Power System Protection
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Lecture No. 51
Wide Area Measurements Basics

Welcome to Power System Protection course, we will start a new module on wide area measurements system based protection.

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Where we will discuss on different lectures, how a PMU technology can be used to have wide area measurement system which can be used for protection application. In the first lecture here we will see the basics on what phasor measurement unit or PMU and then we will go how the wide area measurement system can be achieved. In subsequent lectures we will go for different applications on protection related perspective.

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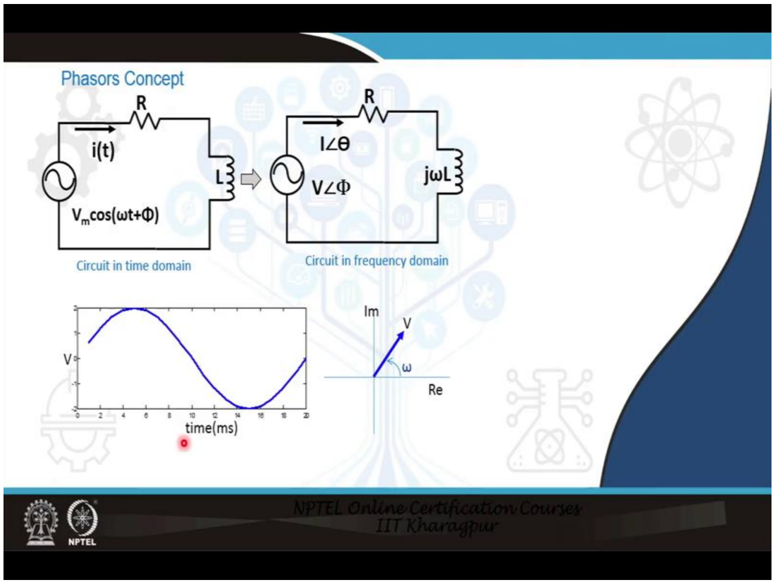

We know phasors that we have dealt with in all the relays, we started with phasor estimation and then based on the phasor estimation the phasor voltage currents and then going for the sequence components which are being widely used for different protection applications, directional relay, differential relay, distance relay and so. Revisiting on that we know for an electrical AC system, for an input voltage of $V_m\cos(\omega t + \phi)$ in this RL circuit the current in a steady state can be obtained by transforming this circuit to the frequency domain where you can write the corresponding R and the reactance as $j\omega L$. Then we represent the corresponding sine or cosine voltage as phasors $V\angle\phi$, and V upon the corresponding impedance in terms of $(R + j\omega L)$, we find the *I*. So, this *I* becomes a phasor with having certain angle based on this voltage angle and the corresponding angle of the impedance.

So, what you do from the time domain we go to the phasor domain and analyze the behavior of the circuit, the analysis in frequency domain gives us the concept of phasors because here in the frequency domain these voltage and currents are represented by phasors, 50 Hz or 60 Hz component. So, for that what we do without the corresponding sinusoidal quantity of voltage, we represent that as a phasor, which rotates anti clockwise with a speed of ω $(2\pi f)$ and then from there we obtain the corresponding current which also rotates in anti-clockwise direction with respect to the voltage, so relative angle between voltage and currents remains same till there is no change in the circuit condition or so.

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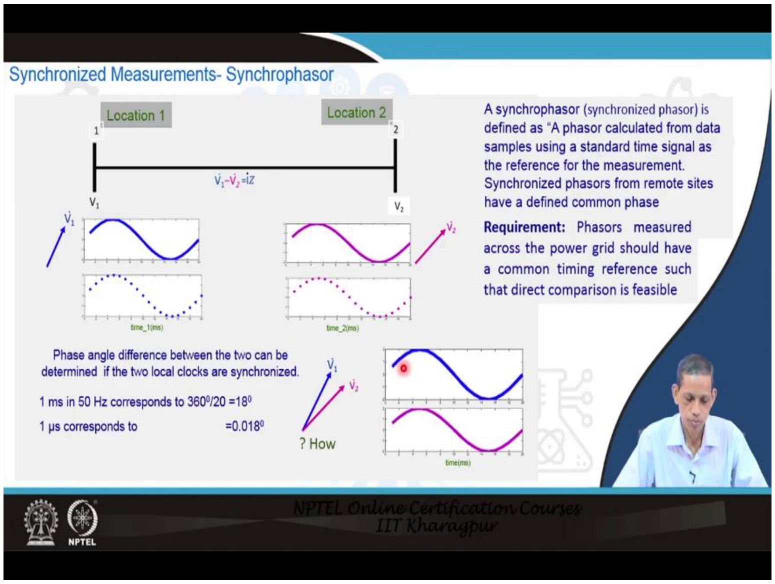

Moving forward, now let us think that two phasors when you require a two different locations, so these are two substations remotely connected by any transmission line which having an impedance of Z. So, we write the corresponding equation of this one in terms of

$$V_1 - V_2 = iZ$$

Here in all these voltages and currents are phasors and we can write the corresponding relations from which we talk about that the impedance Z parameter can be obtained or if two are given the third phasor can be obtained also. So, if you represent these phasors from this corresponding voltage signal here let us say V_1 here and V_2 here and if you like to have (V_1 - V_2) the corresponding phasor here will be V_1 and corresponding phasor will be V_2. But now the question is that how to get this V_1 - V_2 because this is having a time access here and this is having a time access here and device is remotely placed from the other device where the measurements are being taken. So, the clock of this which decides this time access up here for this phasor for this waveform and this clock of this measurements station 2 decides the corresponding time of this waveform and the associated phasors they must be same. Then only we can say that these two phasors can be plotted in one go, it means that the corresponding two waveforms blue one at left hand side and the red one on the right hand side would have the same time access. It means that either they should have the same clock which in this case seems to be impossible because they are hundreds of kilometers away, otherwise this would have a onetime reference from which the corresponding device should get the time information. Then only two waveforms should have this same time access and we can draw the corresponding phasors in one plot. If so, then we can have a meaningful comparison and we can write (V_1 - V_2) or we can play with the phasors. Otherwise, from the fundamental theory these are not possible.

