**Power Quality**
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**Lecture - 07**
**Active Shunt Compensation**

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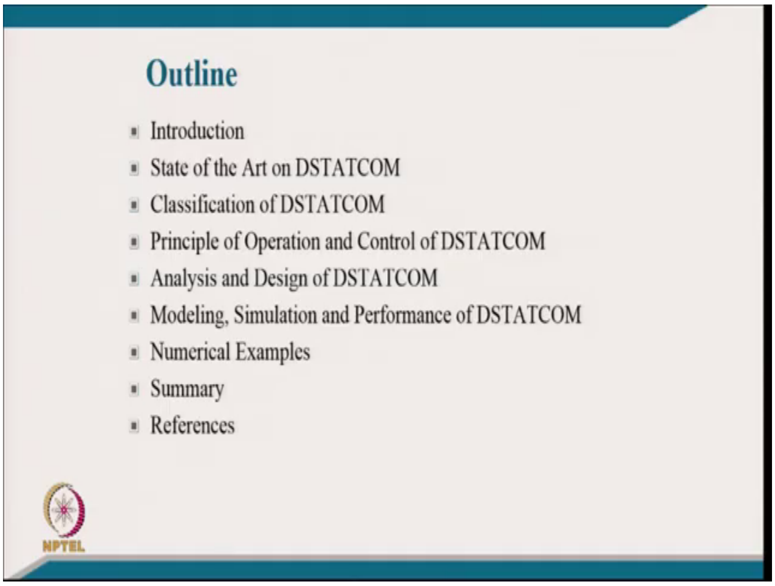


Welcome to the this lecture on Power Quality. [FL] We like to cover today this Active Shunt Compensation; last lecture we covered active passive shunt compensation [FL]. This active shunt compensation, we already discussed in introduction typically consist of basically DSTATCOM, it is also distribution static compensator, in short we call it DSTATCOM [FL].

We like to introduce this I mean today, we would like to talk a state of art on DSTATCOM, distribution static compensator; we will classify of the this DSTATCOM and we will discuss principle of operation and control of DSTATCOM, because it is active compensation [FL], control is also becomes important, passive compensator there was no control, but here we have a control.

[FL] We like to have a then analysis and design of DSTATCOM, we like to then again model and simulate and giving the performance of DSTATCOM; then followed by the numerical examples and we like to summarise with references like.

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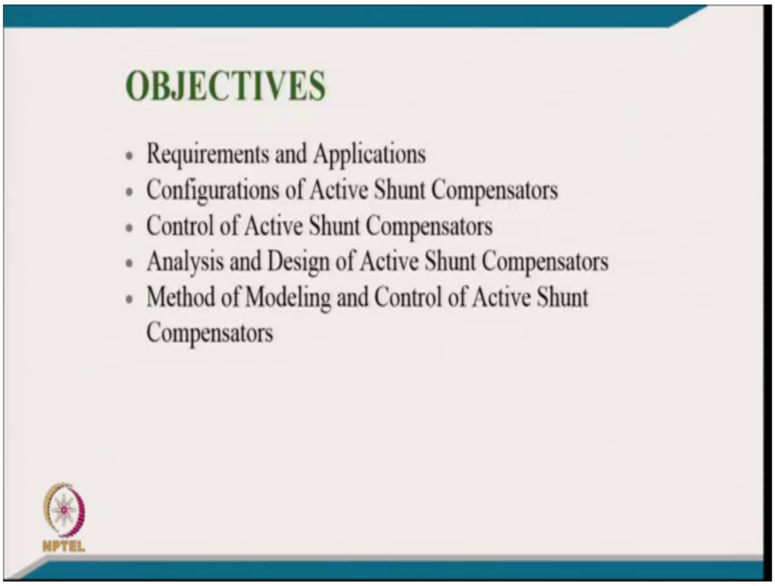


Well [FL], the objective of this is the requirement and applications. So, we like to discuss where the DSTATCOM I mean are needed and where are the applications and we talked to this configuration of active shunt compensator and control of active shunt compensator and analyse a design of active shunt compensator. And we like to have a method of modeling and control of this active shunt compensators, ok.

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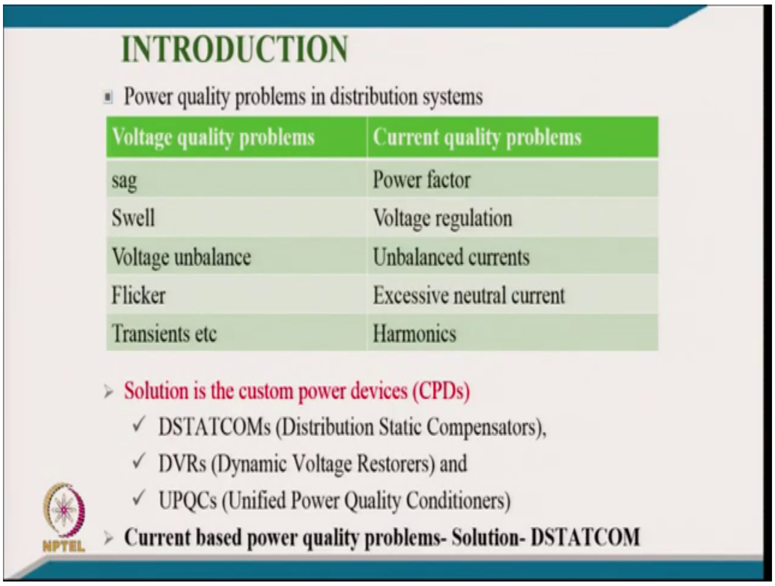


Well, the power quality problems in distribution system, I mean we have a two kind of power quality problem; one is voltage power quality problems, we discussed in the even introduction and earlier lecture, like typically like a voltage sag, swell, voltage unbalance and flicker and transient an example.

And current power quality problems are like a power factor, like a voltage regulation problem, unbalanced current, excessive neutral current and if there are harmonics, then harmonics also like. But here we are we will not like to consider the harmonic in typically DSTATCOM, we will cover that into later on in active shunt filters like.

[FL] The solution for this, I mean we call it the is the are the custom power devices; we also call them custom power devices like DSTATCOM, distribution static shunt compensator, DVR dynamic voltage restorer, and UPQCs unified power quality conditioner. [FL] Current based power quality problems, the solution is DSTATCOM; a distribution static shunt compensator, which I would like to discuss today.

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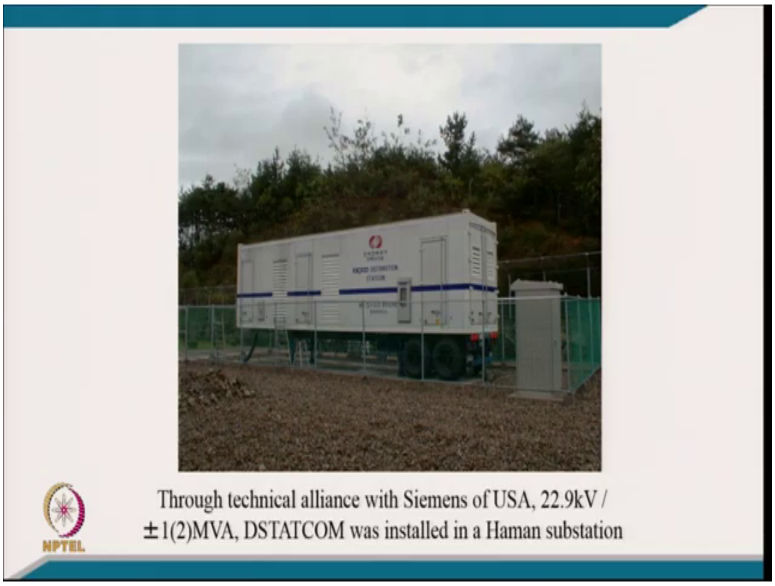


And to give you an example on through technical, this is the typical photograph of a you can call it of DSTATCOM of 2 MVA with which can have a plus minus 1 MVA and installed in Haman substation.

