Digital Protection of Power System
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Lecture No. 10
Frequency Estimation Algorithm

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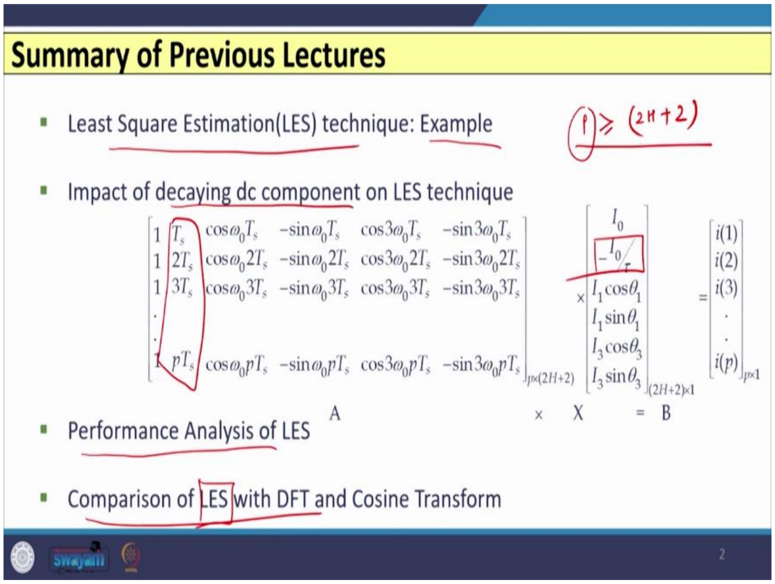

Hello friends. So, in the previous lecture, we have discussed regarding the least square error estimation technique. And in this technique, we have seen one example also and after considering an important example of LES, then we have shifted or modified the same LES, when we use or apply for decaying DC component. And finally, we obtain the equation that is here A into X is equal to B where this portion is modified in A matrix, whereas, this portion is also modified in your X matrix which is unknown.

After that we have discussed the performance analysis of least squares estimation technique and in that we have discussed that whenever we use LES technique for decaying DC components, then this technique provides best estimation compared to the other techniques, like full cycle DFT, half cycle DFT and cosine transform.

The important point which considers here, that is regarding the number of samples required, we have discussed that when we have the value of $p \geq (2H+2)$ part. So, when we have exact number of samples available with reference to the number of unknowns available, then we do not get the accurate estimation of phasor but as an when we go on increasing the value of number of samples available, then we will get the exact value of phaser estimation.

At last we have seen the comparison of this least square estimation technique with the DFT and cosine transform algorithm. And we found that LES technique performs better in terms of accuracy of phasor estimation compared to the DFT and cosine transform specifically when decaying dc component is present in the acquired signal particularly in case of fault and also this technique that is earliest technique provides better result when we have maybe an observational error or measurement error in the acquire signal.

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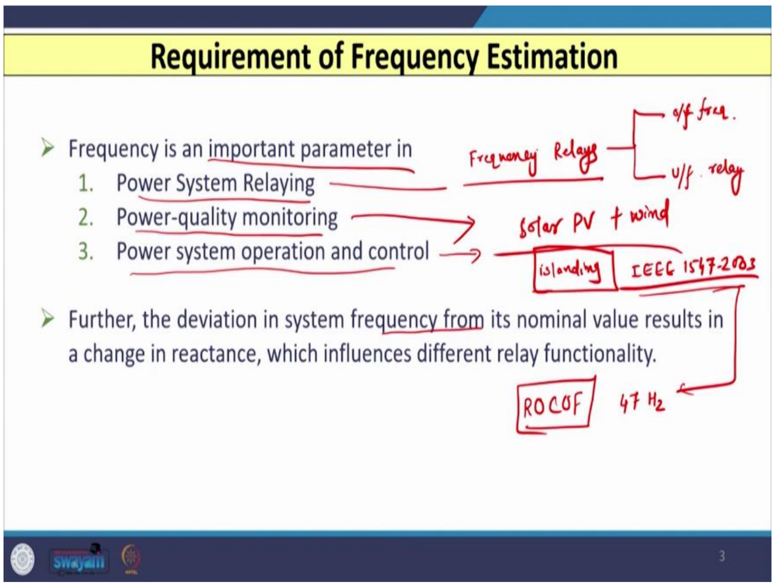

Now, in this lecture, we will discuss regarding the frequency estimation algorithm. So, we know that frequency is an important parameter as far as the power system network is concerned. So, frequency is very much used in case of the power system relaying applications. So, we know that we used frequency relay.

So, in frequency relays, we may have over frequency relay or algorithm or we may have under frequency relay algorithm. So, in both the cases this frequency estimation is must or very important. So, we have over frequency relay and we may have under frequency relay. So, in both cases we need estimation of frequency.

Moreover, when we have an application where power quality is an important issue, we know that when we have the issues like voltage sag, voltage swell, maybe transients, harmonics, voltage deep, voltage flicker. So, in that condition or situation also estimation of frequency is required. Moreover, when we are dealing with the operation and control of power system network then also we need to estimate the frequency.

Further, you know that nowadays renewable energy sources are widely used at the distribution network. So, penetration of renewable energy sources are day by day increasing and in that specifically, we are using solar PV and wind both type of distributor generators we are utilizing. And in this case, also important phenomena which is known as islanding is going to occur. So, whenever we utilize solar PV or wind as an renewable energy sources, then we have to integrate the sources with our conventional grid.

And when we wish to integrate this with the conventional grid, we need to follow certain standards. And in this case, when we integrate the renewable energy sources like solar PV or wind with our conventional grid, then we have to follow IEEE 1547-2003 standard, which will be amended later on in 2012 and in 2018. So, in this standard, it is clearly mentioned the proper procedure that when you want to integrate any renewable energy sources worked as a distributor generators, then we need to follow this standard and what are the different points and procedures we need to follow that is clearly mentioned in this standard.

