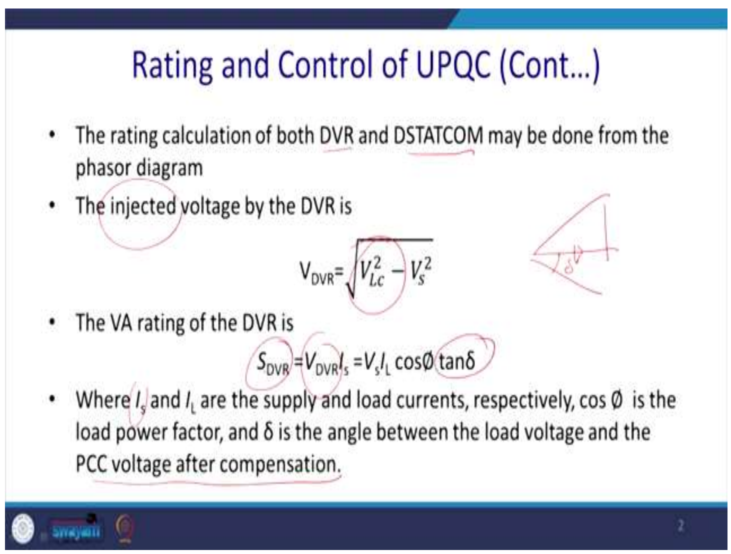
Power Quality Improvement Technique
Prof. Avik Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology, Roorkee

Lecture - 39
Control of UPQC

Welcome to our NPTEL courses on Power Quality Improvement Technique. We shall discuss on the Control technique of UPQC. In our previous lectures, we have talked about mainly the UPQC-Q and now we shall continue the discussion on its rating and its sag control.

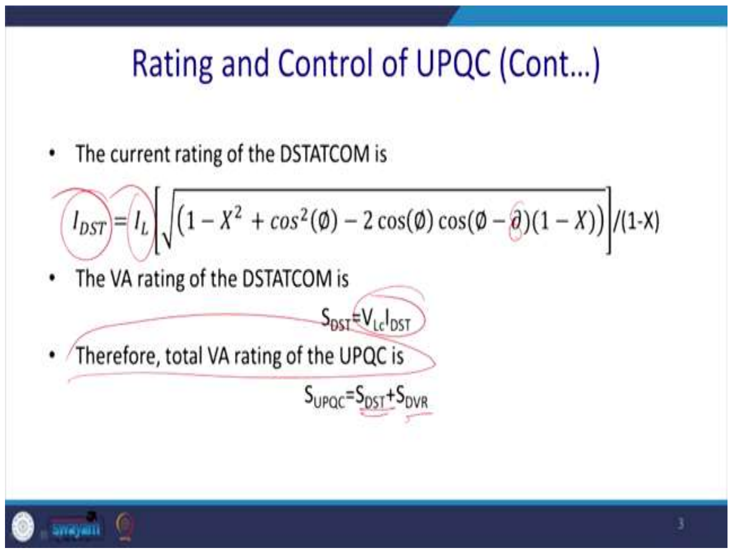
(Refer Slide Time: 00:50)



The rating calculations of the DVR and D-STATCOM can be done from the phasor diagram which we have shown from the previous figure. That is the quadrature and all those things. Please refer back to my previous lectures to correlate. The injected voltage of the DVR is given by under root of this voltage after compensation and this is the voltage before compensation. So, $V_{DVR} = \sqrt{V_{LC}^2 - V_S^2}$.

Then the rating of the DVR is essentially S_{DVR}. That is in kilohertz rating. Voltage rating and the current which is flowing through it because it is a series connection will be same. Ultimately this will be given by $S_{DVR} = V_{DVR} I_S = V_S I_L \cos\phi \tan\delta$, where 'δ' is the new angle between the voltage and current after compensation. Where I_S and I_L are the supply and the load currents respectively and $\cos\phi$ is the load power factor, 'δ' is the angle between the load voltage and the voltage after compensation. Ultimately this will be the case. This will be the rating. You try to minimize $\tan\delta$ so that the rating on the DVR will come down.

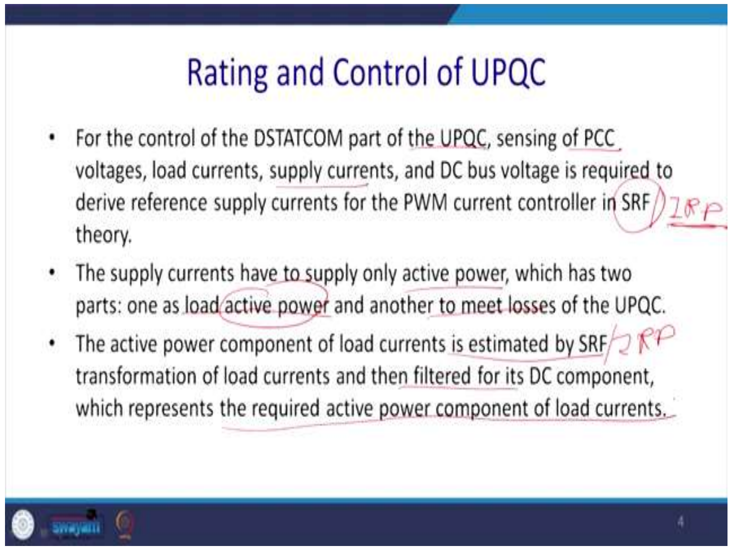
(Refer Slide Time: 02:25)