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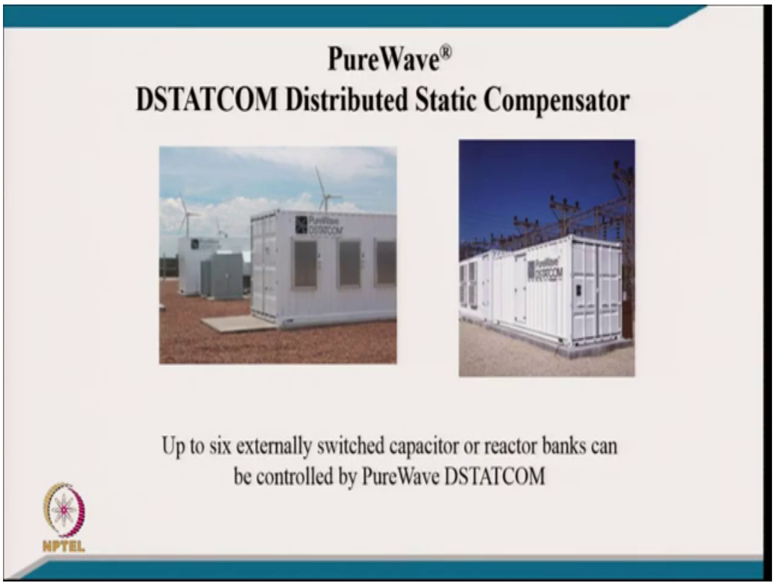

To give you an confidence like I mean the pure wave have manufactured the DSTATCOM distribution static compensator up to six externally switched capacitor or reactor bank can be controlled by Pure Wave DSTATCOM.

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And we like to discuss [FL] that is why the just to give you idea that some manufacturer already manufacturing this DSTATCOM, that is not a really new things; it is already used in practice [FL], we will like to discuss on the state of art on DSTATCOM.

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So, now DSTATCOM you can call it technology the matured technology for providing compensation of reactive power, providing the load balancing and providing the neutral current compensation. And if required we can have a harmonic compensation, also I mean you cannot say if there is a harmonics, then we will not compensate.

But certainly I mean this if you compensate harmonics that will add the extra costs as well as size and weight of the this DSTATCOM system like on; because switching frequency have to be increase.

Because in case of you are only sinusoidal and typically your, typically only the sinusoidal environment with the passive impedances or kind of; if you do not have an non-linear load, then in that case you will have only the to have generate like only fundamental frequency currents for all these compensator, whether for reactive power, whether for load balancing or neutral current compensator.

Well, DSTATCOM are also used to regulate the thermal voltage and to suppress the voltage flicker in kind of fluctuating load like furnaces or other application and to improve the voltage balance in three phase systems like, I mean of course a voltage balancing tendency there if you really compensating the load in shunt like.

And classical technology for mitigating the power quality, I mean earlier what we were using in place of that; the power capacitors in static VAR compensators using thyristor controlled reactor and thyristor switched capacitors, that was the earlier at least and that is you still use in the case of transform, you can say very large rating transmission system.

But the right technology here is the mitigation by DSTATCOM, I mean the region being the power capacitors can give you only lagging leading reactive power; but DSTATCOM give you the leading as well as lagging reactive power.

And DSTATCOM can generative even the can compensate negative sequence current, where the passive element like I mean cannot give you the contractually variable load balancing features; it can be only designed for one fixed kind of the load like on, that is the reason the DSTATCOM is the right technology for all this compensation like.

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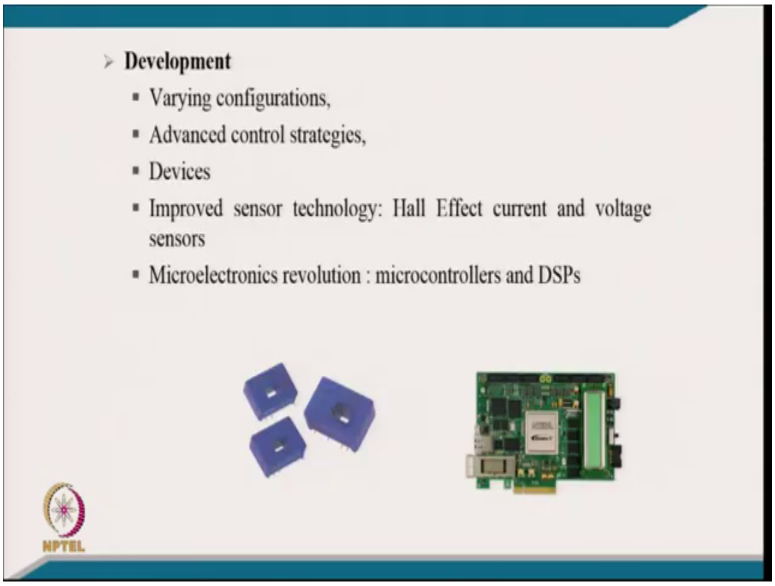


[FL] That I mean coming to the development, there are varying configuration according to the application requirement and there are advanced control strategy; because this active device [FL] we have to put a control method for typically control of this DSTATCOM.

And of course, the what devices you are using into this, like devices in the sense we talk about like a which configuration you are going to use; like whether you are going to use like a typically like a very low rating like a MOSFET, medium rating like a may be IGBT kind of.

And then the another responsible technology, the sensor technology we have a; we have to sends the signal like a current signal and voltage signal [FL], for that we have a hall effect voltage and current sensors like, I mean your current transformer and voltage transformer cannot give a very fast response, which required in the for feedback like.

The another reason for development have been the micro electronics revolution; we have a very fast microcontroller on DSP, digital signal processors for typically for, I mean for the control of this like typically. And now their cost is reducing day by day [FL], it is practically possible to implement all these algorithms in the microcontroller or DSP unlike of this DSTATCOMs like.

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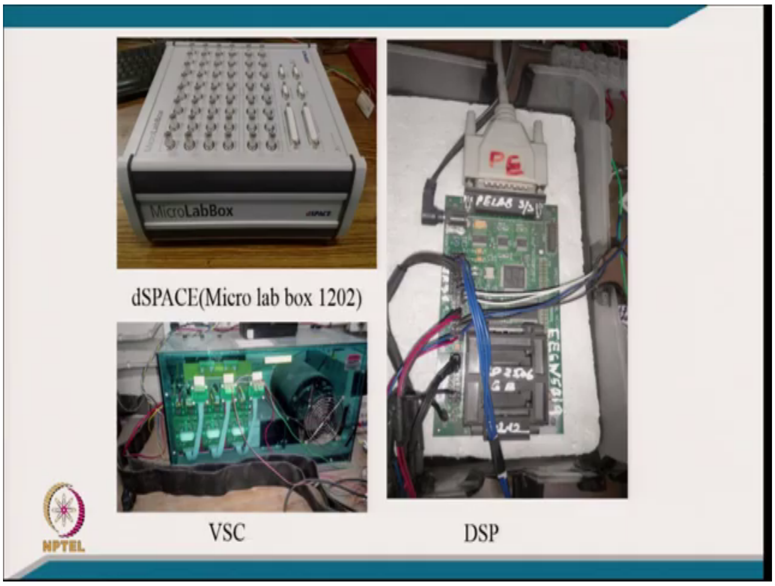


And of course, for the research laboratory environment, we have a DSP which is like a dSPACE, maybe micro lab box 1202 and we require the voltage source converter or this voltage source inverter and then or you can use the DSP like.

[FL] Some of the these I mean are used in laboratory environment, but when in it goes to the industry, of course you have to use the inverter; but which is more compact and apart from that you can put the entire into the simple microcontroller 1 PCB not to have a such a large size also.

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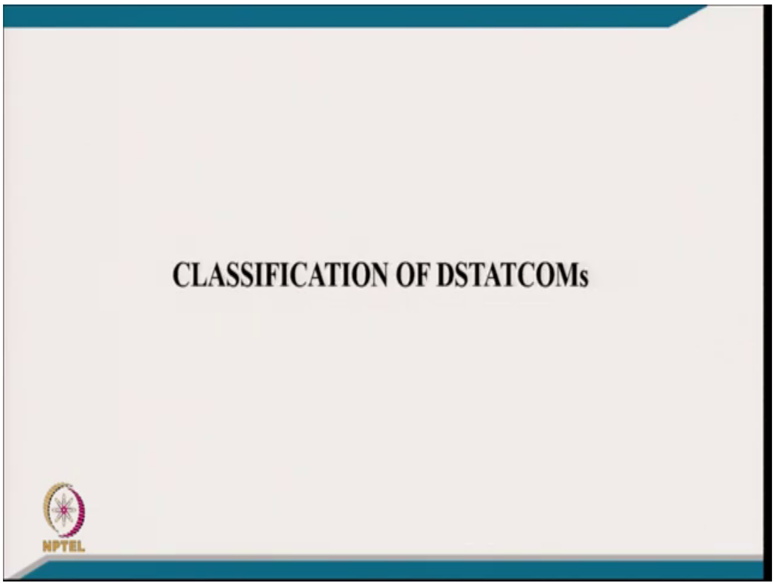


[FL] That is about the little bit implementation effect, coming to the classification of DSTATCOMs.

