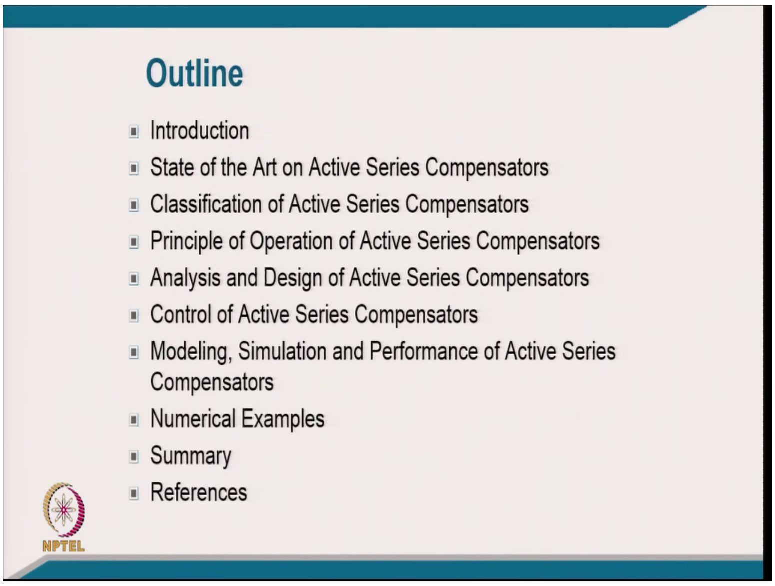
Power Quality
Prof. Bhim Singh
Department of Electrical Engineering
Indian Institute of Technology, Delhi

Lecture - 10
Active Series Compensation

Welcome to this course on Power Quality. [FL], today, we will like to start this topic of active series compensation I mean like.

(Refer Slide Time: 00:31)



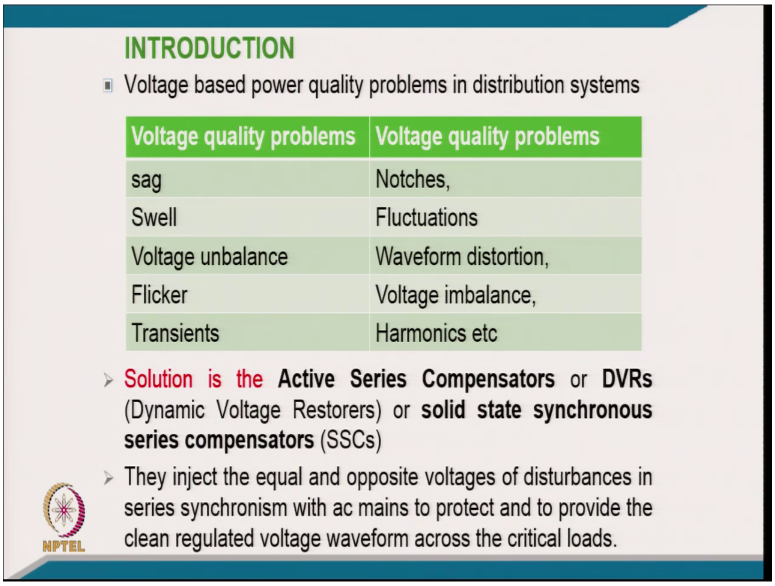
[FL], the outline for today presentation is introduction, state of art on active series compensator, classification of active series compensators, principle operation of active series compensators, analysis and design of active series compensator, then control of active series compensator because it is a active device.

And then we like to take a case of modeling simulation and performance of a some case characterization of active series compensator followed by then some numerical example, and the summary, and followed by references.

(Refer Slide Time: 01:01)

[FL], the very objective of this active series compensator is we would like to discuss first the requirement of it and application. Then we will go to the configuration of active series filters sorry compensator. Then we will go for analysis and design of active series compensator. We will discuss control of active series compensator, and then method of modeling and control of active series compensator.

(Refer Slide Time: 01:25)

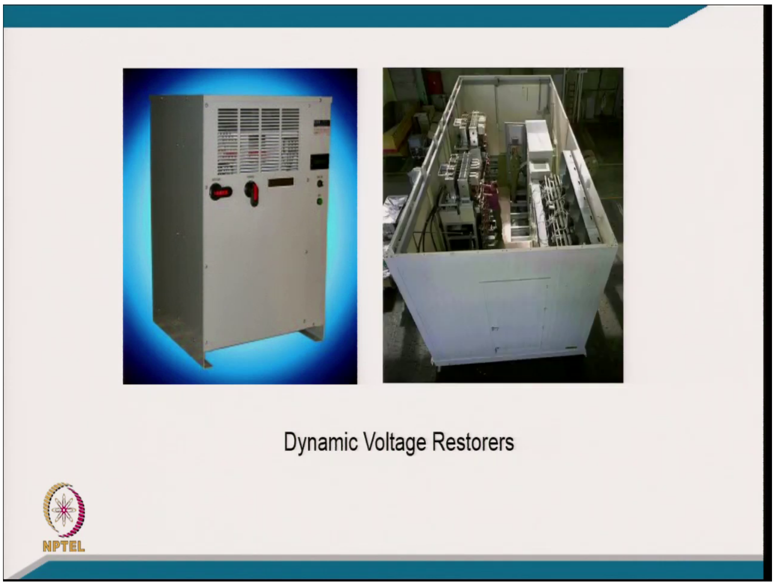


Well, coming to like introduction, I mean typically for voltage based power quality problem in distribution system, I mean what are the voltage based power quality problems like typically voltage sag, voltage swell, voltage unbalance, voltage flicker, voltage transients, then voltage notches, voltage fluctuations, voltage distortion, voltage imbalance, and of course, the voltage harmonics maybe there, may not be there.

[FL], these are the some of the voltage based power quality problems in distribution system like either it is typically we discussed already whether it is natural or it is manmade because of which region is coming into practice.

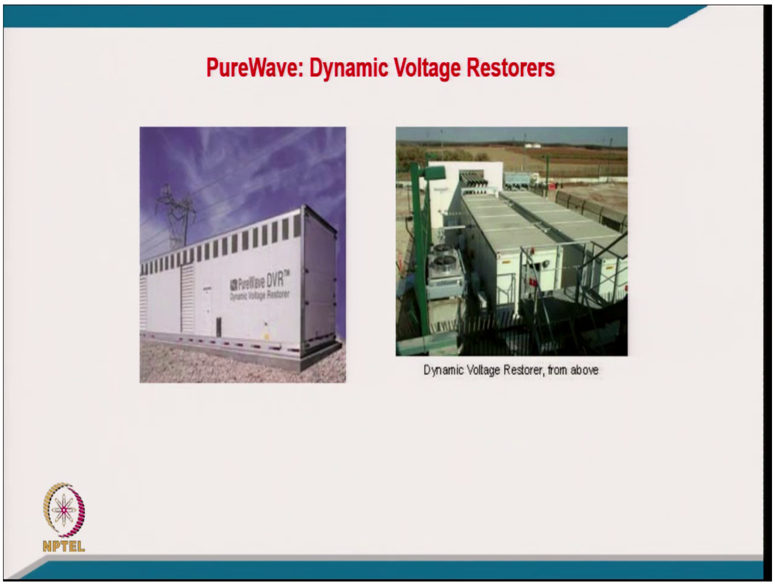
[FL], solution is active series compensator or we call it DVR – Dynamic Voltage Restorers or the Solid State Synchronous Series Compensator – it is also called SSC [FL], the different it is known from different names like. And they inject the equal and opposite voltage of disturbances in series synchronism with the ac mains to protect and to provide clean regulated voltage waveform across the critical load.

(Refer Slide Time: 02:30)



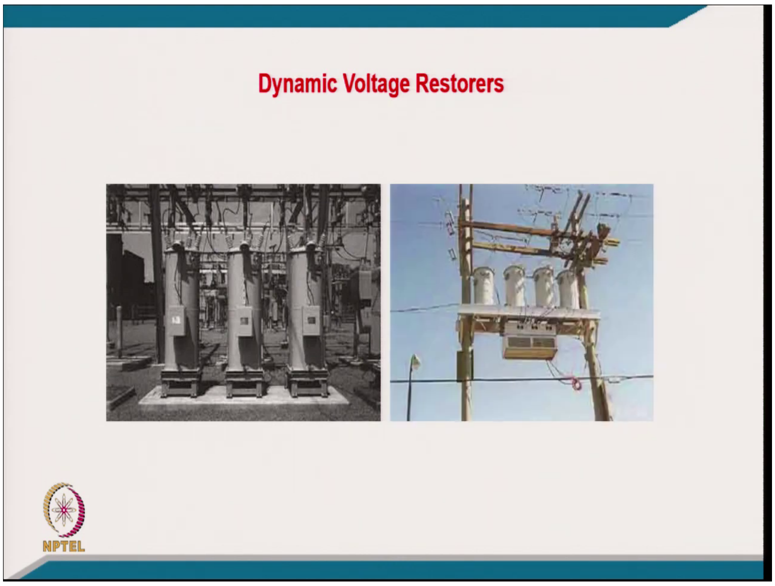
(Refer Slide Time: 02:39)

(Refer Slide Time: 02:39)



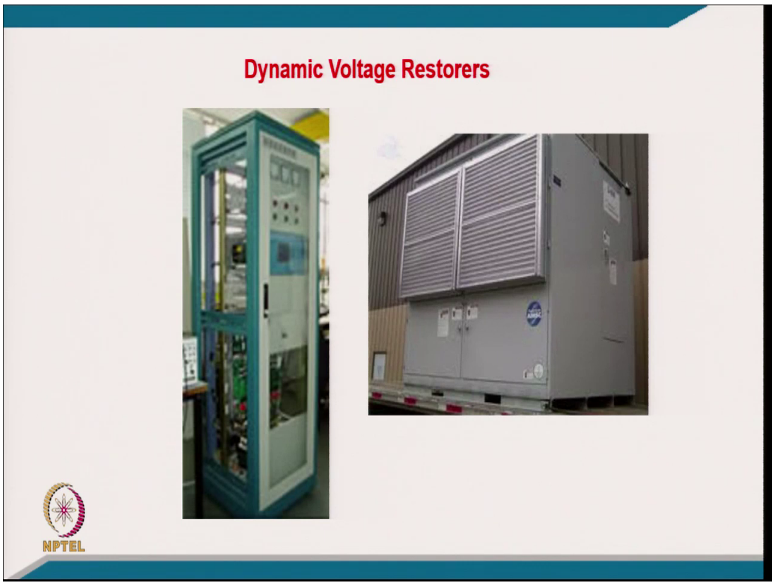
Well, coming to the this dynamic voltage restorer, these are the typically some photographs of the already existing these typically DSTATCOM. And industry pure wave is also manufacturing this DVR Dynamic Voltage Restorer, this is typical photograph of that. And this is another photograph from dynamic voltage restorer from above industry.

(Refer Slide Time: 02:52)



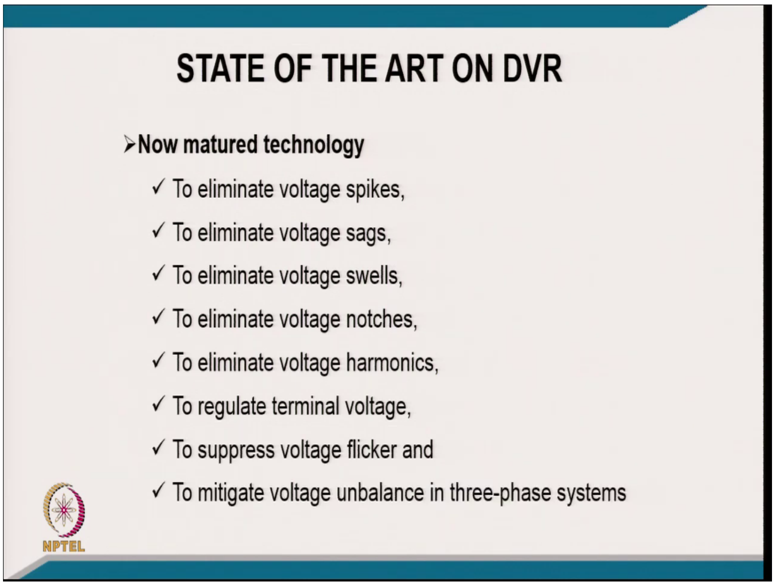
And the dynamic voltage restorer, this is another type of photograph how they are installed in practice where they are allocated I mean virtually.

(Refer Slide Time: 03:00)



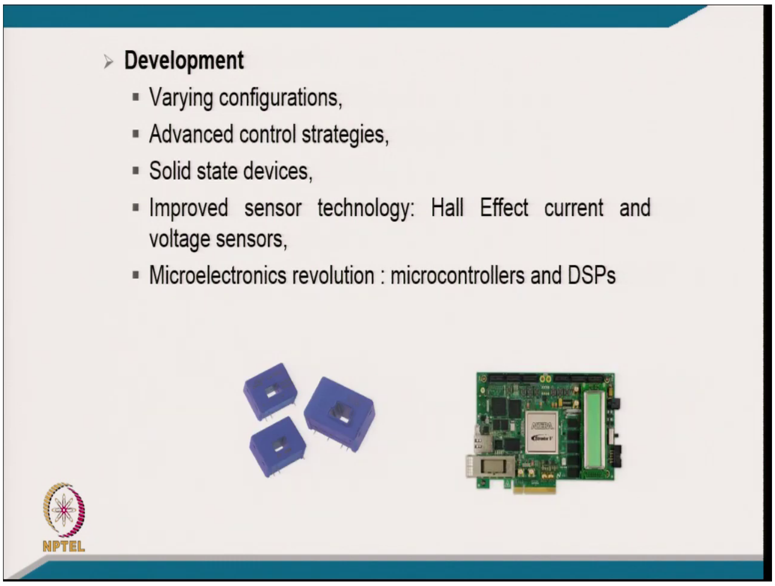
And then the typically for the industry or for process. I mean the typical photograph.

(Refer Slide Time: 03:05)



[FL], coming to that on a state of art on this DVR or series compensator active series compensator, now it is a matured technology to eliminate the voltage spike, to eliminate voltage sag, to eliminate the voltage swell, to eliminate voltage notches, to eliminate voltage harmonic, to regulate the thermal voltage, to suppress the voltage flicker, and to mitigate the voltage unbalance in three-phase system like.

