Power Quality Improvement Technique
Prof. Avik Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology, Roorkee

Lecture – 30
Shunt Active Power Filter – II

Welcome to our NPTEL lectures on the Power Quality Improvement technique. We are continuing with the Shunt Active Power Filter. That we are going to continue. We are discussing about the instantaneous reactive power theorem. So, this was our discussions aim. So, ultimately, we have discussed that the shunt active power filter should not feed any amount of reactive power and based on that this theory is developed in αβ frame.

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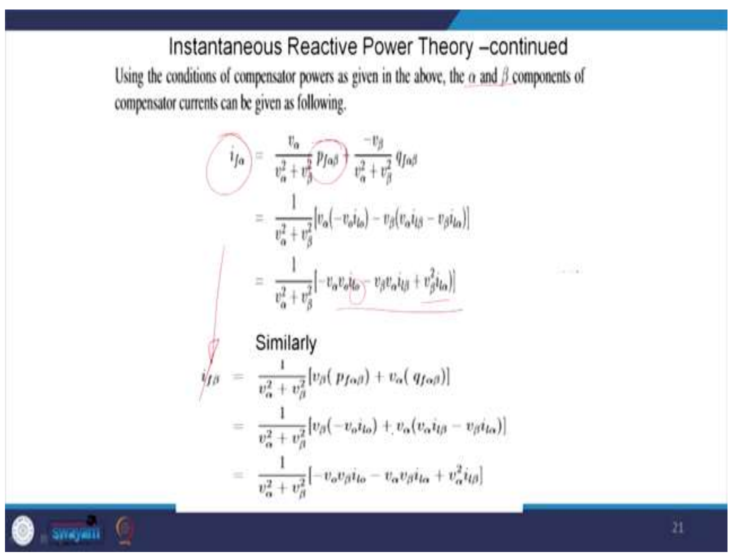

So, let us see that. Using the condition of the compensator power, given above in a previous slide. The αβ components of the compensator can be as follows. So, we can rewrite the value of the shunt active power filters α component and the β component that required to be injected by the shunt active power filter.

So, this v_α plus this denominator that is common and that is the determinant of it. So, v_α square plus v_β square into power of this αβ frame of this shunt active power filter and q_b. Similarly, if you can combine this equation essentially you get this expression. So, it is 1 by v_α square plus v_β square minus v_α v_0 i_{l0} that is the load component of the of this '0' sequence components. Similarly, it is the v_α v_β and $i_{l\beta}$ and similarly i_α.

Thus, this component also comes i_{fb}. So, 1 by v_α square plus v_β square equal to v_β $p_{\alpha\beta}$ plus v_α $q_{\alpha\beta}$ and 1 by v_α square plus v_β square equal to v_β minus v_0 i_{l0} plus v_α, v_α $i_{l\beta}$ minus v_β i_α. Similarly, you got an expression. You see that it is almost same. There is not much difference in it and this denominator is same, it is v_α square where as v_β square minus v_0 beta and i_l. Here since it is i_β, so this will come.

Similarly, this will be the cross component it is i_α i_β into here it is β so there will be α. Similarly, this one it is i_β square here it will the i_α into $i_{l\beta}$. So, there is a similarity and you can check that whether you are deriving the right equation or not. Fortunately, you have a multiple-choice question. But the student of this institute have been asked to derive these equations.

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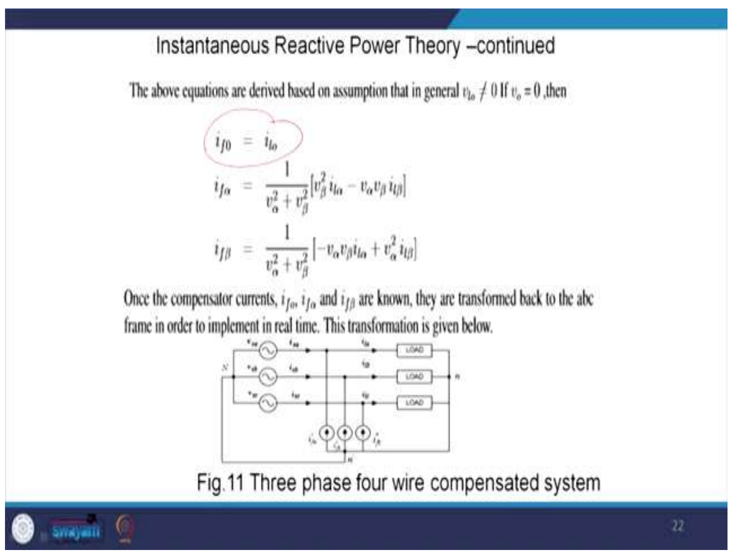

So, ultimately you know that if you connect the three phase three wire system this neutral current will flow through here. So, i_f will be i_{f0} will be essentially I_{l0} and $i_{f\alpha}$ will have this expression and similarly $i_{f\beta}$ will have just negative of it. It is β^2 i_α it will be minus αβ into $I_{l\alpha}$ and this term will come here, but with the β.

So, once this compensated, currents you can correctly compute by this block which is zero-sequence component i_α and i_β are known. They are transferred back again to the 'abc' frame in real time and this transformation is given in the next slide. So, this is the way we can do it.

