Power System Protection
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Lecture 36
Fiber Optic Sensors

Welcome to NPTEL course on Power system protection. We are continuing with module 6 on current and voltage transformer.

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In this lecture we will discuss on fibre optic sensors where first we will see the limitations of CT and VT with specific applications to distance relay and then we will go for Fiber optic current and voltage sensors and its advantages.

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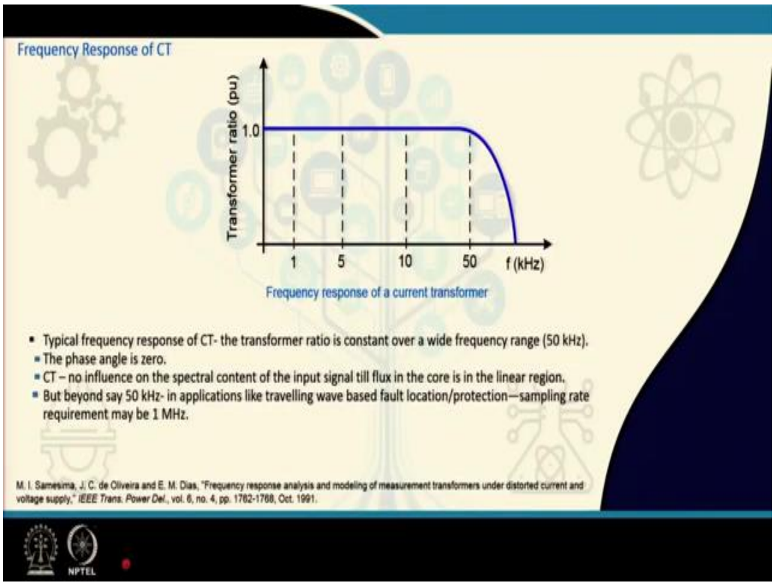

So, let us come to the current transformer and voltage transformer or the capacitor voltage transformer CVT we discussed earlier. So, on the frequency response perspective that means the frequency versus the response of the current transformer. So, you have taken the transformation ratio, how good is the corresponding CT for different frequency input. So, that results in how good is the corresponding CT.

So, for a band of frequency if you see this plot then the frequency up to 50 kHz it provides almost near to the transformation ratio as required. So, it is clear that the frequency response of the CT is very wide range of frequency as per the requirement in the relay operations.

Also you can notice that the phase angle is zero, it means that the relay faithfully reproduces the corresponding current signal during this steady case when it is operating in the linear zone in the BH curve. But, if you see that today in the numerical relaying perspective, if you require beyond 50 kHz, then what? Some of the applications like today in traveling wave and all these things, signals are being acquired as at 1 MHz and so from the current signals. So, in that case, we can say that these CT will find limitations. So, this frequency response tells us that how good is this CT in the linear zone for different relay applications.

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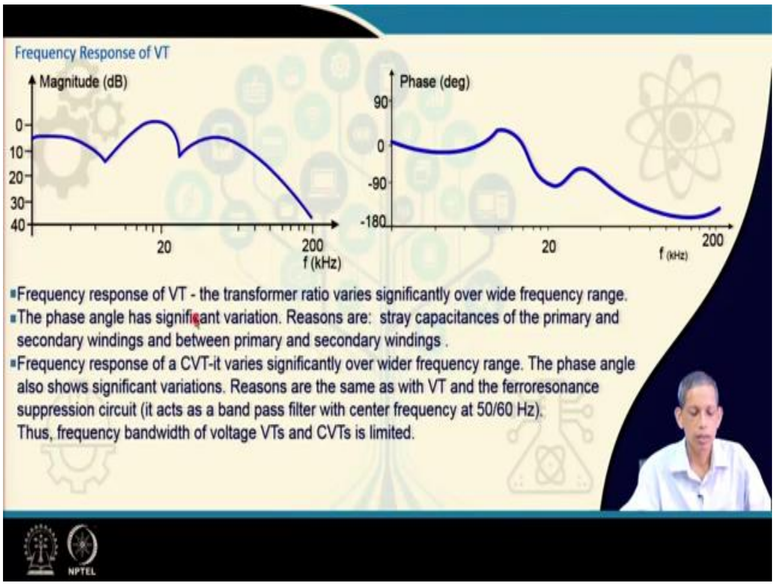

Similarly, when you see the frequency response of voltage transformer VT, the two winding transformer, the plot clearly shows here there is a large variation in the frequency response in both magnitude and phase and that is a concern for VT So, it is selectively in a particular band it may be good at and otherwise it has problem on like that of CT case.

The region behind this such frequency response, it is the stray capacitance of the primary the winding itself, in the secondary winding itself and also between the primary and the secondary windings. So, this is a challenge from the relaying perspective and all these things. Now, when you go to the CVT, capacitor voltage transformer, the response is also similar, not that good that of the CT.

And the region again the corresponding stray capacitance including the ferroresonance suppression circuits, note that suppression circuit is a band pass filter with centre frequency at the nominal frequency of 50 or 60 Hz. So, we see that the frequency bandwidth for which the corresponding signals are good, the VT and CVTs have limited performance.