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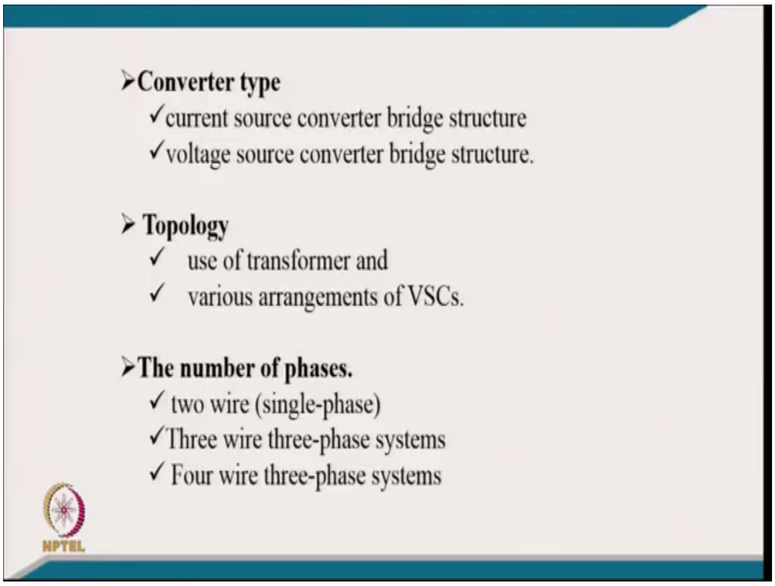


DSTATCOM can be classified into many ways; one is the converter use [FL], we can use the current source converter bridge structure with the PWM control; I mean of course with the IGBT. Nowadays invariably we are using IGBT, where it can go reasonably switching frequency which we expect in this case, I mean or voltage source converter the bridge converter.

Well, the voltage source we will discuss with the circuit like volt why voltage source converter have taken the lead over the current source converter for use this in these application like DSTATCOM. And as they typically the topology, whether we like to use the transformer for interfacing this DSTATCOM with a grid network; because sometime we need the transformer for many purpose, one very purpose is the isolation, another is that you like to use the DSTATCOM at high voltage network.

[FL] The power electronics may not be a optimally designed at such a high voltage [FL], we can use the transformer in between to transform the appropriate voltage at which the power electronics converter or let us say interface with the transformer [FL]; there we use the transformer, like a typically high voltage maybe like a traction application, three examples I can mention it or in the industry of very high power rating.

But in normal distribution system, we can avoid the transformer; because it extra add the cost as well as the weight [FL]. If the voltage is not to be stepped large, then there is no need use of transformer [FL], there are transformer less configuration.

And then there are various arrangement of voltage source converter; I mean like in a sense that you can use like a typically in case of three phase four wire system, either you use the single phase unit or you can use the three phase itself voltage source and four wire system you can use, typically even a four lag voltage [FL], we will discuss all those so, that is a kind of classification.

The another classification is on the basis of number of phases like, whether you are typically it is a system is of two wire single phase or three phase three wire system or four wire three phase system like on or. So, [FL] that is on supply base classification, I mean because your if supply let us say load is only single phase [FL], you need the single phase DSTATCOM; it is the three wire three phase system, then you require a DSTATCOM also for three phase three wire system.

Because you might have to compensate like three in two wire system single phase system like a kind of reactive power, you will like to compensate. And in case of your three wire system, you will like to not only compensate for reactive power; but you will like to compensate the your unbalanced current or negative sequence current and four wire system you will like to eliminate even the neutral current along with the your reactive power and the negative sequence current; [FL] you like to do neutral current compensation also, that is the difference in the typically.

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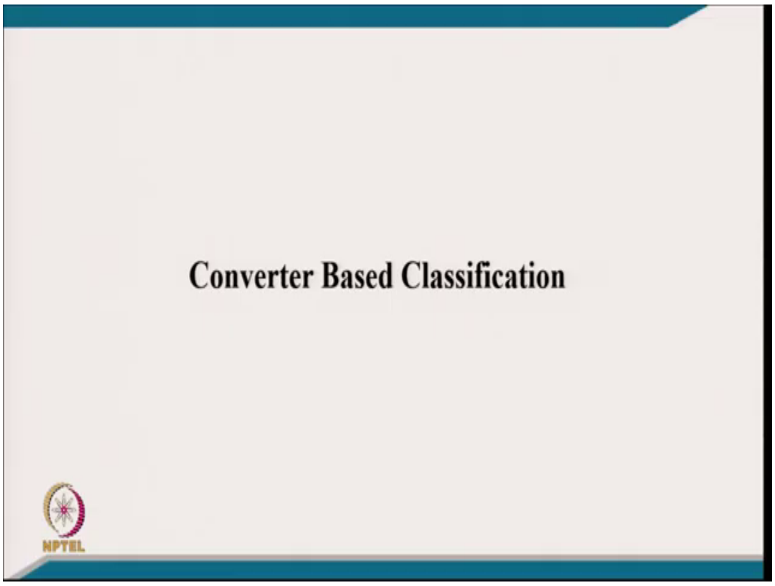

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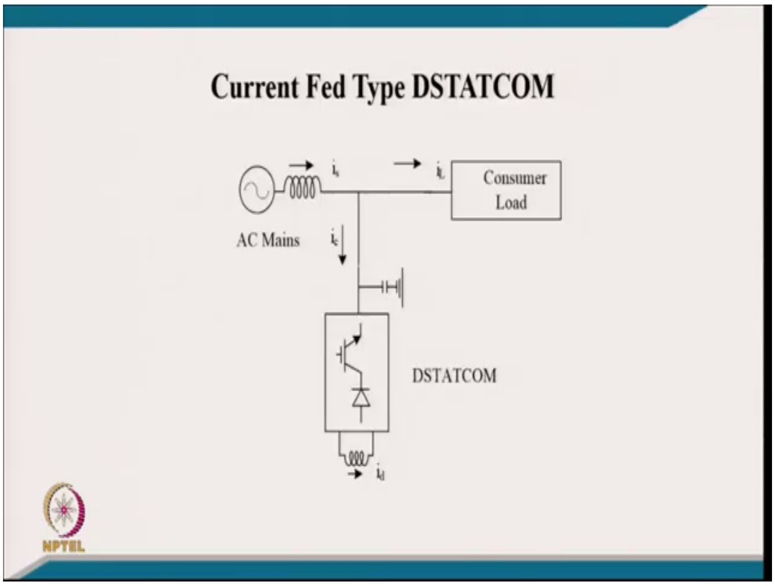


[FL] Coming to first classification on converter based classification [FL], you can use the current fed or current source fed DSTATCOM. In current fed you can see the of course the supply with source impedance connected to the consumer load and you have a this DSTATCOM made with the let us say the current source converter and current source converter; even if you are using let us say cell committed device like IGBT, you need the series diode.

The reason being current source converter needs the negative voltage blocking capability and for negative voltage blocking capability, I mean the IGBT do not have; [FL] we have to connect a series diode which can be the strength for negative voltage across the total switch like I mean also.

And on the DC link side, you require energy storage like a current source, [FL] that can be realised with the help of a inductor across the DC link; of course it can be, you can call it current in the inductor can be controlled well in self controlled manner and we do the self control voltage for the case of shunt compensator.

Here the problem is on the output of this converter, you will be generating PWM current and these currents PWM current segment of the DC link current and to make this current continuous [FL], we need the shunt capacitors which is mandatory here in that case.

So, the major difficulty of course here are one is the on DC link, you need the inductor which is costly, noisy and lousy and weighty and another is then when switch conduct you have a drop of IGBT as well as diode [FL]. You have a loss in the switch also, which may be 1.5 times to 1.5 to twice the switch which is used in voltage source converter like.

And then this capacitor is also meant, I mean mandatory capacitor on AC side you cannot eliminate this also. [FL] You can call it like you are a going to add a such a element which increases the cost size weight and losses also and the response is also not so fast, because of you are putting the inductor on the DC link like.

[FL] In place of this for providing same compensation, we can provide the typically voltage fed type of DSTATCOM, where voltage source converter is used for as a DSTATCOM. And in this case typically on DC link, you have a electrolytic capacitor, which is cheap lighter weight and cost effective and loss less, loss also less in that case and then you have a IGBT switch with the anti parallel diode.

[FL] Here in this switch when it conducts either IGBT will conduct or diode will conduct; [FL] you will not have a, you will have a lower losses in the switch. And similarly on the other side you have a interfacing inductor, you do not have a like a parallel shunt capacitor here. And this inductor capacitor even if you are using a transformer, because of application requirement; then this inductor can be also avoided, the transformer leakage reactance can be adjusted to take care of this your inductor.

[FL] That element also get reduced, either you can use the reactor or you can use the transformer any one of the two in that case. [FL] This here the losses are also less on the DC link element like in a capacitor; the device switching losses are also less, device conduction loss is also less and then of course, the element which was in shunt capacitor in case of current fed, which is not required.

