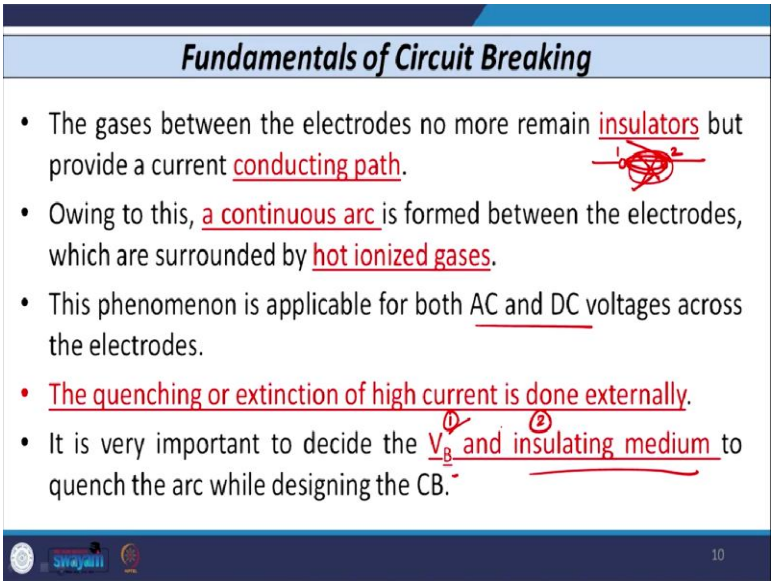

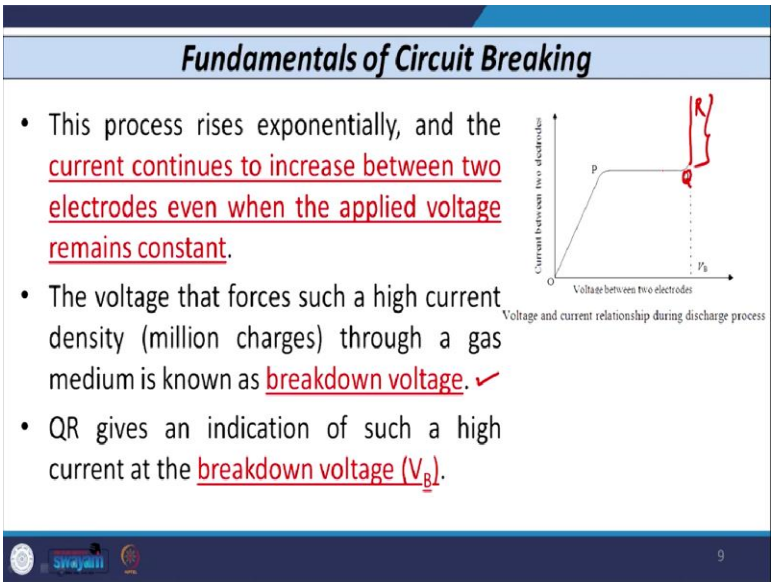

So, all this phenomena from O to P, P to Q, and Q to R, this clearly indicate, if you just look at this curve Q to R, that means at the time of break voltage, the whole gaseous medium, which was earlier act as an insulating medium now it becomes the conducting path.

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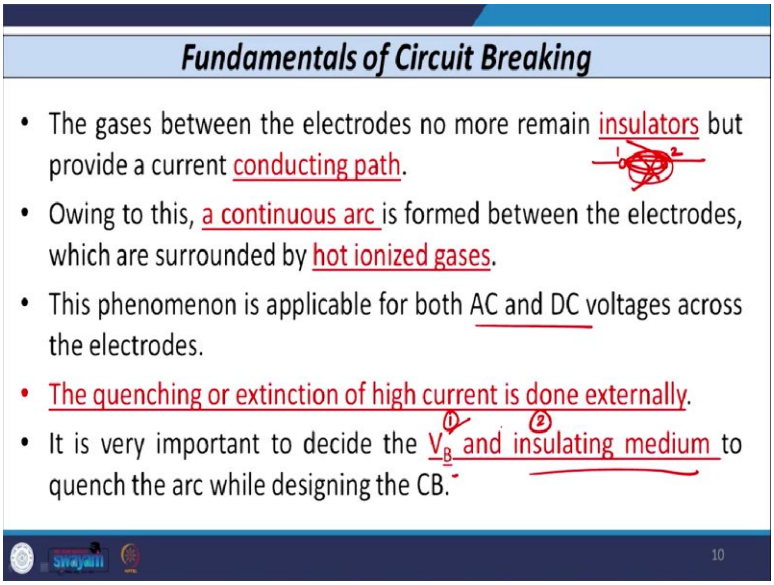

So, because of this, the continuous arc is formed between the two electrodes. So, if I just consider the two electrodes here, right then there is a continuous arc is formed across these two electrode, one and two, and this arc that is surrounded by the hot ionized gases. So, this phenomena is applicable to both AC and DC circuits equally.

And if I want to quench this arc, if I want to remove this arc, if I want to extinguish this arc then some external medium that is required whose dielectric strength must be greater than this strength of the ionized or arc, right, so that the arc can be easily quenched. So, that means, it is very important to decide the breakdown voltage that is VB and the insulating media what type of insulating medium you use to quench the arc. So, when you just design the Circuit Breaker, you need to define these two things, what is a breakdown voltage of the breaker and what type of insulating medium, you are going to use for a particular Circuit Breaker.

