Power Quality Improvement Technique
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Lecture – 29
Shunt Active Power Filters

Welcome to our NPTEL lectures on the Power Quality Improvement Technique. Today, we are going to discuss Shunt Active Power Filter. Shunt active power filter, we shall continue to cover within 2-3 lectures.

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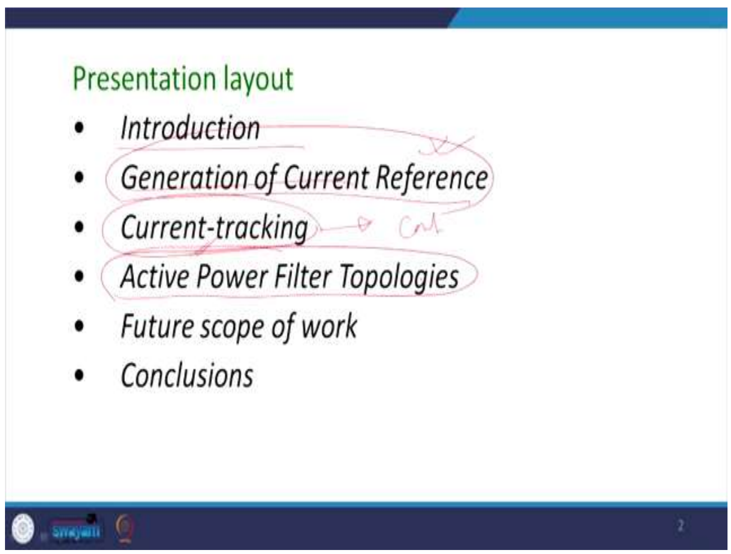

So, our presentation layout will be the general introduction. Thereafter different reference generation technique in time domain and frequency domain and thereafter, we have to discuss about the current tracking. Once you generate the reference we require to track the reference and for this reason we require to have a current tracking algorithm and that will be covered in detail and there we will introduce some kind of non-linear control on it as an example to mitigate the problem and different case studies.

Thereafter, active power filter topologies. That is also something very interesting and challenging. Generally, this active power filter gives a scope to work for the many people in the many background. Those who are from the power system background generally, they are familiar with different kind of optimization technique and due to the advancement of the different kind of heuristic optimal technique.

So, they generally prefer to the generation of this current reference generation technique. What we have discussed, we will be discussing also in the UPQC. Same kind of reference technique can be associated. But there is a difference between the UPQC and the shunt active power filter. Thereafter the current tracking and thereafter the current tracking. The persons from the control background approaching the power quality problem try to find the solution on the shunt active power filter. They mostly contribute on the current tracking. Different kind of modern control technique can be applied here to track the current reference once the reference has been generated quite accurately

Thereafter the power quality engineers come into the pictures and who are supposed to investigate and maybe reproduce the new topologies for the shunt active power filter for better redundancy of operation reliability and also the overall cost reduction of the system and though this work was reported by Akagi in 1984. Many of you have not born then maybe. So, still it is left with any future scope.

We will see that. Because there we can integrate. How the shunt active power filter can be do the multi activity with the integration of the different renewable energy sources? That is a present (I should not say future) scope of work rather present extension of the work and with the conclusion. So, this will be our layout and we will be covering within may be two three classes or more. Ok.

So, we know that for the detailed understanding of the passive filter we require to know that there are limitations of the passive filter. We are not going to reiterate this discussion again here for the lack of time.

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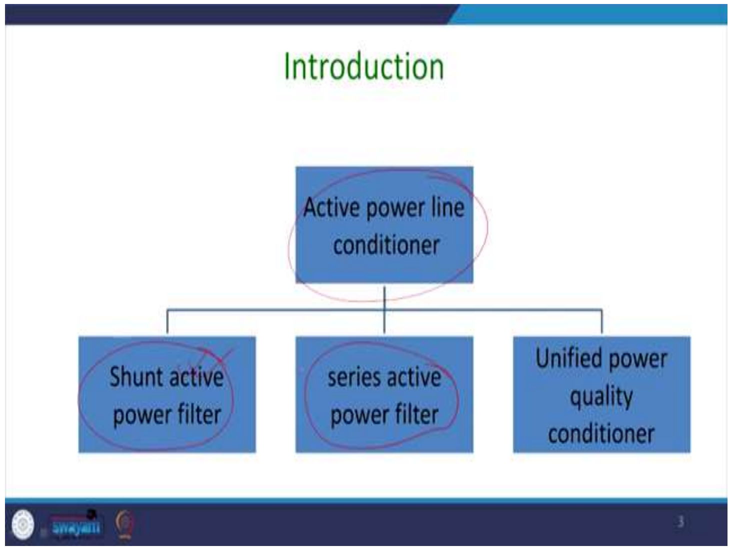

You know the demerits of the passive filters due to that we require to investigate on the active filters and from that we can be come into the heading of active power line conditioner. Thereafter can have a shunt active power filter. We are going to cover that and generally inject the voltage in shunt. We will see the topology in next slide and thereafter series active power filter. It will inject the voltage in series and thus compensate voltage sag or swell and other problem related to the voltage issues. Solution to all that can be provided the by unified power quality conditioner. That is called UPQC or UPFC.