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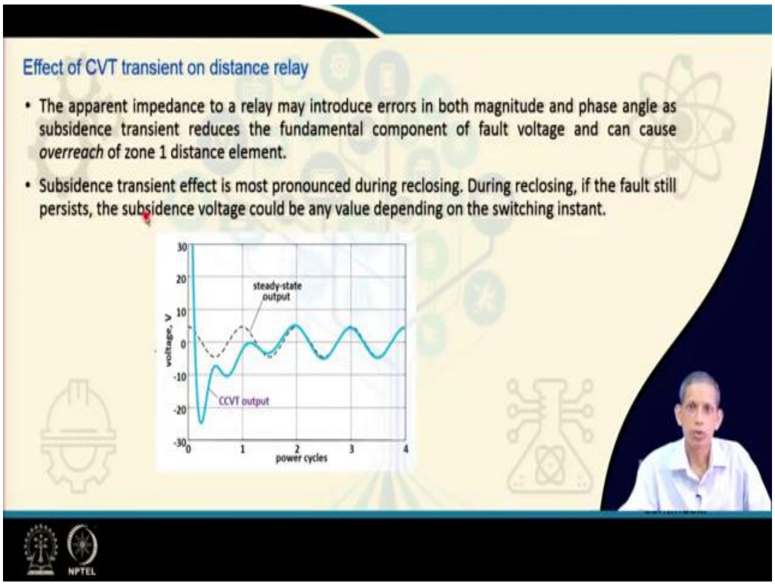

Now, let us see the issue related to CVT transient in high-voltage systems where distance relay is being used. Now, what happens there if see this plot, the worst scenario then the corresponding steady state output a dotted one is expected, but what happens is that CVT provides transient in the edge in the blue curve. So, as already mentioned that this subsidence transient reduces the fundamental component because it is mostly the decaying DC kind of thing and that is sinusoidal so and that leads to fundamental component to be significantly less during this time as expected that leads to the voltage being small that leads to the overreach of zone 1 during that time.

Now, this subsidence transient effect is more pronounced during reclosing and particularly when on to fall we have a reclosing aspect, fault is there and then again, we are reclosing the corresponding circuit breaker. So, in that case this becomes more pronounced and the effect will be observed of significant in nature.

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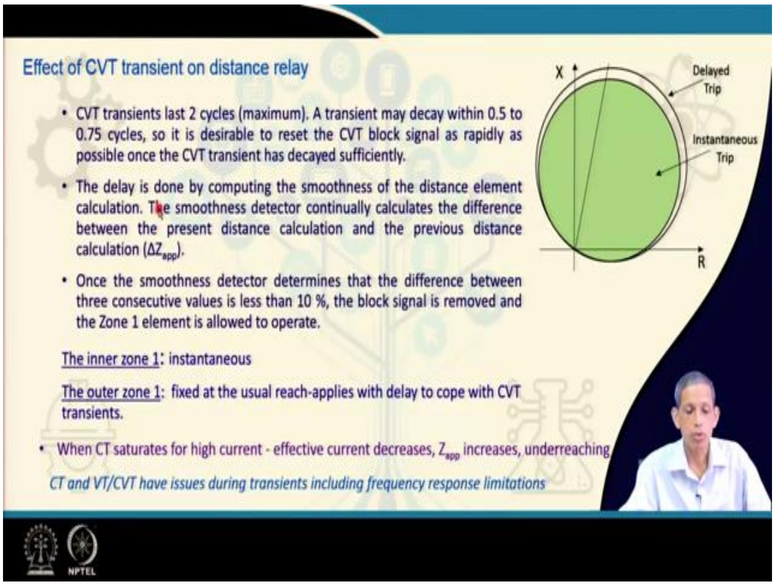

Now, what are the solutions to that? It is being observed that the CVT transient lasts maximum two cycles 1.5 to 2 cycles kind of thing. So, because simply there can you wait and watch and so, but two cycles which take a long duration from decision making process in very high voltage system. But in most of the cases it is observed that the corresponding transient decays significantly within 0.5 to 0.75 cycles.

So, what is being done that we divided the corresponding time into two aspects, in this steady region when it is already two cycles and the subsequent transient is no more, they are in the voltage signal so the relay performance will be as usual. But within that period as already mentioned due to these phenomena, the overreach maybe there and the corresponding situation has to be handle in a proper way.

So, what is being done to detect whether the corresponding situation is going through subsidence transient or not, the Z_{app} is continuously being calculated as usual in the distance relay and then ΔZ_{app} is being calculated in terms of the present Z and just the earlier Z and that is being observed continuously, if there is a large variation in that ΔZ_{app}, then it is assumed that it is going through the subsidence transient and if ΔZ_{app} is not significant, then I say that the signal has settled down. So, this is called smoothness detector and typically if the consecutive three samples of this ΔZ_{app} is less than 10 % variation, then we say the subsequent transient has gone down. So, for that the corresponding output is delayed, the normal setting of the zone 1 and the inner one the smaller one to avoid unwanted tripping due to the CVT and this is instantaneous trip. So, what it means that this is available or the initial the initial state and after that some duration of time when the smoothness test detector clears that the CVT transient has gone down then the relay switches over to the next one.