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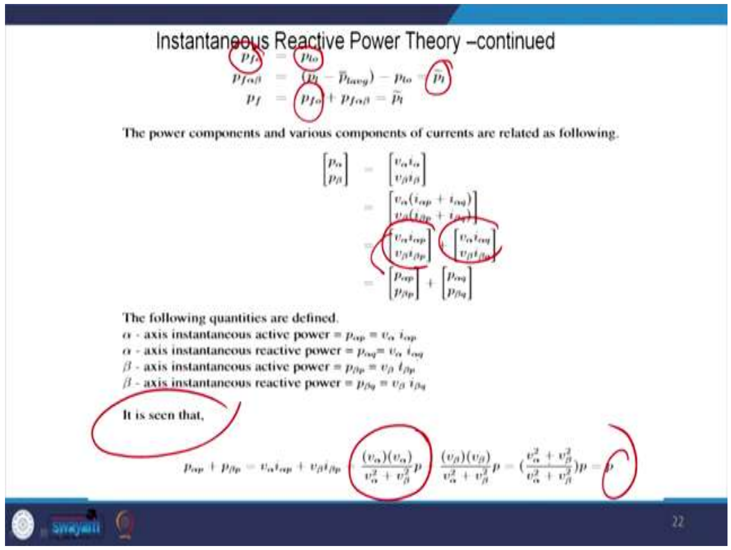

As we are discussing with the instantaneous reactive power theorem, please note that this zero-sequence powers supplied by this active power filter is p_{f0} and this is the load part of this zero-sequence component. Similarly, the active power component in αβ frame should be equal to the p_l minus p average and minus p average load and that should be the power component of this load. That is here represented by $\widetilde{p_l}$.

Similarly, the power of the power filter to be supplied is p_f that equal to the zero-sequence component, that is $p_{f0} + p_{f\alpha}$ and that value will be power $\widetilde{p_l}$. So, thus if you go for the matrix representation the power of component and the various component of the current can be related as follows. Here p_α p_β. We shall use the notation 'p' here, no 'q' will be used here.

So, we shall see that here the α axis instantaneous reactive power. We shall mention in nomenclature, that is $p_{\alpha q}$ that 'q' stands for the reactive power, but we are not and that will be given by v_α into $i_{\alpha q}$. Let us go to this point again p_α and p_β can be represent as v_α into i_α and the second term entity of the matrix will be v_β into i_β. Similarly, it can be expanded as from the previous slide that will be $v_\alpha(i_{\alpha p} + i_{\alpha q})$.

In second term entity of the matrix will be $v_\beta(i_{\beta p} + i_{\beta q})$and that can be split in this forms that is v_α into $i_{\alpha p}$. We go this column wise. Then it is v_{beta} into $i_{\beta p}$ plus v_α into $i_{\alpha q}$ and column wise again, v_β into $i_{\beta q}$. Thus, we can further expand you know this term essentially will be $p_{\alpha p}$ that is α axis real power and $p_{\beta p}$ 'β' axis real power.

Similarly, this multiplication that is cost terms v_α into $i_{\alpha q}$ that will be the $p_{\alpha q}$ and that will be the reactive power in the α axis and similarly it will be $p_{\beta q}$. This has been named here. So, this is the α axis instantaneous reactive power is $p_{\alpha p}$, that equal to v_α into $i_{\alpha p}$. 'α' axis instantaneously reactive power here we shall name it as $p_{\alpha q}$, that is v_α into $i_{\alpha q}$.

Similarly, β axis instantaneously reactive power, that is '$p_{\beta p}$' that will be 'v_β' into $i_{\beta p}$ and β axis instantaneous reactive powers, in this way it will be $p_{\beta q} = v_\beta i_{\beta q}$. Thus, you can expand it. This is a real power essentially $p_{\beta q} + p_{\alpha p} = v_\alpha i_{\alpha q} + v_\beta i_{\beta q}$ and, this terms will be coming from the this determinants, solving the determinants that is v_α into v_α and that is a determinant term v_α square plus v_β square into the total power plus this term β will be v_β into v_β and this determinant term v_α square plus v_β square into p. If you can combine that essentially gives raise to the value of p and this is determinant term we will get canceling numerator & denominator.

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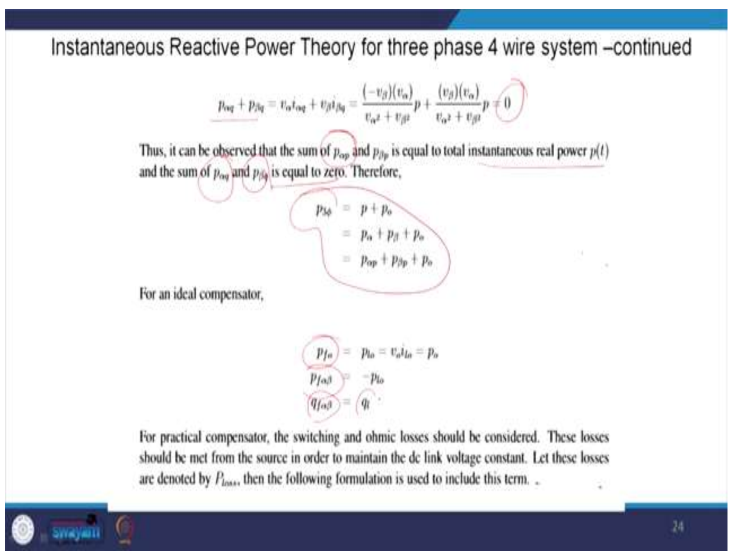

Then you know that for the three phase four wire system, that is what we are continued discussion. This should be '0'. It can be observed that the sum of the $p_{\alpha p}$ and sum of the '$p_{\beta p}$' equal to the instantaneous real power p(t) and the sum of the $p_{\alpha q}$ and $p_{\beta q}$ is equal to 0. Therefore, you can add up this thing and for the ideal compensator, this is the third harmonic component or the zero-sequence of p_{lf0} should be equal to p_0.