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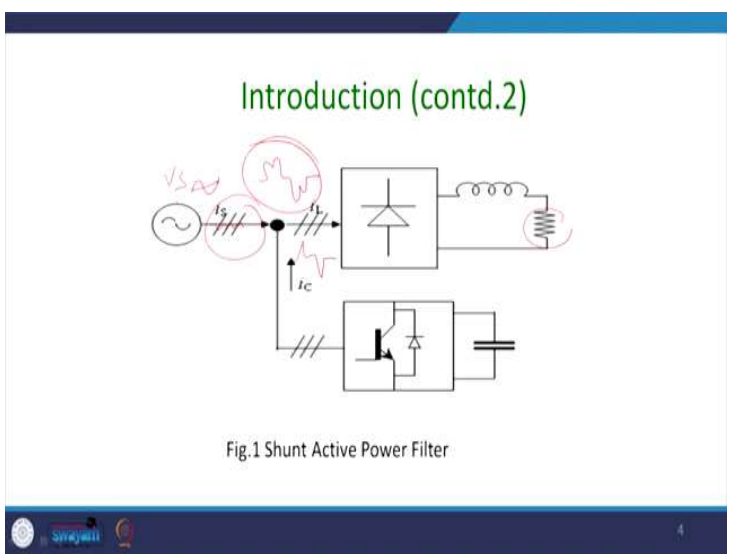

So, this is the topology of the one line diagram of the shunt active power filter. You have a source V_S and thereafter mostly you have a small inductance. This is the source inductance and that can be the leakage inductance of the transformer. Once you pass through a non-linear load, current profile will be this and ultimately you have to inject the current in such a way so that load sees as if a resistive load is connected to it.

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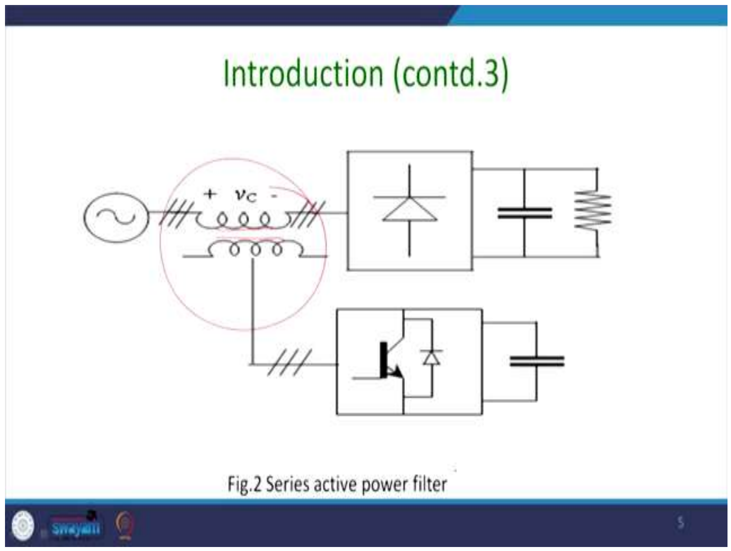

Fig.2 Series active power filter

Another can be your shunt series active power filter where you inject the current. Thereafter what happened? You get the voltage sag or swell. It will be unique, injecting voltage in phase. This aspect, we have covered in the series portion of the UPQC in detail and thus our lecture will be concentrating mainly on the shunt, but as the topology concerns.

So, you can also clear the harmonics, sags and swells by the series injection. One of the advantages is that it does not see the difference of the voltages between the actual voltage and the reference voltage. Thus, power retaining of this device is quite less and if you integrate both this entity, then it became a power quality conditioner or UPQC, unified power quality conditioner.

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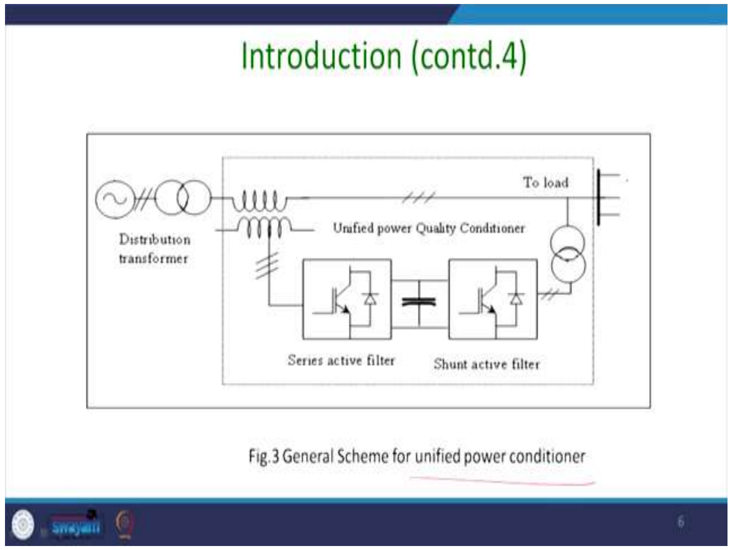

So, this we have discussed in detail in a separate lectures. In last 3 or 4 lectures has been dedicated to it. So, I am not discussing here.