[FL] That is the reason this voltage fed or voltage source converter in DSTATCOM had taken the lead and commercially these are in practice like. But of course, I mean as far as the research equivalent constant that also can do the job; I mean but out of the two options, you considered the best option which is best for you like I mean. [FL] This voltage source converter fed DSTATCOM is considered to be the better than the previous one and it is used in practice like.

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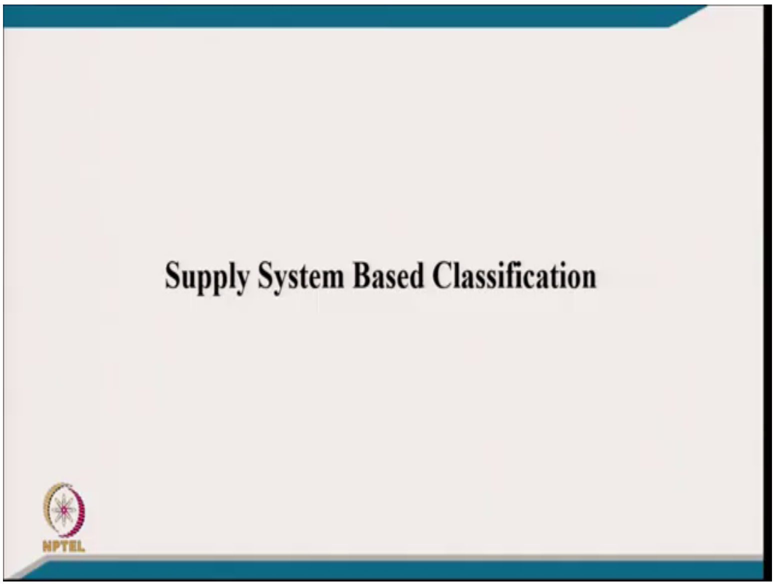

[FL] That is about the converter based classification.

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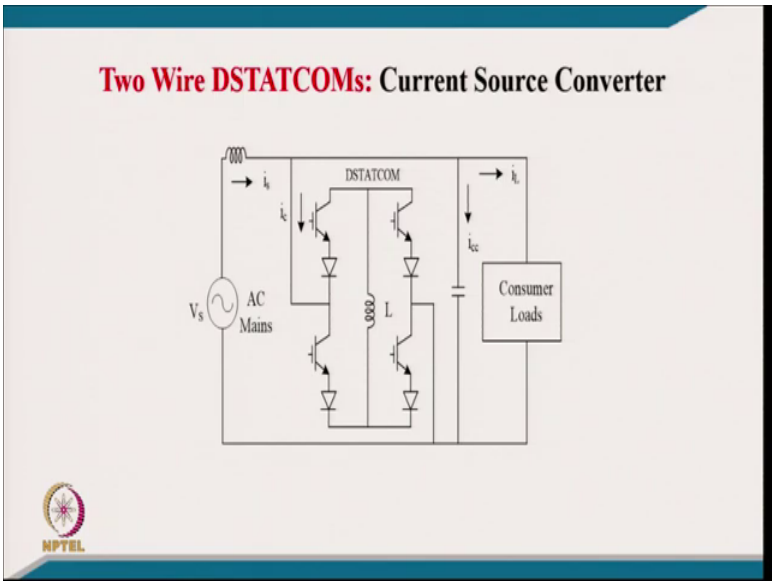


Now, we come to the supply system based classification; I mean the supply based classification can be like a single phase like a two wire DSTATCOM for single phase as you see the single phase circuit here. [FL] We can I mean we can either have a current source converter, [FL] giving you to idea that how can current source converter can be there, I mean use as a DSTATCOM.

[FL] You have a four switches here with the bridge and our DC link we have a typically a inductor; I mean here to derive a kind of a current source or constant current in the inductor. And well we operate this switches in PWM [FL]; when switch operate, you can call it like a typically here the IGBT and diode both are in series [FL] losses of both are there.

And then you have to use a shunt capacitor, so that the net current, I mean some of i c plus i c c that remains the continuous like or so. So, this is a current source converter based just to give you an idea how it look like the DSTATCOM for typically for single phase configuration like.

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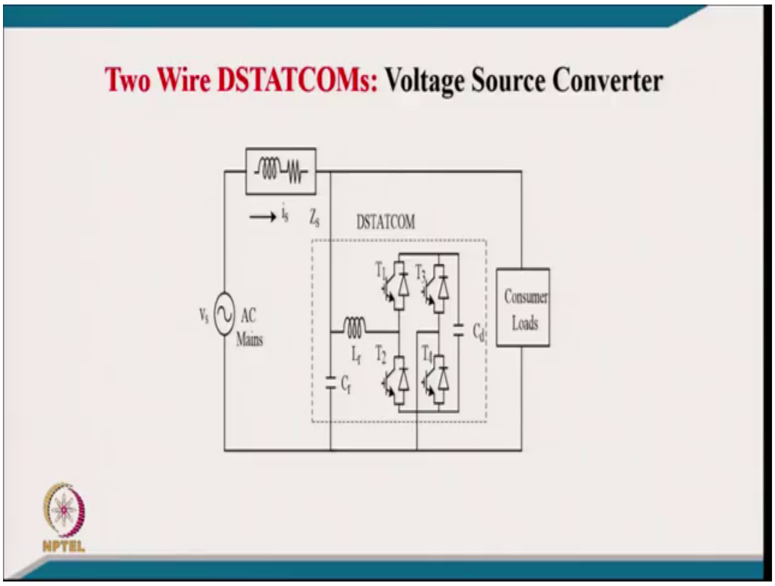


Then this is a voltage source converter, I mean like you have after source impedance, a single phase has reached voltage source single phase, your voltage source inverter with the interfacing inductor and then a small capacitor.

I mean this a small capacitor, I mean is a part of a filter and why we connect this after L r the C r? The reason being I mean the converter will be generating the PWM voltage at the output of AC terminal of this converter and this PWM voltage I mean depending upon the source impedance, this L r this is the interfacing inductor cannot absorb the all the ripple; because the supply voltage is somewhere buried into the system, [FL] you will find if source impedance is higher, you will find a com across the typically across the load.

[FL] To eliminate those all voltage higher voltage ripple and if you put a small value of C r; I mean just like as a ripple filter, we assume that the impedance for DC when a value of capacitor is very small hardly or rough like a typically of 5 micro farad, you will find the impedance for high frequency switching around switching frequency are higher than that, you will have a very low impedance, [FL] it will absorb at I mean all the those harmonics here.

And typically it will like a we have a short circuit for higher order harmonics, [FL] entire ripple voltage have to be absorbed now across the inductor. And for fundamental frequency, this capacitance will be very high impedance [FL]; it will not draw any fundamental current into the capacitor will be very small.

Even some time we put a small reaction, damping reaction and also in series with the reaction, the loss is also negligible in that case like. But improve the voltage profile at the point of common coupling, which is of course because of the switching of this converter like I mean also. So, that is a voltage source converter, I mean best DSTATCOM forcing will face system like or so.

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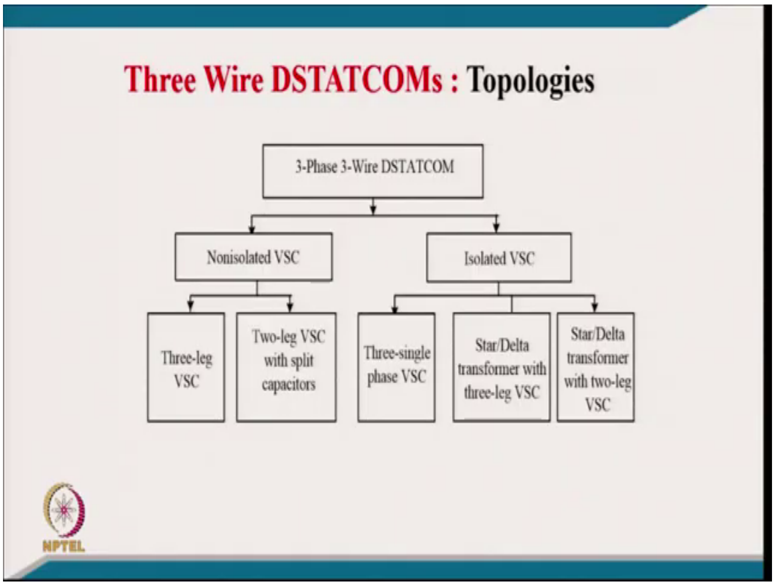


Well for coming to 3 phase 3 wire system, I mean we have a plenty of topology. So, here is the classification for 3 phase 3 wire DSTATCOM. So, either we can have a non isolated topology of voltage source converter, I mean now we like to confine voltage source converter only.

[FL] We can have a three leg voltage source converter or two leg with the split capacitor, I mean like on the DC link. So, that also will have tried to use in very low rating.