Similarly, $p_{f\alpha\beta} = -p_{lo}$ and $q_{f\alpha\beta} = q_l$will be essentially the reactive power, that will flow and come. In practical compensators switching harmonic losses has to be considered.

These losses should be met from the source in order to maintain the dc link constant voltage. Let this loss be denoted after this the P_{loss} and the following formulation to be use this term.

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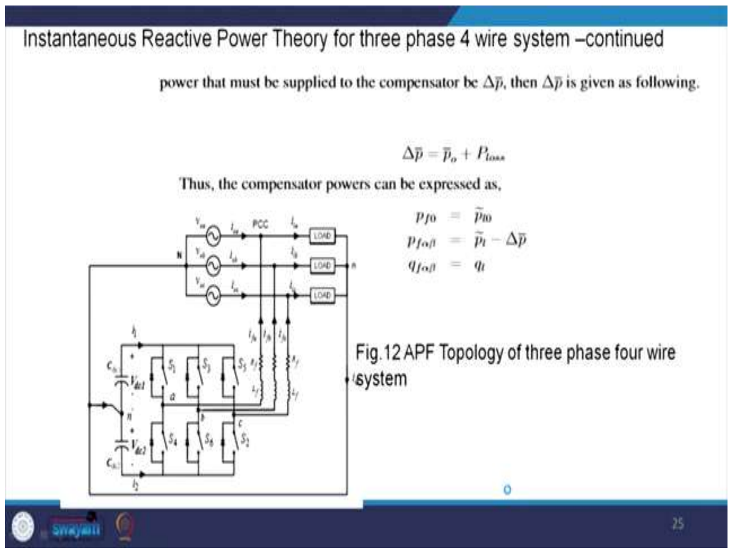

So, we can see that what is P_{loss}. So, ultimately you have the p_0 plus P_{loss} and $p_{f0} = \widetilde{p_{lo}}$ and $p_{f\alpha\beta} = \widetilde{p}_l - \Delta\bar{p}$ and $q_{f\alpha\beta} = p_l$ and this will be the active topology. Essentially this will be the flow of the zero-sequence component, if you do not have any fourth leg.

If you have a fourth leg then you can have the control of the fourth lag also by it. So, this is the way you will control. So, you have the i_{fa}, i_{fb}, i_{fc} and that you will be injecting from here.

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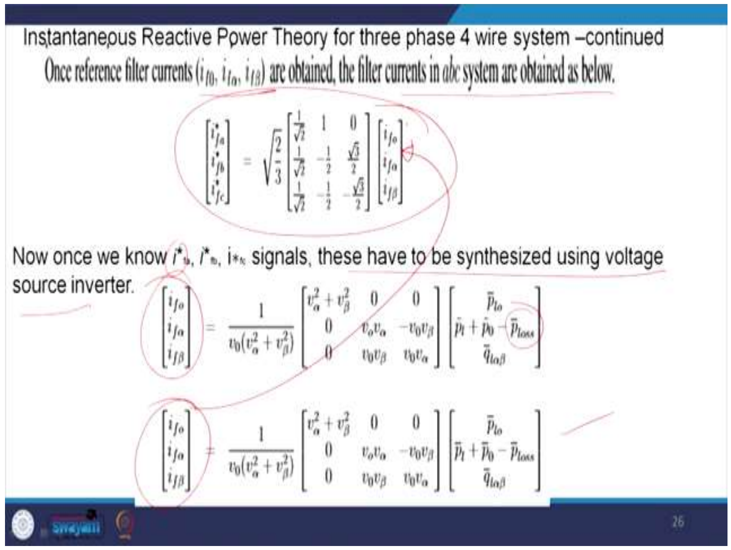

Once a reference currents this are been obtained, the filter current abc system is obtained, as below. As we have shown into the previous slide by the reverse transformation. So, you can have i_{fa} i_{fb}, i_{fc} equal to $\sqrt{\frac{2}{3}}$ of this matrix and, now we know that i_{fa}^*, i_{fb}^* and i_{fc}^* and they have to be synchronized with the voltage source.

So, thus what happens? You know these are the $\alpha\beta$ domain equations and you have to add the extra entity the P $i_{f\alpha}$, to meet the all losses and you will estimate the loss. From there you can have all those entities to be recalculated and refurbish. So, if you go back so now, you get this, from these calculations. From these calculations once you get this you go here and by this transformation you calculate i_{fa}, i_{fb} and i_{fc}. This is the way of calculating reference with the reactive power theory.

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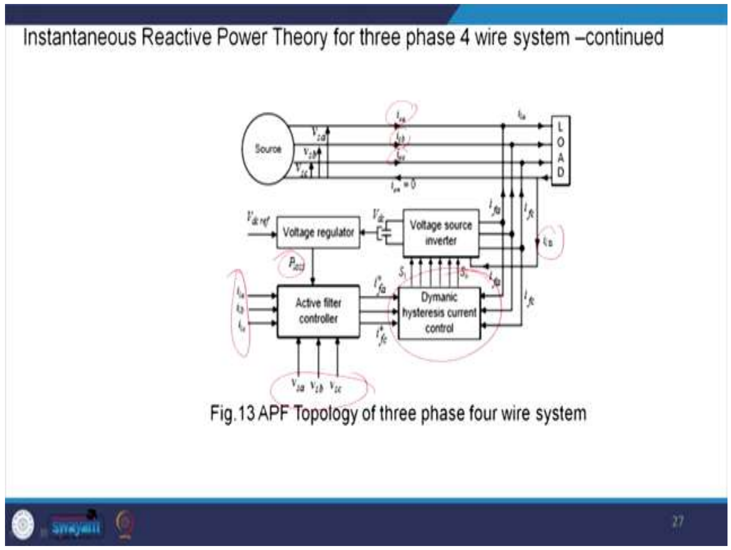

Fig.13 APF Topology of three phase four wire system

So, this is the source and ultimately is a 4-wire system this is the i_{sa}, i_{sb} and i_{sc} then this is zero-sequence component and from there you will be injecting i_{fa}, i_{fb} and i_{fc} and this is the neutral current. It will flow to the midpoint of the capacitors. There after midpoint of the capacitor. Thereafter, you can have a dynamic hysteresis control of the current or the PI control and from here you will have this values i_a, i_b and i_c of the load current.