Further, the deviation in system frequency not though it is not allowed, it has to within certain plus or minus limit, but, if any deviation is going to occur in the frequency with reference to his base value or nominal value, then this is going to result in the change in reactance and that is going to directly impact on the different relay functionality.

So, we know that when we use over frequency relaying or under frequency relaying, then frequency is important even when we want to monitor the load shedding scheme or when we want to talk about load shedding scheme, then the frequency is an important parameter and in that we know that rate of change of frequency that is going to monitor in load shedding scheme.

So, that accordingly if frequency falls below certain value, let us say if we consider 50 Hz fundamental signal then if frequency falls below let us say 47 or 48 Hz, then the rate of change of frequency algorithm is activated and that is going to further, initiate the load shedding scheme or triggering. So, this is very important point.

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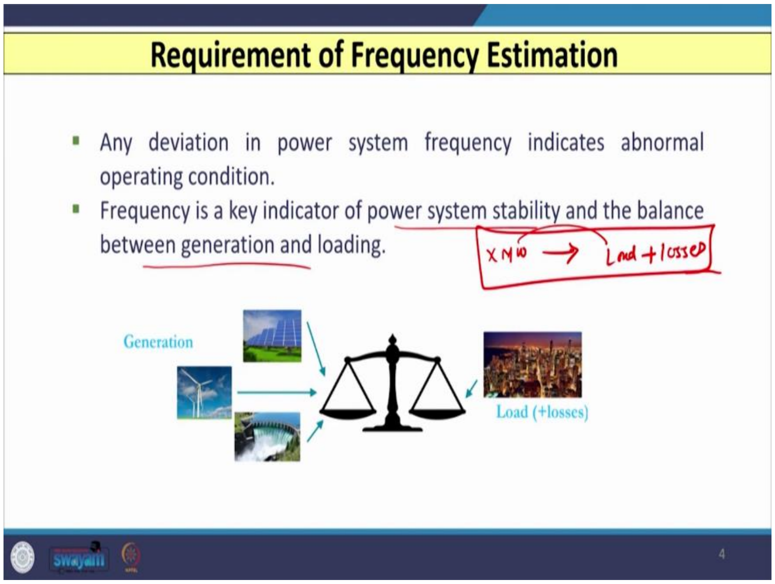

Now, as we have discussed that any deviation in system frequency that is going to indicate abnormal operating condition. So, frequency is very important and it is a key indicator for stability of the system. And it is also equally important in case of balance between the generation and loading.

So, we have seen that the whatever generation in terms of megawatt we have the same amount of load we need to disperse and that includes the losses also. So, let us say if X megawatt of power is generated, then the same amount of power that is required or given to the load with the losses also. So, this balance is an extremely important and this is important particularly when we talk about frequency or system frequency.

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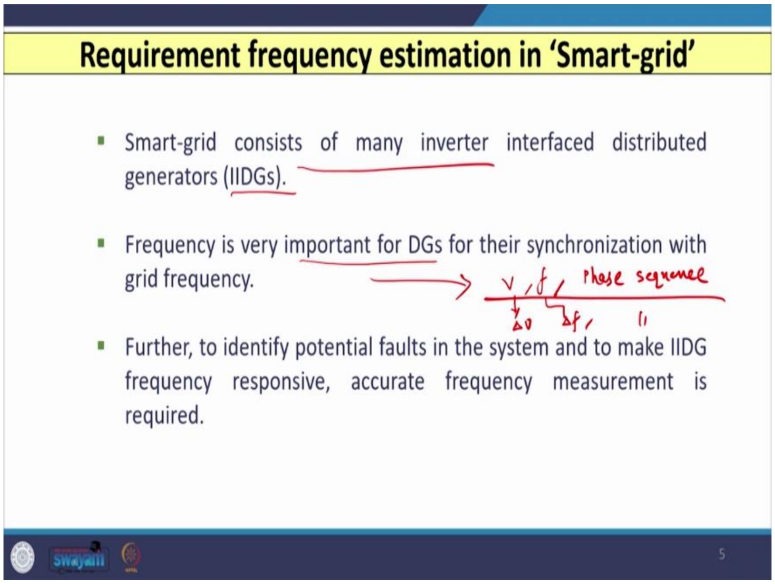

Now, if we consider the importance of system frequency or estimation of frequency in case of smart-grid condition, then this smart-grid consists of several inverter interface distributed generators. So, as I told you, we use solar PV as a distributor generator or we may use wind PV as a distributed generator. So, in that case IIDG's are commonly used. Now, when we use the inverter interface distributed generators, then frequency plays a key role or important role for this type of DG when we want to synchronize this DG with our conventional grid.

And when we synchronize any distributed generator with our conventional grid, three parameters, we need to remember, one is the voltage should be same, the second is the frequency should be same, and third, if we are dealing with AC system, then phase sequence should also be same. Maybe they may talk about instead of voltage they may take the deviation in voltage, so, delta V. They may take the deviation in frequency delta F and phase sequence.

So, when we want to integrate any generators, distributor generators or renewable energy sources with the grid, these three parameters are very important. Now, if we wish to identify faults in the system, and if we want to make our IIDG frequency response you then accurate frequency measurement is required.