So, that adaptive approach is being followed in many relays to avoid to the subsidence transient issue with CVT. Now, this is about CVT solution, we will have examples on the next slide. But in addition to that, we have CT saturation issue with high current in the system and then V upon I if you think about that way to the Z_{app} then I decrease due to the CT saturation that leads the corresponding Z_{app} to be integers and that leads to underreach phenomena or like overreach phenomena due to the subsidence transient voltage. So, we say that CT and VT or CVT they have issued during the transients including we observed that the frequency response limitations in terms of that. Note that the frequency limitations keeps challenges in terms of the sampling of these systems, if you require a very high sampling rate for particular relay decision and so, so also will be a challenge.

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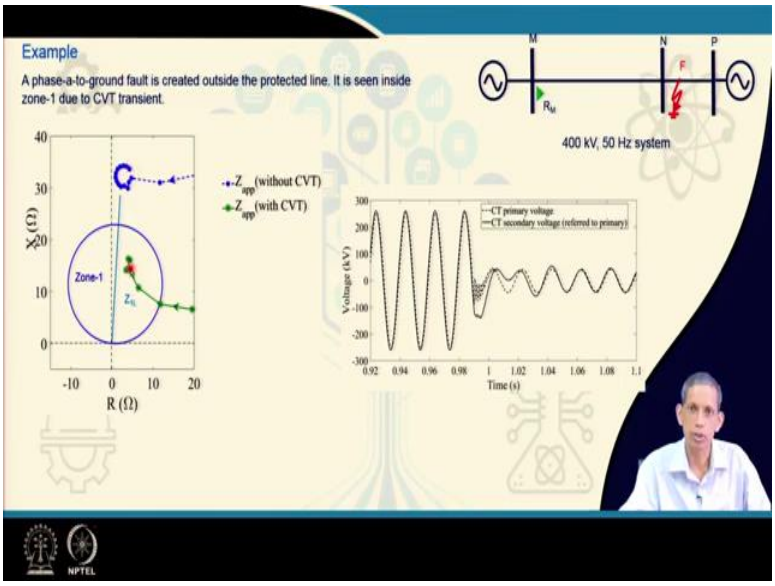

I will go to an example on how the CVT transient creates problem and then we will see how the adaptive philosophy in zone 1 setting can be useful, we like to see through an example. For a 400kV, 50Hz system and for this relay at bus M fault happens to be in subsequent line, zone 2 fault. Then you observe you that the corresponding voltage gone down significantly because the line length is not that large and so three phase faults. So, now what happens here that the CT primary voltage and CT secondary voltage referred to all primary side. So, then we see that the dotted line is about the primary voltage and CT secondary voltage in terms of that.

So, in this portion the CVT transient we observe, then what is happening even though the fault in zone 2 now if we see the Z_{app} calculations here it says the green one that it falls inside zone 1 because you know that the fundamental component reduces and therefore the impedance is smaller and that is a problem in terms of that. If we do not have CVT using the primary voltage if you are using then the corresponding things happens to be like this. So, which is the actual one. So this will lead to the malfunction of the zone 1 in this situation.

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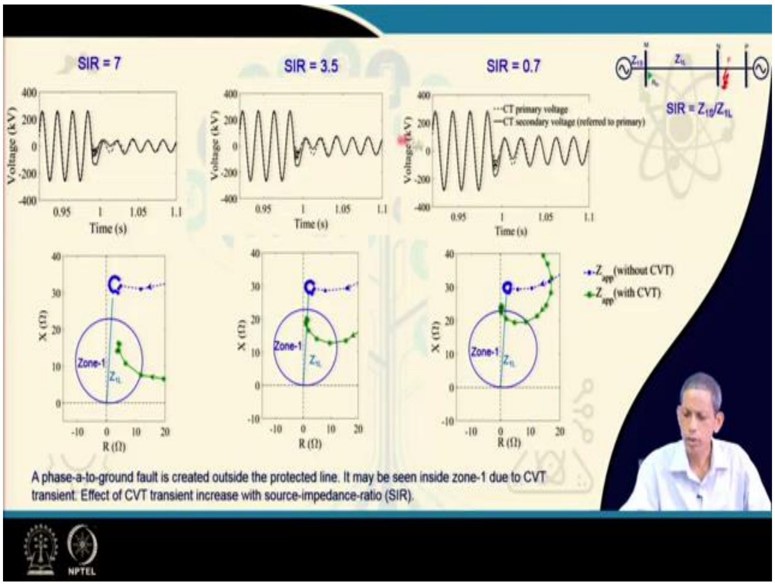

Now, for the same system we will have another study which we have already earlier discussed is on for different SIR source to impedance ratio. So, SIR we define in terms of Z_S upon Z_L that is positive impedance perspective. Now, for higher SIR it means that source impedance is much higher than the line impedance, 7, 3.5 and 0.7.

Now, note that when the corresponding source impedance is high and if fault happens to be there, then the drop in the source impedance becomes significant and at this bus the corresponding voltage becomes much lower at that time the corresponding CVT will be more prominent as compared to smaller SIR. In these three plots for voltage the corresponding plots are CT primary voltage and CT secondary voltage.