(Refer Slide Time: 03:30)



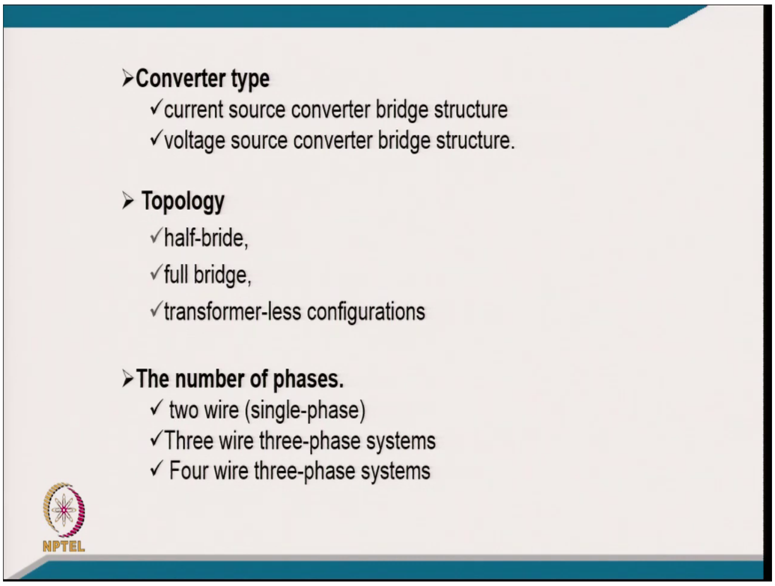
Well, development on this of series compensator have been in varying configuration with the advanced control technique and different solid state devices are used in that. And of course, responsible is improved sensor technology like Hall Effect current sensor, voltage sensor which are now at reasonable cost, but they are very fast and they does they do not distort the signal also.

And another reason for this revolution have been a micro electronics revolution because this microcontroller and DSP they have become at very low cost, I mean by lower cost much much lower cost even the cost less than a even a single power semiconductor power device like IGBT. And these are the typical photograph of if you look into on left side current sensor, on side you right side you see the DSP.

(Refer Slide Time: 04:17)

[FL], coming to the classification of active series compensators.

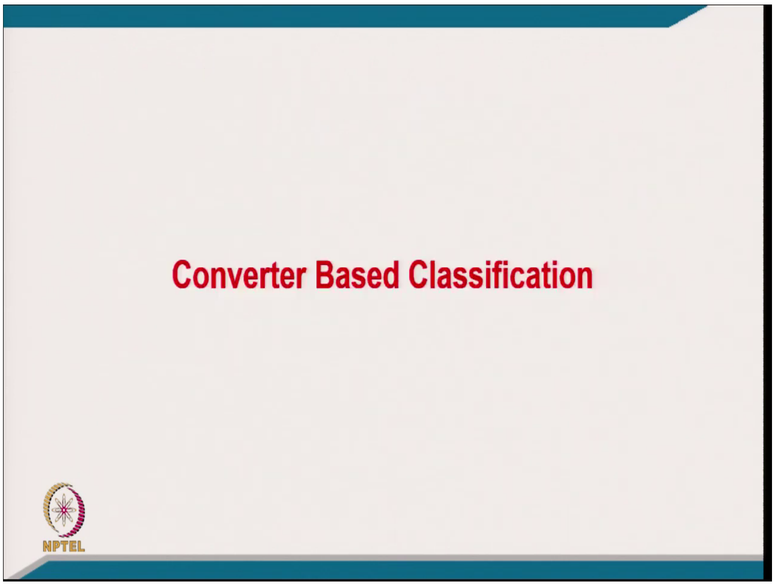
(Refer Slide Time: 04:25)



I mean we classified first on the converter types I mean [FL] we can use of course, in current source converter with the bridge structure or we can use the voltage source converter bridge structure that is about converter based classification. The another classification we give like a topology based classification like half-bridge, like a full bridge, the transformer-less configuration.

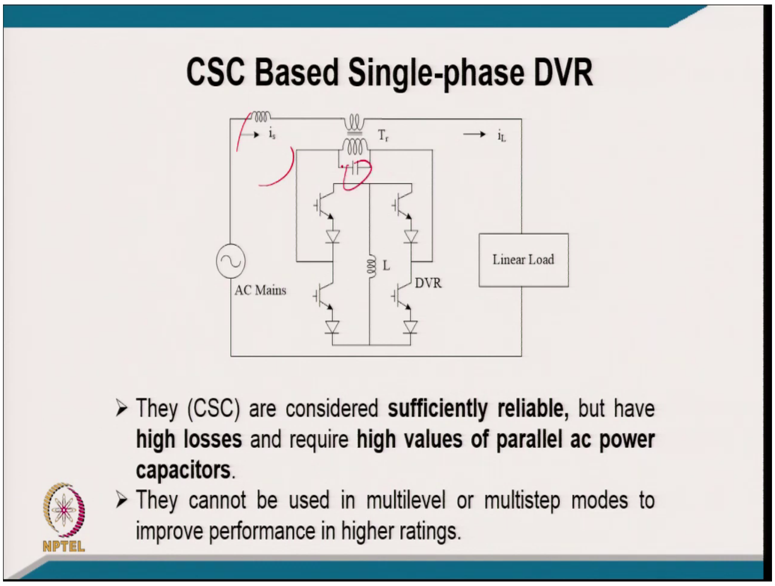
And another classification is based on number of phases like you are going to use it in two phase like a single-phase supply system or you are going to use three-phase supply system, or you are going to use like a three-phase four wire supply system.

(Refer Slide Time: 05:02)



[FL], coming to the converter based classification.

(Refer Slide Time: 05:09)



I mean you can just see the circuit of current source based single phase DVR or series compensator where very purpose is that we have a supply and we have a source impedance followed by the series compensator which is used in current source converter. And of course, regulating the voltage across the load and maintaining the sinusoidal voltage across the load so that load operation is not affected if any quality problem of voltage is there on the load side like a sag swell I mean other similar problem are there.

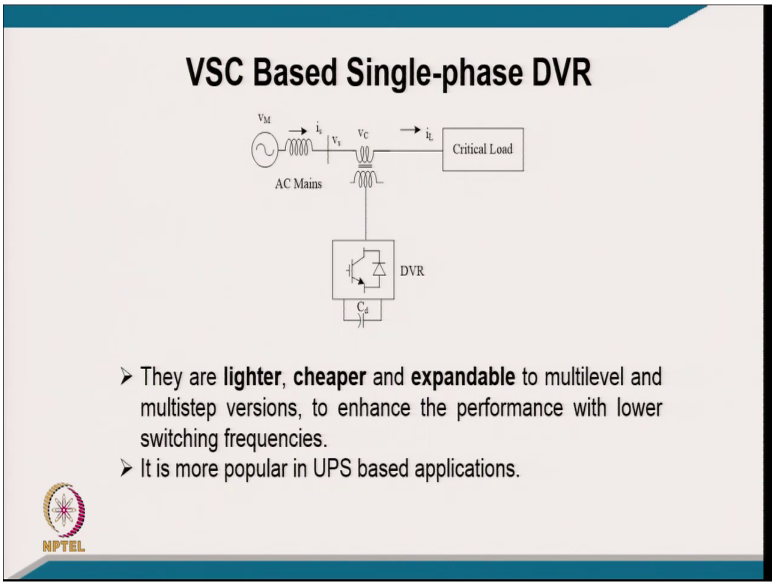
[FL], now this current source converter I mean have a typically you can think about on dc linkage energy storage it needs an inductor. And as a switching device because in current source converter you require your negative voltage blocking capability an IGBT or transistor family either MOFSET or IGBT or typically your BJT do not have a negative voltage blocking capability, [FL] we have to connect a series diode in addition to that to take the voltage reverse voltage block across these.

[FL], when it conducts, it is a loss of both the devices the losses are increased while in conducting and the direct inductor is also costly bulky and lossy compared to the dielectric capacitor which we use in voltage source converter. And of course, we have to this capacitor is also mandatory because these are the PWM voltage or PWM current and you have to make a current in the transformer winding which is a continuous current and sinusoidal voltage. [FL] this capacitor is mandatory for that.

And of course, DVR required sometime transformer does not required. [FL], current source converter have certainly some of the drawback which I mentioned more losses high weight I mean like and typically the bulky structure like. [FL], the they current source converter are considered substantially reliable, but have higher losses and require high value of parallel ac capacitors of this one.

And they cannot be used in multilevel or multistep modes to improve performance in higher rating where the in voltage source converter you can use multilevel as well as multimode type of structure.

(Refer Slide Time: 07:05)



[FL], another structure is like a voltage source converter because here it is shown in brief because we will discuss many structure of this voltage source converter little later. So, we have a supply, and we have a source impedance. And we have a critical load across this we want to keep the voltage even this load may not be drawing a good quality current, but we still need the voltage of good quality across the load regulator voltage.

[FL], this DVR or you can call it the series compensator is supposed to inject the voltage in series to compensate any voltage power quality problem at the point of common coupling like a voltage sag, voltage swell, or voltage notches, spikes, or there is notch, all the kind of this is supposed to become compensated by this with proper control.

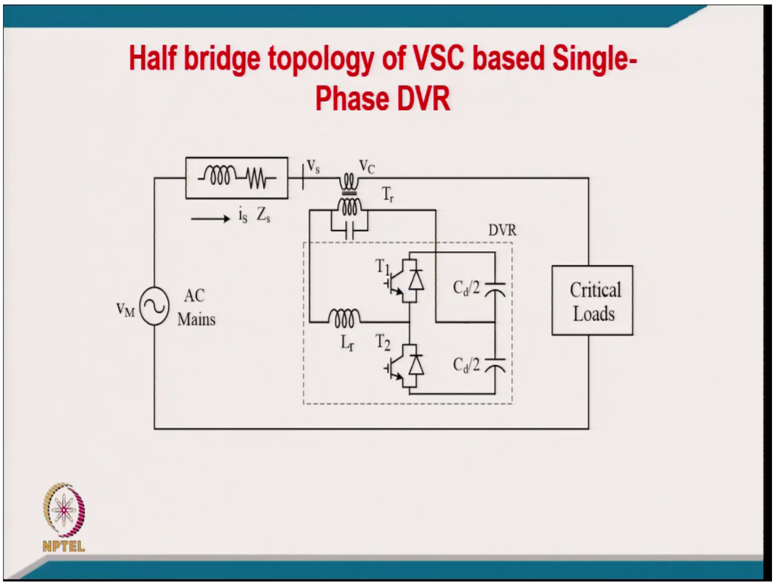
[FL], for this of course, we use since transformer is used, there is no need of interfacing inductor also. We can adjust the leakage reactance of this transformer. And apart from that, of course, you can see the device here it is transistor family support very well with the IGBT with the anti parallel diode to provide the feedback current and as a free link diode. And on dc link, we have a dielectric capacitor which is a very cost effective as well as it has almost negligible losses, and its weight is also quite low.

[FL], in light of these advantages of voltage source converter I mean voltage source converter have taken the lead for even for this DVR applications like. And this is a typical example of single phase circuit. [FL], these with we can call it voltage source based single phase DVR, they are lighter, cheaper and expandable to multilevel or multistep version, and to enhance the performance with lower switching frequency. It is more popular in UPS based application.

(Refer Slide Time: 08:38)

Coming to the another classification like a topology based classification.

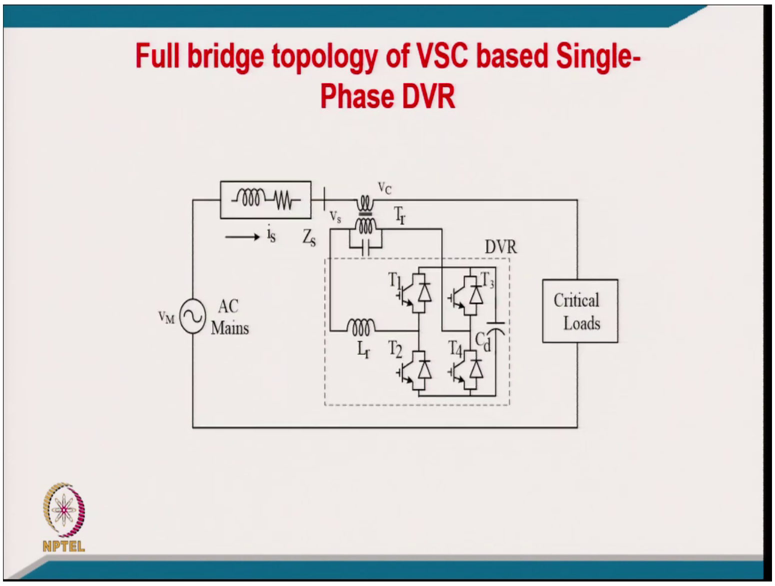
(Refer Slide Time: 08:45)



I mean you can just see here if we give a more detail like maybe like a source impedance, [FL] voltage source converter as we discussed that is better [FL], we can use the half bridge ok is a critical load we have to regulate the voltage across this. Whatever the power quality problem of voltage is there, it is supposed to be mitigated by series compensation provided by series voltage there.

And in the half bridge you of course you save the two devices, but the drawback of this the voltage rating here on the dc link have to be double than the full bridge one. And moreover the entire current have to flow through these dc capacitors and the size of the dc capacitor have to be large or so.

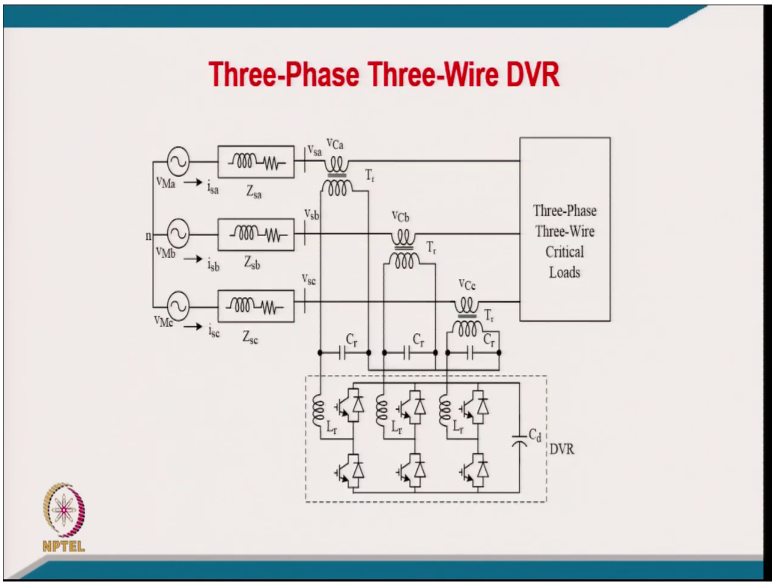
(Refer Slide Time: 09:20)



[FL], these are the typical drawback. And because of this reason we prefer to use the voltage source converter typically in a bridge configuration. This is bridge configuration here. And we have to maintain again a voltage here so that PWM operation is satisfactorily here.