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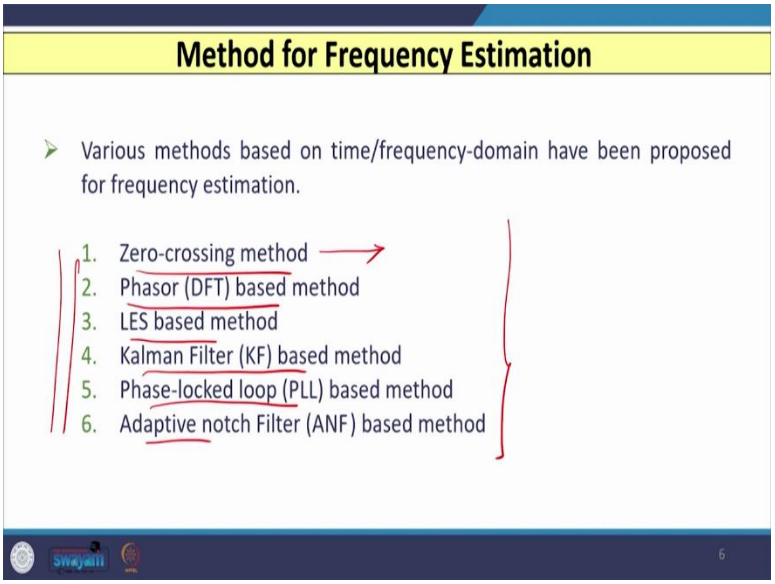

So, let us see how we can achieve this thing. So, various methods are suggested by different researchers and this methods are either time domain methods or these methods are frequency domain methods and the several important methods I have listed here. So, you can see the first important method is known as Zero-crossing method, the second method is based on Phasor or DFT based, the third is the LES based, the fourth is the Kalman filter based, fifth is the Phase-lock loop based, and the sixth one that is the Adaptive notch filter based method.

So, all these six methods are used for estimation of frequency. Now, out of the six methods, we will consider the first method that is how zero-crossing method can be utilized for estimation of frequency. So, let us discuss the Zero-crossing method which is used for the estimation of frequency.

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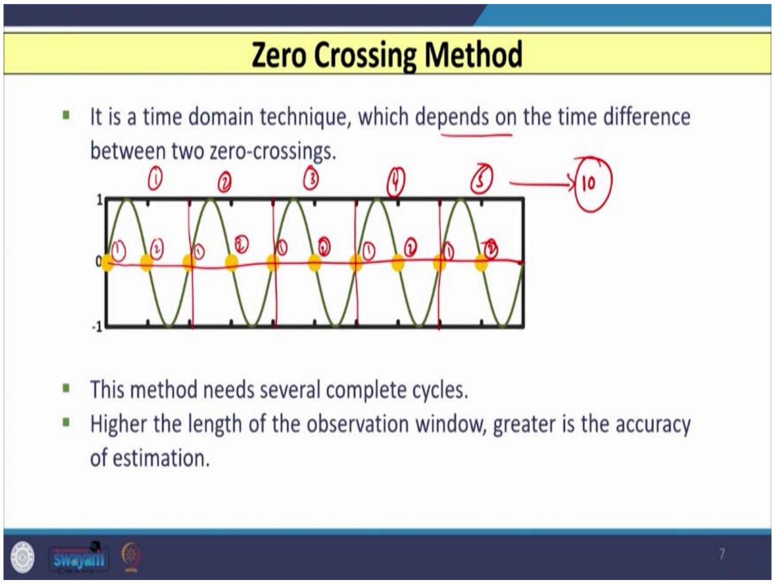

Now, if I consider the Zero-crossing method, then this is a time domain technique and this technique depends on the time difference between two Zero-crossings. So, you can see here I have shown one signal sinusoidal wave and you can see that if I draw this line on x axis then you see that different Zero-crossings I have highlighted let us say if I consider the one cycle, then this is the first Zero-crossing and this is the second Zero-crossing.

Similarly, when we go for next cycle say from here to here, then in this second cycle, this is your first Zero-crossing and this is the second Zero-crossing. And same way as you move from one cycle to the other cycle, then you will have the first end Zero-crossing for each and every cycle. So, if you consider let us say here we have consider five cycles right this is 1^{st} , 2^{nd}, 3^{rd}, 4^{th} and 5^{th} cycle. So, five cycles I have shown and for each cycle you can see there are two Zero-crossings. So, total 10 Zero-crossings are there in this file cycles.

Now, this method that is Zero-crossing method needs several complete cycles. So, as you can see here in the waveform, I have shown five cycles. So, this cycles are required. So, if we have only one cycle, then it would not be possible to estimate the frequency using Zero-crossing method. Higher the length of the observation window or higher the number of cycles available, we will have better accuracy of the estimation of frequency.

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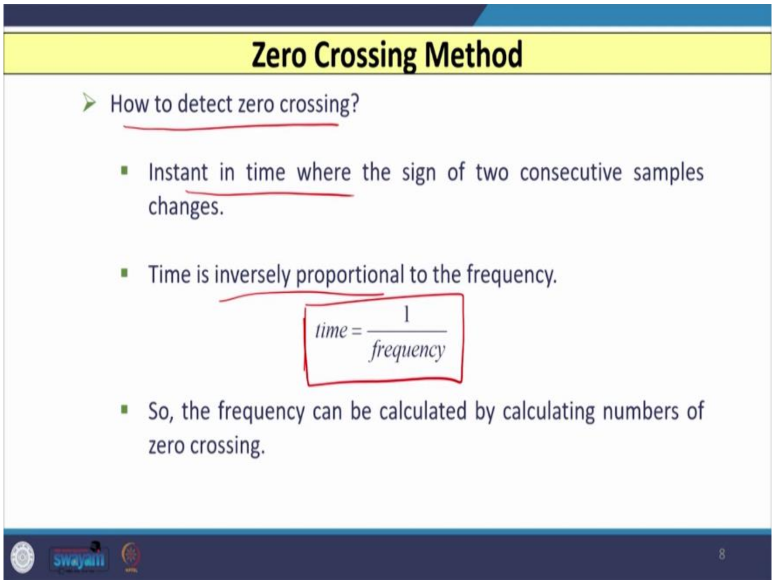

Now, let us see how to detect the frequency in Zero-crossing method. So, detection of Zero-crossing is extremely important when we talk about Zero-crossing method which is used for estimation of frequency. For detection of Zero-crossing, instant in time where the sign of two consecutive samples changes that is going to decide how we can detect the Zero-crossing and we already know that the $time = \frac{1}{frequency}$. So, this is very well known equation and hence frequency can be easily calculated by calculating the numbers of Zero-crossings.