Now, let us talk about the current that is been injected by the shunt part of the devices. Let us assume as in a previous case also the load current is I_L. You have these expressions. We have mentioned in our previous case that X is the sag factor. So, it will be $I_L\left[\sqrt{(1 - X^2 + cos^2(\phi) - 2\cos(\phi)\cos(\phi - \partial)\,(1 - X)))}\right]/(1 - X)$. So, there are few new terms and it will be you know '∂'.

The VA rating of the D-STATCOM is essentially, is the compensated load voltage V_{LC} into the I_{DST}. Therefore, the total VA rating of the UPQC will be $S_{DST} + S_{DVR}$. So, both this has to be added up. This will be the total kilovolt or the megavolt ampere level of this UPQC.

(Refer Slide Time: 03:48)

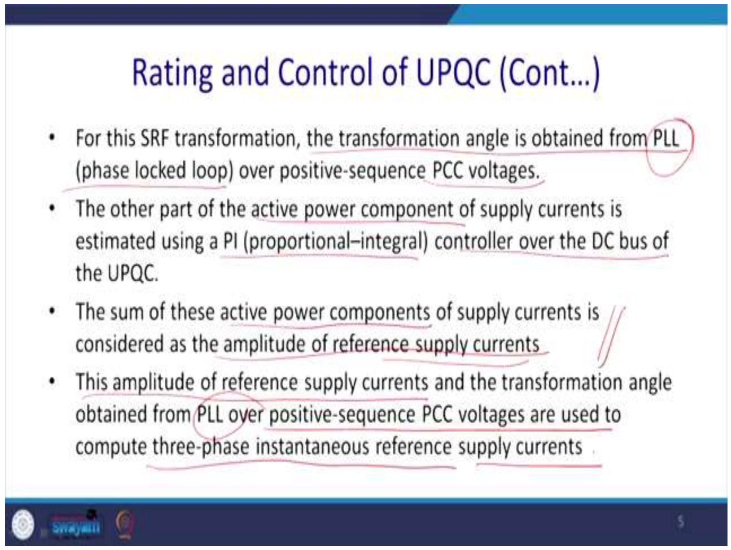


Thus, what we can say? For the control of the D-STATCOM part of the UPQC, the sensing of UPQC voltage, load current, supply current and the DC bus voltage required to be derived from the reference current of the PWM control by SRF or I_R instantaneous reactive power theory or other techniques which has already been mentioned. Whatever maybe this method, you can incorporate it.

The supply current has to supply the active power which has two part. One part is a load active power another part is because of all those elements present which are non-ideal inductor, capacitor. It carries series resistances. So, it required to meet thoes loses and switching losses and conduction losses of the switches of the UPQC. All those will be lumped and it will be load active power plus those loses. It will be taken from the source.

The active power component of the load current is estimated by SRF or instantaneous reactive power theory. We shall discuss in detail SRF transformations of the load current and then filter for its DC component which is present and then the required active power component of the load current.

(Refer Slide Time: 05:54)

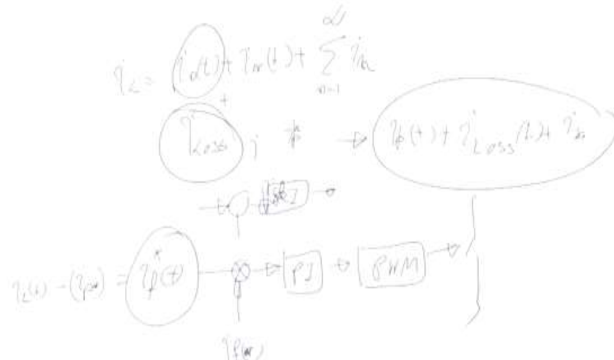


For SRF transformation, the transformation angle is obtained from the PLL. This is very important entity. The PLL is a very important entity. We require to talk about PLL in detail. That will be done hopefully in next class. The phase lock loop for the positive sequence PCC voltage.

The other part of the active power component of the supply current is estimated using the PI controller which I have shown in my previous class. Controller over the DC bus of the UPQC. That is an indirect method. That you can also have a direct method.

The sum of the active power component of supply current is considered as amplitude of the reference currents. That is something we require to take into consideration. Sum of this active power components. These are losses. There is a load current and to maintain the DC bus voltage little higher than the rectified voltage, you required to get some amount of extra voltage. Extra power. All those required to be fed from the source. For this reason, this sum of this active power component of supply current is considered as an amplitude of the reference supply current.