So, in this perspective this two time information of these two devices at location-1 and location-2 have an error of 1 ms that may lead to 18^0 because 1 ms in 50 Hz system leads to (360^0/ 20) ms 18^0 of error and if these two time information of the two devices will having a 1 μs of error difference, then it will lead to 0.018^0 of things. So, this means that if we like to have this meaningful comparison between two phasors at different locations, then the time access must be same so there should be require a time synchronization then only the phasors can be compared in one go.

A time synchronized phasor is defined as a phasor calculated from data symbols using a standard time signal as reference as reference for the measurements. Synchronized phasors from remote sides have a defined common phase. Therefore, we have a standard time signal for these two measurements. The requirement is phasors measured across power grid system should have a common timing reference such that direct comparison is feasible. So, from this discussion what we say that unless there is same time these devices cannot have a meaningful comparison of this phasors as you see.

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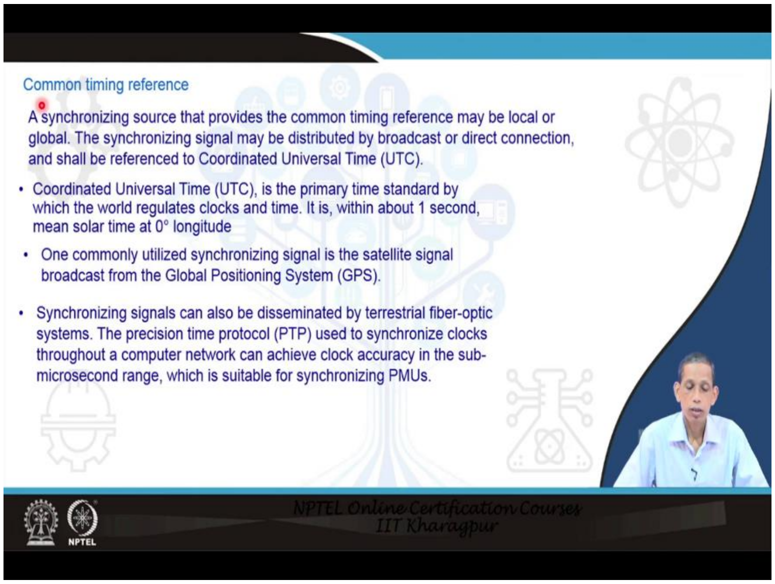

So, what is that common time reference which can be achieved in a power system application perspective? A synchronizing source that provides the common timing reference may be local or global. The synchronizing signal may be distributed by broadcast or by direct connection in terms of fiber optic cable or so and shall be reference to coordinated universal time, UTC time.

UTC time is the coordination universal time a primary time standard by which world regulates the clock and time, so it is within 1 s mean solar time at 0^0 longitude, so that reference time it must be able to provide so that the time information at all the measurements points will be following this UTC time. Commonly utilized synchronizing signal, it is satellite signal broadcasted from global positioning system GPS system widely used in many applications, so this is what we use in power system application also.

The synchronizing signals can also be disseminated by terrestrial fiber-optic signal, the precision time protocol PTP is to synchronize clocks throughout a computer network can achieve clock accuracy in a sub µs range, which is suitable for synchronizing PMUs also and note the GPS technology provides below 1 µs accuracy also.

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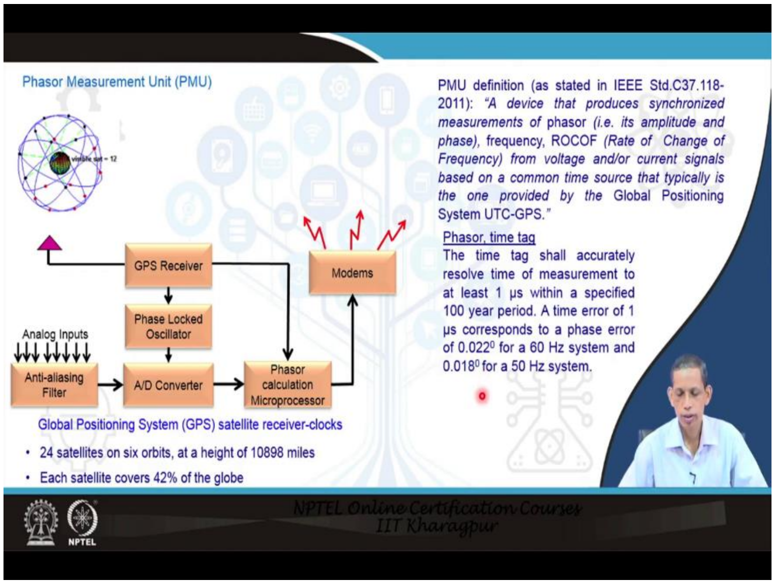

For the phasor measurement unit PMU, this is a device and it is being conceptualized from the relaying area and it has gone to many other areas of applications in power system particularly on monitoring and control application also. So, PMU is a just like a numerical relay kind of thing, so it has analog inputs, anti-aliasing filters to avoid the interference of high frequency components. Then A to D conversion process. So, this analog to digital gives us this samples as you know.

Now, we have the time information of the device. For that the time information comes from this GPS receiver with an antenna outside but this GPS receiver receives time information from the satellite global positioning systems satellite where atomic clocks are there and from that atomic clocks the time information is received by this antenna every 1s, one pulse and that is fed to the corresponding A to D converter process where the corresponding time information of the local numerical measurement device is being updated or goes in accordance with this GPS based time information. The device calculates the phasors just like the relay does more accurately and so we will talk about that and then the corresponding phasors is being provided with the time information called time tagging and then this is being fed to the network in the system to the next destination where the corresponding data are being used for different applications through any communication medium in particular dedicated fiber-optic or so.

In general 24 satellites are there, more redundant are also there on 6 orbits. Each satellite covers 42 %, therefore this satellite information the time of this device is being updated every second. As per the IEEE standard the PMU is a device that produces synchronized measurements or phasors, synchronized measurements or time synchronized as we have already mentioned. A device that produces synchronized measurements of phasor amplitude and phase, frequency, rate of change of frequency from voltage and current signals based on a common time source that typically is the one provided by the GPS based system, which has the UTC as the time reference. This provides the phasor along with the time tagging, each phasor is being time tagged from this GPS based time information. Time can be UTC and can be also provided by this local time information also following the information of the available UTC. The time tag shall accurately resolve time of measurements at least 1 μs within specified 100 year period. So, that should be the resolution of the time tagging. A time error of 1 μs corresponds to phase error of 0.022^0 for 60 Hz system and leads to 0.018^0 for 50 Hz system.