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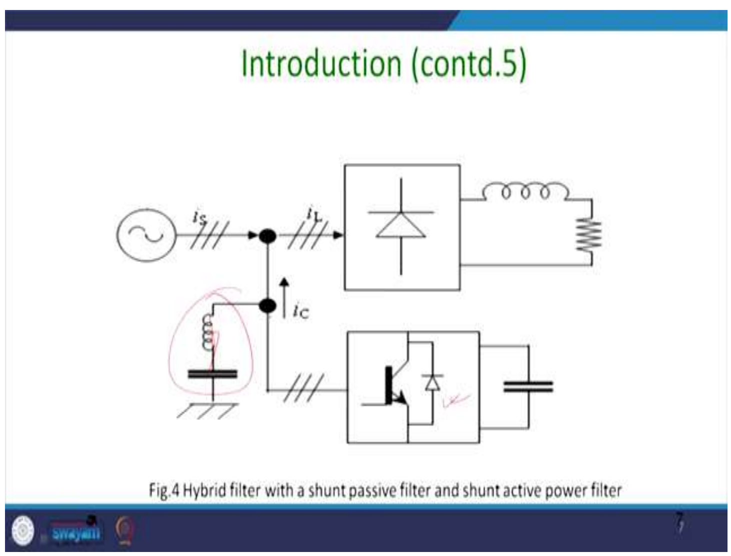

Let us come to another version of it that require a little more discussion. That is called hybrid topology. So, it can have a shunt active power filter and the switches and we can have a hybrid power topology. So, ultimately shunt active power filter may compensate the higher order harmonic, because you can tune to fifth and seventh that can sync from here.

Higher order harmonic, if you try to concentrate then the rating of this devices will be less. Depending on the way of position or placing the passive filter and active filter and which one will concentrate on which harmonic, you can reduce the total harmonic content of the system and it can give you an optimized solution of this total system. Then that is one of the working area and this kind of system with the passive and active power filter said to be the hybrid shunt active filter.

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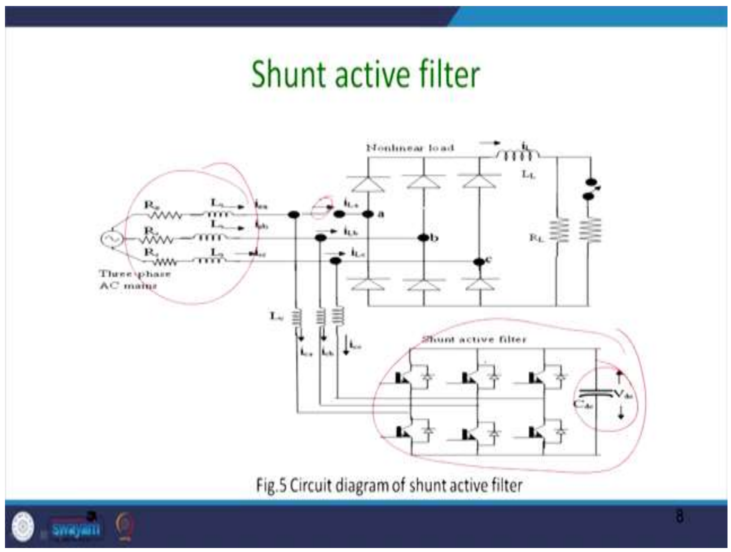

So, this is the total circuit diagram of the shunt active power filter here. You have a source inductance and resistance and you got a non-linear load and you may cut it down. Then it will have a single phasing and you may have a load changing operation and you have a shunt active power filter and generally this capacitor voltage require to be maintained by a maintained actively by a PI controller. Now, there is a two kind of algorithm. One is the all the reference generation technique. We will discuss later that is referred to the indirect method and we can also have a direct method that we would not discuss, because this has some limitation to it.

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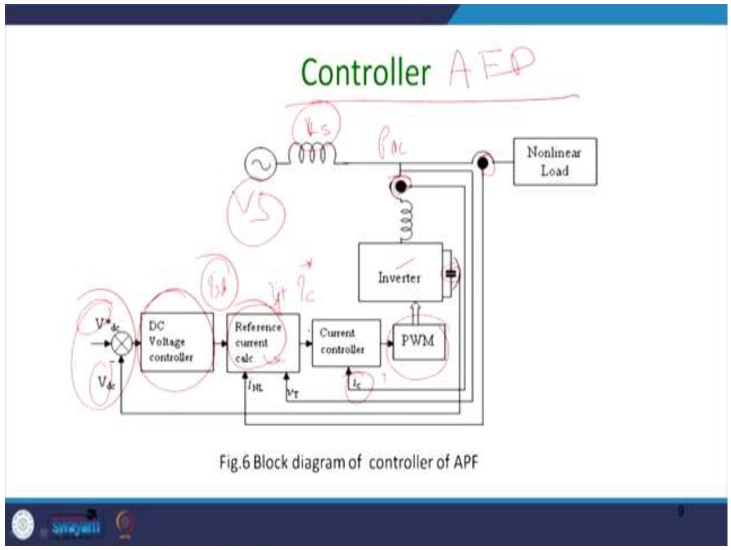

Fig.6 Block diagram of controller of APF

So, ultimately this is a control block diagram of active power filter. So, you have V_S here and you have L_S here R_S has been neglected. You, will sense this load current before the point of common coupling, after this point of common coupling. This point is called PCC. So, you will go to the reference generation calculation and then you will sense this dc bus voltage of the shunt active power filter inverter and that will be there and you require to maintain the DC bus voltage.