Or you have isolated voltage source converter, which I talk about you use the transformer for isolation; when you really want to interface to high voltage system like a traction or railway, I mean for the DSTATCOM using there, because the at substation you will have a quite high voltage, I mean even on the secondary side you will have a 25 kV, primary side you might have a 33 kV and very much higher than that.

[FL] We like to interface such application on high voltage, then you need the transformer; may be power electronic is designer at optimum voltage at which the cost of the total power electronic is quite low. [FL] In this case you can use the three single phase voltage source converter, I mean like 3 H bridges or you can use the star, delta transformer with three leg voltage source converter or you can use a star, delta transformer with two leg voltage source converter.

So, you have a like a typically options around like a 5 options and it depends on application requirement which option is suitable to you, I mean like as I already mentioned.

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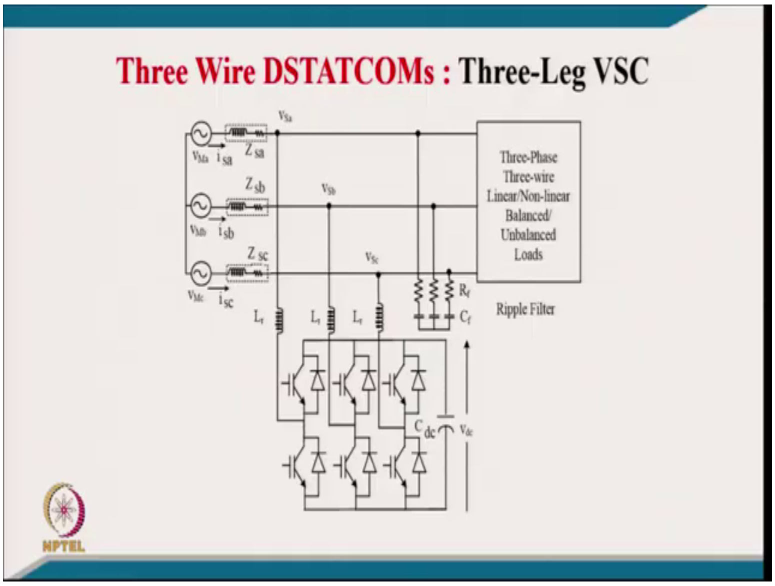

[FL] Considering this typically three leg voltage source converter, I mean you have a typically a three phase supply system with three load, three phase load and we have a three phase voltage source inverter here with interfacing inductance and at the point of common coupling, which were showing the there we have a this ripple filter R f and C f.

It is responsible to eliminate the voltage ripple generated by at the common coupling by this voltage control; I mean this voltage source inverter by switching like. And the DC link voltage across the DC link capacitor V dc, we have to regulate of course, to a constant value reference value; otherwise the this converter will not operate successfully as a four DSTATCOM operation.

[FL] This also we have to control, I mean by taking a little extra power from the same source formatting the losses of this entire system in the sense losses in the interfacing inductor losses in the switching devices dielectric loss in the capacitor. So, that we will discuss in the control in detail like, I mean; but the you can understand the ripple filter is required for improving the voltage profile at the point of common coupling.

Otherwise we do not know the impedance, because the whole I mean source is somewhere like a V Ma. So, the you can call it the entire difference in your this PWM; I mean will be absorbed the source impedance and this L r. And if L r is we cannot increase beyond a certain value, yeah it will increase the cost size and weight, apart from that it will not allow to change the current very quickly, [FL] there is optimum value of L r we would like to discuss in the design.

[FL] If it is it cannot increase to higher and source impedance is high like a weak AC grid system; then this ripple filter play a very important role in the design or operation of this DSTATCOM like.

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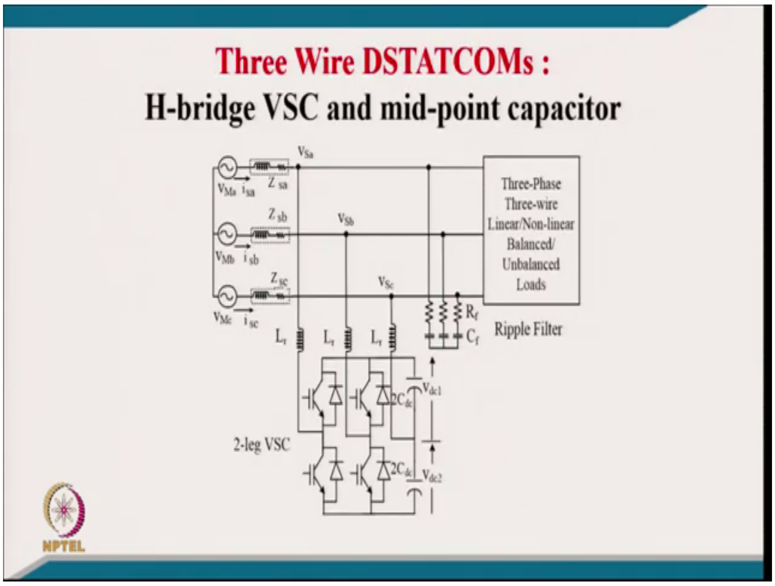


Well, the another topology which normally can be used for low power rating people have mentioned in the literature that, you can have in place of three leg, you can have a two leg and one leg you can take from midpoint of the capacitor.

But here the there are typically two disadvantage of this topology it cannot be used for high power [FL]; one reason being that this you have to use two capacitor now, in place of one on DC link [FL] for deriving the midpoint.

Another major drawback with this it, these capacitors should be able to take the entire ripple current or entire fundamental current, even which is flowing into the typically third phase. So, that is another drawback [FL] size of the capacitor for that increase. This is only preferred for lower rating; but otherwise, I mean we prefer to like a three leg previous topology like I mean or so.

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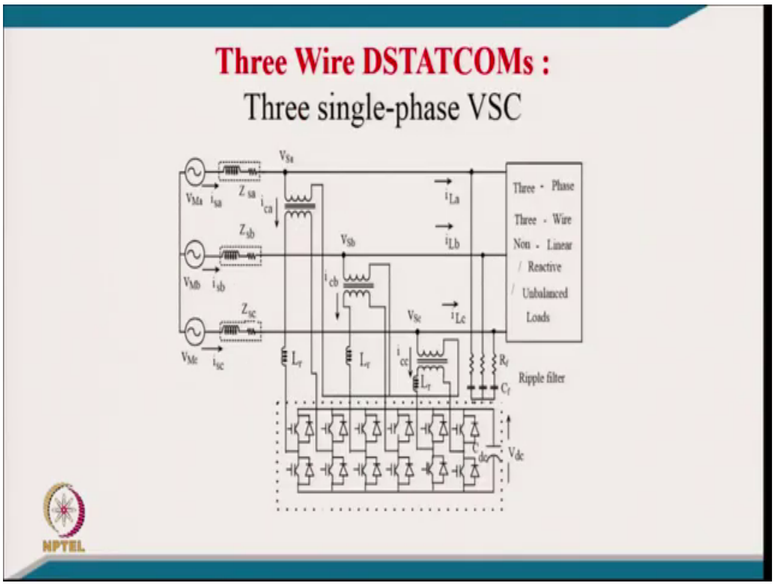


Well, we can use if we use the transformer isolation on which is given here; we can use the I mean if transformer used for isolation, then we can use the three H bridges for three phases, I mean with transformer isolation. I mean this really give a very specific advantage, of course we have to use ripple filter; this L r need not to be now separate, it can be as a leakage reactance of the base transformer.

And the H bridge have a very specific advantage now with the, you can have independent control of each phase current and now you can use the unipolar switching here; unipolar switching you can give a benefit is there that the switching frequency can be reduced to half compared to the ripple frequency of the current which is going through the L r.

And moreover the DC link voltage also reduces here, I mean much lower than even for unity you put a unity gain trans ratio transformer, even then DC link voltage can be reduced to much lower like in the previous first topology if you are keeping like a 700, it can be put only 400 Volt.

[FL] Device voltage rating also can be reduced, even the transformer is used with the your unity trans ratio; I mean the I mean the voltage rating of the all the devices can reduce as well as the your voltage rating of the capacitor can be reduce. [FL] that is a specific benefit, but the disadvantage is that you are using a transformer; if it is not required, I mean in I mean provided some application required transformer, then you can take the benefit of it

Another is that in place of 6 devices, you are using a 12 IGBT here; [FL] that also another you can call it the drawback of this. But of course, if you have if we needed isolation, you are integrating this your DSTATCOM for very high voltage system, certainly this circuit have a many many advantage compared to the other topology like.