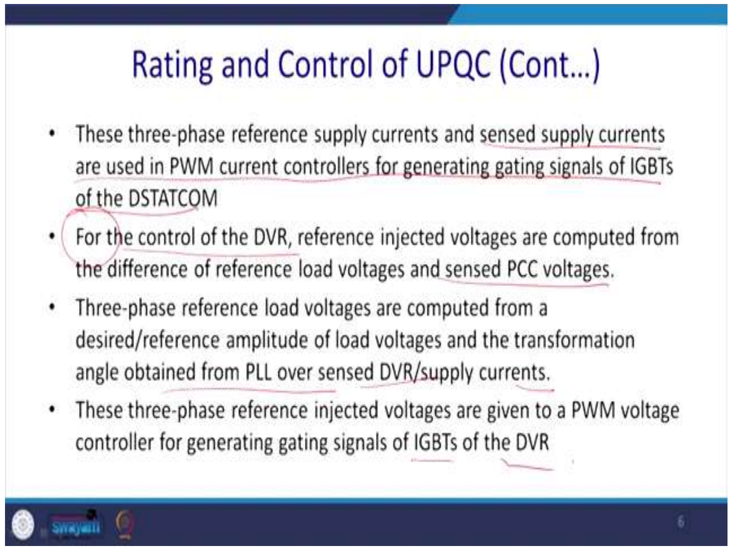
(Refer Slide Time: 07:44)



You have i_L that will have $i_p(t) + i_q(t) + \sum_{n=1}^{\infty} i_h$. So, i_p part should come from the source plus i_{Loss} because there will have some amount of the energy. That will actually accommodate the loss for the switching and there will be some part to maintain the DC bus voltage that is i_{sd} and thereafter that comes from the PI controller generally to maintain the DC bus voltage. So, $i_p(t) + i_{Loss}(t) + i_{sd}(t)$, all of this will be the in-phase component of the current and that require to be fed from the source.

So, the amplitude of this reference supply current and the transformation angle obtained from the PLL. Positive sequence PCC voltage is used to compute the three-phase instantaneous reference supply current. That is something we will see in our next classes. How PLL functions and how we generate this reference in this method?

(Refer Slide Time: 09:19)



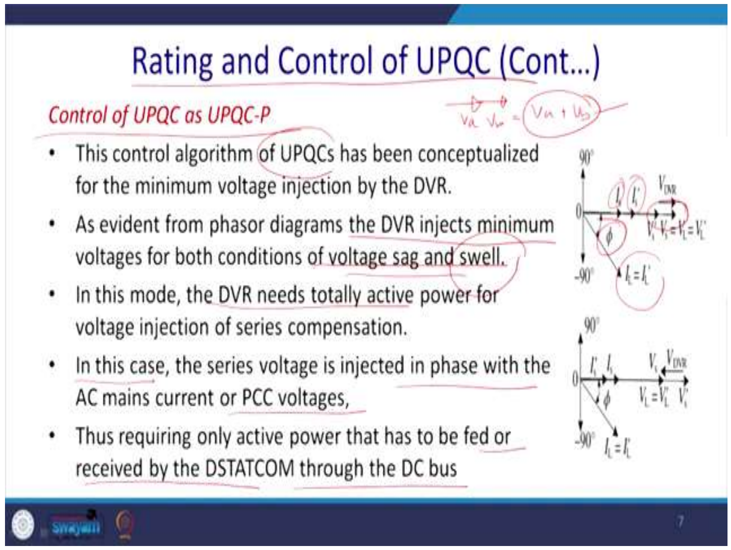
These are the three-reference supply current. Generally, if you have a three phase three wire system, two reference current is sufficient and you can get another current by subtraction from '0' and sense the supply current used in a PWM current controller for generating the gating signal for the IGBT and the D-STATCOM.

So, what happens? Let us go back. How does it work? You have $i_L(t) - i_p^*$and this is letter i_p^*. So, ultimately you got $i_f^*(t)$. You have this reference current and so generally it is been compared in a 'abc' reference. What actually you are injecting? That you feed it to the PI controller, then you have a PWM lock and that have a switch for one leg. Similarly, we have a three such pulses. Generally, it is unipolar in nature for the two-level inverter and accordingly for the multilevel inverter we have a multilevel switching scheme.

For the control of the DVR the reference injected voltages are computed from the reference of the load voltage and the source voltage as PCC. So, we require voltage sensors. We require to check if there is a sag or swell and accordingly voltage will be injected or voltage will be taken out in case of the swell.

The three-phase reference load voltage are computed from a desired amplitude of load voltages and the transformation angle is obtained from PLL over sensed DVR or supply current. The three-phase reference injected voltage are given to the PWM voltage controller for generating the gating signal of the IGBT of the DVR.

(Refer Slide Time: 12:16)



Now, this is the case for the UPQC-Q. Now let us talk about the UPQC-P where the voltage is injected in phase. So, DVR voltage is injected in a phase. Ultimately you do not have much change in the phase angle that will be remain 'ϕ'.