So, the solid land is about the CVT response so you see here all the three case and for SIR of 0.7 the corresponding CVT transient is less significant as compare to SIR 7 due to the mentioned region. We see the corresponding response of the relay during these different SIR, you see for SIR 7 it is inside zone 1 even though fault is in zone 2, this is still in zone 1 but you see here the final impedance shifts in the upward directions towards the boundary of zone 1.

Now you can say that the green one for SIR 0.7 that is the corresponding source is a strong source, then the final green one goes beyond the zone 1 setting. So, this is where the different SIR how the corresponding CVT performance will be seen by the corresponding distance relay in terms of that, this is a phase *a* to ground fault created outside the protection line and then we observe for these cases for different SIR cases.

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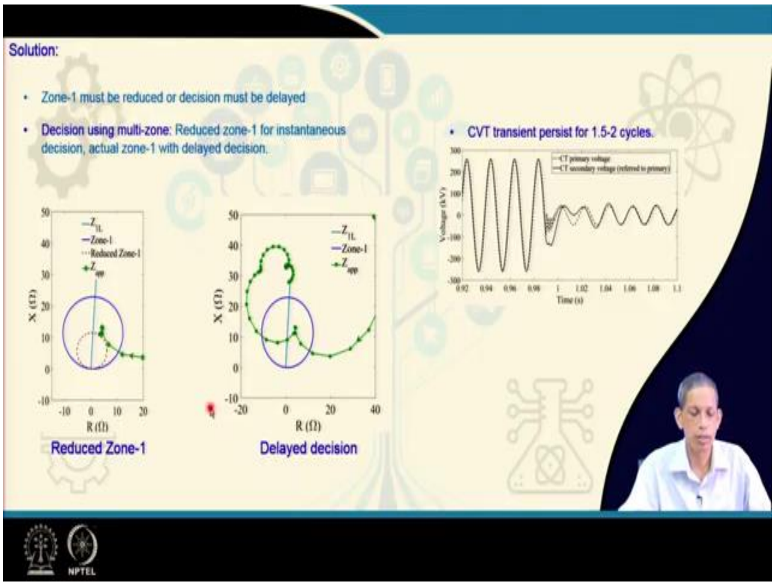

Now, we will go to the philosophy that solution we propose in the earlier slides. And so, which you have already mentioned that typically the corresponding CVT transient when he says within 1.5 to 2 cycles, and that is what we noticed from this plot also. So, what is being done as part of the methodology that once the smoothness test is passed through then we have two settings; one in the corresponding reduced zone 1 setting and the usual zone 1 setting. So, after this smoothness test it should go to the normal setting in terms of that. So now if you see here the reduced zone 1 so even though the fault is here the zone 2, so if you have the reduced zone 1 then yes the fault will be outside the zone 1 setting.

But, if you see the corresponding situation after some time like two cycles also, the corresponding trajectory goes and then finally settles in zone 2. So, let us consider the normal setting can be used subsequently. Note that this smoothness test which we are talking about that the ΔZ_{app} which we will be calculating here the points are very close. So, the ΔZ_{app} will be very small and that is what in this region this smoothness test will qualify.

Whereas, you can say the challenge is that the ΔZ_{app} seems to be larger, and that is why it will not qualify to the smoothness test. So, this example shows that if we use the corresponding adaptive approach where we have a reduced setting compared to the normal setting in the initial period of the transient, and then after some time if you use the normal setting, then the relay performance can be improved otherwise there is a tendency to do malfunction due to the CVT transient.

So, these reveals that, that the CT with saturation, VT with bandwidth on the frequency response perspective, and also in the CVT transient that they have limited performance at different situations, and that may create problem in malfunction issues to the different high voltage system.

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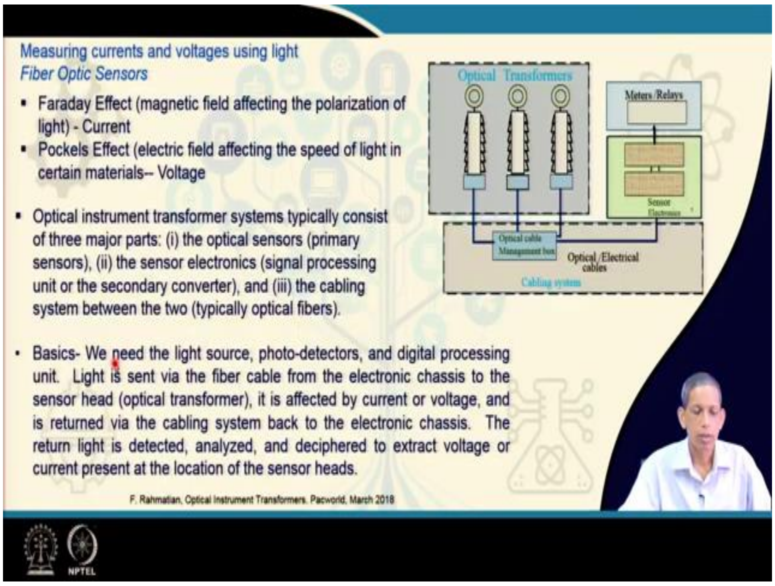

Now, we will go to the better performing sensing devices, and on that perspective, we will discuss on the optical sensors. So, these are with the heading of measuring current and voltages using light. So that issue and we talk about fibre optic sensors both for voltage and current measurement. The technology which is used being is based on pretty old concept by Faraday, and that is magnetic field affecting the polarized light.