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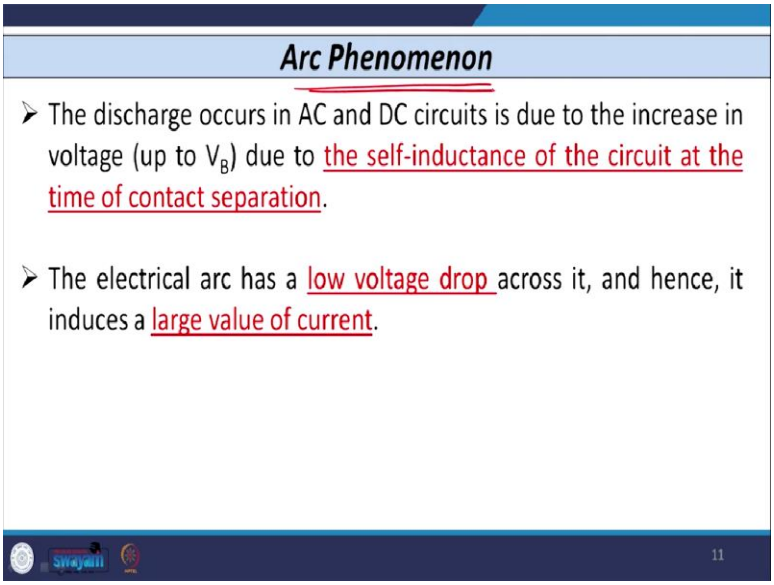

So, with this background, let us see, what is the Arc Phenomenon or Arcing Phenomena that occurs between the contacts of Circuit Breaker or across the electrode. So, as I told you, as we have discussed that the discharge occurs in AC and DC circuit that is because of the voltage beyond the breakdown voltage, VB and this voltage is a self-sustained, it is going to produce the discharge current, which is self-sustained in nature and its magnitude is very high. Whatever this discharge current is there, this discharge current magnitude is very high, this is because of the self inductance of the circuit at the time of the separation of the contact of the Circuit Breaker.

So, wherever the contact of the Circuit Breaker separates, the arc is formed, this arc has a low voltage drop and hence, this induces a very large magnitude of current.

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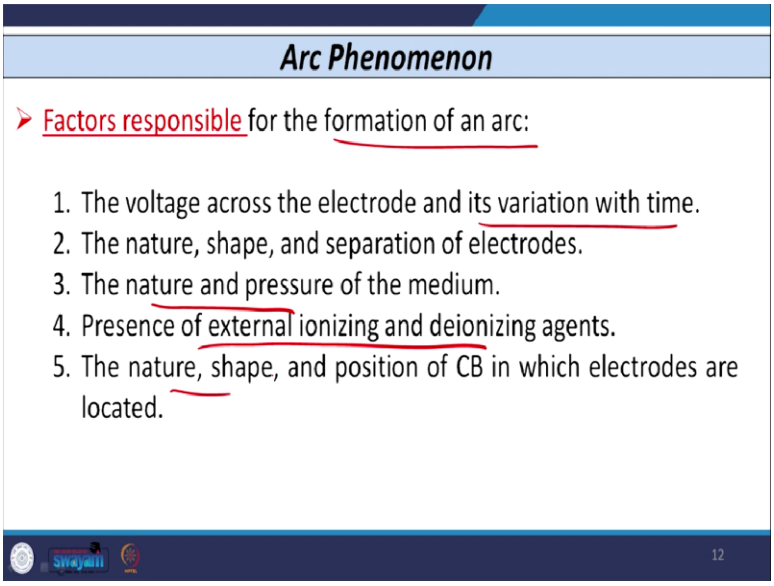

So, the factors responsible for the formation of arc, across the two electrodes or across the contact of Circuit Breaker: These factors are, first is the voltage across the electrode, how much voltage is existing and how this voltage varies with respect to time. So, that is very important. The second factor is the nature of the electrode, shape of the electrode and the separation, how the separation of electrode is carried out. This is very important.

The third point that is again the nature and pressure of the medium, what type of medium whether you are using gas, whether you are using oil or air, so, what is the nature? What is the pressure? That is very important, the presence of external ionizing or deionizing agent, if any external circuitry is required. So, that is also very important. And last that is the future, shape and position of Circuit Breaker in which the electrodes are located. So, what is the nature, shape of the breaker and what is the position of the breaker. So, all this factors are very important for the formation of an electric arc across the contact of Circuit Breaker.

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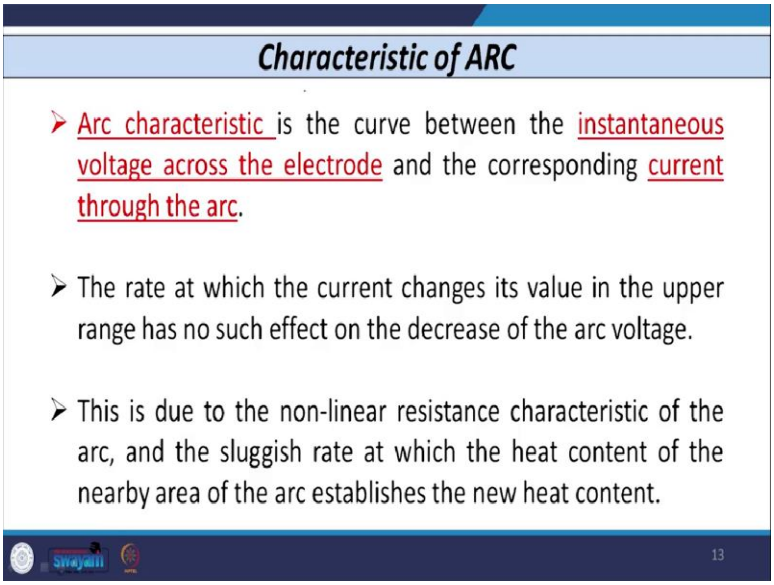

Now, let us see what is the characteristic of an arc. So, the characteristic of an arc is basically nothing, but a curve that is plotted between the instantaneous voltage that is available across the electrode or the contact of Circuit Breaker and the corresponding current through the arc. So, what is the arc current and what is the voltage available across the contact of Circuit Breaker, if you plot this, you will get the characteristic of an arc. This is known as arc characteristic.

The rate at which the current changes its value in some region that has a very little effect on the arc voltage and this is due to non-linear resistance characteristic of the arc, because the arc characteristic is non-linear and the rate at which the arc, this arc characteristic behaves that is also very sluggish, which is going to create the whatever heat content is there nearby the arc that is also very important, when you consider the characteristic of an arc.