And this I supposed to inject the voltage here, I mean in the line to compensate what are the power quality problems. So, that the regulated voltage and good quality voltage waveform are applied across the critical load like. Now, there are plenty of critical load.

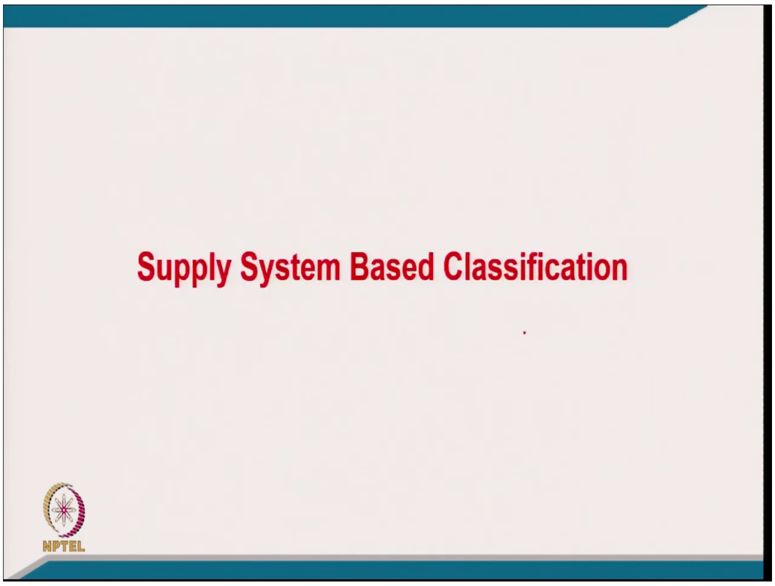
(Refer Slide Time: 09:43)



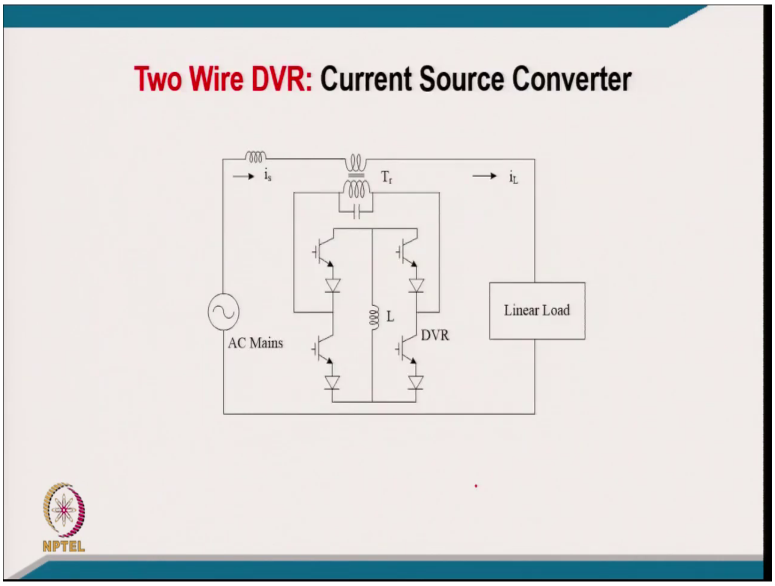
[FL], coming to again the another configuration is basically for three-phase four wire DVR, we have a supply and we have a source impedance. [FL] We have and the this is a three-phase critical load where we want a good quality of voltage with balance voltage sinusoidal voltage regulatory voltage.

[FL], if there are any voltage quality problems here either voltage sags, swell, unbalanced notches, spike, that have to be taken care by this series compensator we call it the DVR. And this PWM I mean along with the transformer this PWM inverter is supposed to inject the voltage with the appropriate quality as well as with the appropriate waveform I mean with self supporting dc bus or you may have a we will discuss those a little later another classification that you must have good quality voltage here.

(Refer Slide Time: 10:27)

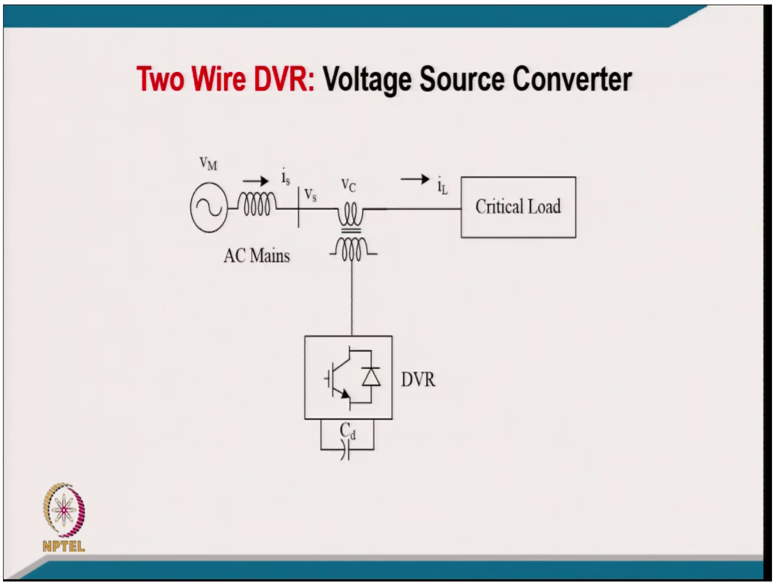


(Refer Slide Time: 10:30)



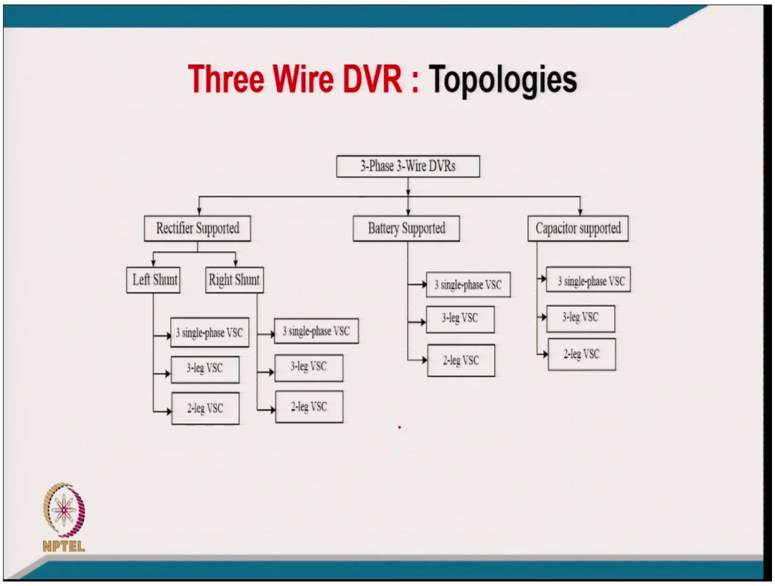
Well coming to supply based classification which we already mentioned it.

(Refer Slide Time: 10:36)



Like it is a single phase I mean two wire DVR with the current source converter we already discussed it across the load. And this is single phase with a voltage source converter I mean DVR.

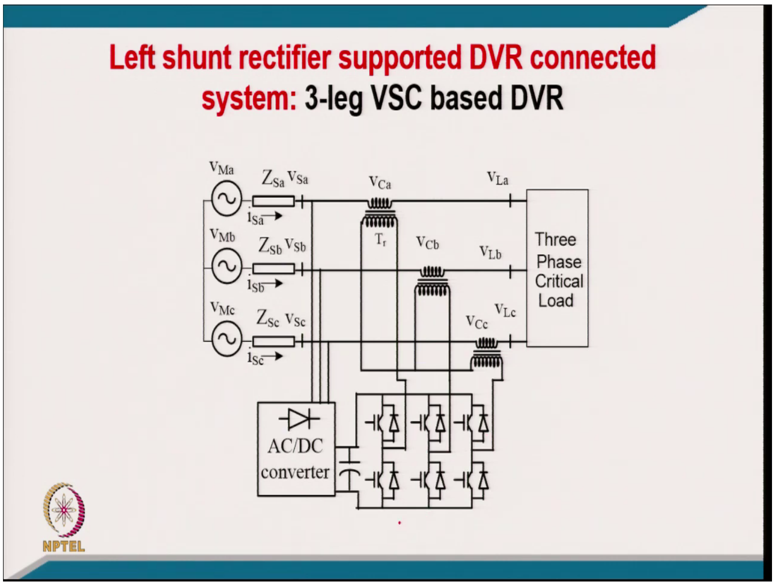
(Refer Slide Time: 10:40)



And then coming to three-wire DVR topology I mean which we classified into different category, of course, this can go the classification in single phase also. [FL], first is the rectifier supported. And now question is dc link how it is supported? [FL], dc link supposed to be that by rectifier we can put the rectifier on left side on supply side, or we can put right side of the typically of series compensator. And of course, we can use the 3 single phase VSC, or 3-leg VSC or 2-leg VSC in both sides of these configurations.

[FL], another how we classified both 3-wire 3-phase 3-wire DVR that we can have a battery supported for all three configuration like 3 single phase voltage source converter or 3-leg voltage source converter or 2-leg voltage source converter, or we can have a self-supported capacitor supported typically of this DVR with the same 3 single phase VSC or single phase 3-leg VSC or 2-leg VSC. [FL], one very important aspect here is I mean you can find it in capacitors supported I mean like as well as rectifier supported you have a some limitations, we will talk about those limitations little later.

(Refer Slide Time: 11:46)

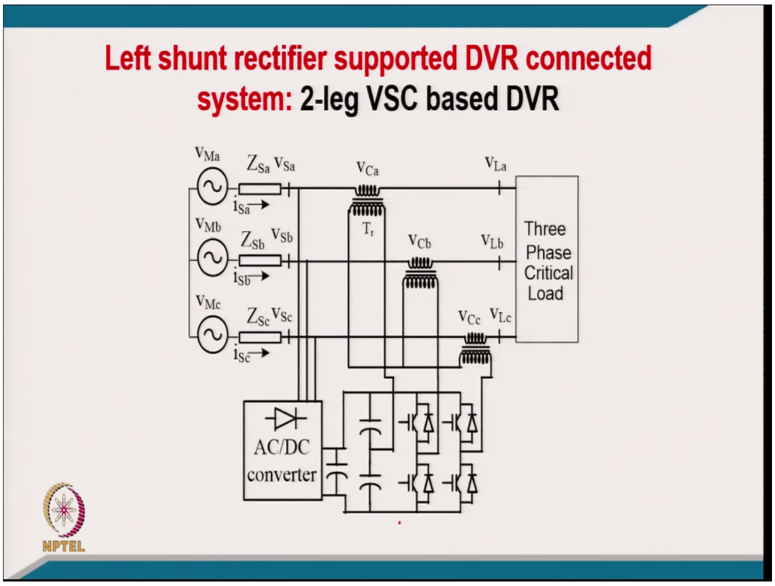


[FL], this is the first case of 3-leg voltage source converter where the rectifier is put on the left side of this DVR. And we are supporting this with the help of extra energy form typically from this rectifier to maintain the dc link voltage. Of course, there is no problem you can put simple rectifier with the proper appropriate voltage here I mean for maintaining these for the transformer size, and the voltage rating have to be accordingly chosen.

The major difficulty of course, in this case is that you can feed the active power you cannot take the active power back here. So, those are the limitations.

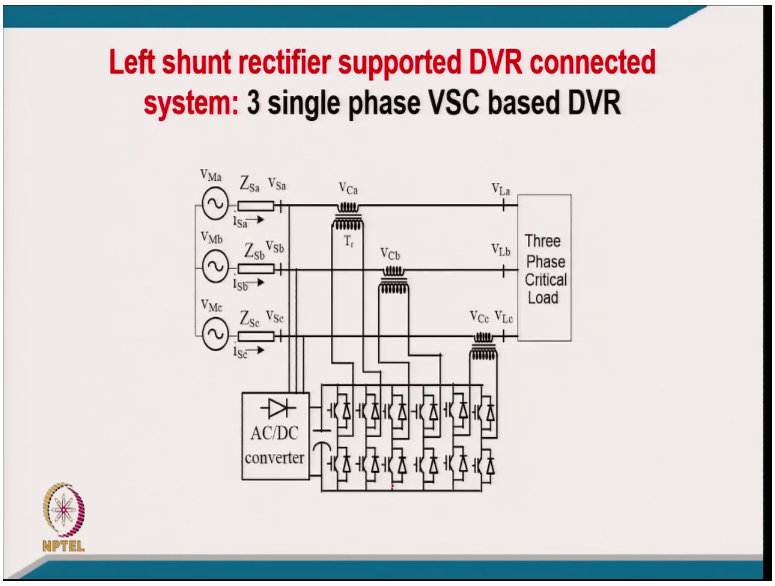
Another is this rectifier, of course, we do not I mean if you are taking a power form here, then certainly this it will draw distorted current that distorted current flows into the line [FL], that is certainly the difficulty here, but this is capable of pi. You can of course, use the reactive power for compensation, but it is small active power you can take in only unidirectional, but it provides the.

(Refer Slide Time: 12:40)



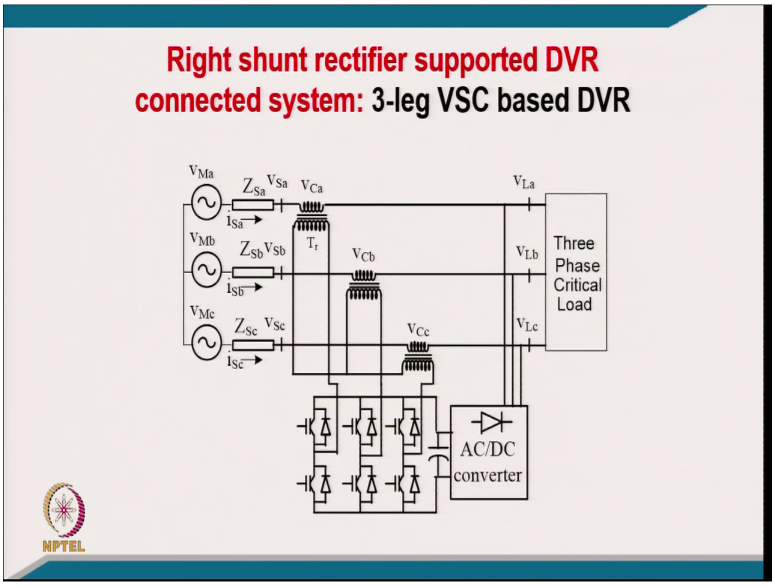
[FL], another one typically is with the 2-leg that was with the 3-leg with the rectifier supported. And this is really 3 single phase with rectifier supported.