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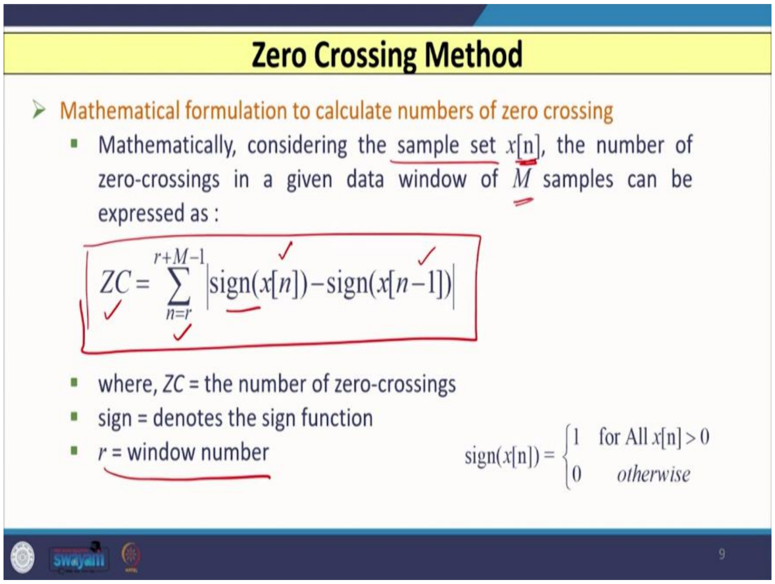

So, let us, see how mathematically we can represent the Zero-crossing method. So, when we use mathematical equation, let us say we consider a set of samples are available with us, that is of x[n], this are available and the number of Zero-crossings in a given data window of M samples that can be expressed by $ZC = \sum_{n=r}^{r+M-1} |\text{sign}(x[n]) - \text{sign}(x[n-1])|$ $\text{sign}(x[\text{n}]) = \begin{cases} 1 & \text{for All } x[\text{n}] > 0 \\ 0 & otherwise \end{cases}$

And in this equation on left hand side, we have the ZC which is known as the how many number of Zero-crossings are available in a particular signal.

The sign indicates the sign function which is going to give you the sign of any sample which you take and r indicates the window number. So, if you start with let us say first window that is by putting r=1, then you have to go up to the M number of samples that is available in a given signal.

Here $x[n]$ and $x[n-1]$are the samples which you are going to take from the set of samples available with you. So when the value of $x[n]$ are any sample which we consider that is ≤ 0, then we will have a 0 value of sign and when the whatever sample we consider if it is ≥ 0 or if its value is > 0, then output of sign we will get that is 1.

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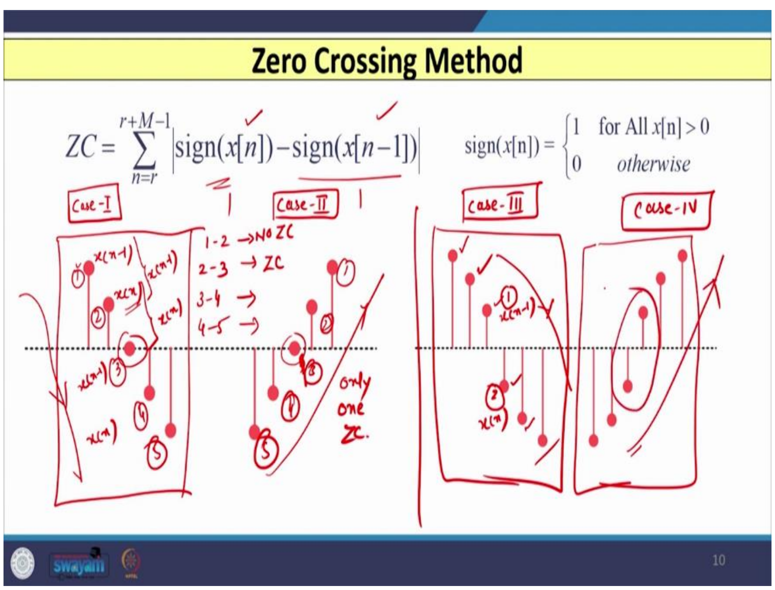

Now, with this, let us consider four different cases. So, here I consider the case number 1. So, in this case number 1 you can see, I have shown this samples for a particular signal. So, you can see that we have to consider two samples; one is $x[n]$ and another is its previous sample that is $x[n -$

1]. So, when you consider let us say this is your $x[n-1]$and this is your $x[n]$. Let us consider these two samples as shown in above slide.

Now, here in this case 1 you can see, I have also consider the samples at this point, 0 point where the 0 actually crosses. So, in this case, when you consider $x[n-1]$, then you can see $x[n-1]$as this is > 0. So, this value comes out to be 1 and $x[n]$ that is also > 0. So, this value also comes out to be 1. So, if you take difference of that and then mode than you will get this value that is again 0. So, there is no Zero-crossing when you consider these two samples.

Now, if you consider this two samples, let us say this is sample number 1, sample number 2, sample number 3, 4 and 5. So, when you can consider sample number 1 and 2, you will have 0 value there is no Zero-crossing, when you consider, let us say a sample number 2 and 3, then for 2 you will have $x[n-1]$, so, sample 2 becomes your $x[n-1]$, and sample 3 becomes your $x[n]$

So, here when you put the value of $x[n]$ that is already 0 and $x[n-1$,, that is again if you put this value which is positive, so, you will have 1. So, you will have 0 minus 1. So, again mod of 1 that is 1, so, you will have a Zero-crossing. Same way, when you consider sample number 3 and 4, then sample number 3 becomes your $x[n-1]$, and sample 4 becomes your $x[n]$. So, if you put this value $x[n-1]$, if you put that is 0 and $x[n]$that is again it is negative value, so, that is 0. So, you are not going to get 0 minus 0 that is 0.

When you take any sample from 3 to 4, 4 to 5 you are not going to get the Zero-crossing. So, this is one case now, this is when you move from positive to negative side from this side. If you move negative to positive considering that we are taking the samples at this instant also, there also if you just mark this number as same as this, let us say this is sample number 1, 2, 3, 4, 5.