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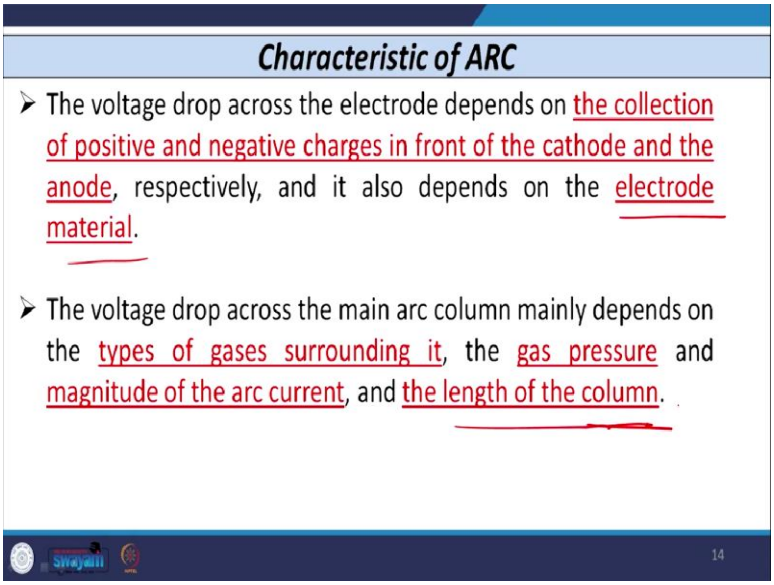

So, the voltage drop across the electrode, basically, across the contact of circuit breaker on the collection of positive and the negative charges may be for cathode and anode that depends on the electrode materials. So, what type of material you have used for electrode that also plays an important role. And that is going to affect the characteristic of an arc. The voltage across the main arc column or across the arc that depends on many parameters, like what is the types of medium gas surrounding across the arc you have used? What is the pressure of the gas, what is the magnitude of arc current? And what is the length of the arc? That also plays an important role. So, whenever I say length of the arc, I say arc column, basically.

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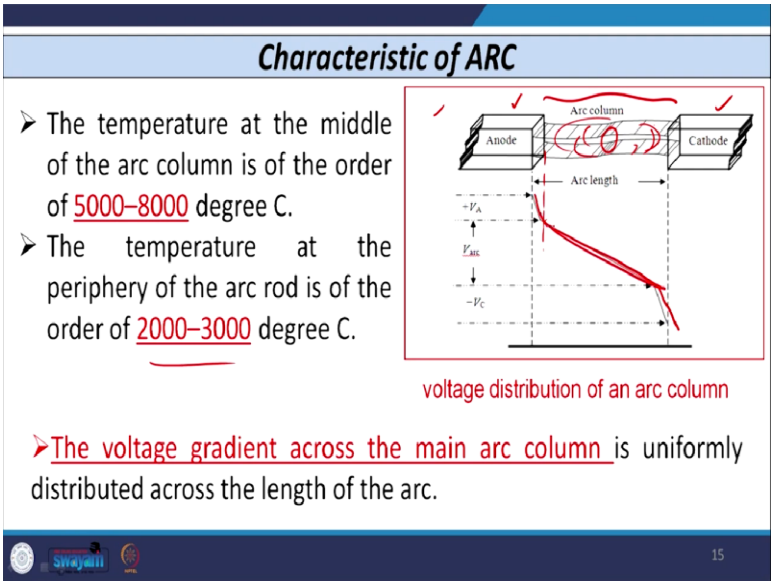

So, you can see here, the figure that is shown, which indicates the two electrodes and anode cathode. And across this there is an arc, which I have indicated with the arc column and the distribution of voltage that is also given, you can see the plus VA indicates the voltage distribution across the anode, plus VC indicates the distribution across the cathode and V arc indicates the distribution across the arc column. So, this is how the voltage distribution across the arc that is to be carried out.

If I just consider the temperature of this arc, the core temperature of this arc that varies from 5000 to 8000 degrees centigrade and the surrounding temperature of this arc that may vary from 2000 to 3000 degree centigrade. The voltage gradient across this arc that is uniformly distributed across its length that is very important and that is why you can see for most of the time, if I just take here below this, then it will follow this type of curve and then it bends like this.

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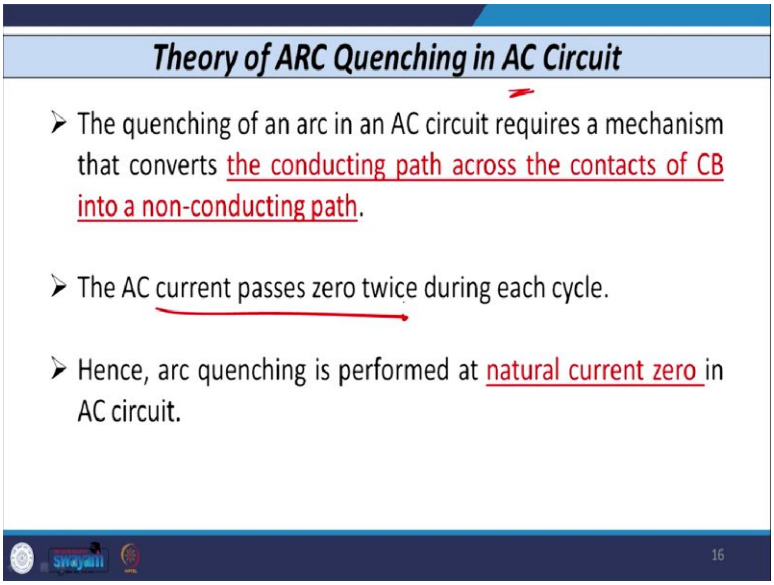

Now, let us see how they quenching of the arc that is to be carried out. So, Theory of Arc Quenching. This is again for AC circuit. For DC circuit the arc quenching is entirely different. Now, when we consider the quenching or extinguishing of an arc in AC circuit then that requires a mechanism, which converts the whole conducting medium across the contact of Circuit Breaker into a non-conducting path or maybe insulating path. So, the whole ionization process that can be deionized, because of some mechanism that is known as known as the arc quenching mechanism.

In AC circuit we know that the current passes through zero every half cycle. So, arc quenching that has always performed at the natural current zero in AC circuit, the same is not applicable for DC Circuit because no current zero that is available in case of DC circuit.