Generally, your DC bus voltage required to be maintained around 20 percent higher than the peak value, because you know if it is only compensating harmonic then the harmonic current is quite less and for this reason very small amount of current will flow. Due to that you can say that these devices will remain at the open circuit voltage. But you have to actively take it around 20 to 25 percent higher than this voltage typically.

So, we will see the different topological variation. There, we can have a different advantage of it and thus we can reduce the switching losses. It is mostly a PI controller and generally it gives you the value of I_{sd} and this non-linear load will generate this. What kind of I_c value is required to be generated?

This has to be added up. Ultimately, ($I_c + I_{sd}$)has to be fed to the controller because this comes from the I_{sd} and this is the actual I_{sd} that has been fed. Ultimately you may have a hysteresis controller or the PI controller then from this reference signal you get the reference modulated technique and this PWM will be fired. The thyristors are mostly of lower rating and thus you will be having the IGBTs.

Then generally if it is a STATCOM you can use thyristors. Then you get a pulse in only one inverter. Generally, it will be IGBT or for the higher power rating it will be GTO because, since it is a PWM, you have a frequent switching on and switching off are required. We will inject the current into the system. Now, let us come to the first part of our discussions that is the reference generation technique.

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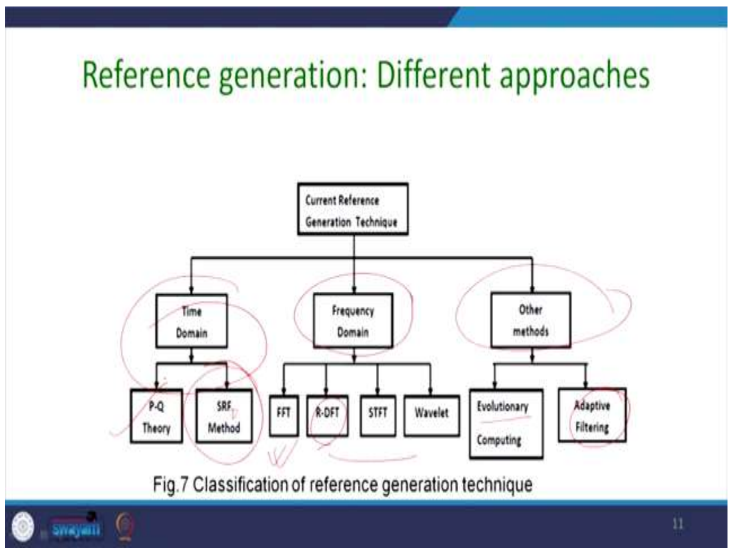

So, reference generation technique can be broadly classified into the time domain. One is the PQ theory: That is proposed by the father of this shunt active power filter, professor Akagi and SRF method: SRF method essentially was derived from the vector control of the induction machine drive. It is quite old method, but it has been taken from there.

So, both this theory is in time domain and both has its own advantages and limitations and then we can have another domain analysis that is FFT. By FFT of the load current, you can find it out what are the component of the frequencies presence and you take it out. Thereafter RDFT. Recursive first Fourier transform from that way also you can find it out the. This is a shifting FFT thereafter wavelet. Thereafter shifting window FFT. There is many other methods that we can use here for the purpose of this frequency domain analysis.

Same way, there is another method or other method. These are mainly evolutionary computing ANN and GA and other method and adapting filtering method where Kalman filtering method. Adapting Kalman filtering method. For sake of time you know we shall discuss PQ theory and since the evolutionary computing technique is getting a huge attention nowadays. We will discuss one theory on the ANN based reference generation technique here.

Now, how does it been done? This is mind it. It is an indirect entity. There is another method which is called direct entity. Ultimately you would leave everything on the capacitor then we have to find the power quality problem which does not solve much. I just explain it. Thereafter I will explain the another way of doing it.

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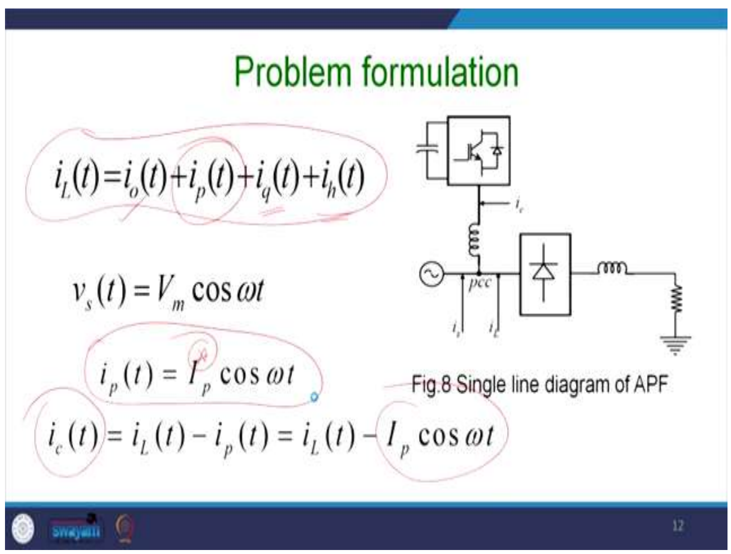

So, load current. It can be expanded with because you have taken a sample and this sample may have a quantization error and due to that you may have some DC component or you may be triggering the thyristors. If thyristors for the non-linear load and if their angle is little different then alpha is required to be compensated. So, for the small interval of time this DC component may come. Ultimately it will be adjusted.