(Refer Slide Time: 12:45)



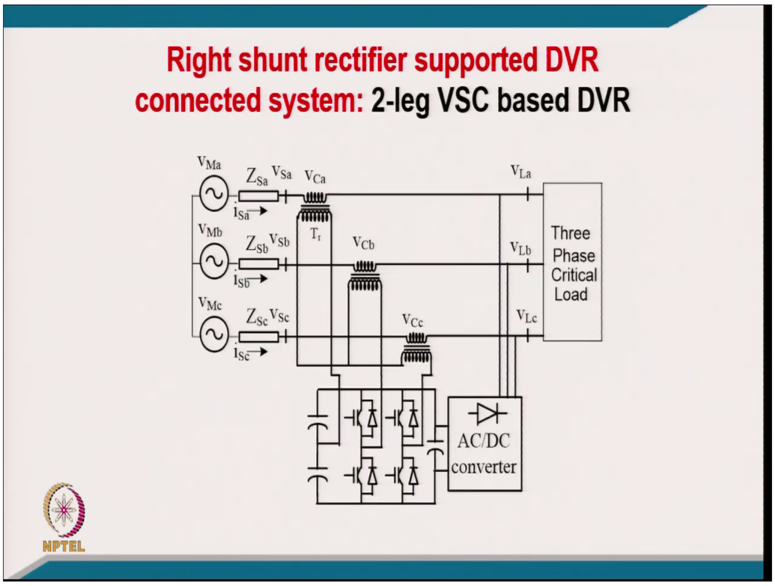
[FL], you have a rectifier supported with 3-leg independent control for all three phase for voltage injection because you may require the separate voltage injection for all three lines separately because the unequal voltage or unbalanced voltage maybe here we would like to balance the voltage across three-phase critical load.

(Refer Slide Time: 13:05)

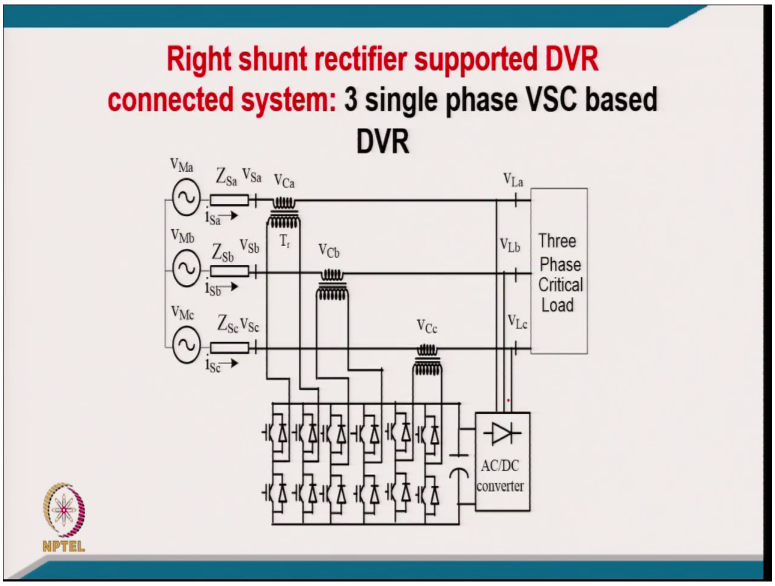


And then this is that if you put the rectifier on load side, I mean like you can have a I mean the rectifier support during this case. Well, this sometime the some of the topology get even the dc link can be of the load that we will talk a little later in some of the maybe series active filter or so, [FL] it can be the rectifier on the left side with the 3-leg, or it can be with the 2-leg rectifiers on the right side.

(Refer Slide Time: 13:26)

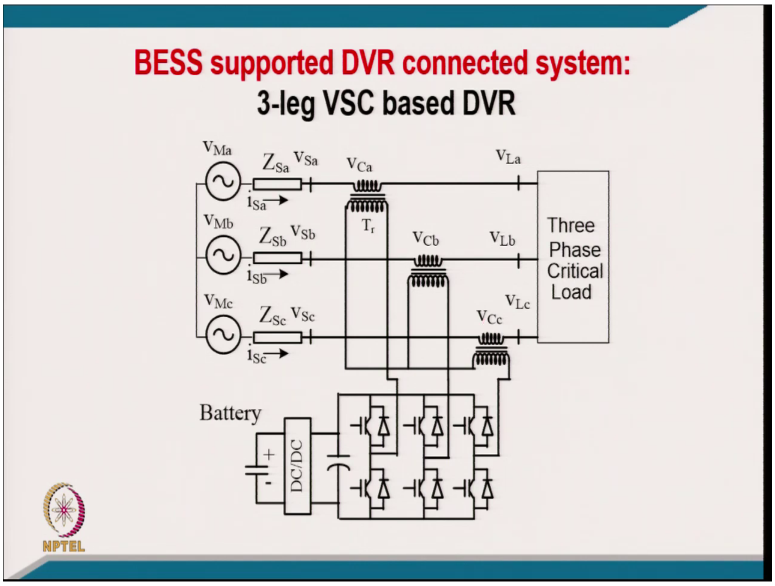


(Refer Slide Time: 13:29)



Or it can be 3 single phase if there are rectifier on the typically right side of the DVR ok.

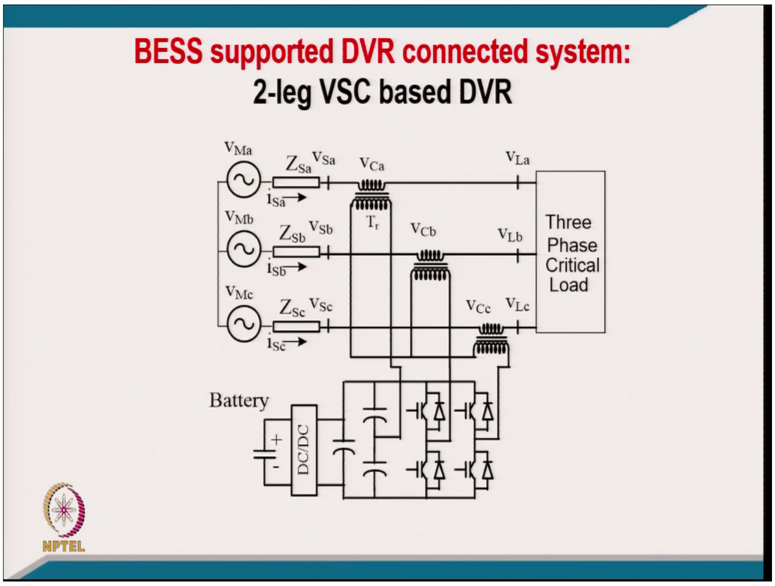
(Refer Slide Time: 13:35)



Or you can have a battery supported. [FL], now battery you can connect either dc link directly or you can connect the battery with the dc-dc, that dc-dc along with the dc-dc converter it allow the two benefit – one is that battery voltage can be at optimum level, the another benefit with this dc-dc converter is that you know to allow the second harmonics to go to the battery or to flow into that [FL] that benefit you can have with the battery. Of course, you have to afford in size and cost, and weight of the battery and maintains requirement of battery.

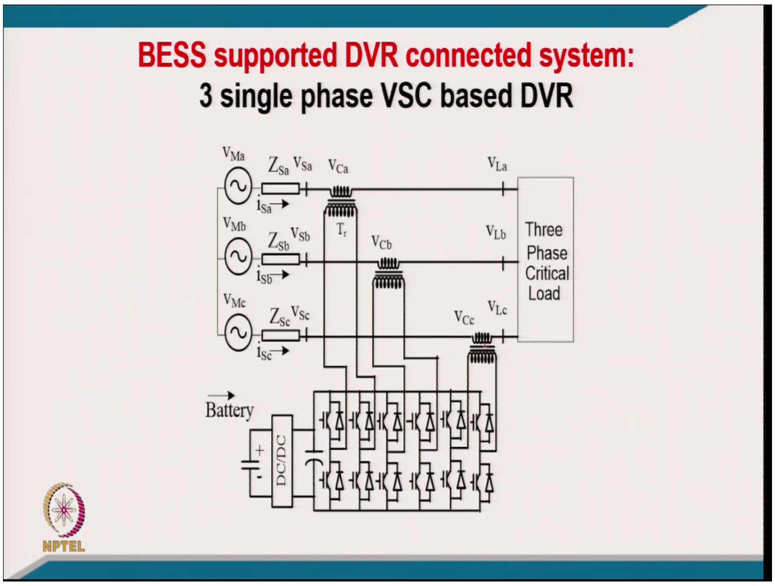
But the very benefit that you can inject the voltage at any angle now I mean because you can take the power, you can feed the power. [FL], you can inject and of course, reactive power you can generate from the converter, [FL] you can inject the voltage at different angle. And you can have a very versatile operation of this 3-leg voltage source converter DVR.

(Refer Slide Time: 14:21)



Similarly, you can have for 2-leg also which is not much because I told you the entire third current flows into the capacitor and capacitor. This capacitor becomes quite bulky.

(Refer Slide Time: 14:29)

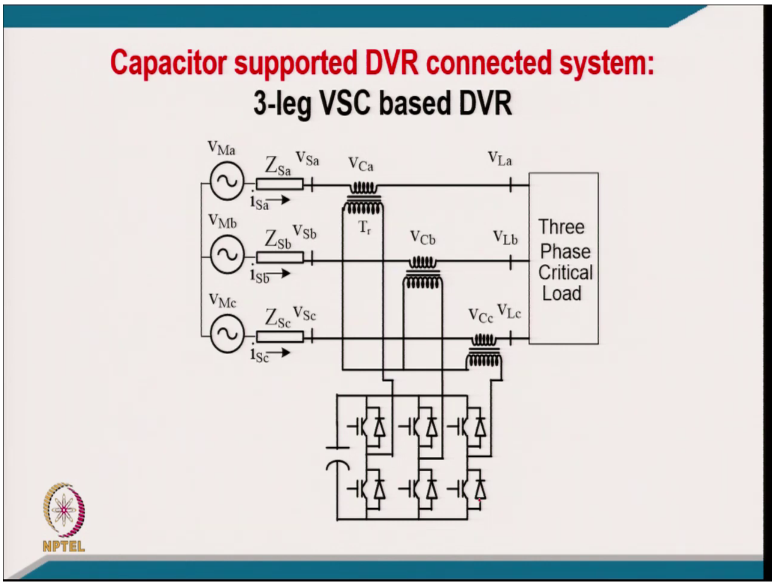


Or, or you can have a 3 single phase one. [FL], you can have a very independent control and this (Refer Time: 14:36) you can design at quite different voltage low voltage also. And accordingly you can select the battery voltage with dc-dc converter like I mean or so. [FL], this becomes very interesting configuration for practical application.

And battery rating need not to be very high if you are not circulating large amount of active power, you are not using for compensation. If you are managing with the compensation with the help of active power reactive power only on during dynamics only you need some kind of active power which you can, but the charging of the battery and discharging of the charging of the battery also have to take place on the same circuit.

[FL], maybe under normal operation, I mean, you have to take some active power to charge the battery and during dynamics you have to take this back. So, that under dynamic condition also you are able to regulate the voltage very effectively in this configuration like.

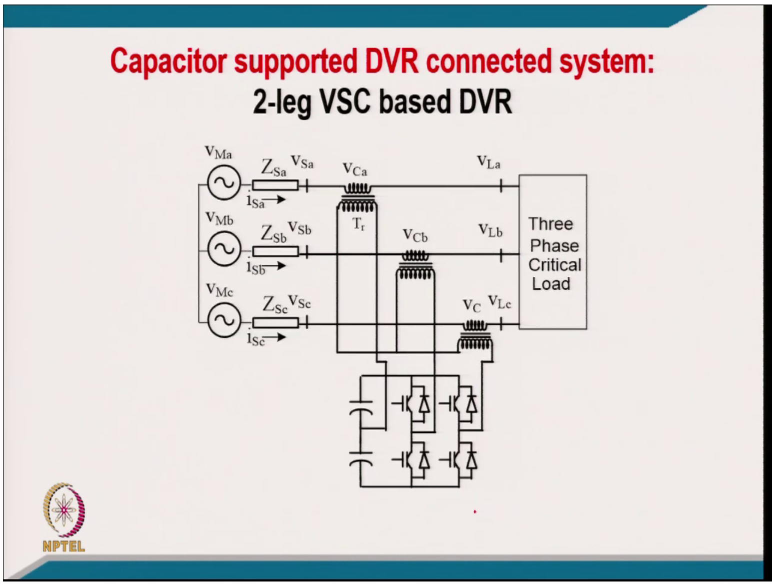
(Refer Slide Time: 15:17)



This is with the typically you can call it the capacitor supported self-supported, capacitor supported. [FL], we take a small amount of active power to support the this voltage across the dc link across the capacitor as we have done in case of DSTATCOM. But you can understand I mean the control become reasonably involved in this case with capacitor supported one.

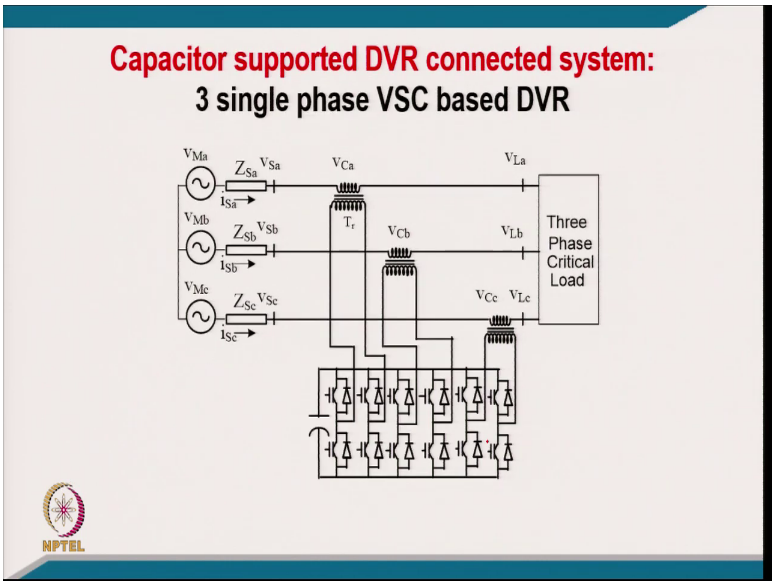
And of course, you can you cannot just to inject the voltage except for very short period you can take some power, some energy from the capacitor, but not regularly again you have to regulate otherwise PWM control will not be successful. Well, but reactive power injection you can certainly regulate the voltage, and you can maintain even a unbalanced voltage also can be injected with the this.