And if you consider let us say sample number 5 and 4, both are negative, so, you know that when they are < 0, then you will have 0 value. So, for both four and five, if you put the value here you will get 0 so no Zero-crossing. Same way, you can move and calculate the value and you see that you will have only one Zero-crossing in this case also. So, only one Zero-crossing in this case also. So, this is your case number 2.

Now, if I consider the third case, let us say this is the case number 3 and this is case number 4 as shown in above slide. So, when you consider this side, this I have shown again from positive to negative this direction, but the only difference is we are not taking any this sample at 0 point. There is no sample in between. So, we have these two samples, let us say we have this is sample number 1, and this is sample number 2.

So here when you move from positive to negative, sample 1 is your $x[n-1]$, and sample 2 is your $x[n]$. So, you see $x[n-1]$, is positive. So, you will get one value here and $x[n]$is negative, so, you will get 0. So, 0 - 1, you will have again 1. So, you will have one Zero-crossing when you move from 1 to 2.

But, for any other samples like this two or these two or any other samples, you will not get the value of any Zero-crossing. Similarly, if you move if you take the another window, same window, but again from you are moving from negative to positive, then also for this two samples only, you will get the Zero-crossing.

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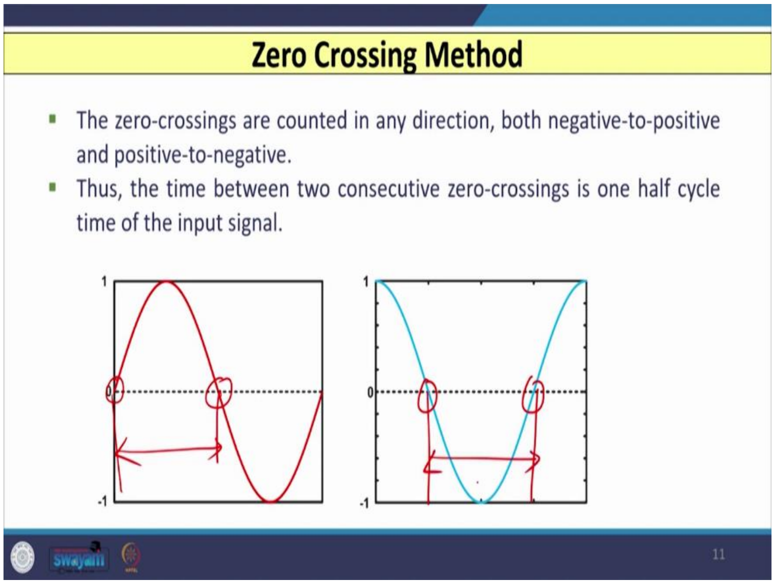

So, what we have considered and found that the Zero-crossings are counted in any direction, maybe you can move from positive to negative or you can move from negative to positive. So, all the four cases we have considered hence the time between two consecutive Zero-crossings. So, if I consider a sine wave as shown in above slide, then we will have this two Zero-crossings and if you consider this time, this time is one half cycle time of any input signal and if you consider the cosine waveas shown again in above slide you will have this two Zero-crossings and again you will have the one half cycle time.

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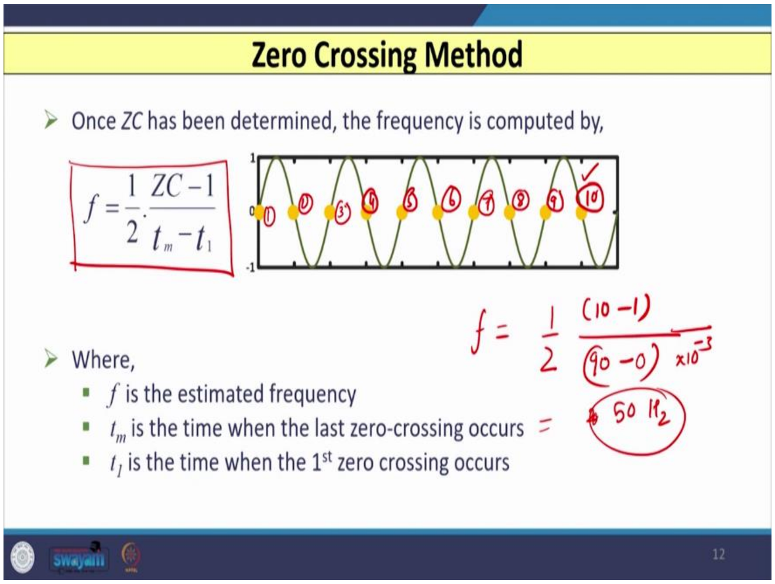

Now, let us see how to determine the frequency using Zero-crossing or ZC. Let us say if we have obtained the Zero-crossing maybe from by moving from positive to negative or maybe from negative to positive. Now, if we have Zero-crossing let us see how we can estimate or determine the frequency.

So, that can be obtained by equation:

$$f = \frac{1}{2}\frac{ZC-1}{t_m - t_1}$$

where f is nothing but the frequency which we wish to estimate that is equal to ½ ZC-1 where ZC is the Zero-crossing and t_m - t_1 where t_m is the time when the last Zero-crossing occurs and t_1 is the time when the first Zero-crossing occurs.

In this signal shown here, the number of Zero-crossings you can see, I marked it from 1 to let us say 7 8 9 and 10. So, as I told you 5 cycles are there, so, 10 Zero-crossings are possible. So, here if I calculate the frequency for this case, then it is one half. ZC number of Zero-crossings are 10 So, it is 10 - 1 divided by you have t_m that is the time when the last Zero-crossing occurs that is this time. So, it is 90 milliseconds minus you have the t_1, that is the time when the first Zero-crossing occurs.