Similarly, i_p is a in phase component of the current with a voltage and i_q is the quadrature axis current. All the harmonics current is represented by this and ultimately, we shall see that $v_s = V_m \cos \omega t$. So, we expect that i_p equal to the in-phase component of the current

$I_p \cos \omega t$. So, the compensating current$i_c(t) = i_L(t) - i_p(t)$. So, you require to calculate this entity very accurately by the reference generation technique.

Thus, what happens? Thus, you got a C, the compensating current will be $i_L(t) - i_p(t)$. that is essentially $i_L(t) - I_p \cos \omega t$. So, this method is called indirect method and with that you add up, if you go back to this circuit. Thus, you get I_c star here and you add up I_{sd} and you have segregated the job. Reference generation technique is this PI controller and maintain the capacitor voltage and this another entity will calculate the reference and it is observed that it gives the better results.

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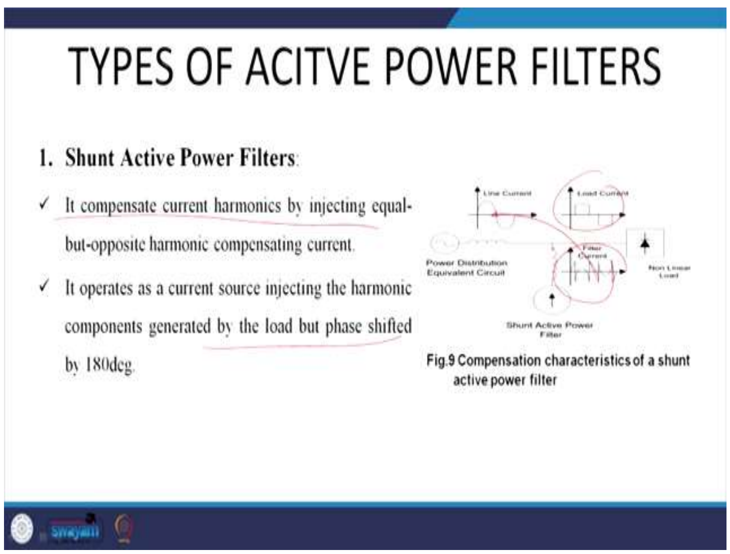

This one kind of shunt active power filter. It compensates the current harmonic by injecting equal and opposite amount of the harmonic compensating current. It operates as a current source injecting harmonic fed by the load 180 degree or out of phase of this injecting current. Thus, your load current is this. Ultimately you inject this. So, source will see that. This entity is sinusoidal as if a resistive load is connected with the voltage source. Now, there is another method. That is called direct current technique.

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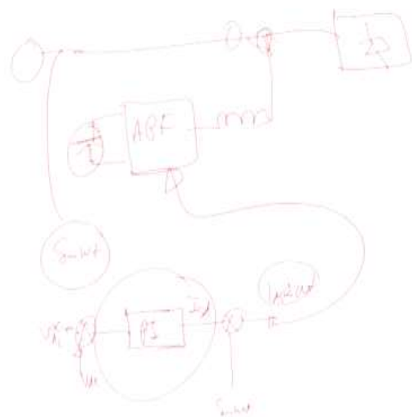

So, there what happens? Essentially this is your APF and here you have the PCC. You have a non-linear load and this is your source. You want to do everything by means of a one single capacitor. What essentially you will do? You will sense $\sin \omega t$ from this entity and thereafter you have V_c^* and you have a V_{dc} from there you will compare it and you know that we require to maintain that little bit higher. Thereafter, you will have this PI controller. PI controller will make this voltage little bit higher. If it is single-phase then $\frac{2V_m}{\pi}$ will be the average voltage because there is a anti parallel diode with the IGBT.

So, it will be maintaining some voltage even if this switch has been closed. But you require to take around let us say 50 volt higher if it is a single phase system. If it is a 440 volt you require to maintain the rectifier voltage around 100 volt higher. How you will do that? Essentially, we will come with the control strategy there. From there you get I_{sd} and I_{sd} will be multiplied with the $\sin \omega t$. So, that will be your $I_{sd} \sin \omega t$.

This will be the reference current and that will be fed to the APF and that is not all you do. You just maintain the dc voltage in a desired level and you try to inject all the current. You try to sense only this current, because you will make this current sinusoidal with respect to it. Then we will say that it is a direct method. But, problem of the direct method is maintaining the dc bus voltage. Compensation of this harmonic current lies on the responsibility of the PI controller. Tuning of this PI controller, that itself is quite challenging.