(Refer Slide Time: 15:57)



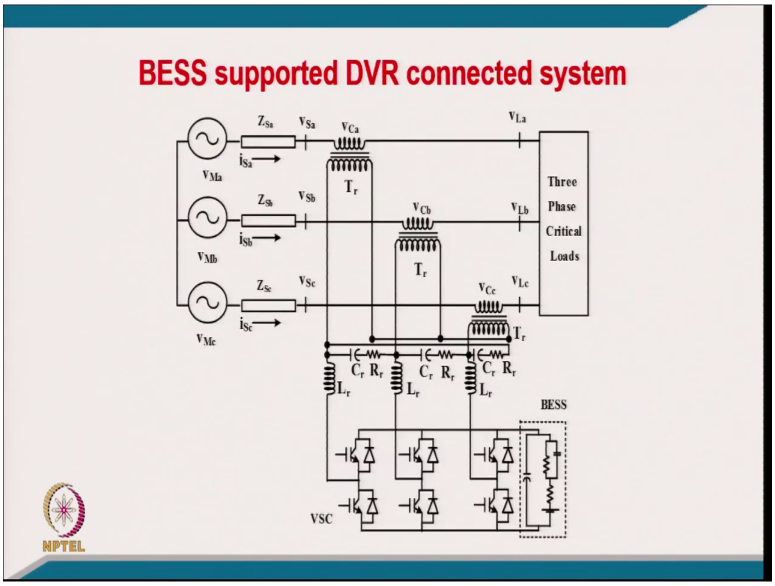
You can use 2-leg also, but I told you the limitations of 2-legs. The voltage rating increases substantially high apart from because each I mean I have to take a typically kind of phase voltage.

(Refer Slide Time: 16:08)



And then 3-leg VSC with the capacitor supported. [FL], this is quite versatile and can be a designed at low voltage. And you can inject it with the self supporting dc bus of this 3 single phase typically of DVR or series compensator.

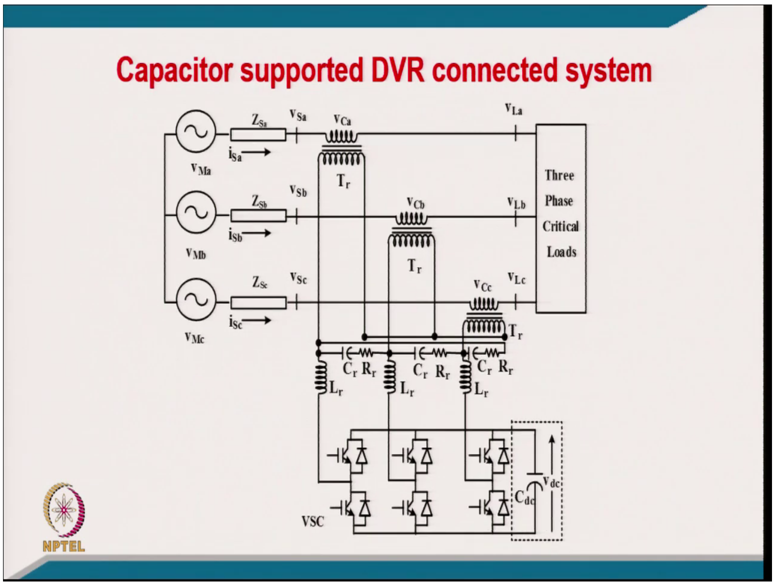
(Refer Slide Time: 16:20)



Or another is that you can support directly on the battery of the dc link like I mean BESS supported we can call it. And along with the capacitor here [FL] battery can be charged or can be discharged because for very short period you can take substantial energy also I mean during dynamics because we call it dynamic voltage restorer it means during dynamics also you might have a voltage typically kind of fluctuation sag, swell, or a transient phenomena.

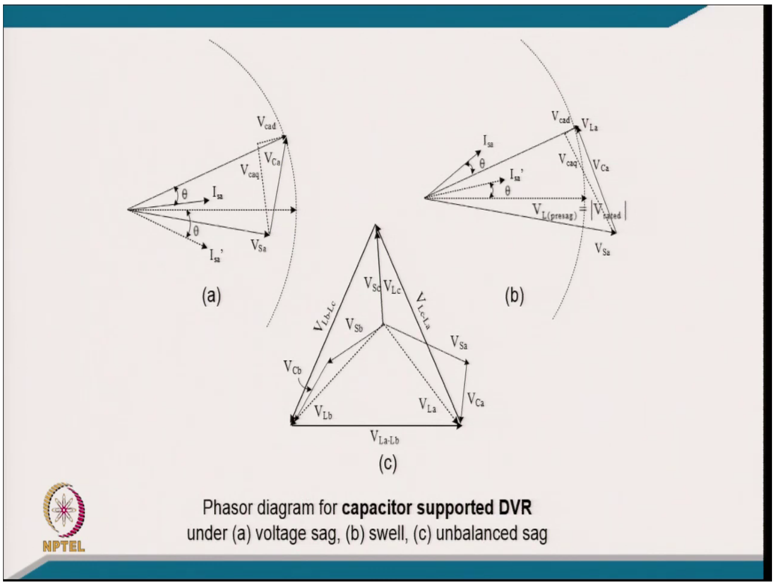
[FL], you require some burst of energy for the compensation also so that this voltage are not affected during sag and swell. So, during swell, it had to take energy and sag it had to feed energy along with the reactive power for the compensation like I mean or so.

(Refer Slide Time: 16:57)



Well, this is like a capacitor supported I mean typically example with the proper component value that you have interfering inductor you have ripple filter. Of course, I told you that if you are using leakage reactance, then this capacitor ripple filter goes across the other secondary side I mean because we cannot put otherwise I mean like on that [FL] that capacitor supported a DVR like I mean.

(Refer Slide Time: 17:18)



[FL], now coming to very purpose that how typically you can think about the different cases I mean here is the phasor diagram of capacitor supported DVR. [FL], for voltage sag condition I mean this is the typically voltage sag we consider this is the rated voltage, but there have been a sag.

[FL], what you have to do? Now, you have to inject the voltage, I mean, and typically this is the current original current, the load current with the voltage. And now I mean current will go this way [FL] you have to inject the capacitive I mean current. This is quadrature axis; this is direct axis.

And you have to maintain this voltage which is the rated could have been with before sag. This was the voltage. After that this is the voltage during the sag, this is the voltage and you have to regulate so this the voltage, and that is possible only when you are able to inject the voltage at 90 degree I mean from the current like I mean because this voltage should be 90 degree; otherwise you will require active power.

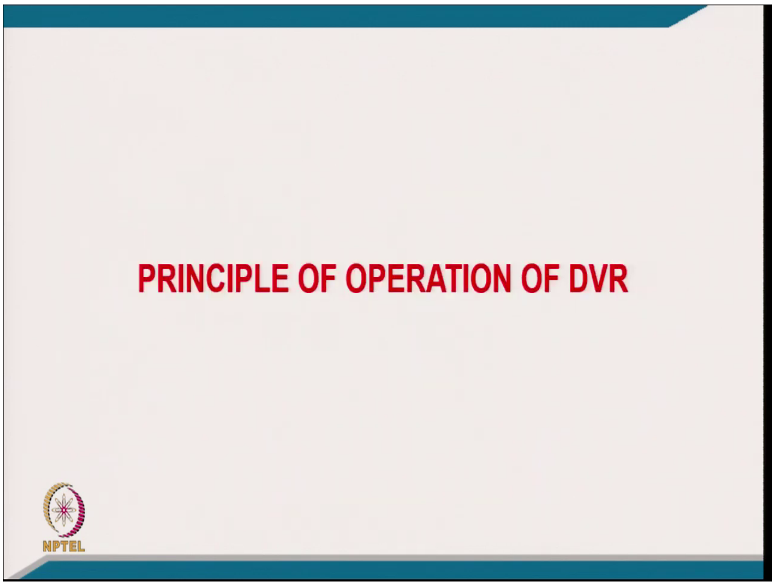
Because it is a capacitor supported, you can have a reactive power, but not the active power. [FL], that is the reason you have to have the this current should be 90 degree with the voltage injection 90 degree with this which can behave like a either inductive behavior or capacitive behavior as far as injection of them.

[FL], the second case is like a voltage swell [FL] voltage your voltage have increased ideally voltage should be lower like this, but suddenly voltage have increased more, [FL] you have to reduce the voltage by again injecting the voltage. But this voltage injection have to be at again exact 90 degree for purpose of your only reactive power injection not the active power because active power in capacitor supporter will not be there.

But, of course, for voltage regulation you may require little active power that have to be accordingly taken care in the way we had diagram also or in three-wire, you might have unbalanced sag, you this is unbalanced sag means, these are unbalanced sag here, but for across the load how will you regulate? You have to inject the voltage here, you have to inject the voltage here, then the line voltage will be a balanced and regulated voltage.

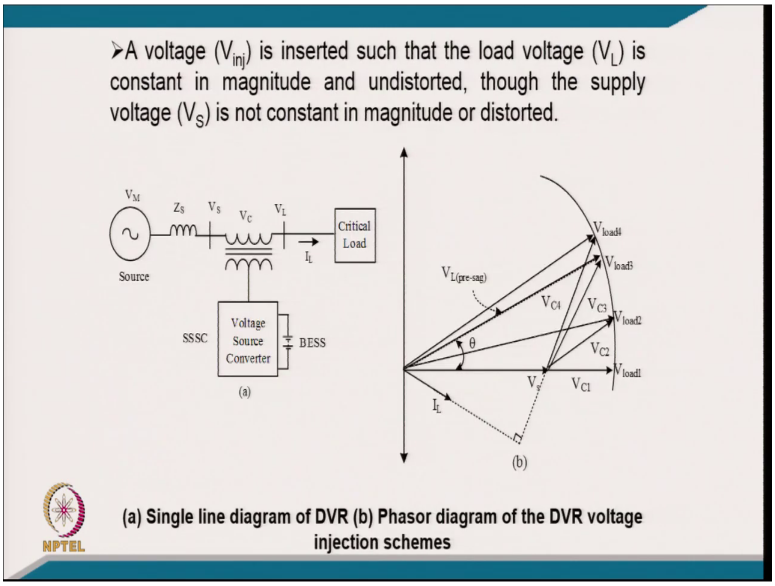
[FL], this voltage are required to be injected in two line only not necessary typically in case of three line, one may be as it is other two line [FL] that also give you a concept that the injection can be in two line to regulate the typically the voltage in unbalanced voltage conditions like I mean or so. There have been some publications corresponding to that like I mean.

(Refer Slide Time: 19:28)



[FL], coming to principle of operation of this DVR and dynamic voltage restorer or series active series compensator.

(Refer Slide Time: 19:39)



I mean a voltage we injected is inserted such that the load voltage is constant in a magnitude and undistorted, though the supply voltage is not constant and magnitude or maybe distorted. [FL], the very principally we have a source voltage, we have source impedance. This voltage may not be regulated voltage ok.

It might be having all the voltage based quality problems, but this voltage should be regulated across the critical load. And we already discussed the critical load lot of process where even a small sag may cause the process to interrupt or the protection may trip.

And by putting this appropriate voltage maybe you can keep the battery also because you can inject the voltage at different angle even during dynamic condition. [FL], you can inject the voltage at a pre put angle with proper control [FL] that is virtually you can call it like how typically the DVR work properly.

And this is the different conditions how the principle of operation why we have considered the battery? Because you will be able to inject the voltage at different case like. [FL], here you have a different condition of the load also. [FL], you can say originally like this is the voltage ok.

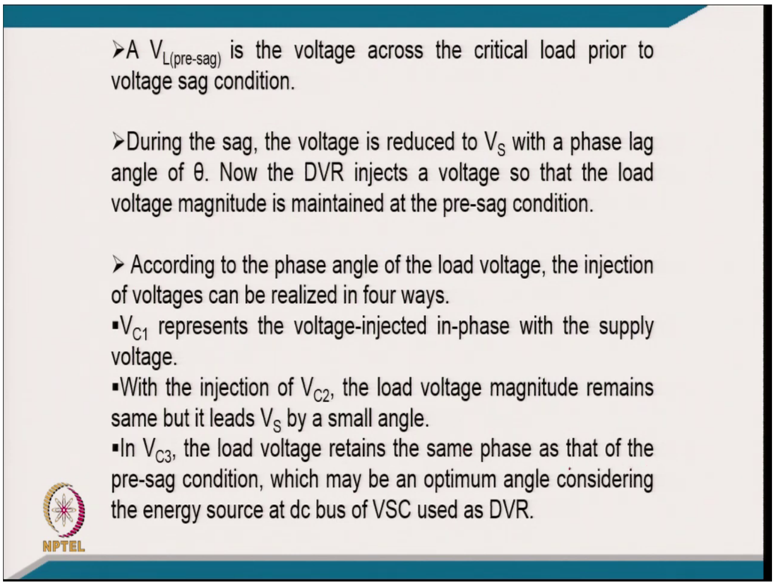
You can inject this voltage in phase ok which require active and reactive power, [FL] I mean you can have a I mean the drop of this voltage in at that perpendicular to the current or in phase with the current [FL] in phase will be correspond to active power quadrature will be reactive power.

[FL], you have to inject this voltage or you have to inject this voltage, or you have to inject this voltage or this voltage which give will the regulated voltage or so. [FL], depends like how you will be able to use the rating for given condition to regulate the voltage across the load.

[FL], there happened I mean you have a I mean typically many conditions corresponding to depending upon the I mean the voltage injection at what angle you are going to keep. [FL], this is like a pre sag, I mean this is a voltage sag how they have been. And after the sag you have to [FL] pre sag means this is where the voltage earlier.

And now after the sag I mean this voltage have reduced virtually this. And now you are going to inject for different conditions to regulate the voltage, so that the voltage across here the load which we call it is all regulated. And these are the injected voltage like V C1, V C2, V C3 or typically like V C1, V C2, V C3, and V C4, so that the load voltage are regulated like. [FL], single diagram and phase diagram of DVR voltage injection.