Because to previously we had a two angle. Because after compensation the voltage between the uncompensated voltage and the compensated voltage become this angle in between in case of the 'Q', but that angle is not possible because you are injecting a voltage in phase with a current. So, what happens here? Your phase will be same, but what happens? You got extra current I_S which was the flowing instead of that I_S' will be flowing and ultimately difference was this DVR voltage. Previously it was V_S. Now it is V_S' and V_L should be the load voltage. That require to be constant because we require to keep the sensitive load at a constant voltage.

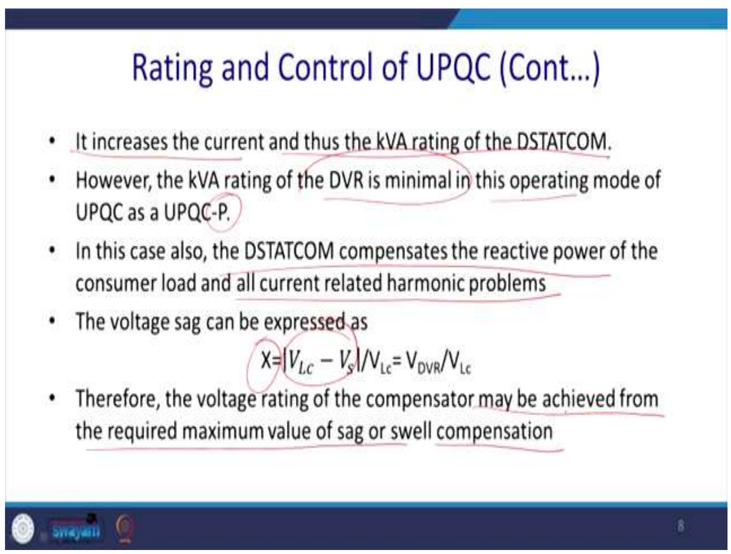
Now, this is the control of the UPQC-P. This algorithm UPQC has been conceptualizing for the minimum voltage injection. Because once you inject in a voltage in phase, maximum force injection will take place. Of course, you got V_a and you get V_b resultant is $V_a + V_b$, when you injected in phase and that is a maximum you can achieve.

As evident from the phasor diagram, the DVR injects the minimum voltage thus rating of this devices is required to be low. That is one of the major advantages of it. For both conditions of the sags and swell and moreover this UPQC-Q does not have a capability to mitigate swell.

Here since it can mitigate swell by injecting a out of phase. So, that swell can be mitigated. But problem lies in, it has to handle not only the reactive power loses, but also this sag. If you are mitigating sag that extra power will come from the shunt path and ultimately inject the voltage. Reverse when there is a high voltage, then it should take out this voltage and ultimately try to flow from the shunt path. If it is not possible then it has to be bled out by the bleeder resistances.

In this case, the series voltage is injected in phase with the AC mains current or the PCC voltage. Thus, requiring only the active power that has to be fed or received by the D-STATCOM through the DC bus.

(Refer Slide Time: 15:40)

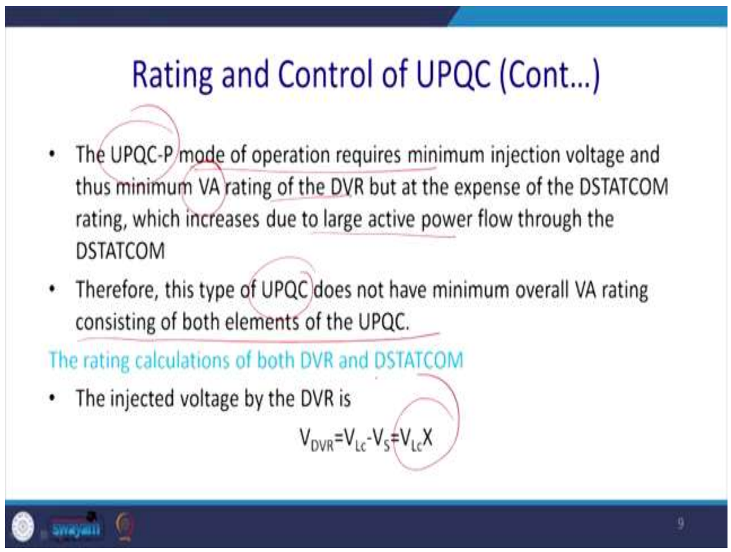


In this, it increases the current. Since the current has to be increased because real current in phase will flow and thus the kVA rating of the D-STATCOM will be higher. However, kVA rating of DVR will be minimal because of the less voltage rating. Voltage rating required to be very low and this operating mode is called as UPQC-P. So, ultimately it passes the work on the shunt path.

In this case, also the D-STATCOM compensates the reactive power of the consumer load. In case of the sag that extra voltage should come from the shunt path. DVR will compensate the sag fine, but that extra current has to flow from the shunt path. So, rating of the devices of the shunt path required to be increased.