For that we will go for the magnetic field created by the current so this will be used for current measurement. The second one Pockels affect, electric field affecting the speed of light in certain materials and electric field will be contributed by voltage so this effect will be useful in the voltage measurement perspective. So, we will see how these basic concepts of Faraday Effect and the Pockel's effect can be useful in measuring current and voltage using Fiber optic technology, which will lead to very high-quality sensing devices.

Now broadly, these optical sensors both for current and voltage these so called instrument transformer actually they are not transformer, but the terminology still goes on. So, such devices can be broadly categorized in terms of this so we have optical transformation, these are conductors, current or voltage whatever may be required.

So, these are the sensing devices and these with the management works for the light source the optical source and these are different cables connected to the different devices and then from the optical bus from after the current and voltage being sensed it goes to the corresponding sensor electronics, where a lot of digital signal processing and all these things have been carried out efficiently to quantify the corresponding voltage or current and then that goes to the meters or relays for usage.

So, if you see these blocks there need to have three important components. The first one is the optical sensors, the optical sensors part, the sensor electronic signal processing unit and secondary converter and the cabling systems. So that is about the cabling systems and the sensor electronics and so, this is about the signal processing part and all these things and the corresponding management of light and the sensing part will be here. So, we need essentially light source, photo detectors, and digital signal processing unit. These are the essential components for this. Light is sent via fibre optic cable from electronic devices from here to the sensor head optical transformation.

It is affected by the voltage or current that of the conductors and is return via the cabling again the management systems to these chassis and the return light is detected, analysed and deciphered to extract the corresponding voltage or current whatever from this effect, whatever from there we can infer that the amount of current or amount of voltage in the conductors and then that is being the input to the different relays and meters as per the required.

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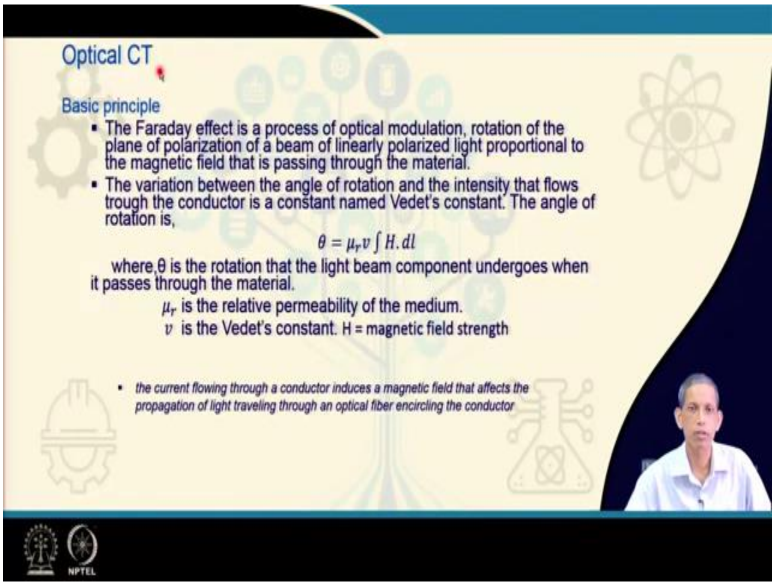

Let us first come to the current measurement optical CT. This is based on Faraday effect and then what is the Faraday effects says that the optical modulation rotation of the plane of polarization of a beam of linearly polarized light proportional to the magnetic field that is passing through the material. So, we see here the polar linearly polarized light is being affected by the magnetic field and that you can see that the rotation of plane of polarization is being quantified to get the corresponding amount of current near the conductor.

The variation between the angle of rotation and the intensity of the flow through the conductor that the current is a constant name called Vedet's constant and the angle of rotation is expressed in terms of a μ_r that is the relative permeability of the medium υ is the Vedet constant the magnetic field strength contributed by this current in the conductor, nearly the elementary length of the loop and then H and dl are vectors so you have a dot product dot product H .dl.

The current flowing through a conductor induces magnetic field and affects the propagation of the light traveling through an optical fibre and encircling the conductor. So, the conductor in the direction of the magnetic field the corresponding fibre optic cable is being wound and that the corresponding linearly polarized light gets affected. So, that rotation against their θ is being quantified and that is related to the current.