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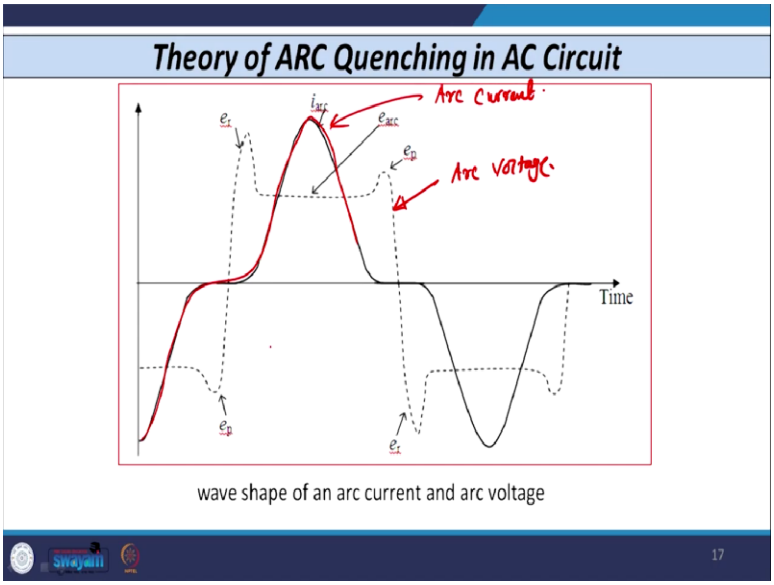

So, if I consider the arc quenching, you can see here there are two wave forms shown, one is the arc current. So, the dark line, this line that is nothing but the wave form of arc current. And the other dotted line that shows the voltage across the arc, that is the arc voltage. So, this is known as the arc current and the other dotted wave shape that is known as the arc voltage. You can see that normally, this two values as the nature of the arc is purely resistive. So, this two values arc current and arc voltage both are in phase.

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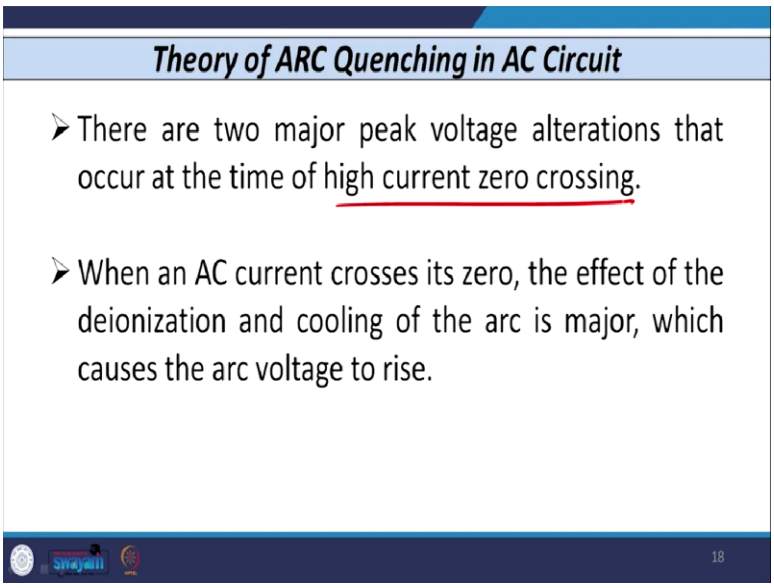

Now, there are two major peak voltage alterations that can occur at the time of zero crossing. And this zero crossing is not simple current zero crossing, it is a high current zero crossing. That is why the some switching operation or some peak voltage that is available. So, in any AC circuit whenever the current crosses the zero, the effect of deionization or cooling of the arc is major, which causes the arc voltage to increase.

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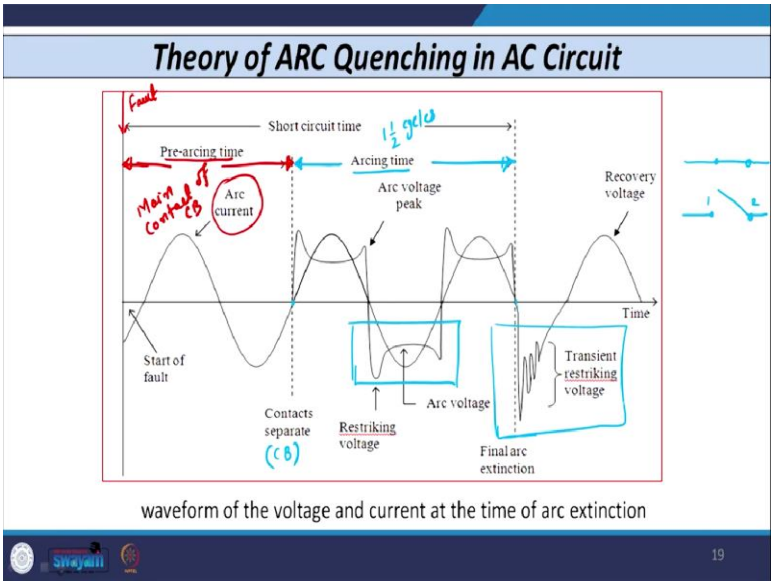

So, if I just consider the different phenomena at different point of interval or time, you can see that this is the point where the fault starts, right. So, this is the point where the fault occurs after

that fault is detected by the relay and it give signal to the breaker. So, the Circuit Breaker as I told you, the there are two timings are there for the Circuit Breaker, one time that is known as the time before the formation of an arc, that is known as pre-arcing time and the other time that is during the formation of an arc.

So, when actually the arc is formed at that time, whatever time is there that is known as the arcing time. So, this arcing time that is also very important and the pre-arcing time that is also very important.

Now, if I consider the pre-arcing time, you can see that, at this instant default occur, so the magnitude of current decreases so, that current I have showed with the name that is arc current, right. So, as this arc current continues and wherever the natural current zero comes the contact of the circuit breaker that becomes separate. So, now in case of pre-arcing time the whatever contact that takes the current that is nothing, but your main contact of the Circuit Breaker.

So the whole current that flows through the main contact of the Circuit Breaker, wherever the neutral current zero comes at this point here, somewhere here, the natural current zero comes. So, the contact of the Circuit Breaker separate this is the Circuit Breaker contact, which separate and you can see as soon as the contact of the Circuit Breaker become open, earlier the contact is like this and now it becomes like this.

So, whenever this contact separates, then there is a arc formation starts. So, you can see that from this point onwards, you have the two things one is the arc current itself and the other that is the arc voltage and this arc voltage is not sinusoidal, you can see right it has some different wave shape.