Similarly, you have a source current and you have a voltage regulator. From there the component of the P_{loss} that will maintain the dc link voltage and these will add up. Essentially with all these calculations has been shown you get i_{fa}^*, i_{fb}^* and i_{fc}^* and you can have a hysteresis or the PI controller to compensate this current. This is a way the instantaneous reactive power theory proposed by Akagi will work.

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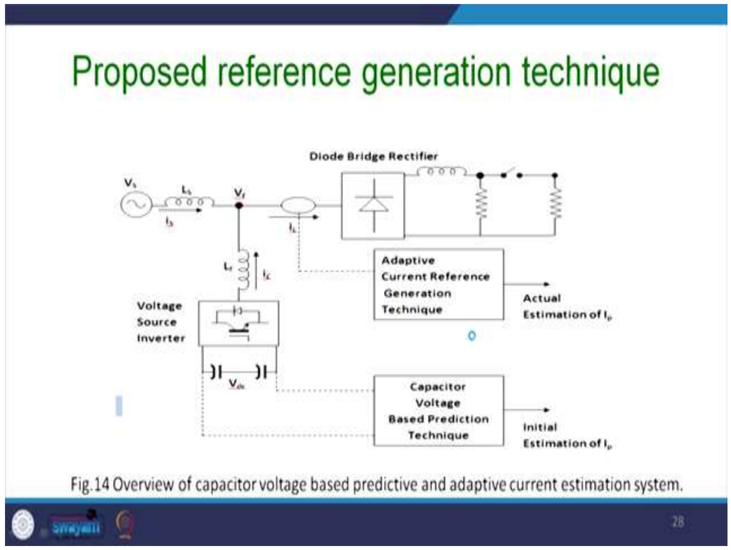

Fig.14 Overview of capacitor voltage based predictive and adaptive current estimation system.

Now, we will propose one reference generation technique as I told you. That will be the ANN based. There is another important method of the time domain is the SRF method.

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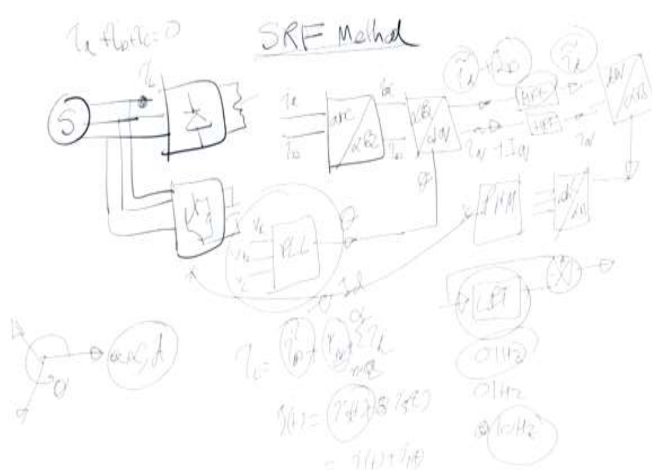

What happens there? You generally have this sinusoidal waveform. Thereafter a system. Thereafter, you have a diode bridge rectifier. Then what happens? You got a shunt active power filter and in SRF method this is derived from the vector control. You will be sensing again the load current i_L.

So, you have these two blocks. We have seen the αβ frame. So, you have i_a and i_b. You have i_a and i_b of course. Since it is a three phase three wire system you know that $i_a + i_b + i_c = 0$. So, you can generate the i_c or if you have a 4-wire system, then you required to sense another current. Since we have considered three phase 4-wire system I am considering here three phase three wire system. Essentially what you will do? You will first convert 'abc' to the αβ frame.

So, that is the Perk's transformation. You have then i_α and i_β. Then you required to get the information of the Θ, that comes from the PLL and you will sense at least 2 or 3 voltages, that is the v_a, v_b and v_c. This is the PLL block. PLL block essentially the phase lock loop block that will generate Θ. I have taken a separate class on PLL. So, you are requested to refer this thing. So, Θ will be there and essentially your αβ component will come into the 'dq' component.

If you take three phase 4 wire system then 'dq0' will come. I am taking a three phase three wire system then 'dq' component will come in the concept of three phase. What happens? What you did? This is your phase 'a' and you aligned α with that. Same way you aligned 'd' with that. Initial angle between these two is '0' and you rotate with the synchronize frame and thus you get Θ. Essentially you get i_d and i_q.

Once you get i_d and i_q see that. What happens? You know that harmonic content of i_l is i. I assume that this dc component is not there, because it comes from the quantization error mainly. So, i_q plus you have a harmonic. Generally, the harmonic is '2' to infinity. If I write it, it does not matter, but it will be you know that i_h, essentially it is third harmonic, fifth harmonic and so on. Third harmonic will not be there because you do not have a neutral. So, it will start from fifth, seventh and so on.