So, what happens? The active power of the consumer load and current related to the harmonic problem. The voltage sag can also be expressed as $X = \frac{|V_{Lc}-V_S|}{V_{Lc}}$. Ultimately, we know that this difference is injected by the DVR. So, that will be ${V_{DVR}}/{V_{Lc}}$. Therefore, the voltage rating of the compensator maybe achieved from the required minimum value of the sag and the swell compensation

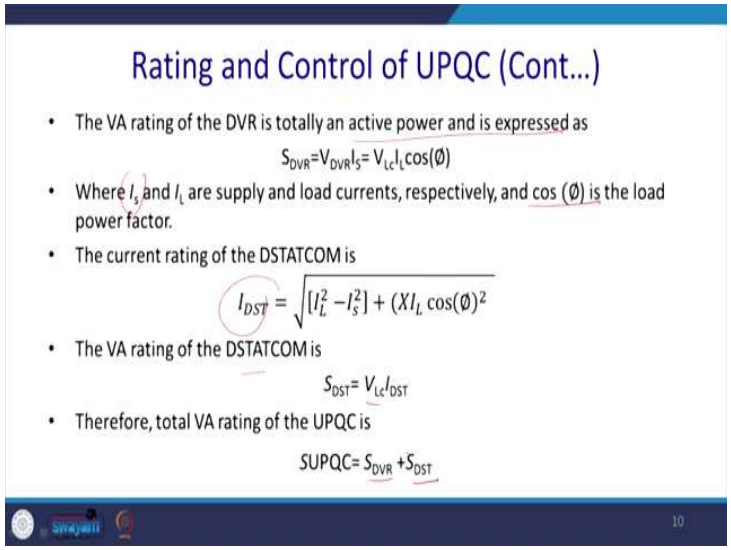
(Refer Slide Time: 17:24)



Now, in case of the UPQC-P as we have mentioned already that mode of operation requires minimum injection of the voltage and thus minimum VA rating of the DVR, but at the expense of the D-STATCOM current rating, which increases due to the large active power flow from D-STATCOM to this DVR. Therefore, this type of UPQC does not have minimum overall rating. It may be the DVR rating is low but D-STATCOM rating is high. So, it is not optimized and consisting of the both the element of the UPQC.

The rating calculation of the both DVR and the D-STATCOM, we can do that. As we have done in case of the UPQC-Q. The injected voltage of the $V_{DVR} = V_{Lc} - V_S$. Ultimately you can refer it as a sag factor $V_{Lc}X$. That is X is a sag factor.

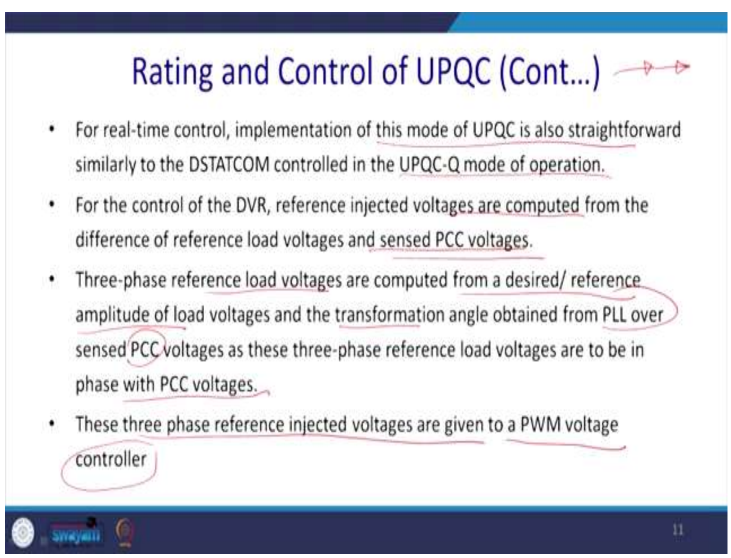
(Refer Slide Time: 18:39)



Similarly, the rating of the DVR in total can be expressed $S_{DVR} = V_{DVR}I_S = V_{Lc}I_S \cos\phi$. Where I_S is source current and I_L is the load current respectively and the cos ϕ is the power factor of the load current.

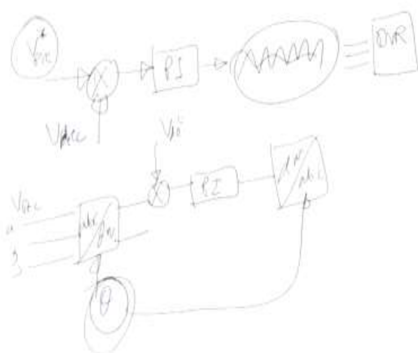
So, current rating of the D-STATCOM will be $I_L^2 - I_S^2$. So, that is the extra current has to flow plus $XI_L cos^2(\phi)$ and from the VA rating of the D-STATCOM will be $V_{Lc}I_{DST}$ and the total rating as we have seen. It is $S_{DVR} + S_{DST}$.

(Refer Slide Time: 19:35)



So, what happens here? For the real control, the implementation of this mode of the UPQC is also little straight forward because you straightaway try to compensate in phase component. Similarly, to the D-STATCOM control from the UPQC mode of operation. Thus, what happen? For the control of the DVR, the reference injected voltages are computed from the difference of the reference load voltage and the sensed PCC voltage.