Now, as after in case of the arcing time, you can see as the current continues to flow after some point of period of time, let us say, if you just observe this current, right, which is sinusoidal in nature then after one and a half cycle from this point of time, you can see that, here the final arc extinguishing occurs that means wherever arc is formed from here and the arc that is fully quenched at this instant that is after one and half cycle.

So, this time is arcing time, which is one and a half cycle here in this case and you can see here the pre-arcing time that is almost one cycle or maybe more than one cycle. So, if you add these

two, that is your short circuit time or the time of operation of Circuit Breaker, which is roughly two and a half to three cycles.

Now, you can see that from this arcing time period, in this interval as soon as the arc is completely quenched, you can see the wave shape of the voltage, there are several peaks and then it will reach this point and then, again the sinusoidal current starts.

So, this period that is very important as far as this increase in voltage is concerned and the other period that is very important that is this period, right. So, the voltage, during the interval of arcing time, you can see when the contacts of the Circuit Breaker separates and after half cycle the voltage suddenly increases, right. So, this voltage is known as re-striking voltage.

Whereas, when the arc is fully quenched, after that whatever voltage is there, right peaks of voltage, that voltage that is known as the transient restriking voltage. So, two different voltages appear when the arc quenching phenomena that is going to be occur, one is restriking voltage, that is during the arcing and the other is the transient restriking voltage that is at the point or time when the arc is fully quenched. And then your normal voltage is available, which is known as recovery voltage, which is the normal value.

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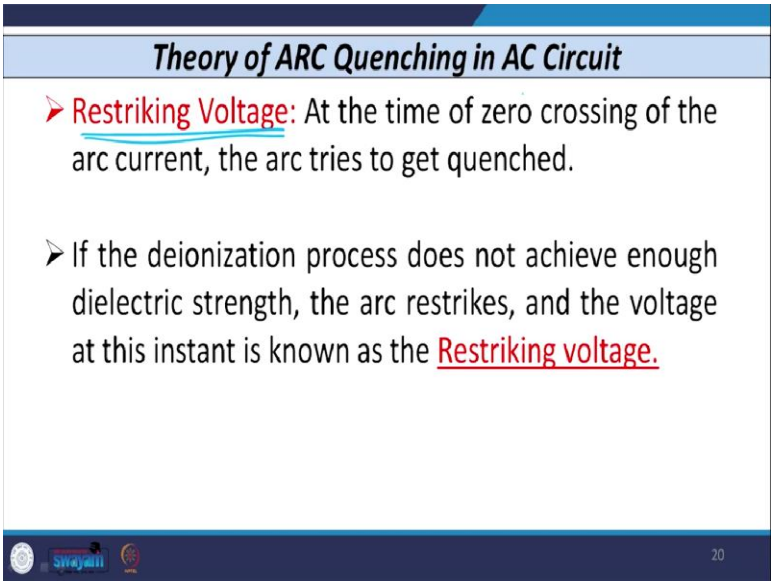

So, based on this, let us define few terms. The first is known as the restriking voltage. So, what is the restriking voltage? So, at the time of zero crossing of arc current, the arc that is going to be

get quenched. So, if the deionization process does not achieve the enough dielectric strength then the arc restrike is and the voltage at this instant that is known as restriking voltage.

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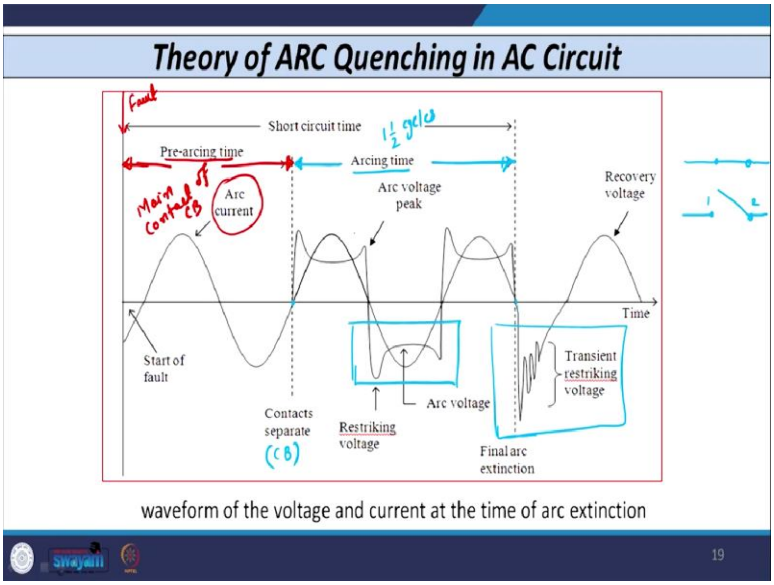

So, you can see that when the contact of the Circuit Breaker separates, so, as I told you the current carried by the main contact of the Circuit Breaker that is transferred to the arcing contact of the circuit breaker and from this instance after this instance whatever is the peak of the voltage that is known as the restriking voltage.

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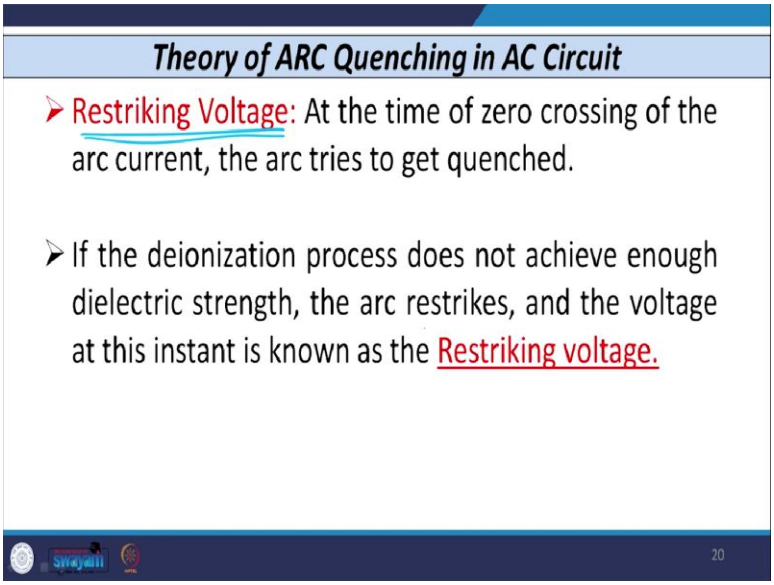

So, restriking voltage is the voltage at the time of zero crossing of the arc current, the arc tries to get quenched, but it is not going to be quenched immediately, it will take maybe one or one cycle. So, that instant whatever voltage is available that is known as the restriking voltage.