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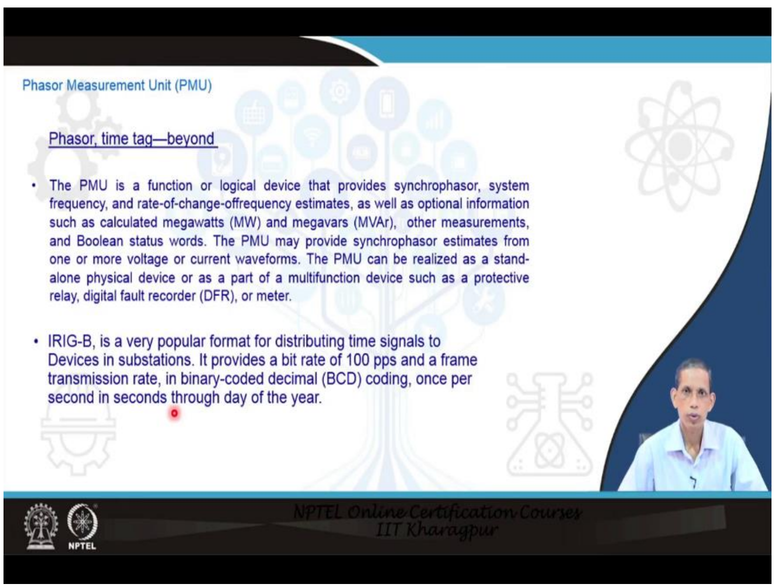

In PMU, we have the synchronized phasor that is time synchronized, these voltage and current phasors should be time tag, so that the time information is embedded with the phasor data. The PMU is a function or a logical device that provides synchrophasors through but beyond that also in today's applications system frequency, rate of change of frequency, already mentioned as well as optional information such as calculated MW, MHz, other measurements and status signal like status of line or circuit breaker are provided.

The PMU may provide synchrophasor estimates from one or more voltage current waveforms, several lines may be there at a bus so it will scan other lines also, the PMU can be realized as a standalone physical device or as a part of the multifunction device such as a protective relay. The PMU can be an independent device or in today's context many relays are having such synchronized phasor capability, digital fault recorder that also can provide such synchronized data. So, these are the scopes of availing synchrophasor. IRIG-B is a very popular format for distributing time signals in substations to different devices once the time information is being obtained from the GPS antenna which receives every second one pulse of time information. It provides a bit rate of 100 pps and a frame transmission rate in binary coded decimal (BCD) once per second in seconds through day of the year, so that is what the utility uses now to provide the time information to such synchronized platform.

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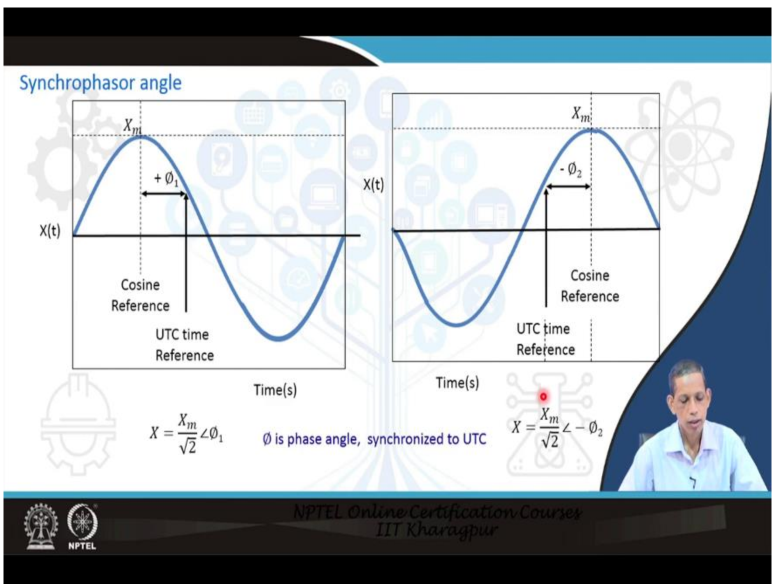

How the angle is being estimated? Otherwise that will lead to improper angle reference and it becomes purposeless application. So, we have this corresponding sinusoidal waveform, now we have the cosine reference having a positive peak in this cycle this UTC time reference as already mentioned this is through by the device measuring PMU relay or so which has the GPS antenna.

Therefore once it receives this UTC time reference, and if the corresponding time reference is ahead of the positive peak at that time reference then the angle between these two is taken as positive angle for the representation of the phasor value, so X phasor for this wave is

$$X = \frac{X_m}{\sqrt{2}} \angle \varphi_1$$

Now, however if the UTC time is behind the positive peak of the corresponding waveform then the angle becomes negative between the corresponding UTC time and the peak value of the cosine reference. So, in that case the corresponding phasor is being assigned with a negative angle. So, this approach is being used throughout the applications of the PMU concept and it is standard practice in this domain.

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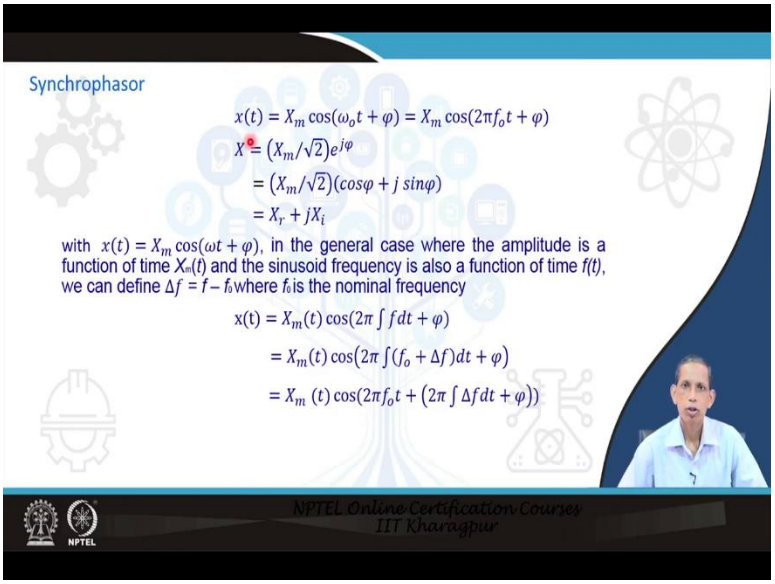

The synchrophasor computes the phasors, note this kind of phasor estimation we have discussed in relay, even that is similar the accuracy level demanded for such application is very high, we did not bother about much on the accuracy of the different protection element because our speed was our more concern.