For this reason, we generally split this work on the indirect method where someone just switch it over. Ultimately someone will maintain the dc bus voltage and another block will actually calculate the reference current and thus combination will work.

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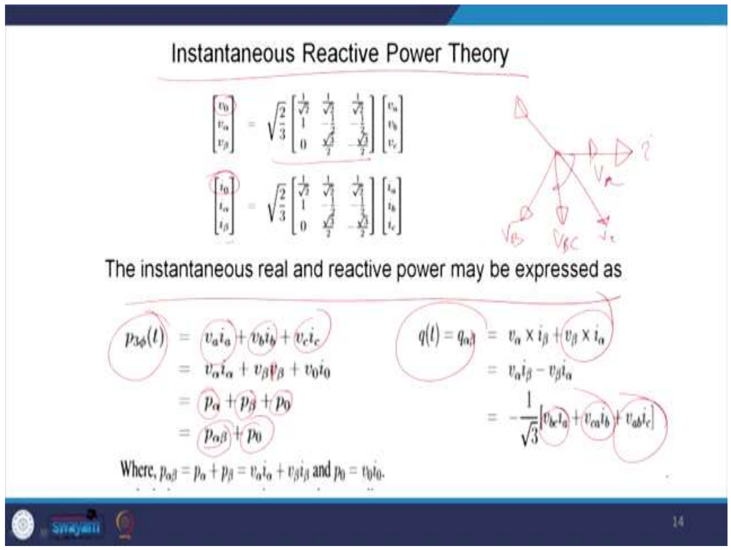

It gives a better power quality solution. Now, let us come to the important reference generation technique that is called Instantaneous Reactive Power Theory. You know, we can transform 'abc' to the 'αβ' frame and there is an advantage. We consider that it is a 3-phase 3-wires system and for this reason zero sequence entity comes. Otherwise, essentially there is an advantage of converting into the 'abc' to the 'αβ' frame. It is essentially that instead of the having that 2-phase 3 entities, we will have the 2 entities. That is a transformation all about.

So, it is a static transformation and for this reason you have a v_a v_b v_c and thereafter, you got a i_0, i_{alpha} and i_{beta} this is a current and voltage transformation from the 'abc' to 'αβ0' frame. So, instantaneous real power and the reactive power in the 3-phase can be represented. You multiply it. So, it is $v_a i_a + v_b i_b + v_c i_c$ and thus is corresponds to $v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0$ and thus you got a $p_\alpha + p_\beta + p_0$ and from there you can write and split this is $p_{alpha,beta}$ real and also the this zero sequence power. This is generally third harmonic power and thus it is also the co-phaser.

Similarly, you have a cross product of it. So, that is $v_\alpha \times i_\beta + v_\beta \times i_\alpha = v_\alpha i_\beta - v_\beta i_\alpha$. So, taking into the negative signs because it is an imaginary quantity and thus the negative sign will come.

So, you can go back from this matrix and you can rewrite that one as $-\frac{1}{\sqrt{3}}[v_{bc}i_a + v_{ca}i_b + v_{ab}i_c]$. Why? If you take the i_a and with the same phase if you take v_a. So, it is v_b v_c. So, ultimately if you extend it. It is minus v_c.

So, you can have this angle which is v_{bc} is 90 degree. So, for this reason this is 90 degree. Similarly, i_b into 'v_{ca}' also the angle between them is 90 degree and v_a into i_c and this multiplication since they are in a quadrature and gives you the reactive power.

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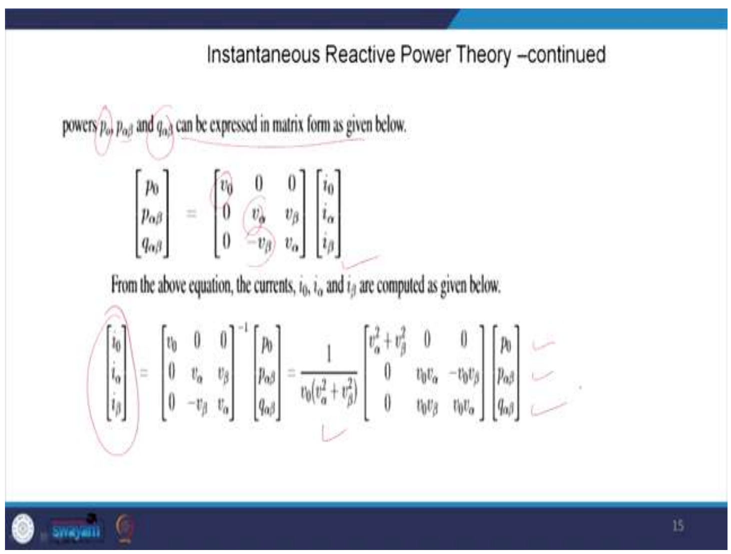

We can rewrite like this. p_α power at zero sequence power as of 'αβ' frame and the reactive power at the 'αβ' frame can be represent as p_0, $p_{\alpha\beta}$, $q_{\alpha\beta}$ is v_0, v_α minus v_β and similarly we just represent like this is a matrix representation of it and thus, if you take the inverse matrix of it you can get this current reference i_0, i_α and i_β. Essentially it is the matrix inverse of it and you get this value.