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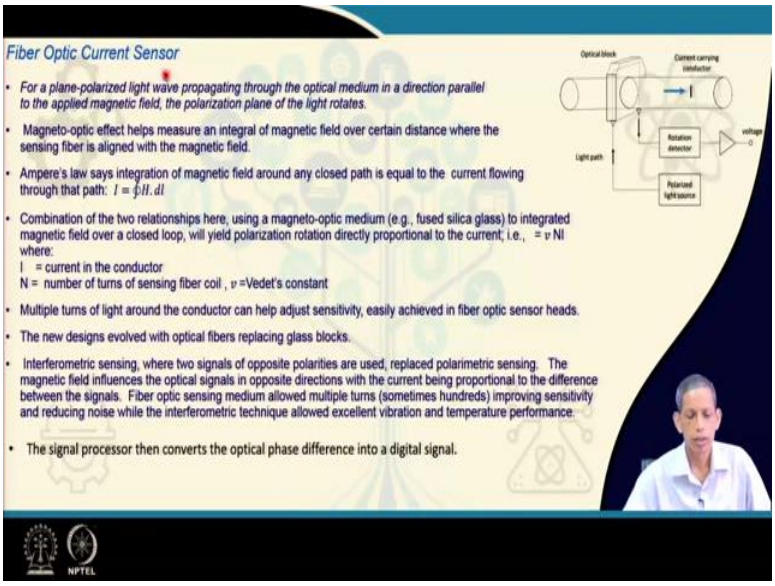

Now, in fibre optic current sensors, basic diagram is like this, if you see here, so, then polarize light is input and then this is the cable single turn or maybe multiple turn current following here and then the field in this direction. So therefore, then the corresponding light received in the cable at the other end the corresponding deviation the θ is being quantified and that is being used for the relay applications.

So, in fibre optic current sensors the plane polarize light to be propagating through the optical medium in a direction parallel to the field of magnetic field to the edge and then because the polarization plate of light rotates the Magnetic effect measure an integral magnetic field over a certain distance where the sensing power is aligned to the magnetic field true, but then again, we know the Amperes law

$$I = \oint H.dl$$

Therefore, combining the two relationships Faraday effect and what we have already seen in the earlier slide and this relation using a magnetic optic medium to integrate with magnetic field over a closed loop this polarized rotation directly proportional to combining these two the polarized light rotation theta is proportional to ν NI, where I is the conductor, N is the number of sensing fibre coil, how many turns we have wound for the fibre coil and where the ν is Vedet's constant as already mentioned from the Faraday's effect.

Therefore, we say from because this constant is constant and the number of cables is also known to us. So, we said that the corresponding rotation gives you directly the current of the conductor. In the new design evolved in fibre optic is a replacing glass of blocks and also more number of turns are being provided to have more sensitivity of the device. Interferometric sensing where two signals of opposite polarity are being used, this concept now replacing the polarimetric sensing.

Now, the magnetic field influence is the optical signals in opposite directions and the current being proportional to the difference between these two signals. Fibre optic sensing medium allow multiple turns, sometimes more than hundred also, improving sensitivity and reducing noise while Interferometric technique allows excellent vibration and temperature performance, and this is the new developments in this field. Now finally, the signal processor converts the optical phase difference into digital signal and that is being input to the relay or meters.

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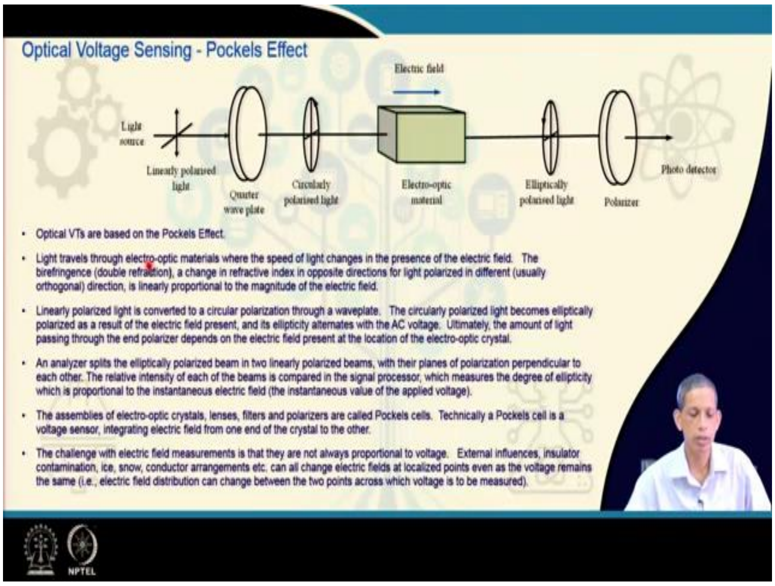

Now, coming to the voltage sensing through optical, so we have light source linearly polarized light and this is due to the Pockel’s effect, this wave plate quarter wave plate then we have a circularly polarized light obtained from the linearly polarized in this one. So, that says this clearly and then we have electric material, you can say a specific material for electric field system that is why we can say that of the system voltage is being applied for the electric field and these electrical affects the corresponding polarized light and then the circular one, the strength of electric field with a transformation of elliptically polarized light. And then the polarized light gives you the photo detector. Optical VTs are based on vocal effect, light travels to the electro optic materials where the speed of light changes in the presence of the electric field, so this electrical field changes the light.

The birefringence or otherwise the double reflection is a change in effective index happens to be there in opposite directions for light wave independently and this change in effective index results in a linear proportional to the magnitude of the electric field. Now, these linearly polarized light converted to a circular polarisation as I already mentioned through a wood plate and that becomes the elliptically available when it goes to the electro-optic material specific material.