So, what happens? I can say. Then the original load current is i_p in 'dq' frame will come as an average value I_d. i_q part in i_d will be '0' and these harmonics will come as the $\widetilde{i_d}$ and I can write I_D. That is corresponds to the in-phase component of the voltage with the current and similarly, you can have $\widetilde{i_q} + I_q$. That is essentially $\overline{i_q}$or the average will be this value, where it is constant. So, what happens there? Thereafter what we generally do? We pass it to the high pass filter. High pass filter is realized by generally by subtracting with the low pass filter.

So, essentially you get the $\widetilde{\iota_d}$. If you want that typical harmonic compensation but not the reactive compensation. You have the reacting compensation with the capacitor and all. So, then rating will be lower and assume that this is the case for it then you have the $\widetilde{\iota_q}$. This $\widetilde{\iota_d}$ and $\widetilde{\iota_q}$ again reconverted into first dq to the αβ frame, then αβ to again 'abc' frame and then it will be fed to the PWM and this point will go to this point.

So, this is the way SRF model will work. For sake of time I do not want to go for the detail discussion of the SRF model and it has a many variant. Like if it is unbalanced then what happens? Then we have to add a negative sequence of it. Then we have to generate another sequence ϴ and $-$ϴ. So, then the PLL has to perform differently. Since the 'd' is something that rotating in a synchronies frame once you have a positive and negative sequence, positive sequence will look likes stationery.

But negative sequence will be rotating at a speed of the 50 Hertz opposite to you. It will appear to the double frequency harmonic. So, those are few challenges and then PLL is been challenged to get that real actual value in that case. Any way these are the complex problem with the SRF system.

Now we shall take out one example with this ANN and here the concept of this SRF will be combined. Ultimately how accurate you generate this? Ultimately h_f is split with this high pass filter, low pass filter and it is been subtracted here.

So, this the constitution of the high pass filter. What happens here? How accurately you set this? Because it is a dc value. You can set the cutoff frequency of 0.1 Hertz, you can set the cutoff frequency of 1 Hertz. You can set the cutoff frequency of the 10 Hertz and so on. So, more less this cutoff frequency you set more accurate and that will be the value of the delta. But there will be a delay in calculation because this low pass filter required a time for the settling, and ultimately, we required to optimize.

We can train this optimization and use this ANN. So, that is one of the works of the ANN, I am going to present in your case. For this reason, initially we have talked about the direct method and I told you that it is not quite accurate. But it can be used as an initial guess. So, for this reason this capacitor-based algorithm goes for predicting the initial value of i_p as it has been done in case of the direct method. But direct method cannot bring the value of the THD quite satisfactory low, because everything you put it on this filter.

There will be a tuning that will be done by the adoptive filter to give you the accurate results. This is a predictive adoptive combination of the ANN that gives you the better results. I can show you this result of the simulation as well as hardware.

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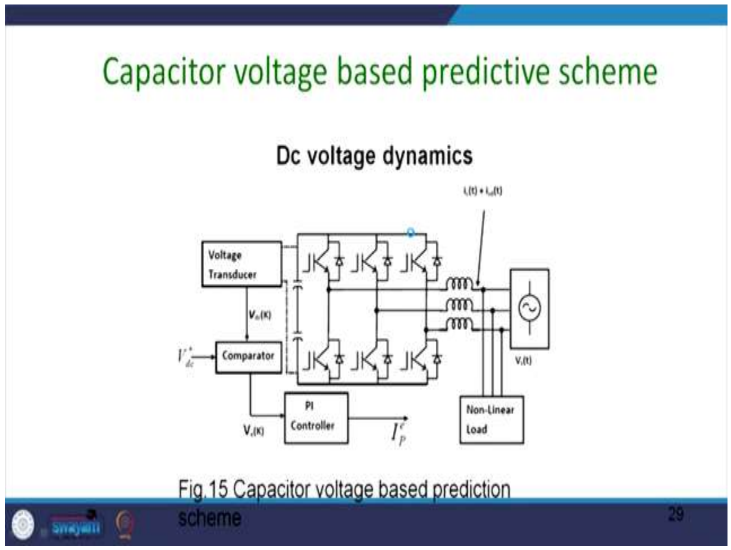

For you to understand this phenomenon, we required to understand in detail about the dc bus dynamics. So, we will be discussing now the dc volt dynamics in detail. This is the voltage transducers from there you got a compensator and thereafter since we work in a digital domain everything is in digital. So, you got a predictive value of Ip.

Of course, once these sags come in the capacitor voltage because of the increase in the load then Ip will estimate the value of the Ip. So, you got $i_c + i_{sd}$ that will flow and maintain the current and from there you try to guess the initial value of the Ip. That is quite important, because if you get a very closer value of Ip then convergence of it will be faster. Hence the ANN will be faster and ultimately you know that $P_w = P_{dc} = C_{dc} v_{dc} \frac{dv_{dc}}{dt}$.