Let us see this x(t) signal represented in terms of

$$x(t) = X_m \cos(\omega_0 t + \varphi) = X_m \cos(2\pi f_0 t + \varphi)$$

Where, f_0 corresponds to the nominal frequency, this can be represented in the corresponding phasor form as

$$X = \frac{X_m}{\sqrt{2}} e^{j\varphi} = \left(\frac{X_m}{\sqrt{2}}\right)(cos\varphi + jsin\varphi) = X_r + jX_i$$

However,

$$x(t) = X_m \cos(\omega t + \varphi)$$

Where ω is a general frequency which is different from this ω_0 or the corresponding f_0. Also the amplitude of the signal also may be a function of time, so the sinusoid frequency is also a function of time f(t), time varying then you can define

$$\Delta f = f - f_0$$

So for f = f(t), Δ f also changes with time. then you can represent this corresponding x(t) as

$$x(t) = X_m(t) \cos\left(2\pi \int f\, dt + \varphi\right)$$

$$= X_m(t) \cos(2\pi \int (f_0 + \Delta f)\, dt + \varphi)$$

$$= X_m(t) \cos(2\pi f_0 t + (2\pi \int \Delta f\, dt + \varphi)$$

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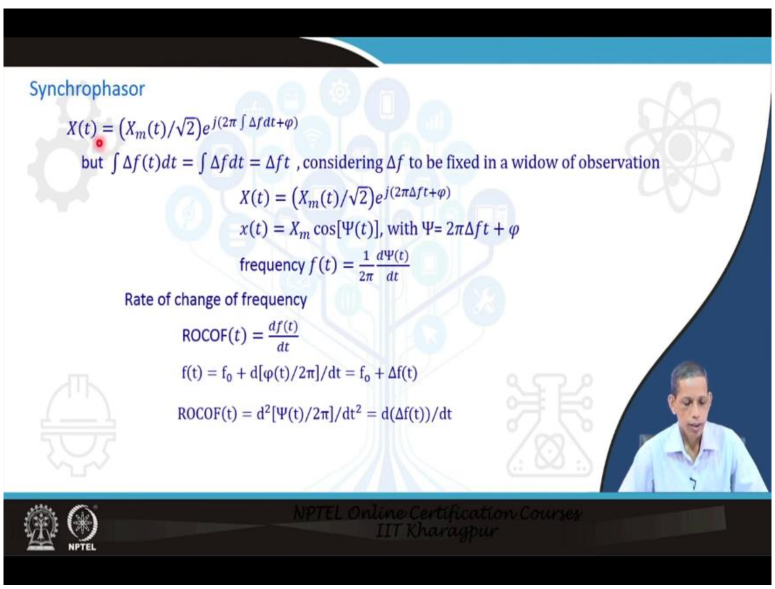

So, the corresponding phasor X at instant t will be

$$X(t) = \left(X_m(t)/\sqrt{2}\right) e^{j(2\pi \int \Delta f dt + \varphi)}$$

But, $\int \Delta f(t)dt = \int \Delta f dt = \Delta f t$, considering Δf to be fixed in a widow of observation

$$X(t) = \left(X_m(t)/\sqrt{2}\right)e^{j(2\pi\Delta f t+\varphi)}$$

and this can be written in terms of $\Psi(t)$

$$x(t) = X_m \cos[\Psi(t)], \text{ with } \Psi = 2\pi\Delta f t + \varphi$$

Then you get the corresponding frequency to be

$$f(t) = \frac{1}{2\pi}\frac{d\Psi(t)}{dt}$$

Rate of change of frequency

$$\text{ROCOF}(t) = \frac{df(t)}{dt}$$

Where, $\mathrm{f(t) = f_0 + d[\varphi(t)/2\pi]/dt = f_o + \Delta f(t)}$, Therefore

$$\mathrm{ROCOF(t) = d^2[\Psi(t)/2\pi]/dt^2 = d(\Delta f(t))/dt}$$

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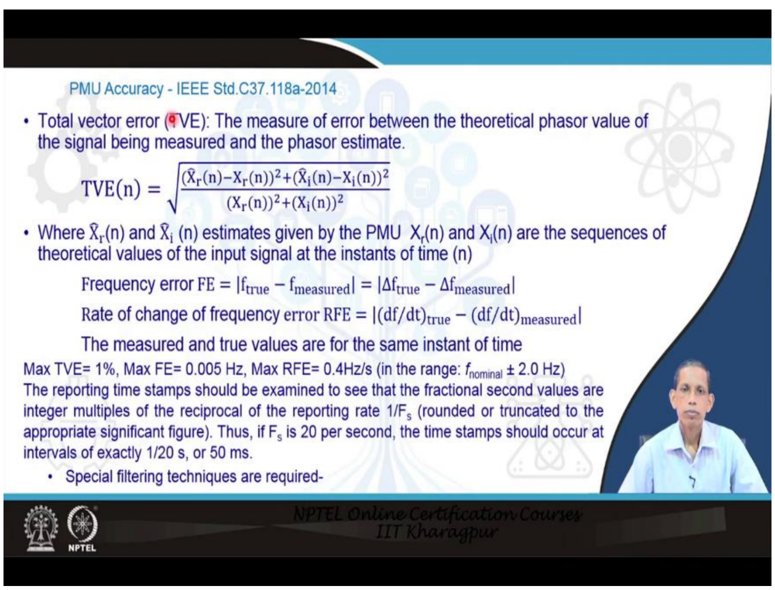

Now, we have seen that the corresponding PMU provides not only phasors, also provide frequency and rate of change of frequency and we are concerned about more accuracy here. So, the PMU accuracy follows certain standard, IEEE standard IEEE Std.C37.118a-2014 governs the level of accuracy the PMU must have. Particularly on the protection application perspective.