(Refer Slide Time: 21:58)



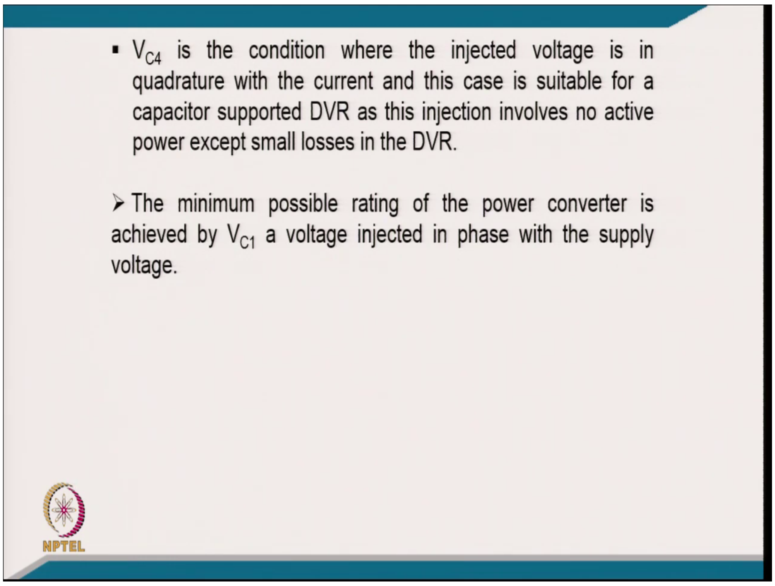
[FL], a pre sag is the voltage across a critical load prior to voltage sag condition. [FL], during the sag, the voltage is reduced to V S that is virtually you can call it like a typically this one, it reduced to this one. Earlier it was typically this, this one I mean we call it pre sag, this is the load voltage.

And now it is reduced to this. And now we have to see how we will be able to typically during the sag the voltage is reduced to V S with a phase angle of theta. And now the DVR inject the voltage inject a voltage, so that the load voltage magnitude will maintained at the pre sag condition.

And accordingly to the phase angle of the load voltage, the injection of voltage can be realized in four ways. [FL], V C1 represents the voltage-injected in-phase with the supply voltage. The injection of V C2 the load voltage magnitude remains the same, but it leads by V

S by a small angle. And V C3 the load voltage retains the same angle as the pre-sag condition; it may be an optimum angle considering the energy source at dc bus of VSC used DVR.

(Refer Slide Time: 23:02)



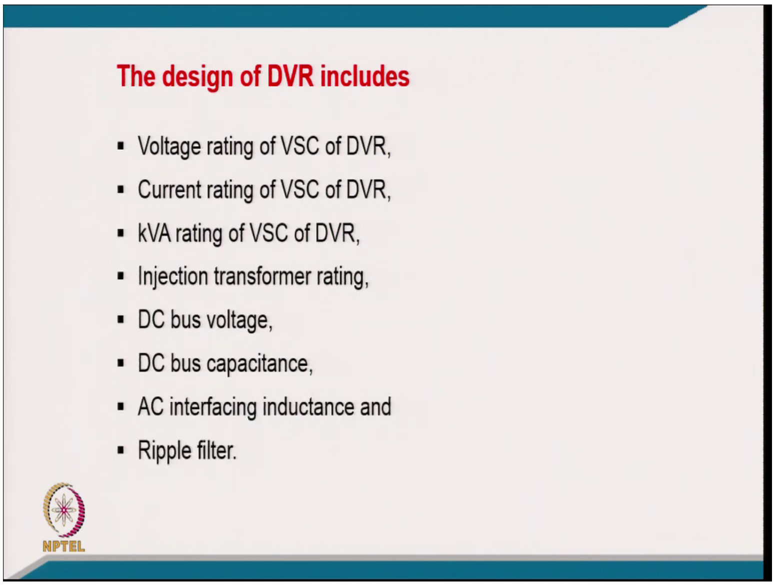
And the V C4 is the condition where the injected voltage is in quadrature with the current and this case is suitable for capacitor supported for a DVR, and this injection involved no active power losses in the DVR. [FL], this is the condition I mean you look into if it is a typically this condition.

Because this is at 90 degree from the current [FL] it needs reactive power only like kind of things like I mean [FL], that is a fourth condition. [FL], the minimum possible rating of the power converter achieved by V C1 when voltage is injected in phase with the supply voltage because that is directly algebraic sum of them does not matter what active and reactive power it needs or so.

(Refer Slide Time: 23:40)

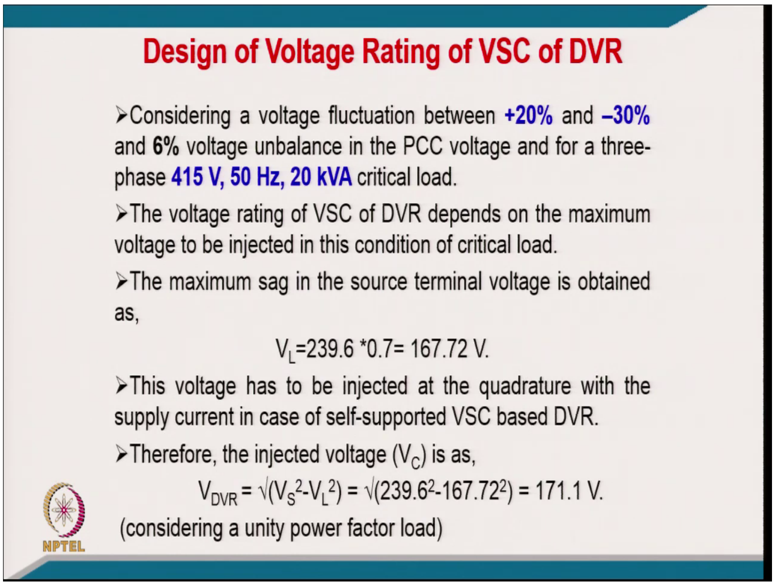
[FL], coming to like analysis and design of this DVR.

(Refer Slide Time: 23:47)



The design of DVR includes the voltage rating of voltage source converter of DVR, current rating of voltage source converter of DVR, and estimation of kVA rating of the voltage source converter of DVR, and the injection transformer rating, then DC bus voltage rating, DC bus capacitance rating, and AC inductor interfacing, and ripple filter rating.

(Refer Slide Time: 24:09)



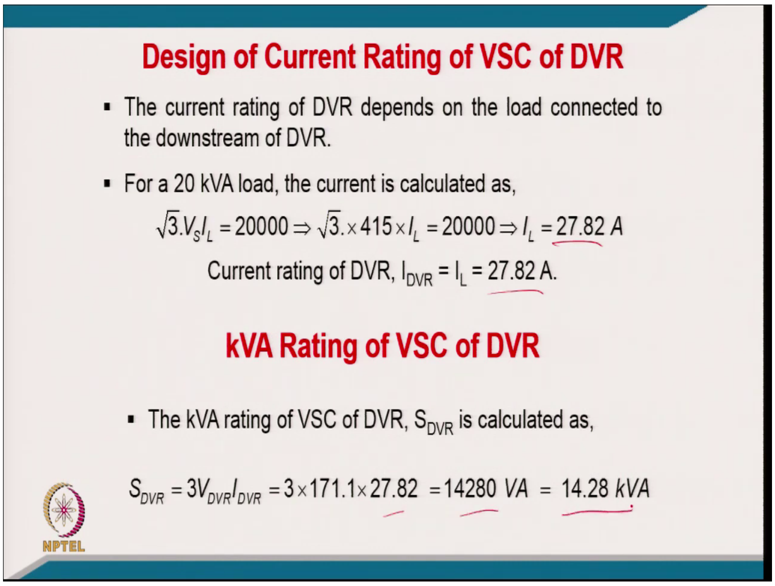
[FL], coming to the design of voltage rating of the voltage source converter. [FL], considering a voltage fluctuations between plus 20 percent and minus 30 percent, and a 6 percent voltage unbalance in the PCC voltage for a three-phase 415 volt 50 hertz to 2 kVA 20 kVA load for which we are designing critical load for which we are designing these DVR.

[FL], the voltage rating of VSC of DVR depends on maximum voltage to be injected in this condition of critical load. The maximum voltage sag in the terminal voltage is obtained as your typically load voltage will be 239.6 multiplied 7, [FL] it comes one sixty two point 167.72 volt.

And now this voltage have to be injected at the quadrature with the supply in case of self supporting dc bus DVR, therefore, injected voltage will be your V S square minus V L. So, this is you want you are calculating the DVR voltage. [FL], this is the supply voltage this is the load voltage ok or we want this voltage across the load, but this has gone to sag.

[FL], this is the voltage at which are injecting quadrature because we want self-supported means we want only reactive power the voltage to be injected by the reactive. [FL], this is the rating voltage rating of DVR considering the unity power factor load for just most simplest case.

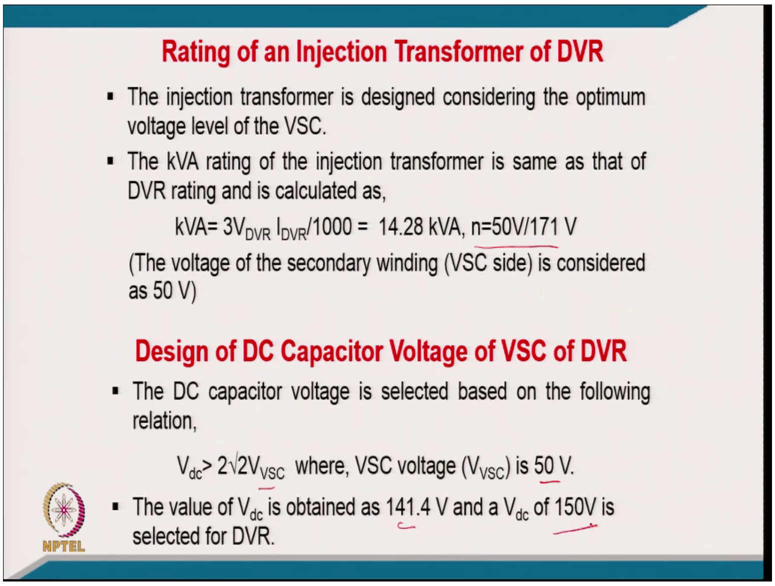
(Refer Slide Time: 25:23)



And the current rating of DVR depends on the load connected to downstream of the DVR or you can call it current rating of DVR is same as the load current rating. [FL], we have a 20 kVA load and current can be calculated from this relation root three V S I L.

And from this, we get the I L equal to 27.82 ampere. [FL], current rating of DVR will be also the same. And the kVA rating of the DVR will be typically of your 3 times the voltage injected by DVR and current rating of DVR 3 into 171.1 into 28 point, and this comes 14 point 14280 VA and 14.28 kVA.

(Refer Slide Time: 26:02)



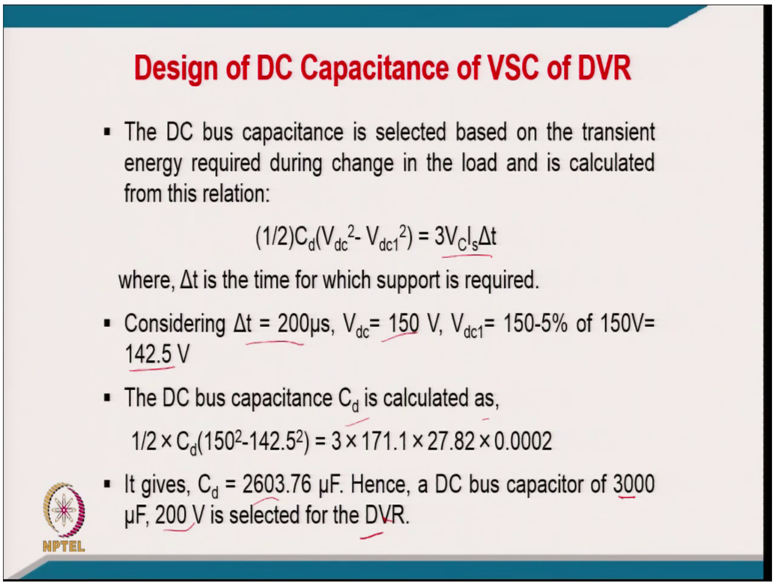
[FL], rating of injection transformer, I mean the injection transformer design considering the optimum voltage of the voltage source converter, and kVA rating of the injection transformer is same as that of DVR rating which is calculated earlier 3 V DVR by 1000 [FL] 14.28 kVA.

And the typically the turns ratio we can select because this is the voltage to be injected on line side, and this is the voltage we want on secondary side on which we are putting the inverter.

[FL], voltage rating of secondary or winding or VSC is considered here 50 volt. And now from this, we can design the value of a capacitor of voltage source converter.

[FL], the dc link voltage now dc link capacitor voltage is selected based on the following relation that V dc equal to 2 root 2 into VSC, where VSC is the typically ac voltage is 50 volt and value of V dc will be correspond to 141, and we can round off this to 150 volt of the dc link on inverter side.

(Refer Slide Time: 26:57)

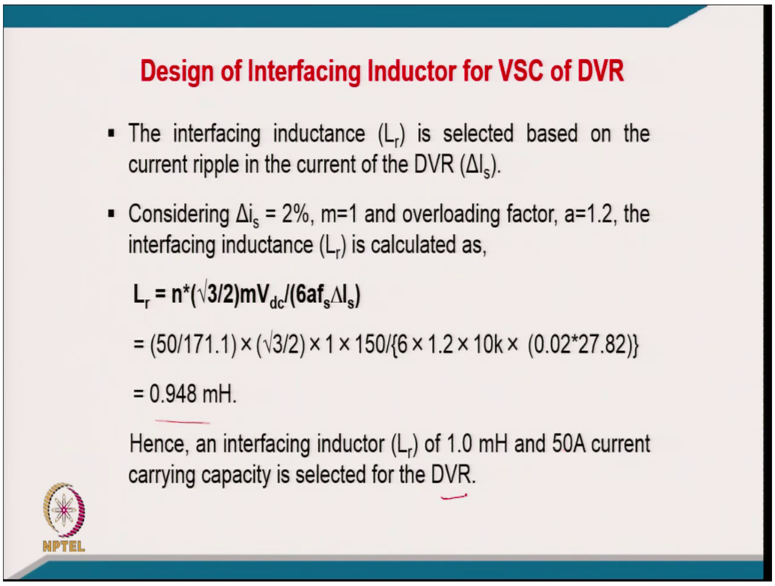


Coming to dc link capacitor of this voltage source converter of DVR with the transformer. [FL], dc link voltage is selected based on the transient energy required during change in the load and is calculated as a half C v half C d in bracket V dc square minus V dc1. And this is the minimum voltage. This is a nominal voltage. And then the energy have to come certainly from 3V c I s into delta t. [FL], delta t is the time for which you require the support required.