That is $\frac{1}{v_0({v_\alpha}^2+{v_\beta}^2)}$ and these are the diagonal element of it and these are the power. Power you can measure. So, that is the one of the advantages of it and thus you can get the current in the 'αβ' frame.

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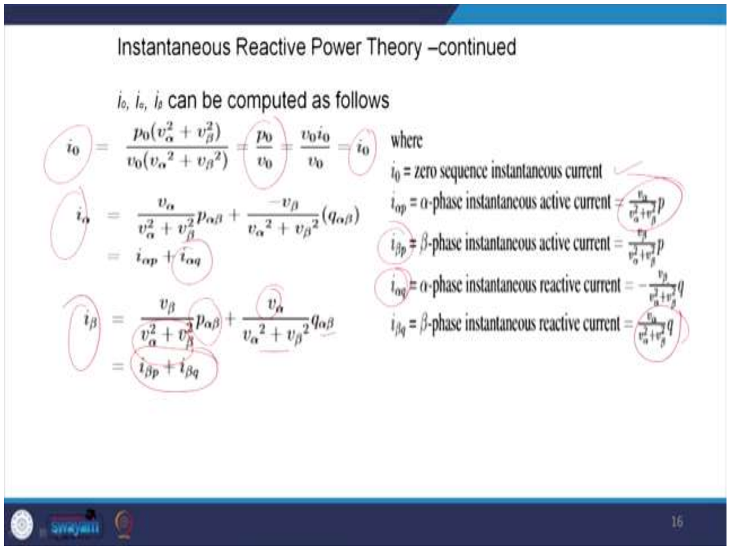

So, this i_0 i_{alpha} i_{beta} can be computed as follows. So, it is $\frac{p_0({v_\alpha}^2+{v_\beta}^2)}{v_0({v_\alpha}^2+{v_\beta}^2)}$. Essentially everything will cancel and it is $\frac{p_0}{v_0}$ that is essentially i_0 and here, i_α you can split it like this $\frac{v_\alpha}{{v_\alpha}^2+{v_\beta}^2}p_{\alpha\beta} + \frac{-v_\beta}{{v_\alpha}^2+{v_\beta}^2}q_{\alpha\beta}$. So, you get $i_{\alpha p}$, please refer to my previous slide, $i_{\alpha q}$. Similarly, for $i_\beta = \frac{v_\alpha}{{v_\alpha}^2+{v_\beta}^2}q_{\alpha\beta} + \frac{v_\beta}{{v_\alpha}^2+{v_\beta}^2}p_{\alpha\beta}$.

So, ultimately you get $i_{\beta p}$ plus $i_{\beta q}$. So, that will be the refer i_β. So, you can write like that little bit of synchronised way. Zero sequence instantaneous current is i_0. So, $i_{\alpha p}$ is a in phase component of the active current that is $p\cos\omega t$sometime we refer $I_p \cos\omega t$. This will be this expression, $\frac{v_\alpha}{{v_\alpha}^2+{v_\beta}^2}$ into the actual power consumed.

So, 'β' will be in phase component of the current which will be p_β by this. This is the same denominator. Again, these are the cross component that is a real power in 'α' that is in phase component of the reactive power that is $\frac{-v_\beta}{{v_\alpha}^2+{v_\beta}^2}$. Similarly, it will be with the 'q'.

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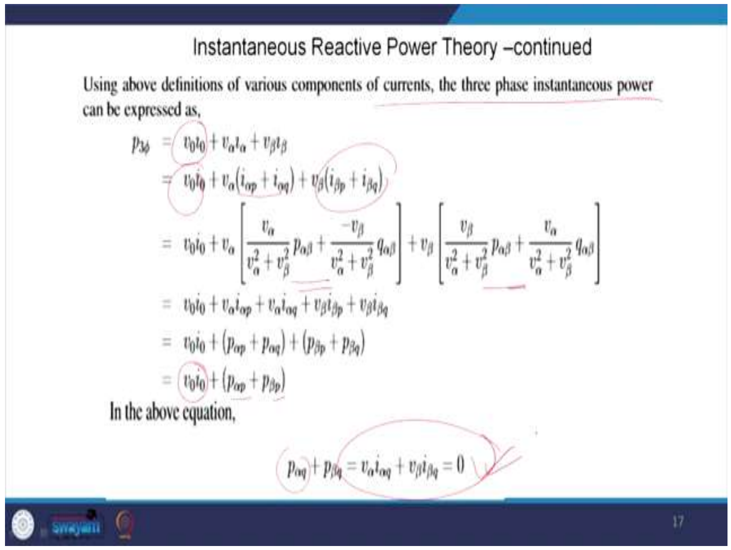

Using the above definitions of various components of the current the 3-phase instantaneous power can be expressed this, this and this of course. Thus, it remains same as it is. v_α i_α can be changed and we can write like this and similarly, i_β can be changed. We write like this. So, we have a very big expressions as we can see. So, it is $v_0 i_0 + v_\alpha \left[\frac{v_\alpha}{{v_\alpha}^2+{v_\beta}^2} p_{\alpha\beta} + \frac{-v_\beta}{{v_\alpha}^2+{v_\beta}^2} q_{\alpha\beta}\right] + v_\beta \left[\frac{v_\alpha}{{v_\alpha}^2+{v_\beta}^2} q_{\alpha\beta} + \frac{v_\beta}{{v_\alpha}^2+{v_\beta}^2} p_{\alpha\beta}\right]$.