(Refer Slide Time: 20:23)



So, what happens? You know that what should be the reference PCC voltage and what actual voltage at PCC you might be calculating from your PCC voltage, from your voltage sensors.

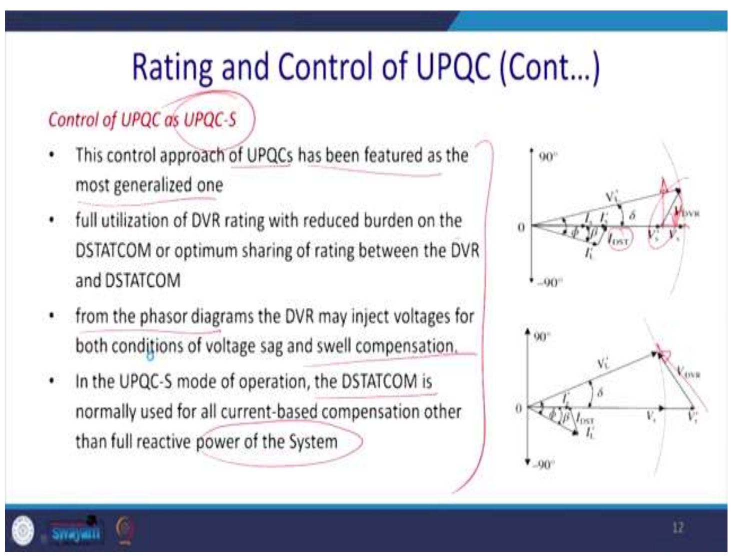
So, that voltage we generally always put to a PI controller. Why? Because PI is a history. Proportional because your switching by PWM. Thus, you require a proportionality constant because your sin triangle ratio is such that we require a proportionality constant and to eliminate the steady state error, we require to put the PI controller. Ultimately you got some value, a sinusoidal value. This has to be a sin triangle PWM and from there you get the gating pulses. From this your DVR acts to compensate the sag.

So, this is the way of operation for your DVR part. That is all it is. The control of the DVR reference is injected. Voltage has computed from the reference between the load voltage and the sensed PCC voltage. The three-phase reference load voltage are computed from the desired or the difference amplitude of the load voltage and the transformation angle is obtained from the PLL. That is something we require to see. How does it PLL works? In case of the dirty environment when voltage is not cleaned for PLL. Over the sensed PCC voltage at this three-phase reference voltage are to be in phase with the PCC voltage.

So, you require to inject the voltage. What is there? It is this. That is been done with the help of the phase lock loop. The three-phase reference injected voltage as given to the PWM voltage controller to control the voltage. So, what happens? You know. If you go back, I require to little modify. Ultimately this generally converted. All are converted from 'abc' to 'dq'. From ϴ, this 'ϴ' comes from the PLL. So, your actual PCC voltage is available. This is the PCC voltage, 'abc' and ultimately you got d and q. Generally, q does not count. You got some value of this voltage and this is your V_{dc} reference. You have got a PI because PI works better in DC.

Now, again you reconvert into 'dq' to 'abc' and same 'ϴ' is applied and 'ϴ' is generated from 'ϴ' or 'ϕ' whatever maybe is generated so that it ensures that you inject the voltage in phase at the PCC. That is what it is been written here. This three-phase reference injected voltage are given to the PWM voltage of the controller.

(Refer Slide Time: 24:21)



Now, this is the phasor representations of it, but this is for the 'S' type, where you try to optimize overall kVA rating of the UPQC. Generally, what happens? In case of the 'Q' your D-STATCOM rating is slow, but power rating of the DVR is high, but in case of the 'P', your DVR rating is low, but D-STATCOM rating is high. But here you try to optimize the overall kVA rating of the UPQC. So, this is the purpose. Let us discuss what has been written in this slide. Thereafter we shall discuss the phasor.

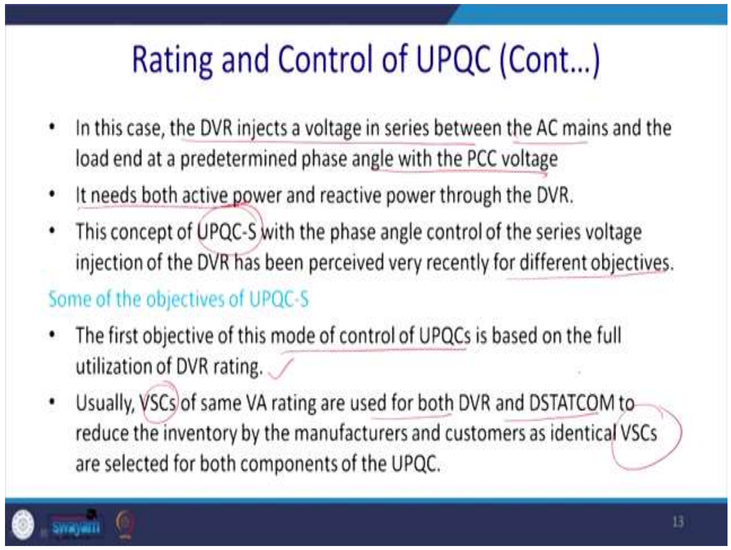
We have already discussed this, because if you want to have a sag compensation instead of compensating at this angle in phase in case of the ‘P’ or in case of the quadrature, you can inject the optimal angle by choosing the effective utilizations of the DVR and your D-STATCOM rating. So, both will be optimally loaded. It is not that very high amount of the current will flow through the D-STATCOM as in case of the ‘P’ or very low amount of current will flow in case of the ‘Q’, but your DVR rating is high.