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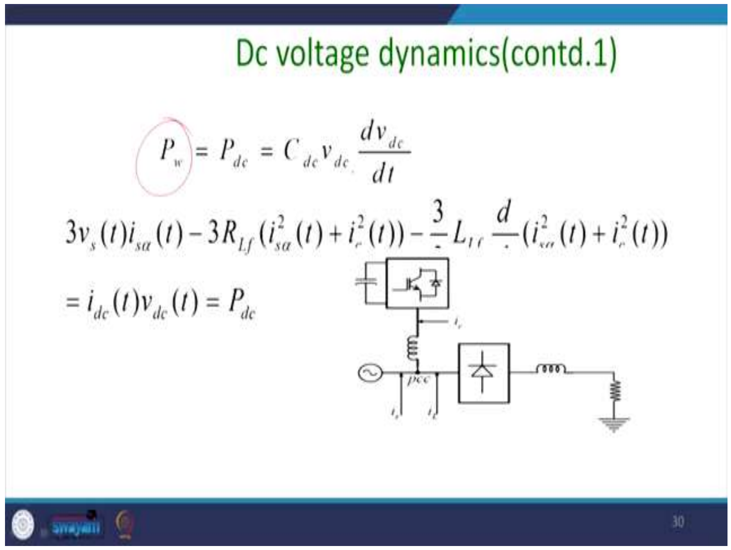

So, this is the value of i_c and that current will sink to the capacitor into i_{dc} and this is the part in a α frame. So, if you write in a three phase, that is basically i_α and i_β and essentially this value is going to give you the value of the P_{dc}. That is the power consumed by the capacitor. So, from that you can understand what is mentioned as a P_{loss} here. it is P_{dc} that we want.

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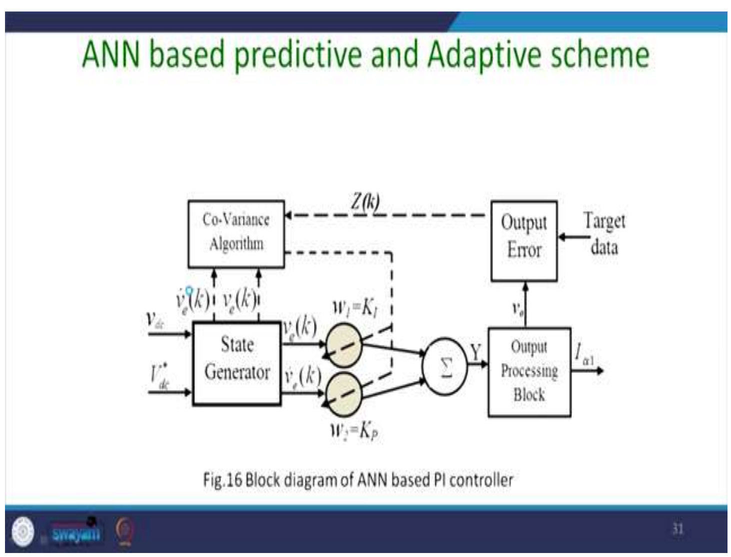

This is a tuning of it. Essentially, we tune the weights of the ANN and this weight is going to be essentially equal to the value of the i_p and i_q. How close you can match it? You have the target data and the error data. You have a covariance algorithm here that have been used. You can use any other algorithm back propagation algorithm or other. You have v_{dc} and I_{dc} and you tune it and you get the value of the I_α and it has to be turned offline and once it is tuned offline it will predict quite easily and satisfactorily.

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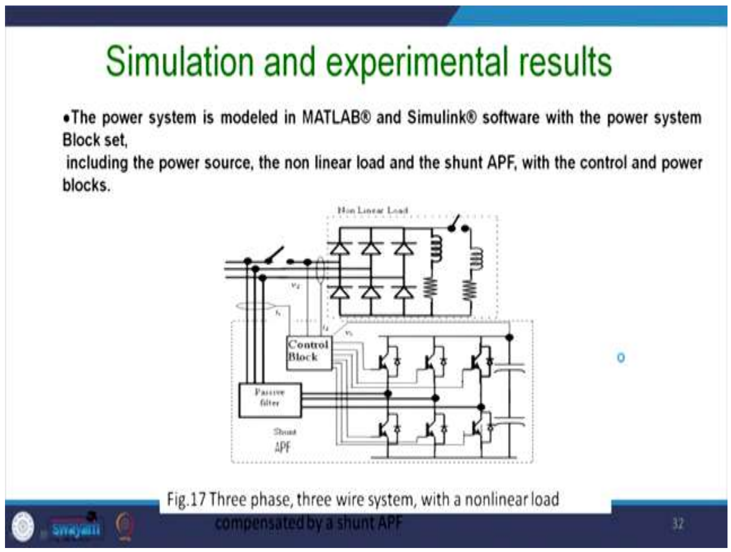

Now let us come to the solution and some experimental results. I am showing simulation and experimental results. It has been done with the MATLAB, Simulink and for sake of showing it, I put simulations and experimental data one by one. This is for the three phase three wire system and I have shown the same circuit here so that you can create single phasing.

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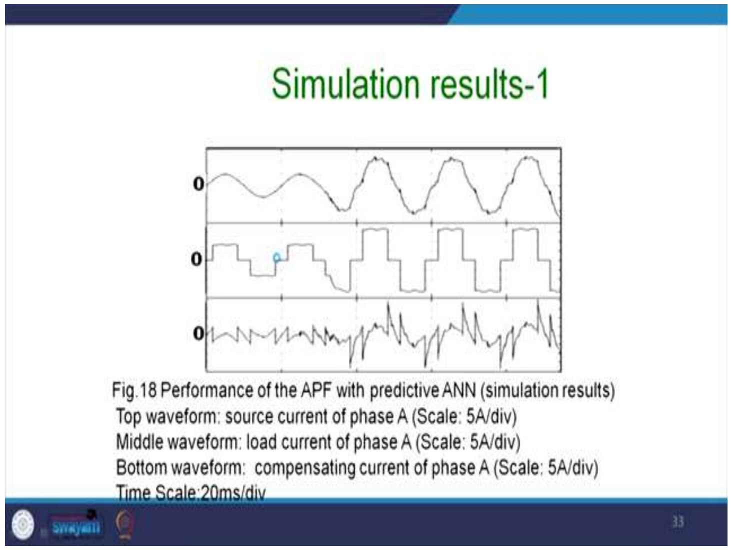

This is the case of the simulation and the performance of the active power filter with predictive algorithm. So, you do not have to tune it further for the adoptive algorithm and you got this kind of a waveform. It was quite sinusoidal. Thereafter even if it gives you this value of the compensating current, still it cannot maintain the desired level of the THD.