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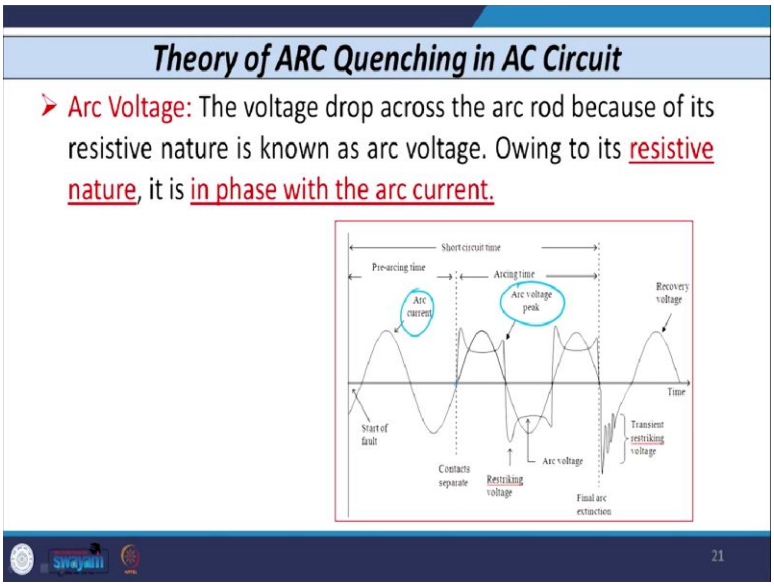

The next that is the Arc Voltage. So, the voltage across the arc rod or the across the contact of the Circuit Breaker or across the electrode, because of its resistive nature, that voltage is known as arc voltage and as it is in resistive in nature, so it is always in phase with the arc current.

So, you can see that as I told you the arc current is somewhere here, whereas, the arc voltage that is available immediately, when the contact of the circuit breaker starts separating.

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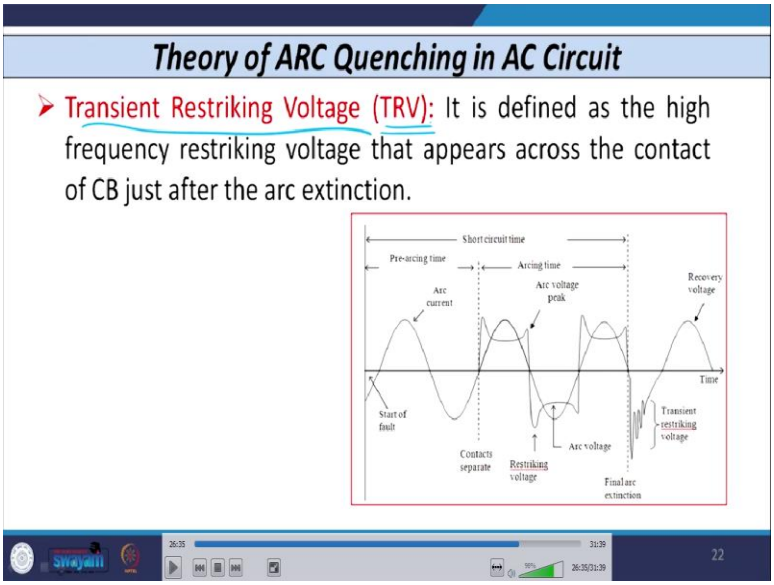

The next phenomena that is known as the Transient Restriking Voltage also known as the TRV. So, Transient Restriking Voltage is defined as the high frequency striking voltage that appears across the contact of Circuit Breaker immediately after the arc extinction.

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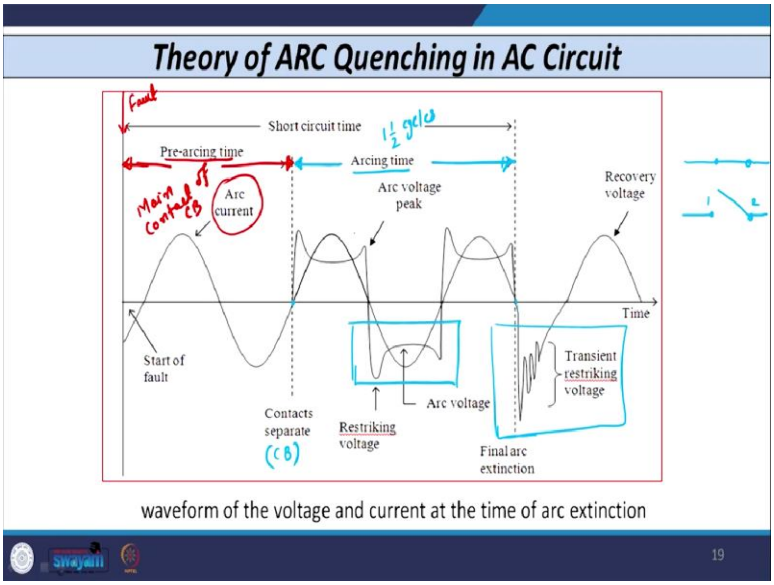

So, you can see here in our original wave shape, the TRV that is available when the arc is fully quenched. So, immediately after the arc extinction, whatever is the voltage available across the electrode or across the contact of Circuit Breaker that is known as the Transient Restriking Voltage. Whereas the restriking voltage itself that is available when the arc is already there, at that time arc is not quenched fully. That is the fundamental difference between the restriking voltage and the Transient Restriking Voltage.