Define an index total vector error TVE is the measure of the error between the theoretical phasor value of the signal being measured and the estimated phasor. The theoretical, the true value and the estimated value. So, TVE at n^{th} instance becomes equals to the real part of the estimated value minus the real part we have the true value square plus the imaginary part of the estimated value minus the imaginary part of the true value square upon the true value real part square plus the measurement part square. So the TVE can be expressed as,

$$\mathrm{TVE(n)} = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{(X_r(n))^2 + (X_i(n))^2}}$$

Where $\hat{X}_r(n)$ and $\hat{X}_i$ (n) estimates given by the PMU. $X_r(n)$ and $X_i(n)$ are the sequences of theoretical values of the input signal at the instants of time (n). The frequency of error FE in index can be given by

$$\text{Frequency error FE} = |f_{true} - f_{measured}| = |\Delta f_{true} - \Delta f_{measured}|$$

So, measure is the estimated one and true will be the reference value which is known for this signal. Rate of change of frequency error RFE, so there may be error in the rate of change of frequency also ROCF, so that is called RFE is expressed by

$$RFE = |(df/dt)_{true} - (df/dt)_{measured}|$$

The measured and true values are for the same instant of time so all cases are for the same instant of time. The maximum TVE, (Total Vector Error) is 1 % that shows how accurate the PMU measurement should be. The maximum frequency error (FE) is 0.005 Hz and the maximum RFE is 0.4 Hz /s for the frequency range of $f_{nominal}$ (50 Hz or 60 Hz) ± 2 Hz perspective. So, within that band of signal the PMU should provide a TVE of 1 %, frequency error of 0.005 Hz, and maximum rate of change of frequency error of 0.4 Hz /s.

The reporting time stamps should be examined to see that the fractional second values are integer multiples of the reciprocal of the reporting rate $1/F_s$ (rounded or truncated to the appropriate significant figure). Thus, if F_s is 20 per second, the time stamps should occur at intervals of exactly 1/20 s, or 50 ms. So, this means that to accomplish this kind of accuracy standard of a different measuring situations like both steady state and the dynamic state estimation process for which the corresponding TVE, FE and the X_r being defined in terms of the standard, so this requires special filtering techniques beyond that the DFT or so what we have learned in relaying perspective. So, that for different windowing concept are being used generally and window, rectangular window all these things for the estimation of phasors and frequency, etc.

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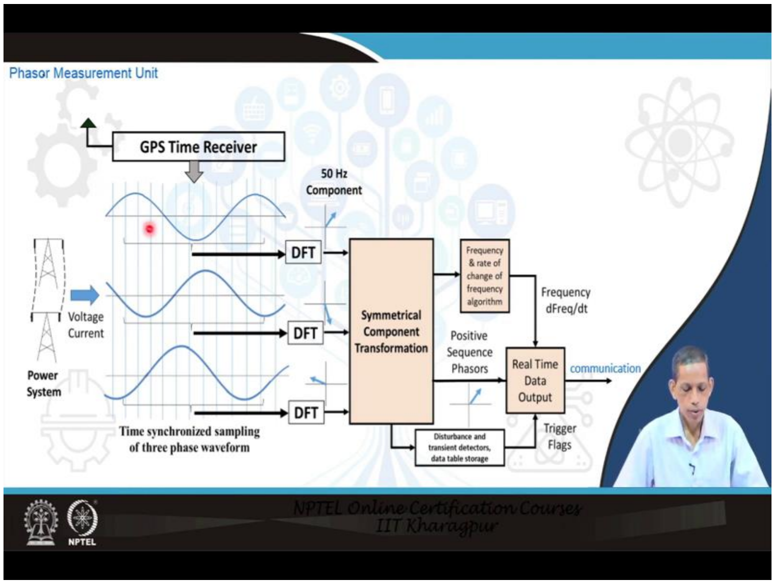

So, we see that the phasor measurement unit receives GPS time information, scans the voltage and current samples from CT, PT or CVT from where it applies a DFT and all the filtering process to obtain the corresponding phasors, from the phasors it computes the symmetrical components and it also computes the frequency and rate of change of frequency. And then the corresponding data are to be transmitted to the next destination. It has also storage for disturbance and transient record as data base storage at the local level also.

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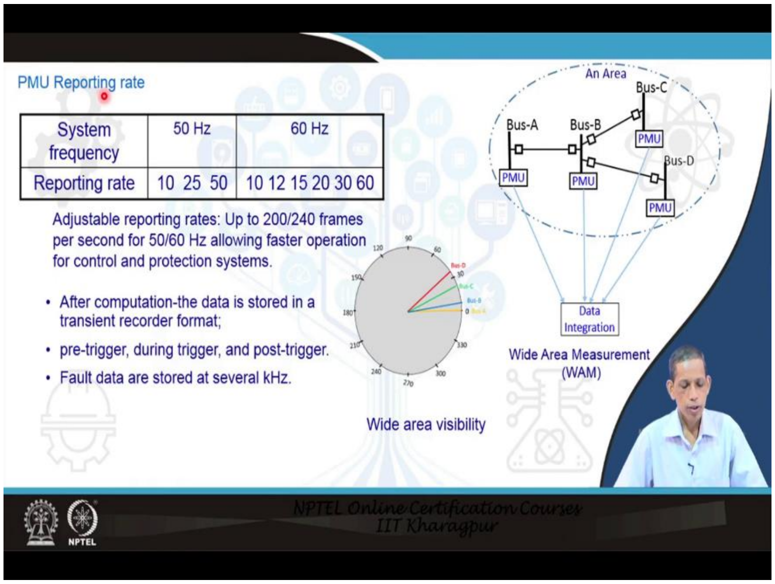

This PMU reporting rate sends data to the different destination like we have a different buses where we have PMUs in a system, this is an area where we have different buses PMUs are there not in all the considered buses or so, in this diagram we have shown bus, all the buses are PMU buses and they are remotely placed and these data are being collected at one destination for that area, we call this as wide area measurement system because they may be a very large area or so, a system a grid may have several such areas where the corresponding data are being collected and in each area those data may be transmitted to different particular destination, a centralized destination also.