What you essentially get is $p_{\alpha p} + p_{\beta p} + v_0 i_0$. So, this is the real power. Then here $p_{\alpha q} + p_{\beta q}$equal to instantaneous reactive power. We want that active power filter should not inject any real power thus the sum required to be '0' instantaneously. For this reason it is called this instantaneous reactive power theorem.

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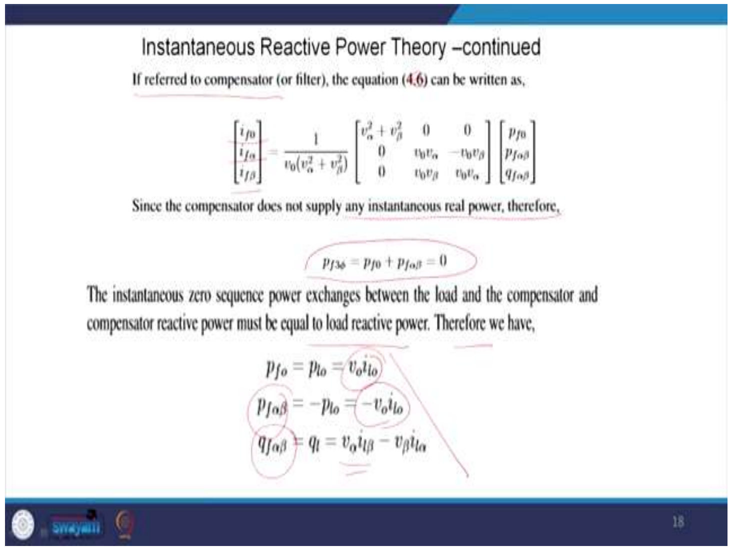

So, based on that we refer the compensator of the filter and this can be written as follows. This is the ‘αβ’, this is the component of this active power filter. This will be the zero-sequence component, this will be the ‘α & β’component of the shunt active power filter. That will make that instantaneous real power to be ‘0’.

We can rewrite it like that and since the compensation does not supply an instantaneous real power, but strictly speaking it is not because it requires to take a little bit of real power to maintain the capacitor voltage. This will be the expression. So, instantaneous zero sequence power exchange between the load and the compensator and compensator reactive power must be equal to the reactive power and thus we have this relation.

So, it is $p_{f0} = p_{l0} = v_0 i_{lo}$ and $p_{f\alpha\beta} = -p_{l0} = -v_0 i_{lo}$ and $q_{f\alpha\beta} = q_{l0}$. That is the reactive power that require to be compensated by the shunt active power filter and essentially it is $v_\alpha i_\beta - v_\beta i_\alpha$.

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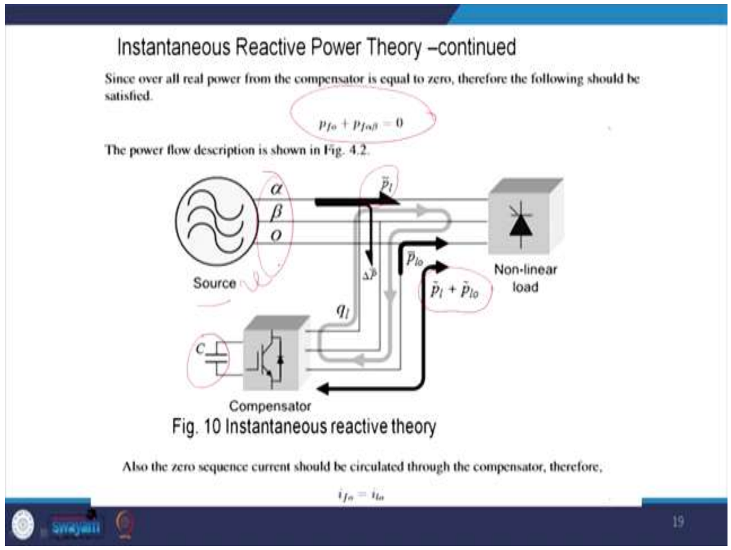

So, this is the pictorial diagram of the shunt active power filter in the domain of the power quality. We know that this is '0' as per the shunt active power filter. So, this is the figure we have considered and here we represent it into the 'αβ' frame instead of the source current 'abc'.

So, p_l will flow and Δp will come that will actually make the DC bus voltage higher than the required voltage to operate properly and this is the p_l and p_l load. This will go back. This will be the real power flow diagram and ultimately q_l (this is the ash line you can see that) will circulate within this line and thus source does not require to supply any q_l from the supply. Thank you for your attention. We shall continue with some portion of the instantaneous reactive power theory. Thereafter we will be looking after other control theory also.

Thank you.