So, this is 0 millisecond 10 20 30 40 50 60 70 80 and 90. So, it moves every half cycle you will have 10 millisecond. So, it is 90 minus the first one that is 0 and this is in milliseconds. So, you can convert it into seconds, if you solve this then you will have the frequency that is 50 Hz. So, you know that it is 10 - 1, so, 9/90. So, you will have 1/2 ×10 that is 20, So, 1/20 millisecond, so, we will have 50 Hz.

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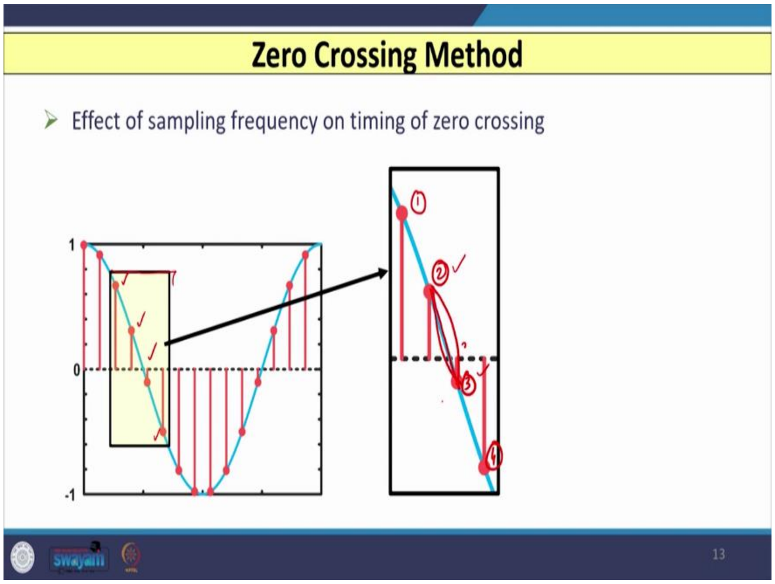

So, now, what we have considered is when we have let us say this signal we have considered and in this signal I have shown this window where you can see four samples I have shown. So, if I just zoom this, then you will have this four samples, which are shown in the zoomed graph.

Now, if you consider sample number 2 and sample number 3, it is really very important to find out what exact time Zero-crossing is going to occur, because you can join this graph like this, it may be like this or it may be like this (as shown in above slide).

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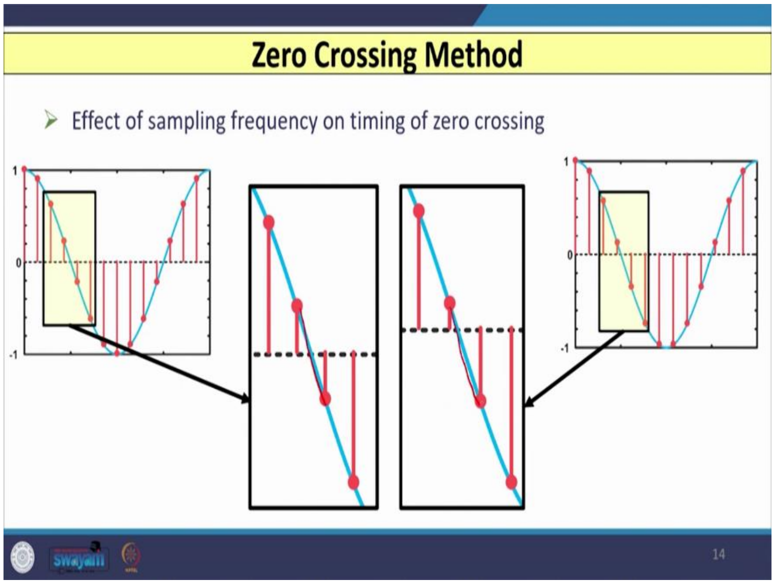

So, if I consider the other cases you can see. So, Zero-crossing that can be possible either directly linearly, maybe it may have like this (as shown in above slide).

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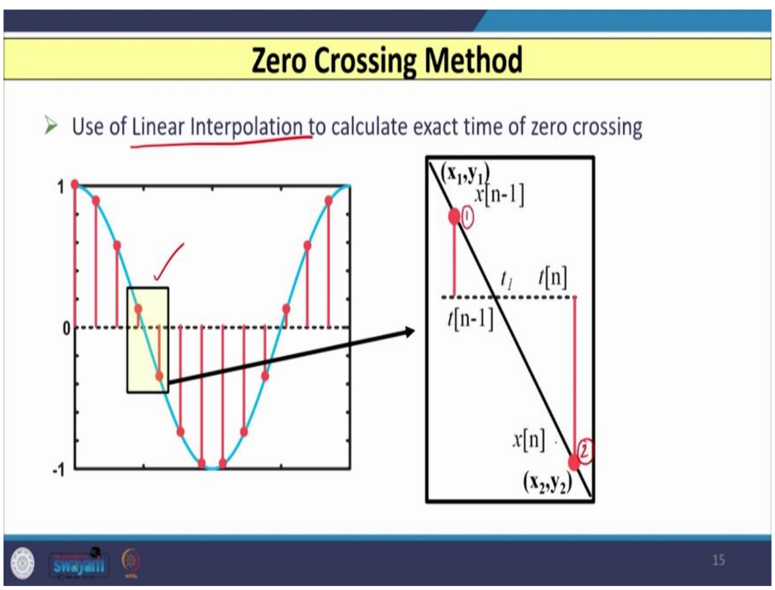

So, the exact timing of Zero-crossing that plays an important role and that we need to calculate. So, let us see how we can calculate this. So, this can be calculated using linear interpolation. Now, let us see how we can calculate this using linear interpolation. So, let us consider the signal, in this we have considered this window and that I have shown here. So, we have two important points, this is point number 1, and this is point number 2 (as shown in above slide).