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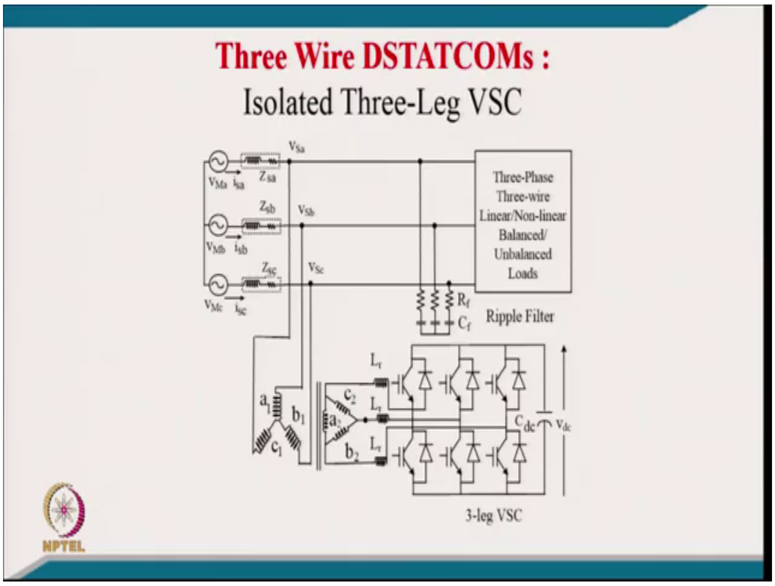


Then you can have this even the isolation with the simply started the transformer; there of course you not to have a three single phase, but you can use a three voltage source, three phase voltage source, three leg voltage source convertor. And that also can serve the purpose as far as the you are integrating to this to high voltage network; I mean if we taking a power electronics part on at appropriate voltage and low voltage. And this L r just it is shown simple, but it can be like leakage reactance of the transformer; I mean take care to take care of this your interfacing inductance like also.

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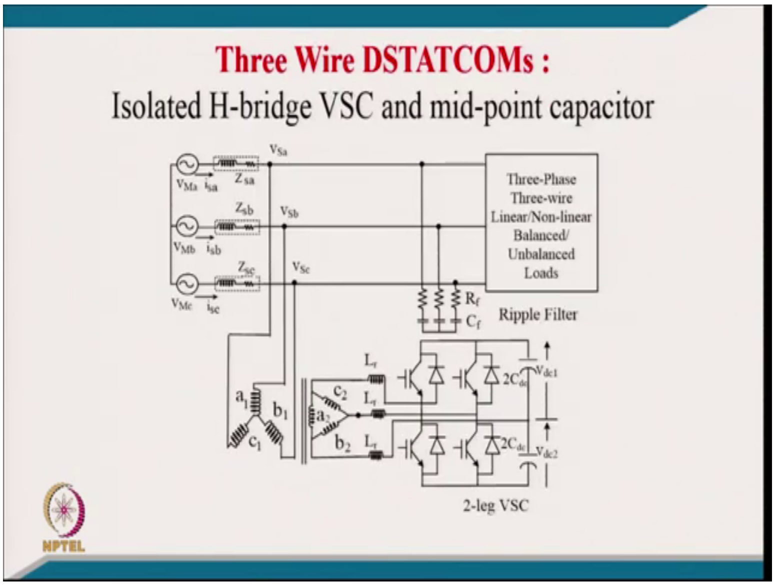


Well we can have like a now isolated single H bridge; in this also in place of three leg, we can use the two leg. But I have already mentioned the drawback in case earlier also that, you required two capacitors to derive the midpoint and secondary its advantage that entire third phase current flow through these capacitors. So, capacitor values should be very large, [FL] certainly it is not preferred for large rating like I mean or so.

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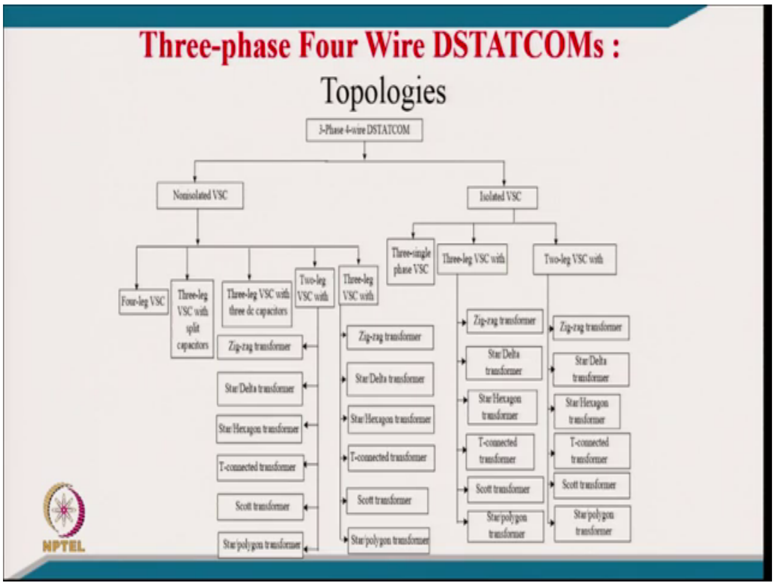


So, these are typically the topology of three wire system; coming to the topology of three phase four wire DSTATCOM, you can see the large number of topology, I mean here for three phase four wire DSTATCOM. [FL] We can have a like a non-isolated topology, you can use the four leg voltage source convertor or three leg with the split capacitor or you can use the three leg voltage source converter with three DC capacitor.

We will discuss with that and we can have a two leg voltage source converter with the transformer isolation, different transformer isolation or three leg voltage source converter which can be normal practically used with a different transformer isolation and transformer isolation can be like a zigzag transformer or a star delta transformer, star hexagon, T connection, Scott connection and a star polygon connection.

What I mean the transformer can be three phase transformer for use for isolation can be connected, sorry without isolation can be connected here for the purpose, here with the three leg or four leg here for four wire; because that can have a neutral current compensation also in this four wire system.

Coming to isolate topology, we can have a three phase VSC or we have a three leg VSC with the this transformer connection, considering the neutral current is taken care by this transformer itself and then two leg also we can use by that, as we already discussed here with a transformer connection like I mean isolation. [FL]

All these transformer provides wherever the topology are there, virtually it provide the sometime the neutral current compensation as well as it provide the isolation also. So, we like to discuss some of the topology there with the circuit configuration.

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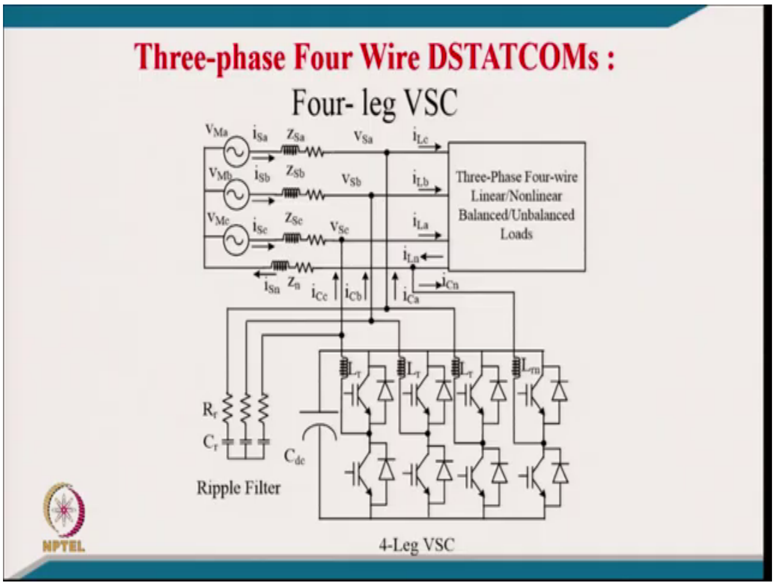


[FL] this is the first we call it a very normal configuration which is normally preferred to you is a three phase four wire topology. [FL] In for three phases, we use of course three leg and one additional leg we use for neutral current compensation; as you can see typically it is written here the fourth leg were also in turn facing inductance sometime, it is different, it is not equal to all L r, it can be L r and or so.

And [FL] this responsible to compensate neutral current locally, so that supply current i Sn can be made 0; because there may be load unbalanced load. [FL], the negative, you can call it neutral current for the load can be compensated locally; it is not necessary to flow into the grid, where you want to rely this as a balance typically the balance load after the compensation, even with it is a unbalanced load and having a neutral current.

[FL] Once you have a balanced load, unity power factor load, then the neutral current can be made 0; even for voltage regulation and balanced load, you are using that in that case neutral account also will be 0.

So, fourth leg is used for basically neutral current compensation here like on. So, it does not need the transformer. So, it is a very economic configuration, I mean like and you have to regulate the DC link voltage for you can call it like a for self-supporting DC phase by control, we will discuss this controller little later on.