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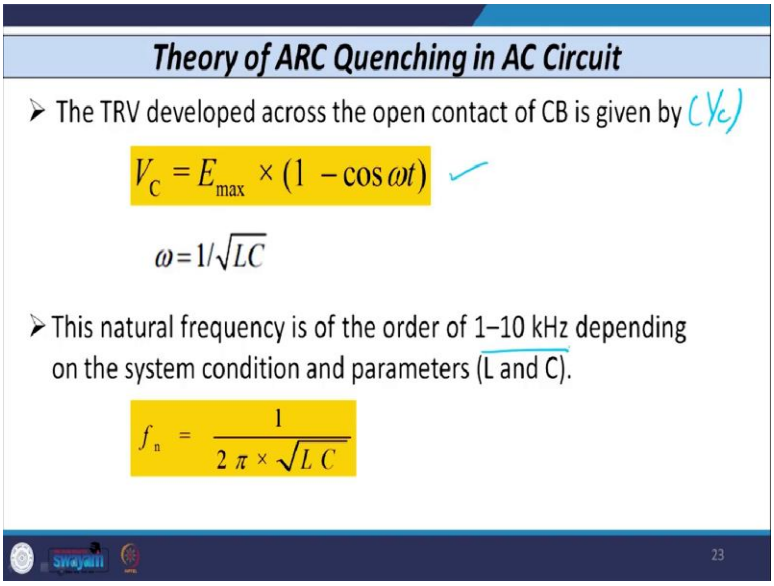

So, you can also easily find out the Transient Restriking Voltage, which is available across the contact of Circuit Breaker immediately after the arc extinction and that is denoted by the VC Transient Restriking Voltage across the contact of Circuit Breaker and it is given by this equation that is EM into one minus cos omega t, where omega is equal to 1 upon under root LC.

So, the natural frequency when the oscillation takes place of this voltage that is of the order of 1 to 10 kilohertz and it changes depending upon the system conditions and as well as the parameters of the system that is L and C. And the frequency of oscillation that can be easily determined by this equation that is the frequency of oscillation or natural frequency of oscillation that is 1 upon under root LC into 2pi. So, this is how you can calculate the Transient Restriking Voltage.

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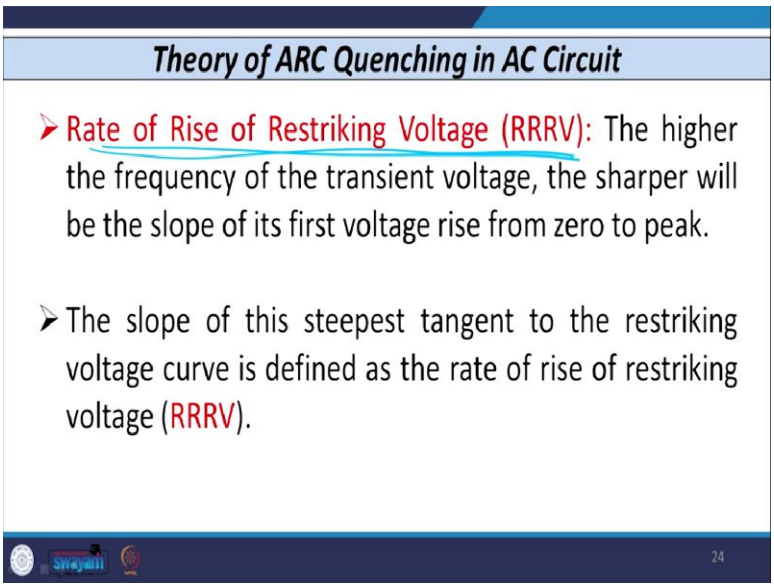

The next phenomena that is known as the Rate of Rise of Restriking Voltage, sometimes it is also known as RRRV. So, the higher the frequency of TRV, sharper will be the slope of its first of all voltage rise from the zero to peak. So, the slope of this stupid tangent at the time of restriking curve that is defined as the Rate of Rise of Restriking Voltage.

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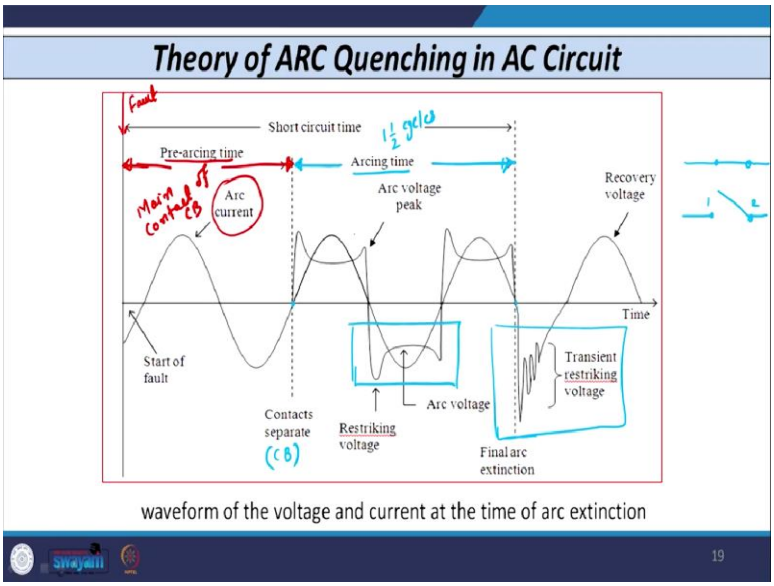

So, you can see here in our original equation, from this instant from zero to first peak, so, if you take slope of the Transient Restriking Voltage, then that is known as the Rate of Rise of Restriking Voltage.

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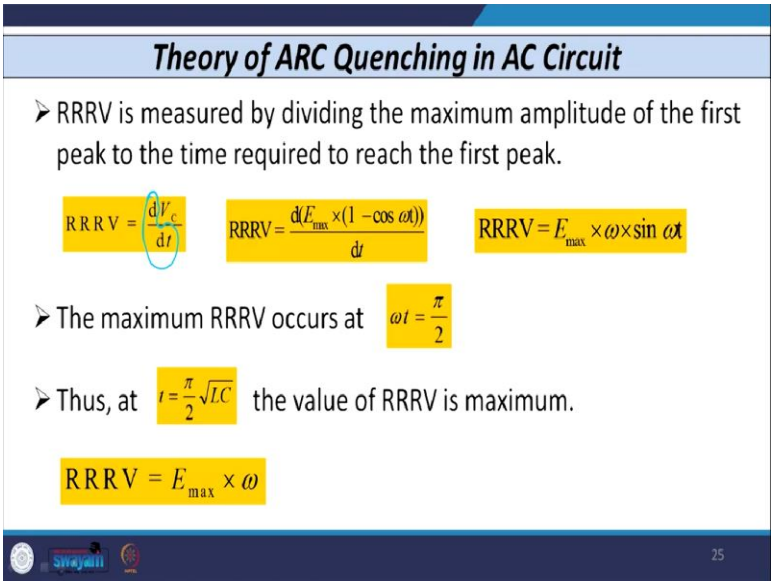