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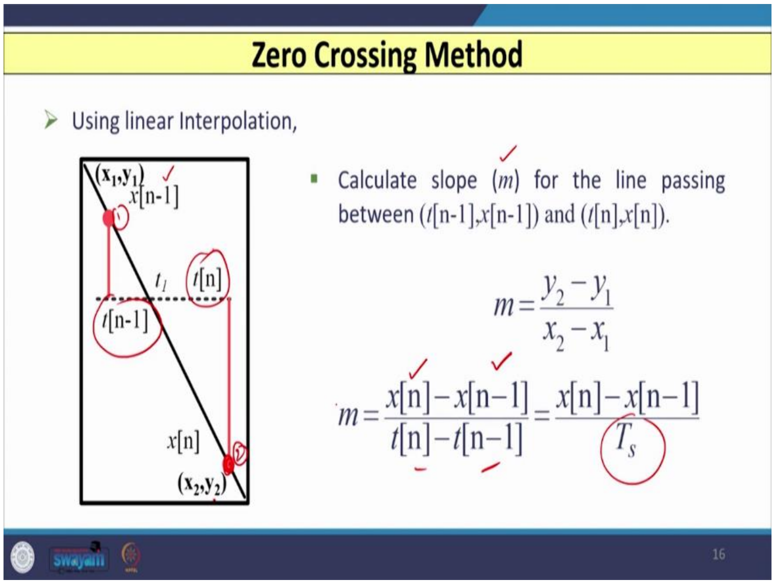

So, here you can see that if I calculate the slope, let us say slope is given by m for any line passing between these two samples 1 and 2, then this can be given by $m = \frac{y_2 - y_1}{x_2 - x_1}$ where x components that is x_1 and x_2 are the whatever coordinates are available on time axis x and y that is whatever you have the samples that is x[n] or x[n-1].

So, in this case, if I consider this two-sample number 1 and 2, then y_2, which is nothing but your x[n] for this sample 2, if you consider your value of sample is x[n], so, I put here minus y_1, so, y1 is nothing but x[n-1]. So, that is available here and x_2 minus x_1, so, you have x_2 that is t[n] and you have x_1 that is t[n-1]. So, you can put it here.

$$m = \frac{x[\mathrm{n}] - x[\mathrm{n}-1]}{t[\mathrm{n}] - t[\mathrm{n}-1]} = \frac{x[\mathrm{n}] - x[\mathrm{n}-1]}{T_s}$$

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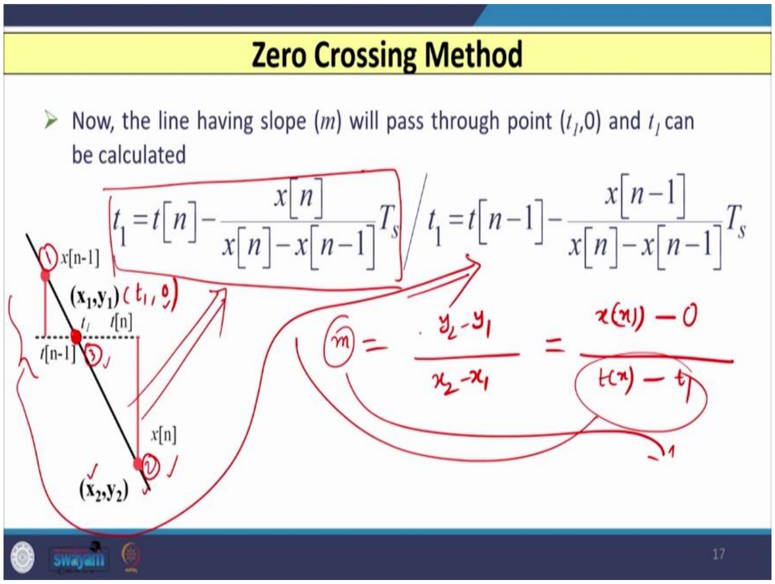

Now, what we have, we want to determine this point that is the exact timing of Zero-crossing. So, what we can do between these two samples, which we have considered 1 and 2, we can consider either sample number 1 and 3 because slope m is known or you can consider sample number 3 and 2 and then you can determine the exact time. Let us say for sample number 3 which is unknown, we have x_1 and y_1 points and let us say we are utilizing these 3 and 2 samples to calculate the value of this time, let us say this time which is unknown is given by t_1.

So, at this point sample number 3, x_1 y_1 is nothing but you can have y_1 is 0 and x_1 that is your t_1. So, this value is nothing but $t_1$and 0. And at sample number 2, x_2 and y_2 both are available, your x_2 is also available and at y_2 is also available, because here we have already determined that, what is x_2? x_2 is available here t of n and y_2 is also available, that is x[n]. So, this two we have already seen.

So, if you use these two, and then you can have the value of m for this, that is y_2 - y_1/by x_2 - x_1. So, you can see here the y_2 for this sample number two that is nothing but you have x[n]minus what you have that is y_1. So, what is y_1, this is x_1y_1, so, this is 0, because this point is 0 and divided by x_2 - x_1. So, you have now x_2 that is available that is this case.

So, what is the value of x_2 available here? You can see here when we consider this the value of x_2 available that is this t[n]. So, you can put this value here that is t[n]minus you have this time t_1

and you can take this equation here and m here and if you solve this, then you will have the value of t_1 that is given by this equation $\frac{t_1=t[n]-\frac{x[n]}{x[n]-x[n-1]}T_s}{t_1=t[n-1]-\frac{x[n-1]}{x[n]-x[n-1]}T_s}$

So, you will have finally the value of t_1. So, in this case, we have considered sample number 3 and sample number 2 and we obtained this equation. You may consider sample number 1 and sample number 3, these two and also you can solve this you can have the equation like this of t_1 and you can still you are able to calculate the value of t_1.