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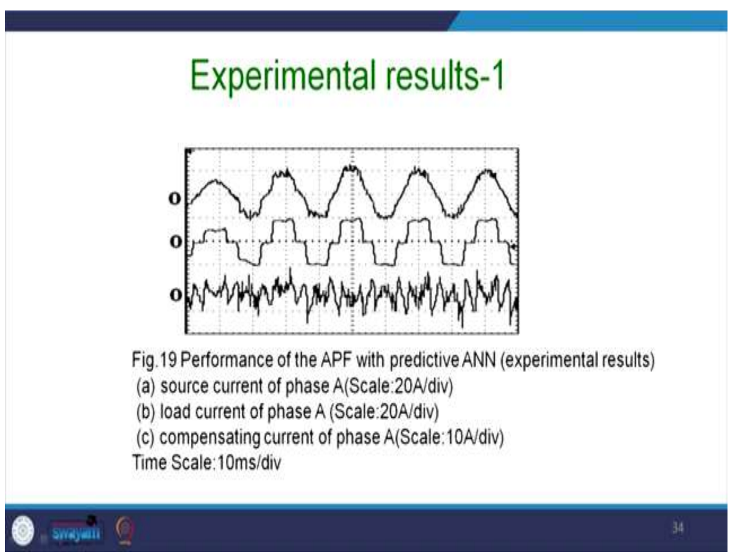

This is the same waveform, with the experimental results that you will get with the ANN based predictive method and also you can expect almost same kind of data with the active method. For this reason we required to have a tuning.

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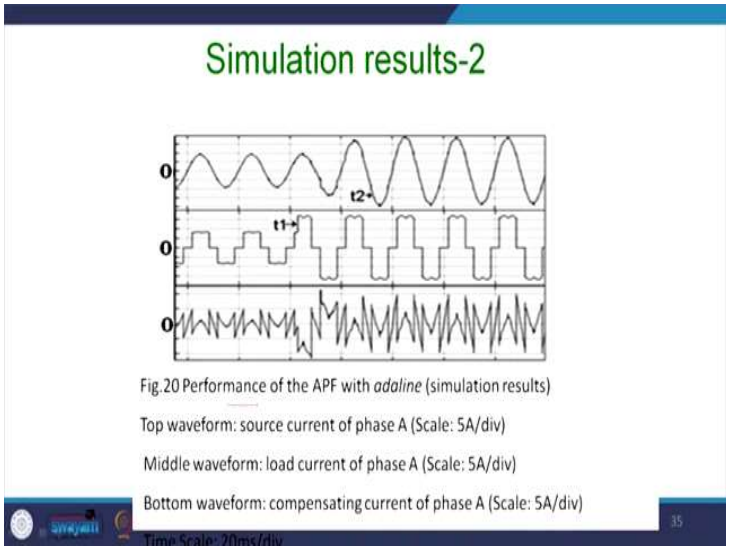

This is the case of the simulations. Where performance of the APF with Adaline. What happened? You can see that load change has been detected. It takes this much of time to run because it takes the data and will tune online. Ultimately this matches the values of the in-phase component of the power ‘p’ and ‘q’. This double checks it and gradually makes this voltage and current sinusoidal.

This is the top waveform is a source current. Middle waveform is the load current and the bottom waveform is the compensating current and the scale has been taken as 20 millisecond per division.

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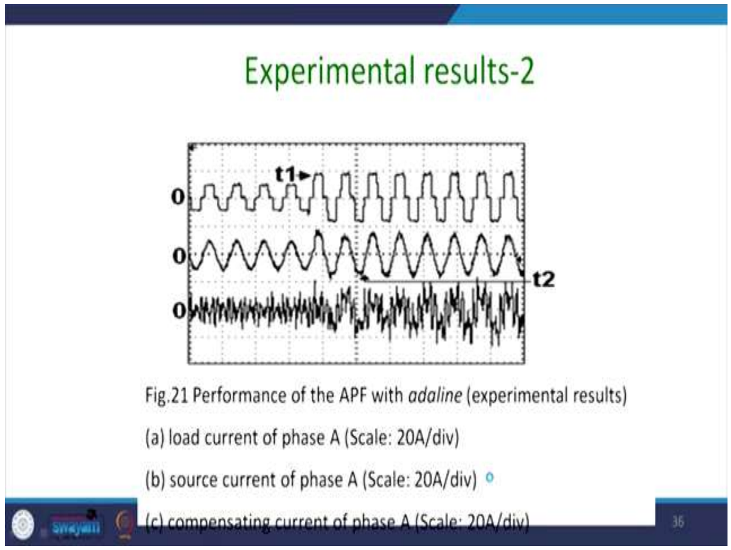

Similarly, this is the corresponding current. This is a load current and still you can see that it is not sinusoidal. After this, this interval of time t_2, it is sinusoidal. So, here both these algorithms are working.