Now, for this region for a utility applications of such synchronized data obtained from this PMU with time information, time take, generally the reporting rates to which the corresponding PMU sends, the PMU sends at a rate of these phasors with time tag for 50 Hz as per the applications available in the power system 10, 25, 50 frames per second and for 60 Hz system 10, 12, 15, 20, 30, 60 frame per second, so such a rate is being followed or to be reported by this different PMUs in the system.

Today we have more powerful PMUs, they have adjustable reporting rates and they can send report, phasor data at a rate of 200 to 240 frames per second or so for the 50 or 60 Hz system. And this gives us faster operation in control and protection domain in general. This data after computation is being stored in a transient recorder or format in the PMU level. Pre-triggering, during triggering and post triggering level like the any recording device for the protections and so including the relay does. Fault data are stored at several kHz just like the data logger or so.

Now, what happens that once we have this data at one centralized location, we can plot the phasors and this is a polar plot where all these bus angles are being plotted and from this angle we can infer that which line or which bus is highly loaded or so. If we have such plot for the whole systems you can have a wide area visibility where it can infer that which area is being stress or not. Even this area having one PMU and several such area may be there, then this PMU information will reveal that the area is under stress with respect to other or not.

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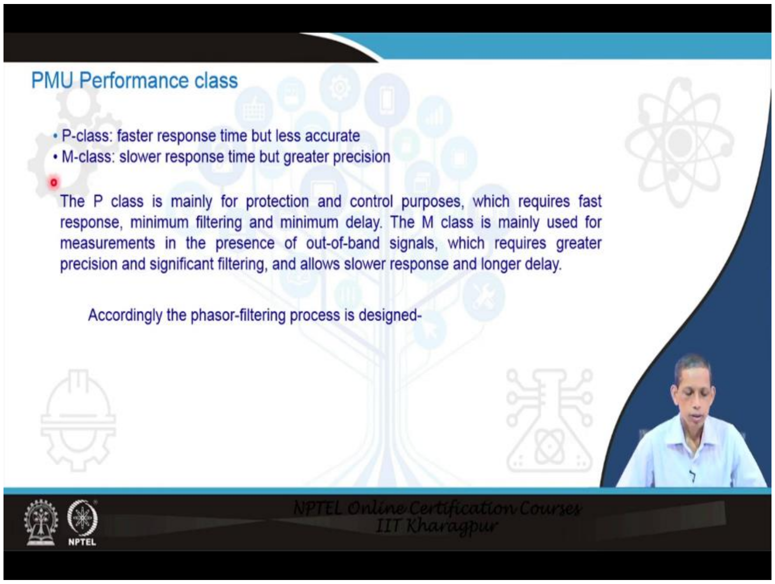

PMU are again divided into two class P class for the protection class, M class for the measurement class. The P class or the protection class is for the fast response, time but less accurate, and M class for slow response but of very high precision. P class is mainly for protection and control purpose which requires fast response, minimum filtering and minimum delay, so that it can be used for the protection perspective. M class is mainly used for the measurements in the presence of out of band signals which requires greater precision and significant filtering and allows slow response and longer delay for monitoring and metering purposes or so which is of significance at the grid level metering and so. Thus, depending upon the P or M class or the applications, the phasor filtering process is to be designed to make the required accuracy standard and so and the speed of operation.

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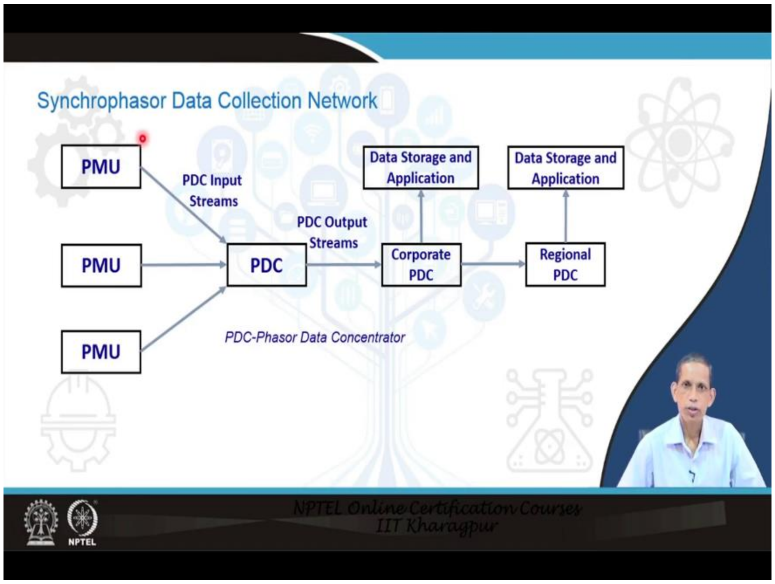

In the synchrophasor or the synchronized data which are being provided by this PMUs in the systems and they are to be collected to have meaningful applications of those data. So, from different PMUs the phasor data concentrator collects at the substation level or at zonal level, the corresponding *n* number of PMU data are being collected, collated and integrated. Again, it is being send to the different next level of PDC like, corporate PDC, regional PDC level.

So, this centralized phasor data concentrator, they collect the data and then they stored it for different applications or they are being visualized, used for different applications to command, or decide through the protection arrangement and other application perspective.