This elliptical polarised light sensor that alternates with the AC voltage which we apply at this point. Analyser splits the elliptically polarized light here into two linearly polarized beams and with their plane's polarizations perpendicular to each other and this relative intensity of the beams is compared in the signal processor as already mentioned in case of the current sensing also, which measures the degree of ellipticity which measures the degree of ellipticity and this ellipticity is often considered by the amount of electric field and that measurement gives us the instantaneous value of the applied voltage.

The assemblies of electro-optic crystals lenses, filters and polarizer are called the Pockel cells, all the combination is called the Pockel cell. Technically Pockel cell is voltage sensors integrating electric field from one end to the crystal of the other but there are challenges, in the electric field measurement that they are not always proportional to voltage that this effect is not proportional to voltage always because of external influences, insulator contaminations, no conductor and so many issues.

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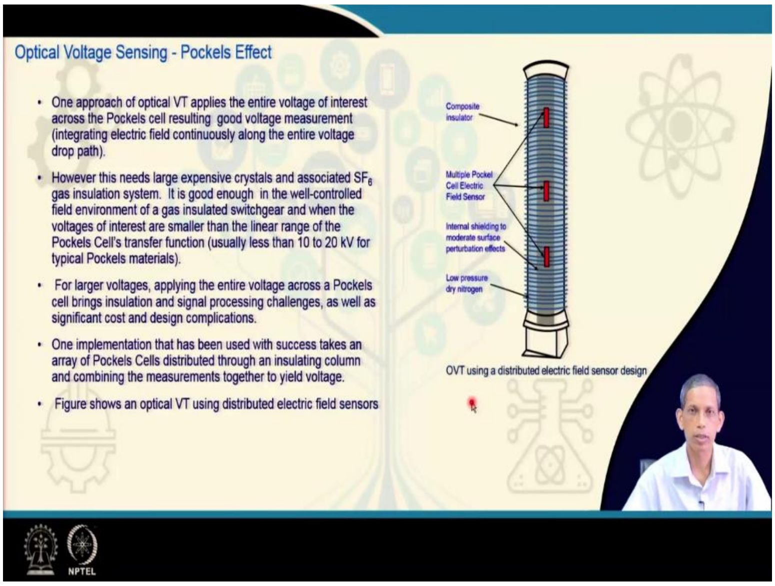

Then to mitigate these solutions so what is being done is that we will see here one approach on that solution is optical VT applies the entire voltage of across the Pockel cell resulting good voltage measurements, because it goes for a integration of electrical continuity along the entire voltage drop path but this needs expensive crystals and also associated sulphur hexafluoride, it is good enough to well control the field environment gas insulated switchgear, but see this has a limited voltage to 10 to 20 kV for Pockels material.

Now, these are the limitations of the approach, but if you go for a larger voltage like an extra voltage system or so, then the Pockel cells during insulation and signal processing challenges emerge and then the associated cost become also too high. So, to avoid that one implements on that has been used successfully is to use array of Pockel cell distributed through an insulating column and combining the measurements together to yield the voltage. So, these are the approach you can say is bound down for high voltage measurements. So, we have distributed Pockels and then these are being multiple Pockel and these are being combined to obtain high voltage measurement through the optical sensing using Pockel effect.

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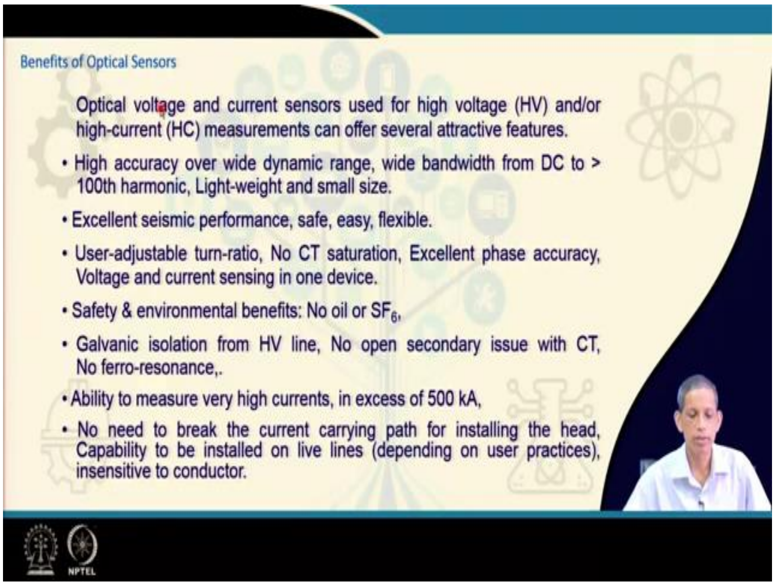

Numerous benefits that of the optical sensors for current and both voltage. Optical voltage and current sensor use high voltage high current measurements, can offer several attractive features. The bandwidth which have the limitations in case of CT VT and CVT you found out, here we see it goes from DC that is 0 Hz to 100th harmonic, absolutely no problem. Lightweight, small size, these are added advantage, excellent seismic performance, safe, easy and flexible, no oil also any insulating things required here, user adjustable turns ratio, no saturation, that gives better strength, excellent phase accuracy, no problem with phase angle also, voltage and current sensing in one device also there, we can combine both voltage and current sensing in the system also. So, that is environmental benefit, safety aspect that I told you about the oil and so, and that sees the environment benefit from SF6 perspective, galvanic isolation is also ensured on CT secondary open issue that high voltage issue no more valid in this case. No ferroresonance issue with CVT and so, so that is also eliminated, it can measure currents as high as 500 kA also, no need to break current carrying path, there you do not require to connect the corresponding like CT connections required, you can install it even the live conductor and so if it is required. So, these are the some of the benefits are which are the optical sensors possess and that you can search way, but only thing is that the limitation is in terms of the cost.