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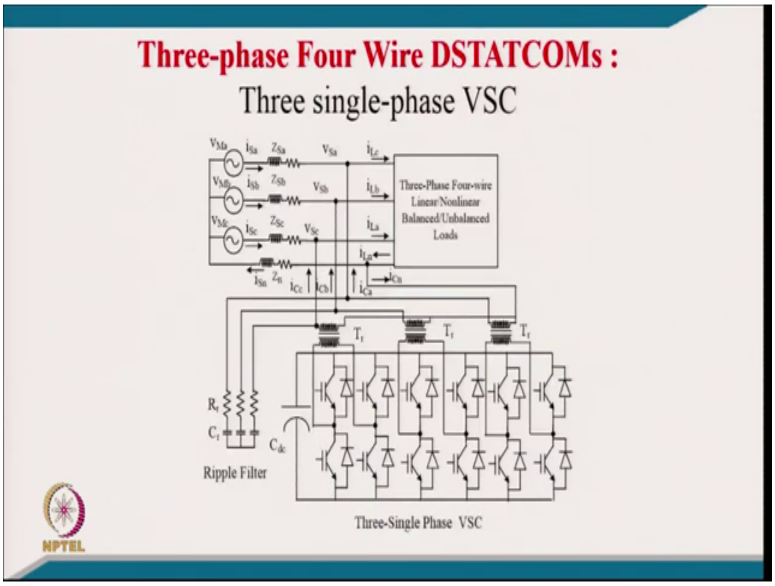


These are another configuration for three phase, this configuration we have shown earlier also; but now we are using like a three phase three single phase with the transformer isolation and, but the inverter all three legs, all six legs are connected. So, that you can save the; the one way that you can have a three single phase inverter, a separate capacitor or you can have a on one capacitor on the DC link, really certainly will help to reduce the number of component like you can have a only one capacitor here.

And you have a independent already earlier also; we discussed independent control of all three phases. [FL], I mean the with the star connection of the grid side, I mean you can have a neutral current compensation also here as it is the your star point connected to the neutral, I mean of this of second.

See in the sense on the which is on the grid side or so. And power electronics cost here also you can design the power electronics at appropriate voltage, optimum voltage at which the cost of power electronics is low, I mean like or so.

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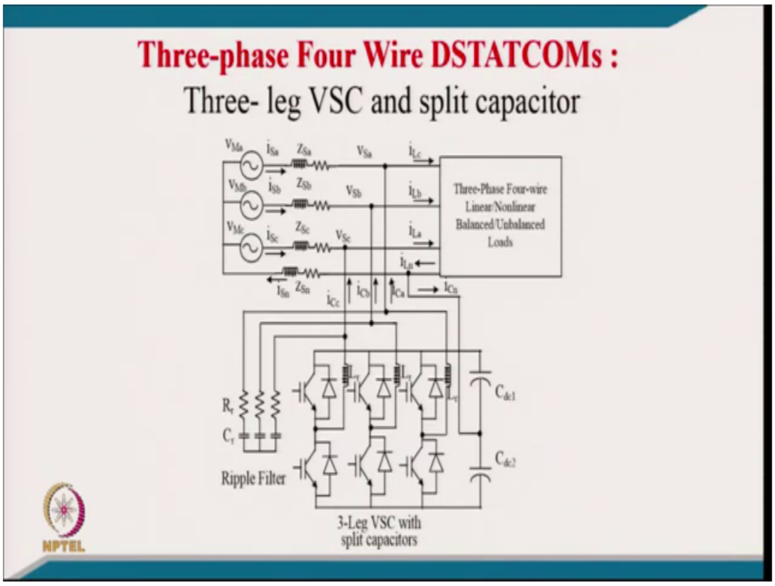

There is another topology of course, you can have a three leg with the midpoint capacitor, which takes the responsibility of your neutral current.

But the again reason is the entire neutral current will be flowing through even that can be even a fundamental current as a maybe unbalanced load. So, entire neutral current, one is that you need the two capacitor, another is to derive the midpoint and other disadvantage that the entire this neutral current have to flow these through these capacitors to go to the circuit like I mean; [FL] certainly it is not certain people for high, you can call a power rating I mean like.

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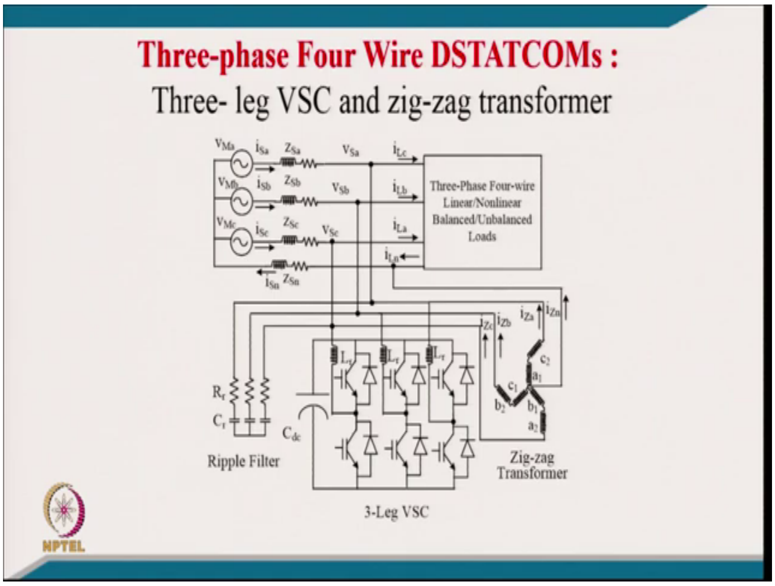


The another connection of course, in like a developing country we consider it that, for three phases you can use the three leg voltage source converter and then for neutral current compensation, you can use the zigzag. Because zigzag connection is quite effective of the transformer for eliminating the neutral current or deriving the local neutral I mean like.

[FL] Here that is the reason what we are connecting here the zigzag transformer for neutral current connection; the only typically disadvantage that the transformer is little bulky, I mean compared to like you could have taken a one more leg, but of course, sometime the inverter costs is higher, that is the reason it is consider.

Of course, the another benefit of this of I mean even neutrally is not there of the supply, you still you can get a very stable neutral for the load side; I mean if neutral is also neutral conductor bursted or isolated, you can have a stable neutral for your load. [FL]

Load we go on experiencing the here itself the stable neutral also with this zig zag transformer; [FL] that is not only purpose that it is really share along with your DSTATCOM, but it also serve the other purpose like. Or you can have a like a typically for this typically neutral current compensation, you can have a star connection and close deltas on the secondary side.

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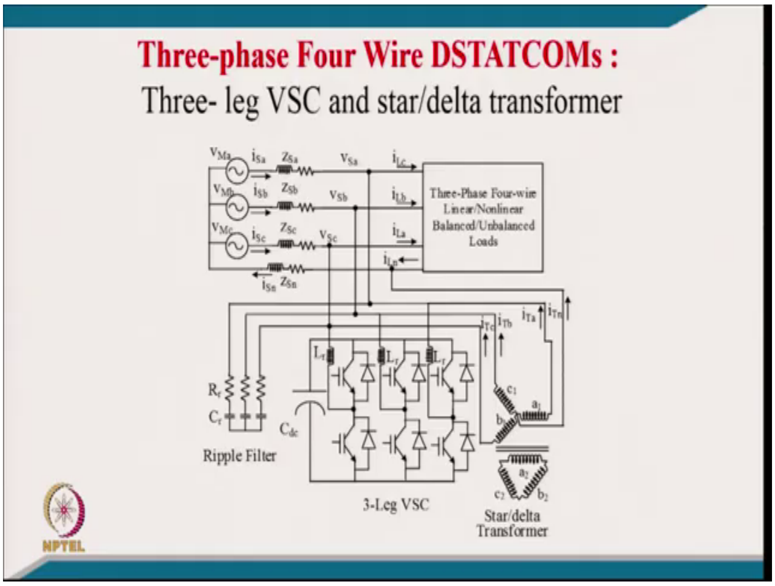


But of course, the disadvantage compared to zigzag of this is that, you have a losses in the typically on the star side as well as in delta loop also, which were the your zero sequence current or this your neutral current will be flowing into that like I mean.