So, if I just need to find out what is the RRRV, then the RRRV that can be measured by dividing the maximum amplitude of first peak with reference to time required to reach the first peak. So RRRV is nothing but d by dt of your Transient Restriking Voltage VC,

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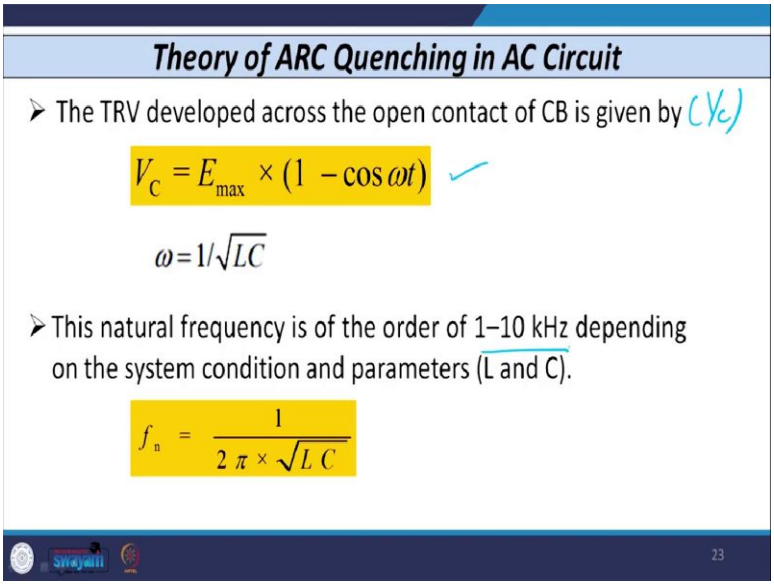

Which is given by the EM into one minus cos omega t that is this equation.

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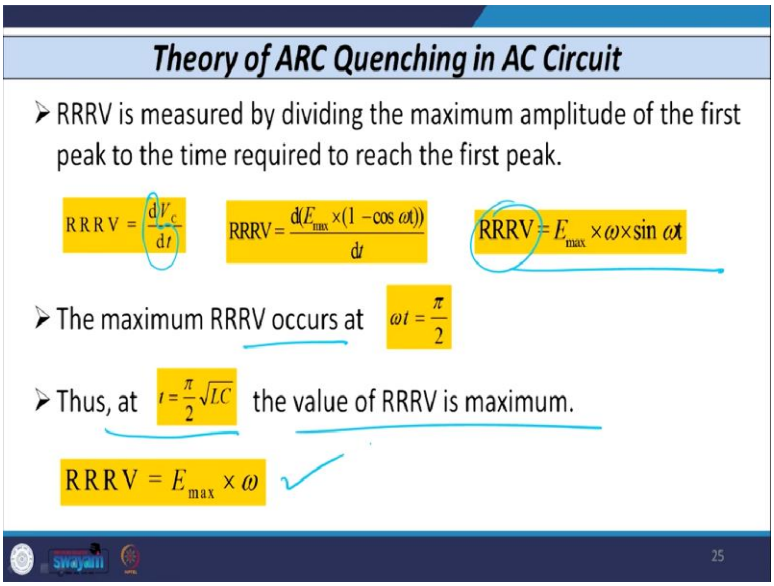

So, if you just take differentiate this, then you can easily find out the value of RRRV that is EM into omega into sine omega t. So, the maximum value of this RRRV that occurs when the omega t that is equal to pi by 2. So, that means, at t equal to pi by 2 under root LC the value of RRRV is maximum and it is given by E maximum into omega. So, this is the maximum value of Rate of Rise of Restriking Voltage that occurs and this is how you can find out its value.

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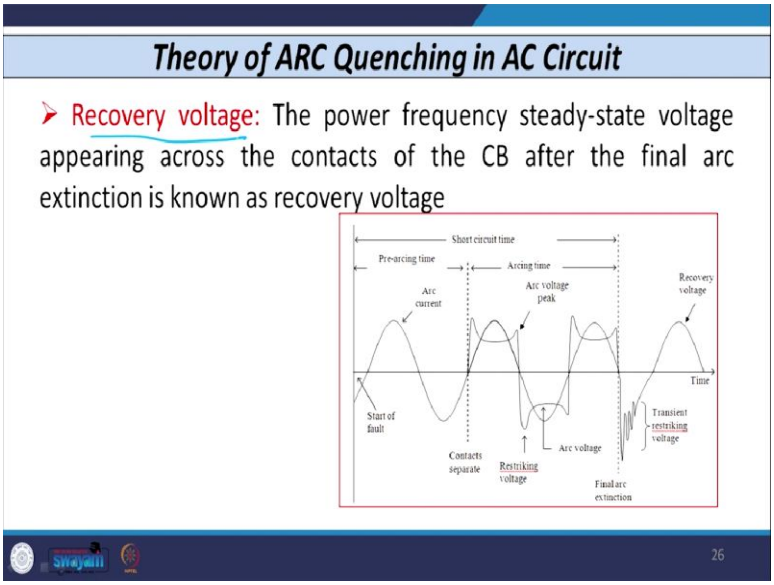

And the last point that is the recovery voltage. So, recovery voltage is the power frequency steady-state voltage appearing across the contact of Circuit Breaker or across the electrode after the final extinguishment of the arc, that voltage is known as the recovery voltage. So, from this instant you can see whatever voltage is available that is known as the recovery voltage.

So, with this background, I stop here. In this class, we have discussed what is the characteristic of an arc. What are the factors that is to be affected for the formation of an arc. We have also discussed how the arc is formed. What is the nature of current. What is the breakdown voltage across the contact of Circuit Breaker or across the electrode. And then, we have we started discussion about the theory of quenching the arc in AC circuit and we have defined several terms starting from the Arc Current, Arc Voltage, Restriking Voltage, Transient Restriking Voltage, Recovery Voltage and the Rate of Rise of Restriking Voltage.

So, I stop here and we will continue the discussion in the next class. Thank you.