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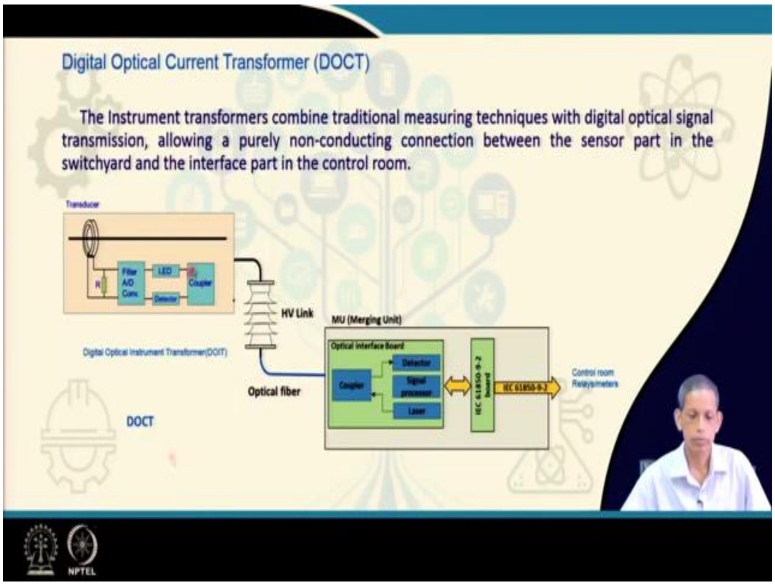

In relation to the conventional sensors using the today's systems on optical sensors and the conventional CT and VT and CVT, we have another version which is being used in the substation, it is called the digital optical current transformer. So, what is being done here as usual we can say that CT and then it transforms the corresponding CT current signal or the corresponding associated voltage signal to the A to D conversions and convert to the light signal and transmit to the control room by the merging unit (MU). So, the instrument transformers combine traditional measuring techniques with digital optical signal transmission allowing a purely non conducting connections between these sensors part and the switchyard.

These induces the electromagnetic effect while transmitting the corresponding signal from the sensor to the switch to the controller room. The additional benefit is there this signal being optical signal so therefore, we can say that these are digital signals and then it is useful for IEC 61850 compatible and that can go to the control room or be released as a digital signal and that can be used and inserted directly by the relay. So, this is the concept in the digital substation concept which is the digital substation of use do use.

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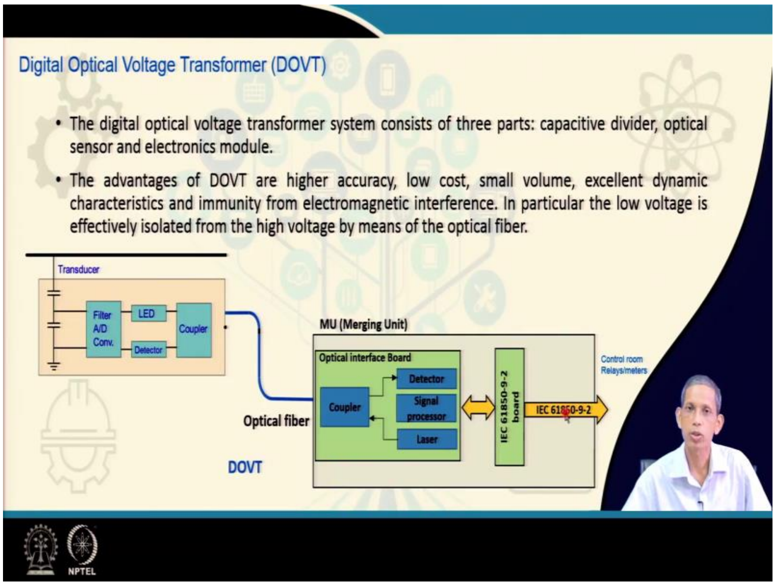

Similarly, for the digital optical voltage transformer. So, here we are talking about here again the CVT so that signal is again converted to A to D and then we convert the light signal to the optical cable it transmits to the merging unit and the merging with signal passing and so it transmits the corresponding signals to the control room useful in digital substation.

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So, what we see you from this earlier decision is that the digital instrument transformer DOCT or DOVT, these are associated electronic transformation of optical signals in digital measurements, sample values and that are directly used by the digital instruments IEDs or so, and that as an integral part of digital substations going in the new subsystem technology.

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So, we see in overall, that CT, VT and CVT they have limitations in terms of frequency response, in terms of CT saturation, in terms CVT transients and so, which affect the corresponding distance in performance significantly that we notice. Optical sensors they perform excellently and they are very suitable for digital substation also. So, in overall we see that this finishes on CT and VT and CVT including other sensing devices using optical technology in this lecture. Thank you.