Accordingly, you will choose this injection angle and thereafter you had current initially that is I_L and you will inject this current and there is a volt angle between I_S and I_L that angle was ‘ϕ’. Ultimately you will inject the DST. So, that will make this component in phase with the supply voltage.

Similarly, in case of the swell, it can also compensate the swell and ultimately you can see that this injects like this. So, you get a proper utilization of both the entities DVR as well as the D-STATCOM. Thus, what we can say here is, this control approach of this power quality conditioner has been featured as a most generalized one

Full utilization of the DVR rating will reduce burden on the D-STATCOM or optimum rating sharing between DVR and the D-STATCOM. It has been featured into this UPQC-S base system. From the phasor diagram of the DVR, (as I explained little earlier) the DVR may inject the voltage in both condition voltage sag as well as the voltage swell compensation. The UPQC-S mode of operation that D-STATCOM is normally used for all current based compensation other than the full power system compensation. So, this is the way it will work.

(Refer Slide Time: 27:44)



Thus, what happens? In this configuration, in this case the DVR inject the voltage in series. The AC mains and the load end of the predetermined phase voltage and that will be optimally compensating the rating with respect to the PCC. Not that end phase or not that end quadrature. It is some optimal angle that required to be calculated.

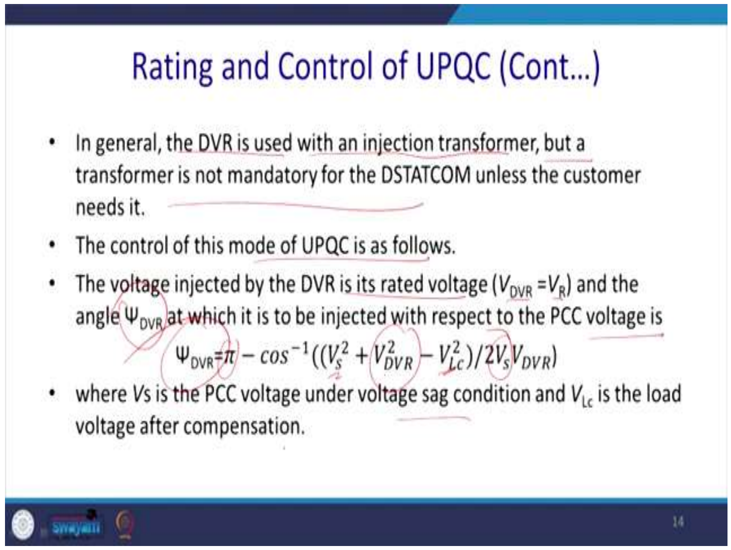
It needs both active and the reactive power through the DVR. The concept of UPQC-S with the series voltage injection of the DVR has been perceived very recently for different objectives. So, let us see that what is the objective?

First objective is to utilize the proper rating of this devices. So, first objective is mode of control of UPQCs based on full utilizations of the DVR rating. Rating has to be fully utilized, then only you load the current handling capability of this D-STATCOM.

Usually, VSC of the same VA rating used for DVR and the D-STATCOM to reduce the inventory for the manufacturer and also you if you have a different voltage rating for the different switches your inventory cost will increase. So, you try to maintain the same voltage level for DVR as well as the D-STATCOM. For this reason, first you will load the DVR to fullest and then the current rating will follow.

Thus you can have a total optimization or you may have a different optimization. You may refer to the paper so that rating can be optimized by any soft computing technique also. It has been reported. To reduce the inventory by manufactures and the customers, identical voltage source converter are selected for both the component of the UPQC.

(Refer Slide Time: 30:15)



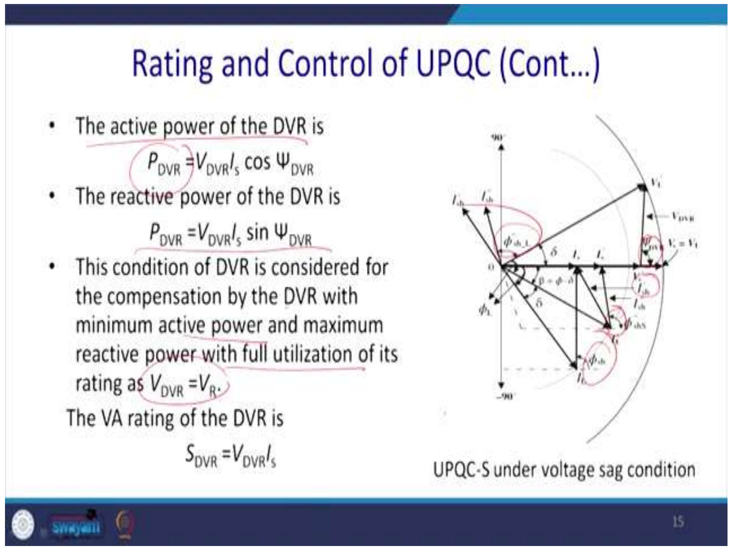
In general, the DVR is used with an injection transformer to get rid of the high frequency noises which we have seen in our or the high frequency switching ripple which we can see in our previous lecture.