[FL], considering the typically delta t 200 microsecond V dc 150, and 5 percent reduction in this [FL] allowed let us say we allow 5 percent reduction in dc link voltage to take the energy back during dynamic condition. [FL], it comes 40, 142.5 volt. And dc link capacitor C d is calculated as from this relation, and it comes 2603.76.

And the dc link capacitance round off (Refer Time: 27:51) 3000 microfarad of rating of 200 volt can be selected for DVR or so, because during dynamics it can go the voltage during 150 volt, more than 150 volt or so.

(Refer Slide Time: 28:01)

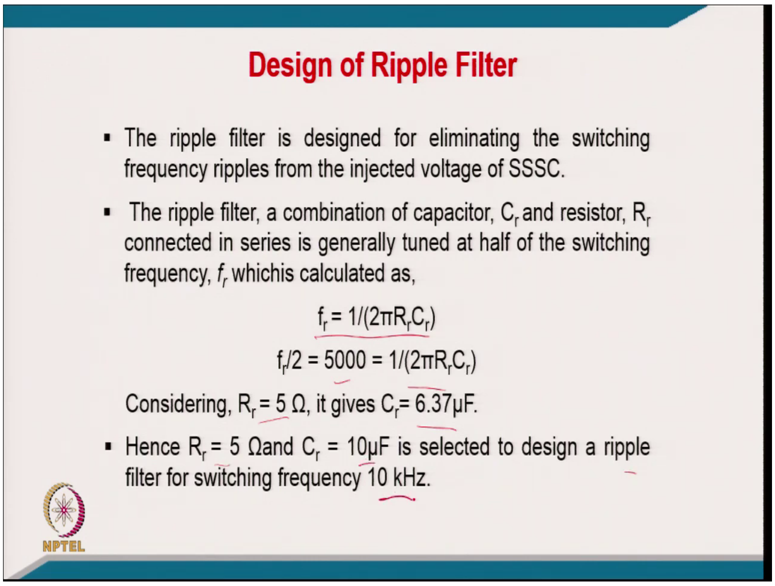


[FL], coming to the design of interfacing induction inductor for voltage source converter of DVR. The interfacing inductance is selected based on the current ripple in the current of

DVR. And considering the current ripple of 2 percent with a modulation index 1 and overloading one factor of 1.2, the interfacing inductance can be calculated from this relation.

Putting the value it comes like a typically 0.948 milli henry which can be of course adjusted by leakage reactance of injection transformer also. And hence an interfacing inductor of 1 milli henry 50 ampere current carrying capacity is selected for the DVR.

(Refer Slide Time: 28:38)



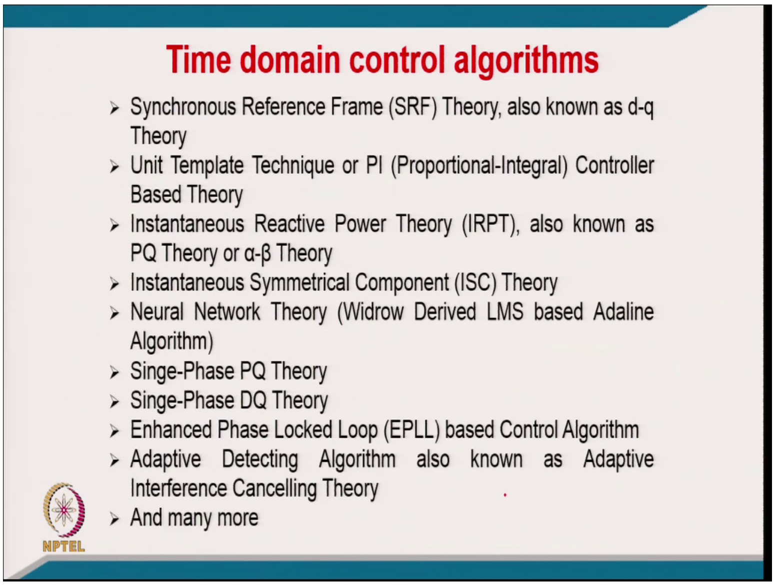
Coming to the design of ripple filter. The ripple filter design for eliminating the switching frequency ripple from the injected voltage of this DVR or series synchronous steady compensator. [FL], ripple filter is a combination of C r and resistance R r connected in series generally tuned at half the switching frequency, f r.

And that is half the switching [FL] considering 5 kilo hertz half the [FL] we can find out typically I mean from this value [FL] selecting the resistance of 5 ohm. And this is easily available we can get the capacitance value of this. And then we can select the next value [FL] coming to R r equal to 5 ohm, and C r 10 ohm is selected to design a ripple filter for switching frequency of 10 kilohertz.

(Refer Slide Time: 29:21)

Coming to the typically the control of DVR.

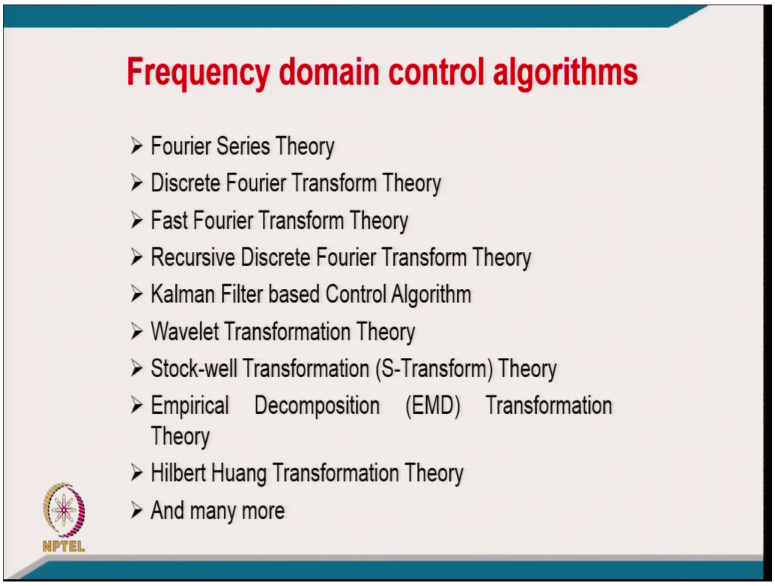
(Refer Slide Time: 29:25)



I mean the we already discussed the controlling DSTATCOM, [FL] we can classify the control algorithm on the same basis like time domain control algorithm, like a synchronous reference frame theory, also known as d-q theory, Unit Template Technique or PI Controller based Theory, or Instantaneous Reactive Power Theory also known as PQ theory or alpha beta theory.

Instantaneous Symmetrical Component Theory, and Neural Network based Theory Widrow Derived LMS based Adaline Algorithm, or Single-Phase PQ theory, Single-Phase DQ theory, Enhanced PLL based Control Algorithm, or Adaptive Detecting Algorithm also known as the Adaptive Interface Cancelling Theory or many more. [FL] there are plenty of algorithms are available now in the literature which can apply these DVR.

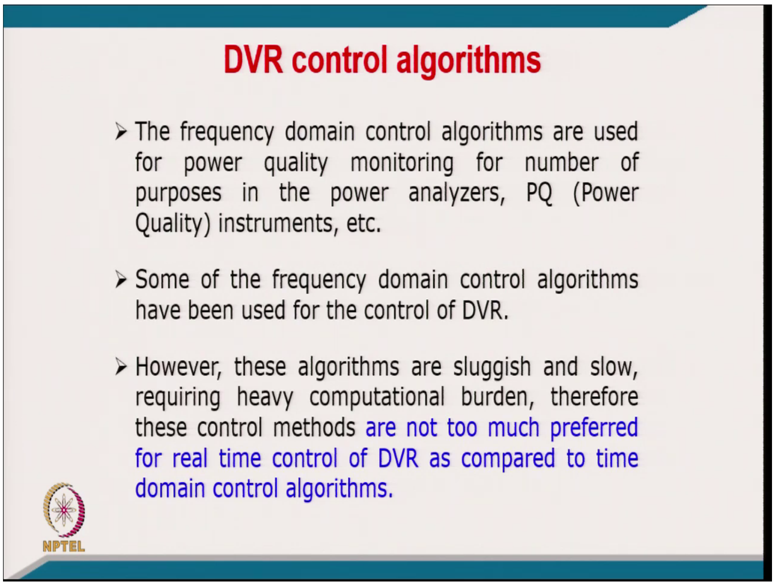
(Refer Slide Time: 30:05)



Similarly we have a frequency domain control algorithm also like a Fourier Series Theory, Discrete Fourier Transform Theory, Fast Fourier Transform Theory, Recursive Discrete for Theory, Kalman Filter based Control Algorithm, Wavelet Transform based, Stock-well Transformation based Theory, and Empirical Decomposition Theory, and Hilbert Huang Transformation based Theory, and many more.

[FL], these are frequency based of course, they are slow, but people have modified because now processor available very far [FL] even we can implement these also on this control of this like I mean.

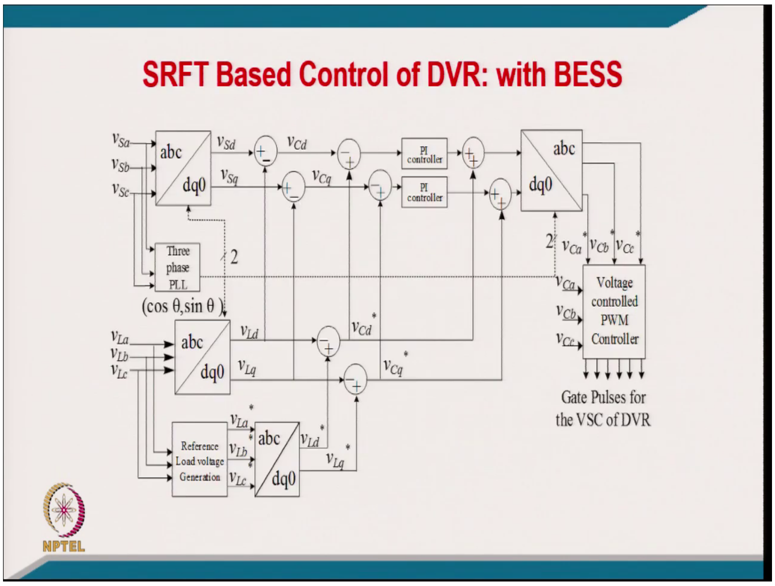
(Refer Slide Time: 30:35)



[FL], coming to like a DVR control algorithm. The frequency domain algorithms are used for power quality monitoring and number of purpose in the power analyzer, power quality instruments, etcetera. [FL], some of the frequency domain control algorithm have been used for the control of DVR.

However, these algorithm are sluggish and slow because requiring heavy computational burden, therefore, these algorithm methods are not too much preferred for real time control of DVR as compared to the time domain control algorithm. [FL], frequency domain control algorithm are used for power quality monitoring and power analyzer and some of the frequency domain used.

(Refer Slide Time: 31:15)



[FL], these typically the you can call it the synchronous reference frame theory based control algorithm of DVR with battery support with DVR. [FL], what I mean if we look into this algorithm, the very purpose of DVR to regulate the voltage across the load. [FL], here we have a source voltage we are sensing and from PLL of this, we are getting either PLL or we can take a template.

[FL], we are getting cos theta sin theta which is required for transformation, I mean both sides I mean we require a transformation here, we require transformation here, and we require final transformation here. You can understand the transformation is required in three times in synchronous reference frame theory.

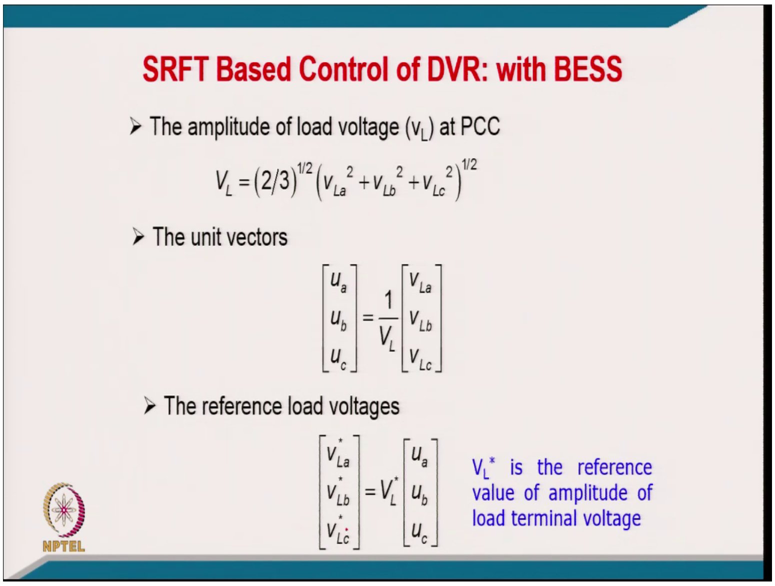
So, we take the source voltage I mean like you can just see the source voltage we have a sense load voltage [FL] we convert dq. And the dq, we get the source minus the load voltage. So, this is the typically equivalent to we can call it compensating voltage, and we have a form load voltage we can find out like a reference voltage we have ok.

From template, we can get a reference voltage. And then from reference, we can have a dq component. And we can add form load, [FL] we will get a compensating voltage here. And this compensating voltage with the difference of this, we can have typically controller here pi controller to regulate these voltage. And then after output of this, we add these voltage feedback, we call feedback.

[FL], we are getting virtually to be injected voltage here in dq and with the transformation back, we get the compensating voltage which we have to have a compensating voltage. And these are the sensed voltage across that DVR. And we get the gating pulses of DVR.

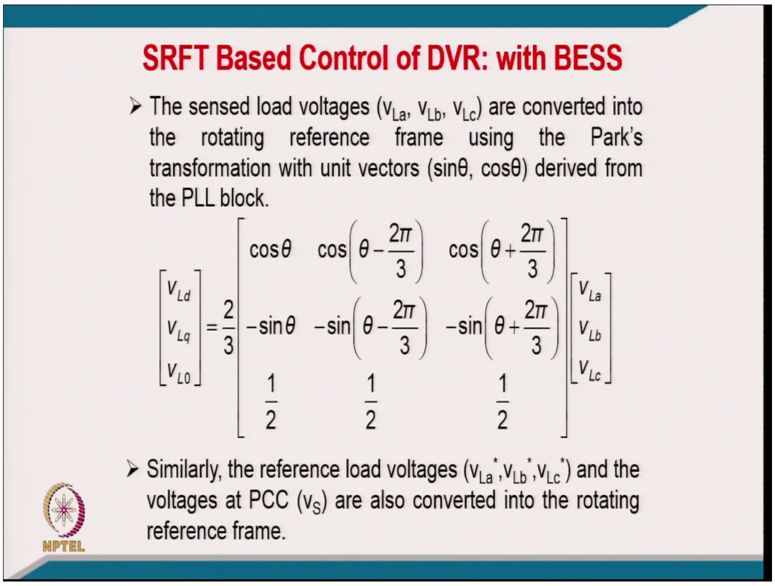
So, this is how we modify this SRFT theory – Synchronous Reference Frame Theory for control of DVR with battery supported. Why we are considering here battery supported? Because we can inject the typically the voltage at any angle. We are not considering the angle here because we are not sensing the typically the current load current, we are just only sensing the all load voltage, and then the source voltage, and then even the voltage of the compensator like [FL] these totally on control on voltage based theory like.