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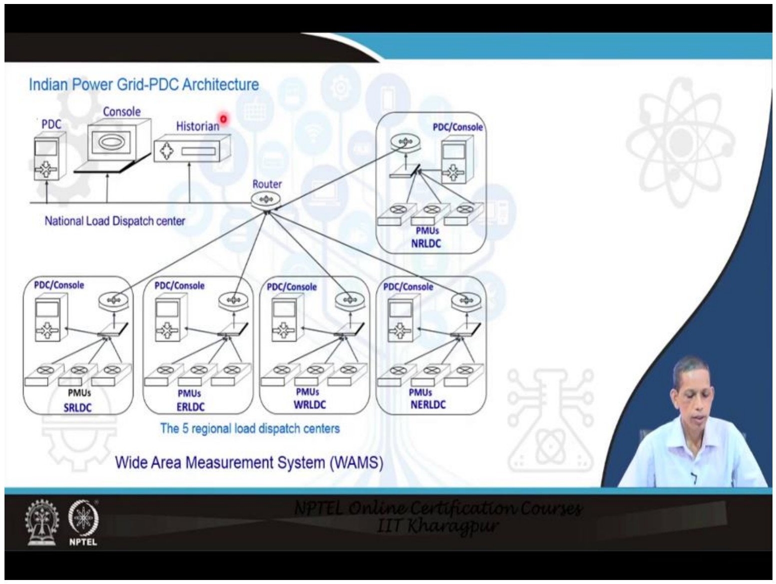

In Indian Power Grid we have 5 areas, the Southern, Eastern, Western, North-East and the Northern region. So, these areas having their own phasor data concentrator PDC, so these are being again connected to the National Load Dispatch Center at Delhi where the corresponding PDC collects the data, integrates the data, align it with time allotment then the time information being available for each phasors through the single phasor technology provided by this PMU. The other historian and console and all these things they take this corresponding data for other applications perspective.

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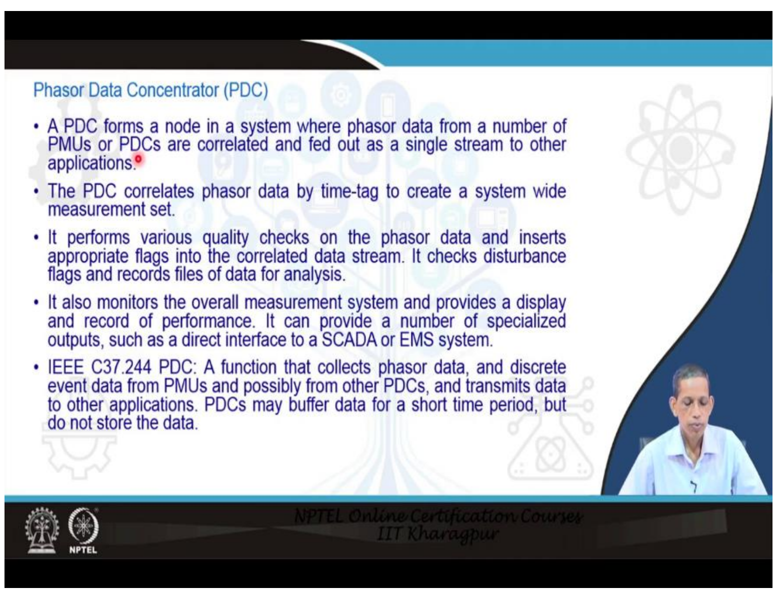

Phasor data concentrator forms a node in a system where phasor data from a number of PMUs or PDCs are correlated and fed out as a single stream of other applications, if it is a PDC and so it has to send to the next level of PDC, it sends as a single stream. The PDC correlates phasor data by time-lag to create a system wide measurement set. So, the time take which is being available with the each phasor, that is being used by the PDC to align the corresponding different phasors so that the measurements sets becomes better useful for the different applications on monitoring, protection and control.

It performs various quality check the PDC on phasor data and inserts appropriate flags into the correlated data stream, it checks disturbance flags and records files for data analysis. So, for further analysis and all these things it performs with different quality checks. It also monitors the overall measurement systems and provide a display of performance record and also integrates the scalar data for the energy management system (EMS) applications.

So, there are different standard for PDC also, C37.244 for the IEEE, a function that collects phasor data and discrete event data from PMUs and possibly from other PMUs also and transmit data to other applications. PDC may buffer data for a short time period but do not store the data. The purpose of PDC is not to store data.

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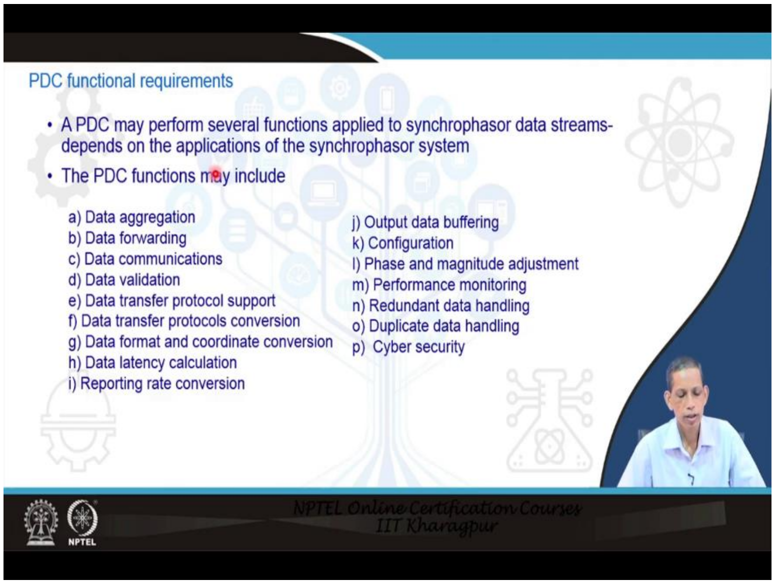

PDC functionality can be of several ways, data aggregations, data forwarding, data communications, data validations, all related to data, reporting rate conversions, output data conversing, redundant data handling and so, even including cyber security perspective because these are having communication system and also the computer technology associated.