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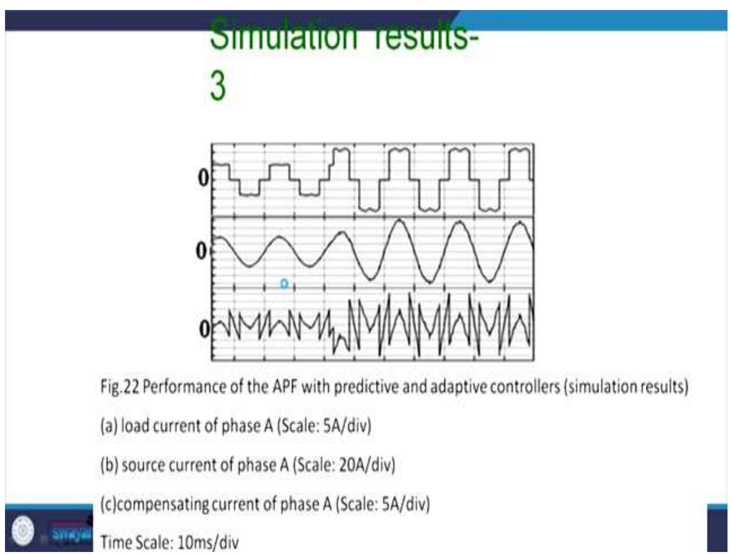

This is the performance of this adaptive and predictive controller both are working together and thus you can expect faster action. Performance of the predictive and algorithm controller as thus you can see that there is a load changes occurred so, it almost within a one cycle. This has reached the steady state value. Why it is better? Here it works. It does not have any guess. how much will be the starting point of it? It takes huge amount of time for the convergence

But here since you are fed with the predictive algorithm you can guess a closer value. You can always converge faster without much loading because once you have tuned, it will predict. So, prediction is easier. Amount of the voltage and sags and all those criteria, amount of the load these are the data. So, it will predict the value of the Ip and after that you required to tune it and it will converge very fast and you can see that within a one cycle it can simulate.

But if you do the same thing that I have done in SRF technique, it is equivalent to setting the cutoff frequency of 1 Hertz. If you set the cutoff frequency of one hertz then we have seen that we required at least four cycle to get the desire THD. Whereas you are getting this THD within one cycle. So, this is the advantage and thus people now going for it because of the higher processor rate and all those things. We are talking about the ANN base system. So, same SRF base system is been reproduce by the ANN and you can see the benefit of it and you can compensate quite fast and accurate.

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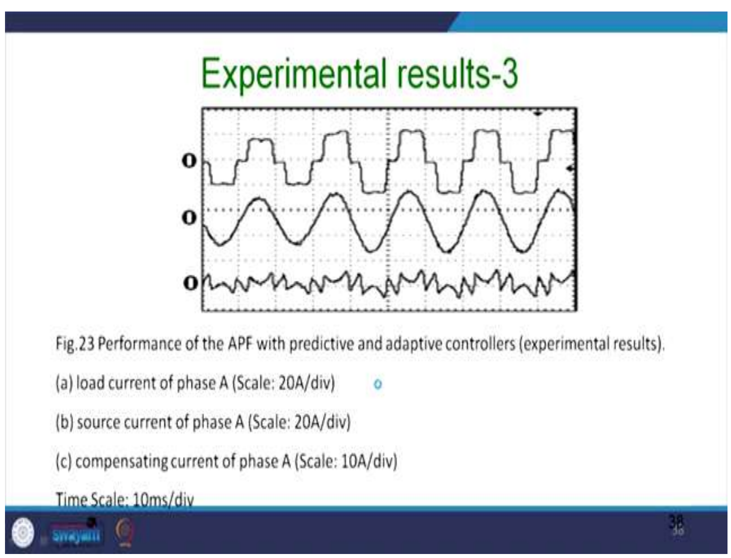

So, this is a corresponding hardware result of this. This is the load current. This is the source current where the load change has occurred and from this point to this point there is a load change. So, it has compensated. You can see these two peaks are almost same. That means by the time it has been converged. That is what the harmonic spectrums are.

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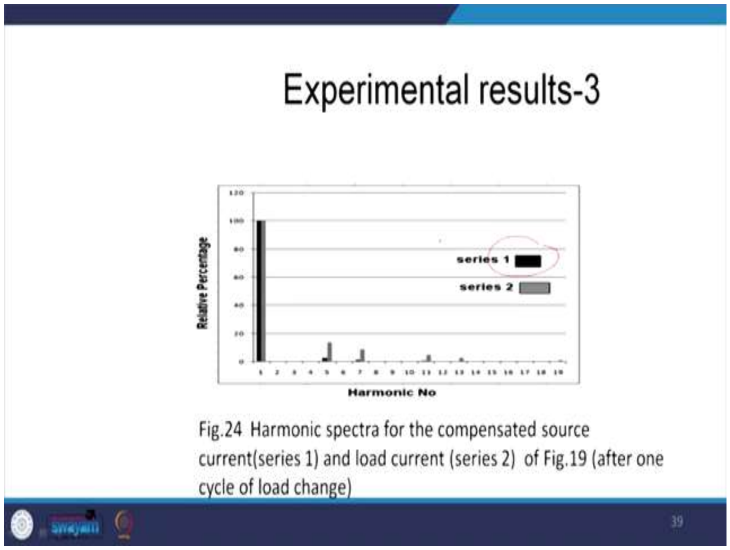

So, you can see that harmonic spectrum. that black one is your compensating current and the gray one is your uncompensated load current. You can see that black one is hundred percent thereafter this one is fifth harmonic, this one is seventh harmonic, this one is eleventh harmonic and so on. This is the harmonic spectrum of the load current after and before compensation. Thank you for your attention I have covered different generation technique in our discussions.

In next class I shall take on the control aspect of the shunt active power filter. That is essentially a very interesting aspect and you are requested to revisit the control system again. Students are requested to brush up their basic state space modeling and all those issues. So, they can understand it better. Thank you so much indeed for your attention. We shall continue shunt active power discussion in our next class.