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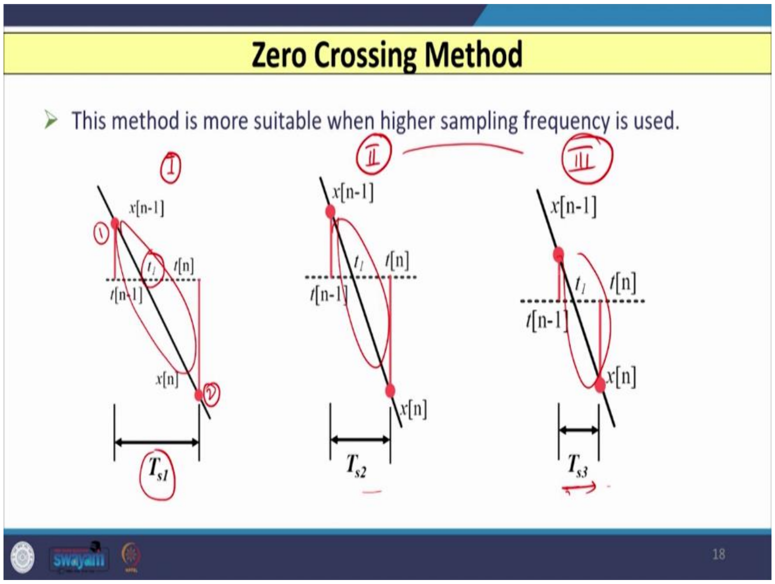

So, when we consider this two points, that is at sample number 1 and 2, one is positive another is negative to determine the value of t_1, then the sampling frequency plays an important role. Here in this case, case number one you can see that sampling frequency that is 1/Fs1 that is nothing but your time sampling time that is given by Ts1.

Now, if we increase the sampling frequency from case number 1 to case number 2, then you can see your sampling time Ts2 that is going to reduce and further, from case 2 case 3. If you still increase the sampling frequency your sampling time reduces and hence, you can see that this portion that becomes more linear and you will get the accurate answer result.

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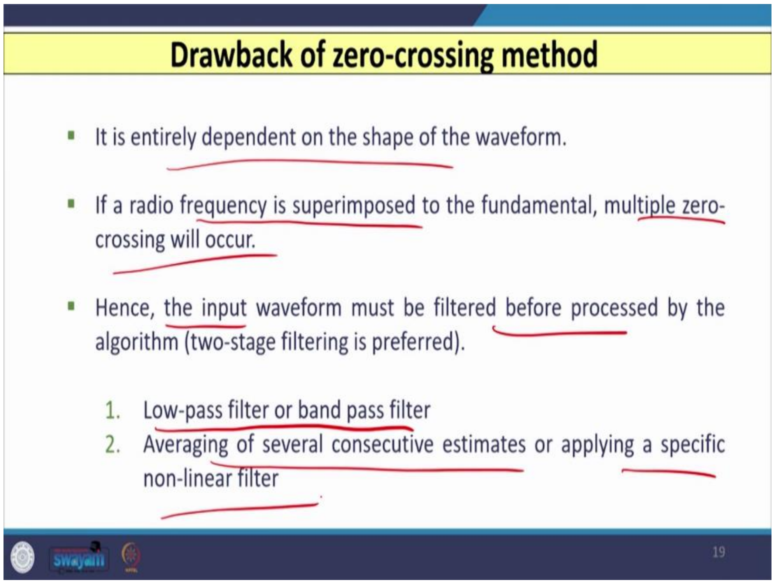

However, there are certain drawbacks of Zero-crossing based method for frequency estimation. The first is this method entirely depends on the wave shape of the whatever waveform we are going to acquire. If that wave shape contains the frequency other than the fundamental component, then you may have multiple Zero-crossing. For utilizing this method it would be really difficult to estimate the frequency or if you estimate it will give erroneous result.

Hence, the input waveform if I want to avoid this, then the solution is that the input waveform when we acquired it has to be filtered first and that can be done by using low pass filter we have already discussed the anti aliasing filter or you may have averaging of several consecutive estimates or you can apply a specific nonlinear filter which are available in the market.

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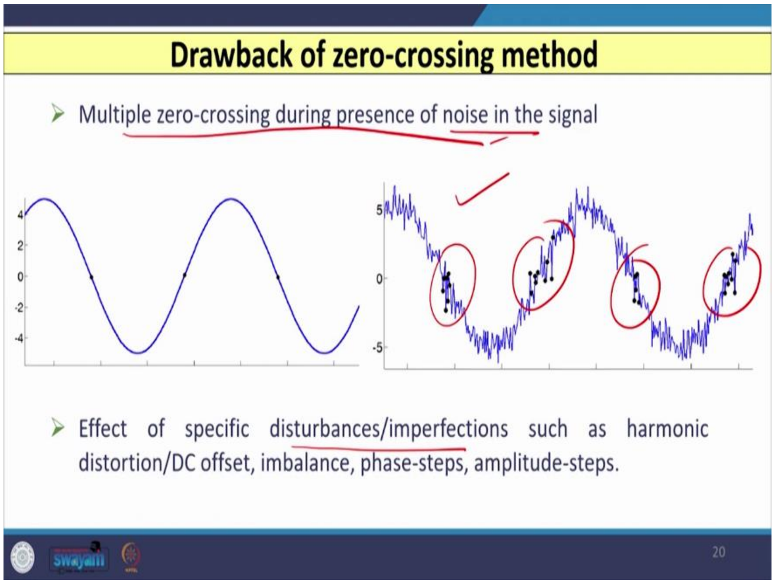

So, the first disadvantage of Zero-crossing base method for estimation of frequency is, multiple Zero-crossings can be identified if the acquired signal contains noise. So, you can see that in this signal noise that is present and you will find that at this point when you estimate the Zero-crossing multiple Zero-crossings that can be identified.

Further, as I told you earlier if the acquired signal contains harmonic components, maybe other than the fundamental or any distortion is present or any step value or amplitude steps are available in the acquired signal or if suddenly it happens, then this type of method is not suitable for such estimation of frequency. In that case, we have to use some other method.

So, in this class, what we have discussed is we started our discussion with the estimation of frequency, and then we have discussed that there are several methods available for estimation of frequency and then the first method that is Zero-crossing base method that we have discussed. And we have seen that as we increase the number of sampling frequency than the estimation of frequency using Zero-crossing based method that is more accurate because of reduction in sampling time and the portion between two samples that is going to become more linear. Thank you.