But a transformer is not mandatory in case of the D-STATCOM unless a customer needs it or the grid court forcibly enforce it. For this reason, the control of this UPQC method maybe as follows. The voltage injected by the DVR is the rated voltage that is $V_{DVR} = V_R$ and this angle ψ_{DVR} at which it is to be injected with respect to the PCC voltage.

You can calculate ψ_{DVR}. That is the one of the challenges online. $\psi_{DVR} = \pi - \cos^{-1}\left((V_S^2 + V_{DVR}^2 - V_{Lc}^2) \big/ 2V_S V_{DVR} \right)$. From there we can optimally calculate the value of ψ_{DVR}. So, why it is optimal? You know value of this V_S may be changing due to sag and swell accordingly the injection angle required to be change.

Where V_S is a PCC voltage under the sag condition and 'V_{LC}' is the load voltage after compensation. In that way we require to calculate and inject this voltage ψ and compensate this voltage. In this way this will continue.

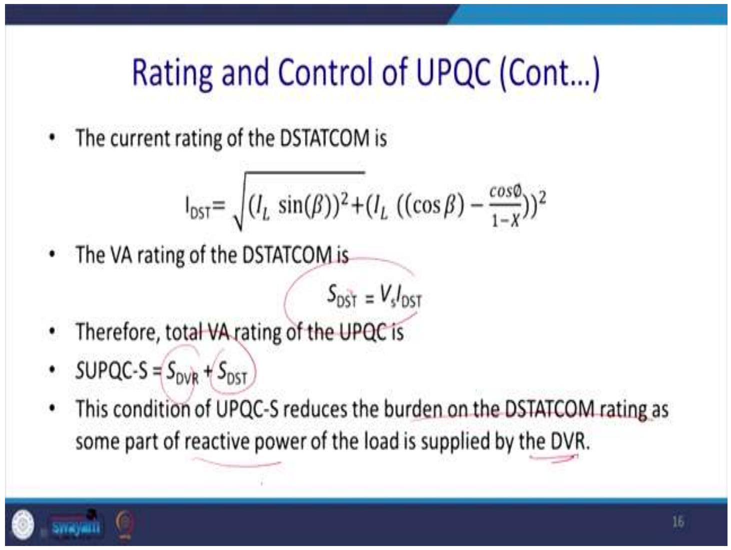
(Refer Slide Time: 32:21)



Now, the active power of the DVR is $P_{DVR} = V_{DVR} I_S \cos \psi_{DVR}$. Similarly, it is $\sin \psi_{DVR}$ and let us explain the phasor diagram. Here you know you will apply this angle optimally. This was 90 degree and this is a applying voltage. Similarly, you know, you had this value of I_S and you can apply the shunt compensation 'I_S ψ' and it maybe at a different ψ and thus you get a ψ'' and you may get this injection and you get ψ'' again.

So, what does the phasor says? From this angle you can have a different value of ψ compensation. So, you can play around with 'ψ' and magnitude of the compensation current. This condition of the DVR is considered for the compensation by DVR with minimum active power and maximum reactive power with full utilizations of the DVR rating. That is $V_{DV} \;\; = V_R$ and this VA rating of the DVR is $S_{DV} \;\; = V_{DVR} I_S$ and thus it follows like this.

(Refer Slide Time: 34:06)



From there what we can say? That, the current rating of the D-STATCOM equal to $\sqrt{(I_L \sin(\beta))^2 + \left(I_L \cos(\beta) - \frac{\cos\phi}{1-X}\right)^2}$. X is the amount of the sag and the VA rating of the D-STATCOM is definitely is equal to $V_S I_{DST}$. So, total rating will be definitely $S_{DVR} + S_{DST}$ and this configuration. What happens? UPQC-S reduces the burden of the D-STATCOM rating. As some portion of the active power of the load is also supplied by the DVR.

So, thank you. Thank you for your attention, we have discussed about the control techniques of the 'S' type. 'S' type UPQC that has been featured and been used for its superiority over UPQC-P as well as 'Q'. In next class, we shall discuss about this grid connected voltage source converter and the PLL. These are the two entities which has been frequently used. Mostly today we have concentrated on the compensation of the DVR and we have also seen that how to employ D-STATCOM and we shall discuss about at least two important techniques that is SRF method and the instantaneous reactive power flow.

Thank you for your attention.