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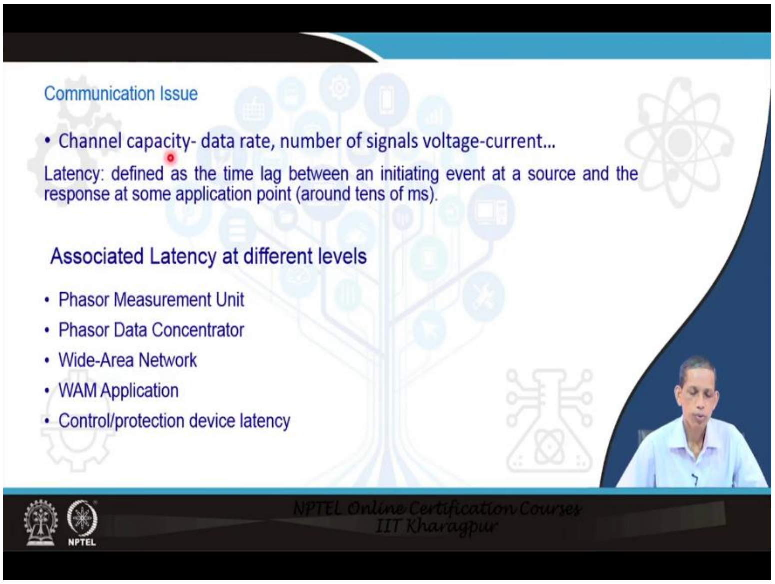

The communication issue is the most challenging things here as it requires dedicated communication systems on the PMU and the wide area measurement system perspective. The channel capacity of the communication system depends upon as you know data rate that is the number of voltage current signals, what are to be passed to that communication and to how many PMUs or PDC perspective so that will decide the channel capacity.

The important aspect from the application perspective is the latency defined as the time lag between an initiating event at a source and the response time, response at some application point around which happens to be in terms of milliseconds. So, point of latency talk about the late arrival of data at a destination because of the processing and the associated communication system or so.

So, at different levels there are different latency in terms of the time information, in terms of how much millisecond of delay or so. Phasor measurement need the calculation process, acquisition of data and so. The PMU also sends data, reports data. Therefore the associated latency also. Phasor data concentrator aligns and collects data, then sends the data to the next level of destination.

Wide area network, it has a communication system and then the corresponding router and so. WAM applications, wide area measurement application perspective in terms of protection, control or visibility, the monitoring system or so. These application software will have its own time of delay. After receiving the command, the execution at the control or protection level also relates to this and different device level of latency. In overall you see that for any applications there are different stages of latency and their latency should be compatible to the particular applications so that must be checked thoroughly.

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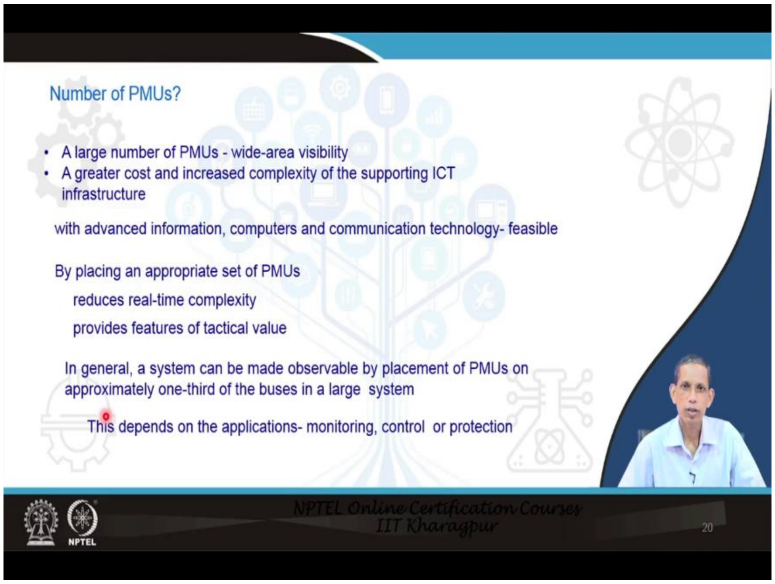

The other important factor is how many PMUs in a system for particular application, more and more PMUs means the visibility will be better, more inside you can see of the system behavior. But this has a greater cost associated in each complexity with handling the data and the ICT infrastructure with advancement in information technology, computers and communication technology such a voluminous data platform is feasible today. By placing an appropriate set of PMUs reduce real time complexity, provides features of tactical value. So for that we do not need all the PMUs and all these things if you can manage it is welcomed, sometimes the PMU data may not be available with that situation also the corresponding application should be viable and so.

In general systems can be made observable from simple observability point of view. From that application perspective a typical figure is one third of the process of a large systems. But all these depends upon how many PMUs, it depends upon the applications, whether it is for monitoring purpose, control applications or protection application.

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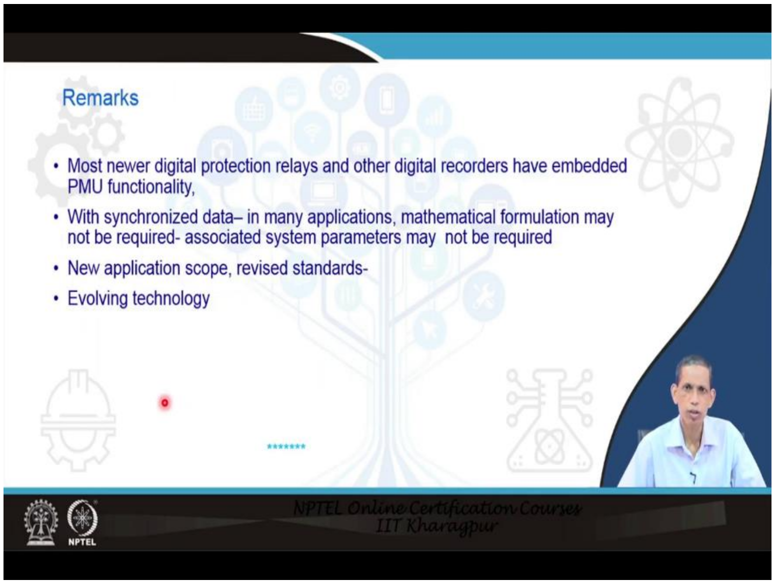

So, in overall we see that the phasor measurement unit which provides time synchronized data or called synchrophasor. Protection or control applications becomes viable with that kind of time synchronized data which has also the time information, with each phasor.

So, today most new digital protective relays and other digital recorders have embedded PMU functionality with the GPS antenna integrated. With synchronized data many applications possible and we have data of the system, so we do not require for many applications the mathematical formulation of the system, in details; no modeling, many times we do not require the modeling also for those kind of applications because the corresponding delta angle and the corresponding phasor are being avail directly.

New application scopes, there are also the technology is being moving forward more and more revised standards are also coming up for the more stringent and accurate accuracy level. The technology evolving and we will see that in tomorrow it will have more scope of applications in different domains. Thank you.