(Refer Slide Time: 33:14)



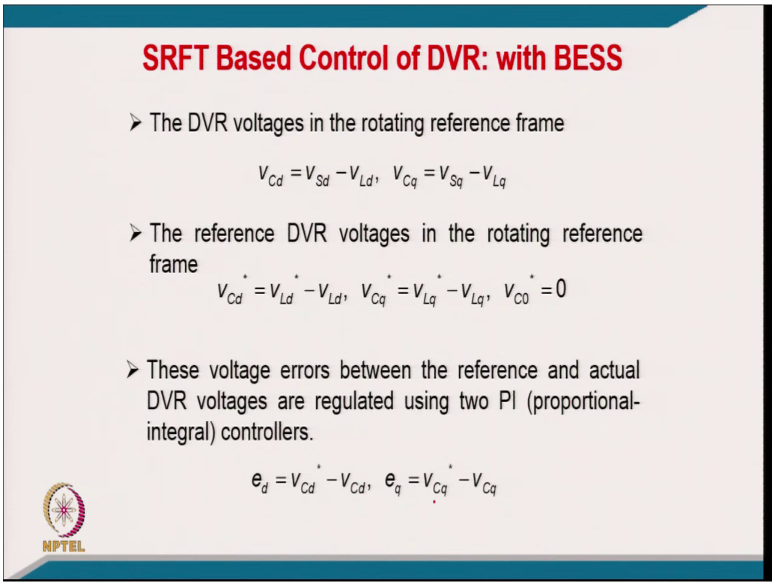
[FL], SRFT based theory typically I mean the equations for if you look into the amplitude, we have to find out the voltage which we like to regulate. We like to calculate the template which we discuss it. And from template and reference voltage, we can find out the reference load voltage like I mean your template required from load voltage only that should be typically the same voltage magnitude required.

(Refer Slide Time: 33:35)



And then from this same way form load voltage using this again the Parks transformation, we can find out even the dq voltage of the load also. And similarly the load voltage reference also from PCC also converted into dq reference frame I mean [FL].

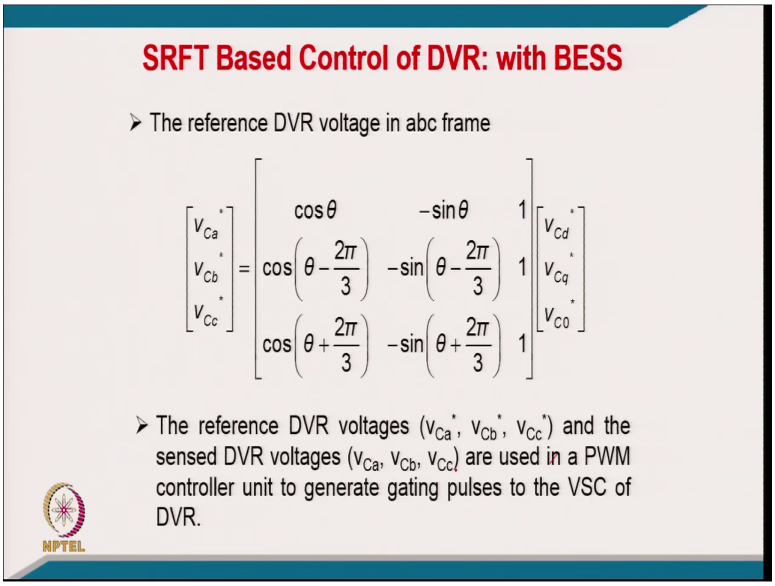
(Refer Slide Time: 33:52)



Both are in dq load as well as the source voltage, [FL] we can get a now the difference of this of this dq in compensating one. And from we can find out the even a compensating reference voltage also. [FL] These are actual compensating voltage, these are reference compensated voltage because we have a reference load voltage minus the actual load voltage.

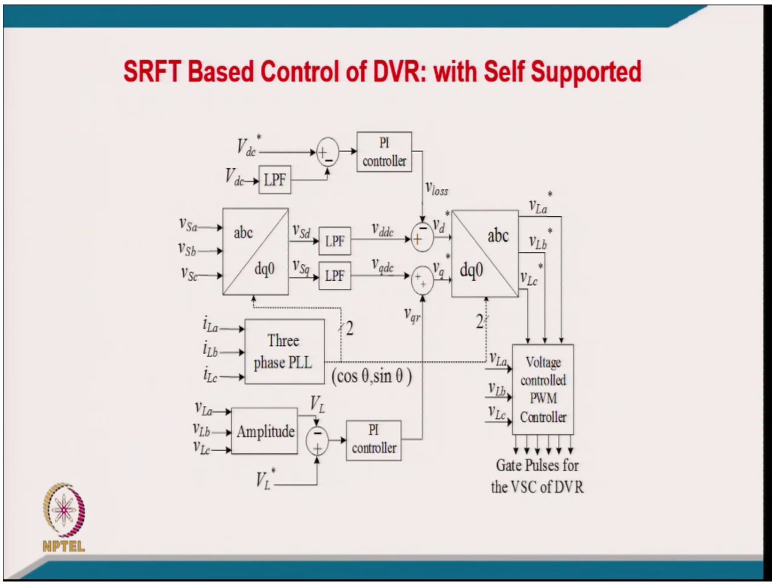
[FL], we can get typically from there. And then these voltage error between the reference and actual DVR voltage in dq are regulated using pi controller I mean these are the typical error in dq.

(Refer Slide Time: 34:23)



And using pi controller we are able to get typically this reference dq of course zero sequence is not there because of three-wire. But we get a dq compensating reference voltage from which we can get three-phase compensating voltage. And these we can compare with the sense compensating voltage to get the regulated voltage across the load. [FL], reference DVR voltage and the sensed DVR voltage are used for PWM controller to generate the gating pulses for the voltage source converter of DVR.

(Refer Slide Time: 34:50)



This is of course, typically the again synchronous reference frame theory based control with self-supported dc bus. Of course, we discussed already the self supporting dc bus it means we have to put it. We have to maintain the dc link voltage. Apart from that, the injections should be of voltage preferably at 90 degree because it should need the reactive power only.

[FL], here of course, with this voltage source converter, we have a reference voltage, we have a feedback voltage. As I told you that here also you might have a even some of the ripple even the second harmonics say voltage unbalance has to be compensated.

[FL], this low pass filter is required to get dc component, then we have a pi control. This represents the voltage corresponding to the loss which we have to inject for getting the power from the same circuit I mean like you can call it will be injected in phase with the current. So, that active power is taken.

[FL], similarly from source voltage, we transform into typically into abc to dq. And from current we are taking now PLL, that is also more important there, so that current is are taken care into that we inject some voltage. Most of the voltage in quadrature, but a small voltage is injected for power a real power is only at the phase, [FL] we get V Sd, V Sq.

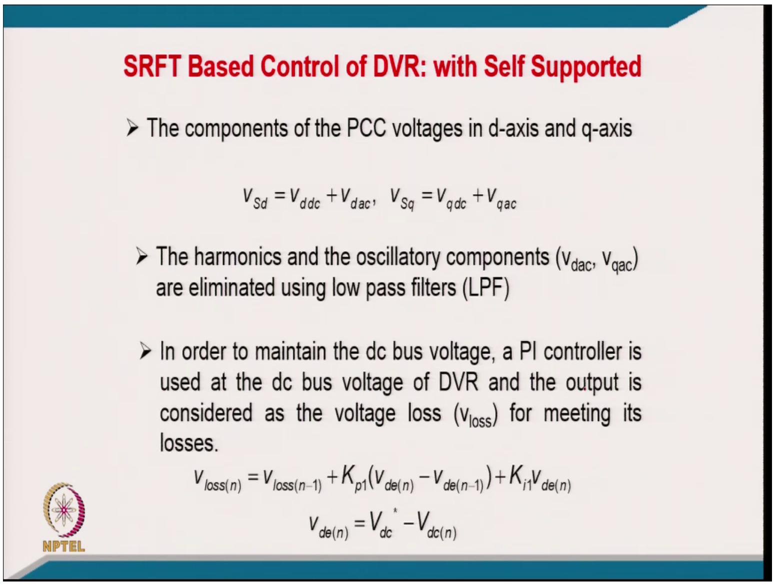
And of course, this might also because have a ac component also because of distortion, [FL] we use low pass filter to get dc component. And we loss we subtract the loss form here, [FL] we get injected typically corresponding to the this as a active component of the voltage.

And similarly for reactive component, we add from this voltage regulator. [FL] We have a load voltage, we have a reference amplitude of load voltage, and we have estimated load voltage. We put pi controller [FL] we get corresponding to the voltage to be kind of injected by this series compensator. We add the load and then we get the total voltage across the load.

[FL], we get two component of load voltage. And then we take a PLL. [FL], we get the load voltage I mean three-phase instance load voltage which are sinusoidal balance, and regulator voltage V S and the actual voltage load voltage and we calculate them. [FL], this is indirect voltage control you can call it as we talk about indirect current control in case of DSTATCOM.

[FL], but in its support is self-supported because we are sensing the current. And we are injecting the typically the voltage most of the voltage at you can call it in quadrature with the current, so that you does not need active power. [FL], a small amount of voltage is only injected for you can call it in phase with the current which require active power, so that self supporting dc bus is maintained like I mean or so.

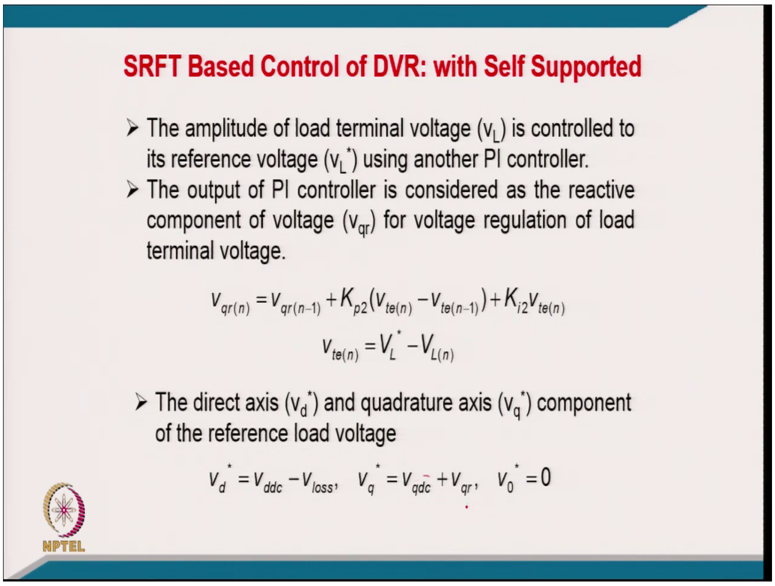
(Refer Slide Time: 37:21)



[FL], while coming to the equation for this, these are the I mean typically the component of PCC voltage in d and q-axis. [FL], we can call it the source voltage is dc part, and this is for ac part comes out from source side because source side might have a power quality problem.

[FL], you might have a ac as well as dc component for dq. And the harmonics and oscillatory component in this are there are eliminated using low pass filter. In order to maintain the dc bus PI control is used at dc bus of DVR and the output is considered as the voltage loss for meeting its losses. And this is a PI controller which meets the losses. [FL], this is the dc link voltage error of DVR, and this is the PI controller one.

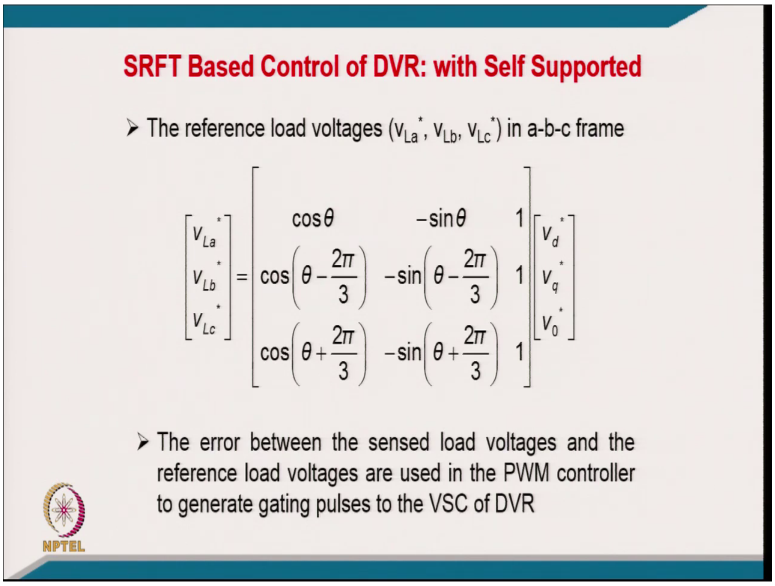
(Refer Slide Time: 37:59)



And similarly for regulating the voltage for perform to reactive power for regulation of voltage, we have a load voltage, reference load voltage, we have a reference load voltage amplitude. And we put the PI controller for that that give you the typically the injection of voltage at 90 degree from the current and corresponding reference we get from there.

And from this we can find out direct and quadrature axis. [FL], here we have direct axis we take a loss minus because that have to be taken from there. And quadrature axis we of course, the corresponding to the what we want more than that to be injected and zero sequence is 0.

(Refer Slide Time: 37:33)



And now we transform this V d, V q, V 0 to directly the load voltage because these are the voltage across the load we require. [FL], we have a instantaneous sinusoidal balance regulated voltage reference voltage, and we sense the load voltage, and we put the load volt on this load voltage PWM current control.

[FL], we call it this is indirect voltage control across the load. [FL], error between the sense load voltage and the reference load voltage are used in the PWM current control generating gating pulses of VSC of the voltage source converter of the dynamic voltage restorer.