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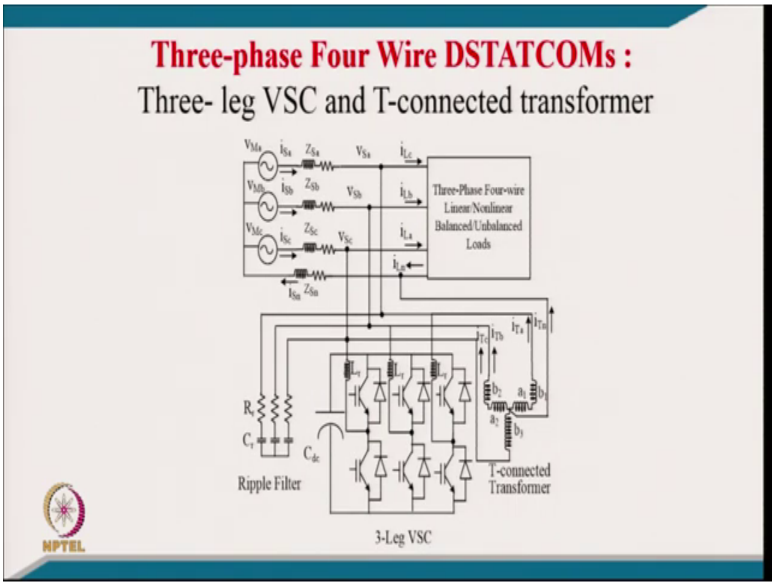


Or you can have a typically in place of this your zigzag connection; for neutral current compensation you can have a T connection, T connected transformer I mean. [FL] that also can provide the purpose of that like I mean.

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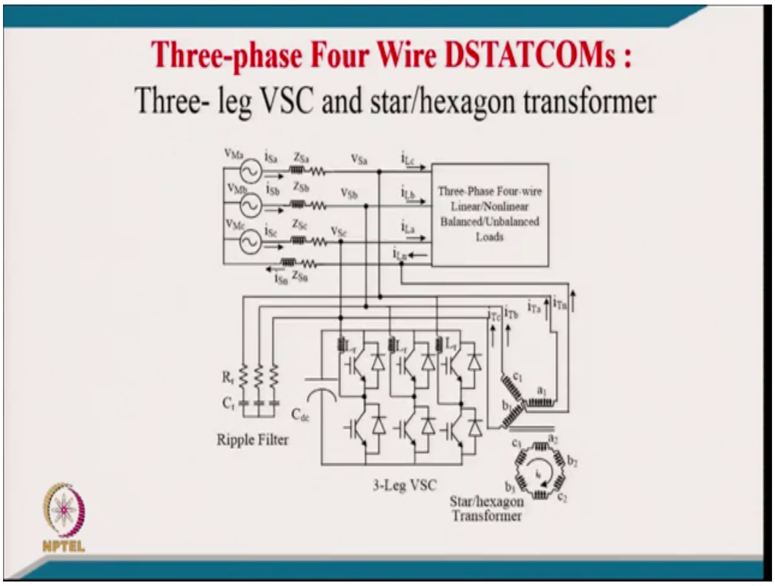


Or you can have a typically or star connection with the hexagon for closed path; you must have a closed path for neutral current compensation, which is normally otherwise you might have seen that normally in distribution transformer on the supply side, we can have delta loop for providing this.

And the secondary side we have to connect the star; because you need the neutral thermal for providing the connection for, you can call it the for single phase load of the, I mean the consumers like.

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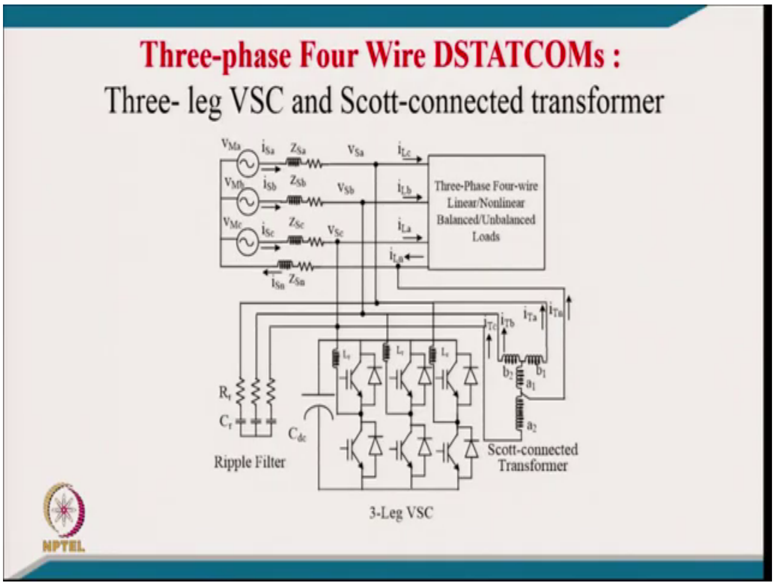


[FL] Similarly you can have again T connection, Scott connection also. Scott connection is quite famous, connection for converting like a; [FL] here also Scott connection also can eliminate the your neutral current like I mean or so. [FL] We have a without secondary three connection like a T connection, Scott connection and typically your zigzag connection or so. And of course, you can use the three leg or you can typically take a even a two leg also.

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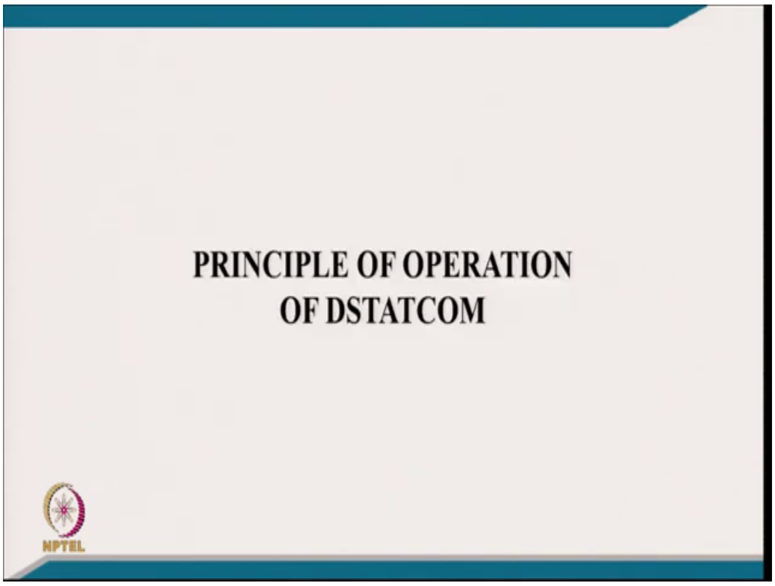


So, these are the typically important connections or configurations of your typically of your DSTATCOM; we have considered single phase, we have considered three phase three wire configuration, a three phase four wire configuration like. There may be many other configuration which are reported, but these are the kind of important one or with the industry, I mean which are used in the industry like I mean also.

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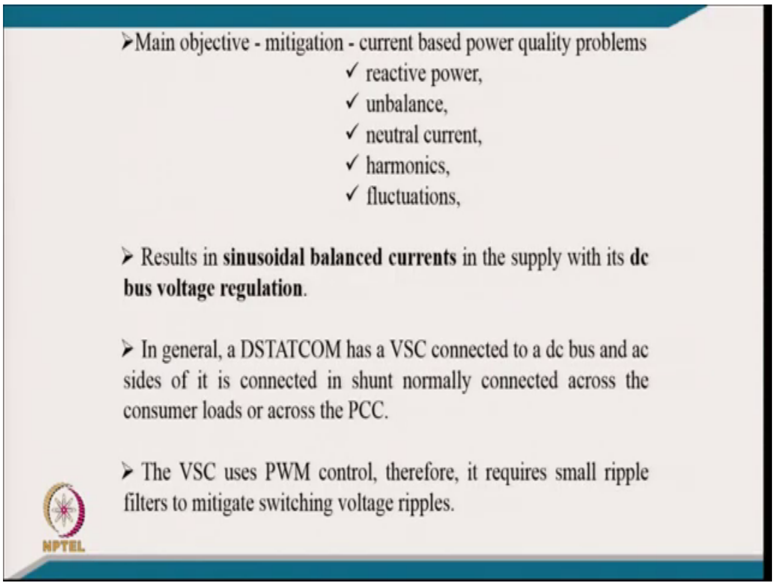


Well, the as far as typically we go to principle of operation of DSTATCOM, the main objective is the mitigation of current based power quality problem by compensating typically the reactive power, unbalanced current, and neutral current, and typically the harmonics if it is required and then of course, the typically fluctuations like. [FL] Result in after putting a compensator with proper control, it should result; I mean the sinusoidal balanced current in the supplied and with the dc bus voltage regulation.

Dc bus voltage regulation for all the DSTATCOM configuration is the mandatory requirement, otherwise the DSTATCOM, PWM will not function properly like I mean. [FL], well we can call it in general a DSTATCOM has a voltage source converter connected to dc bus and ac side of it connected to the shunt normally connected across the consumer load or across the point of common coupling.

And these voltage source converter use the PWM control, pulse width modulation control; therefore it requires a small ripple filter to mitigate the switching ripple like I mean.

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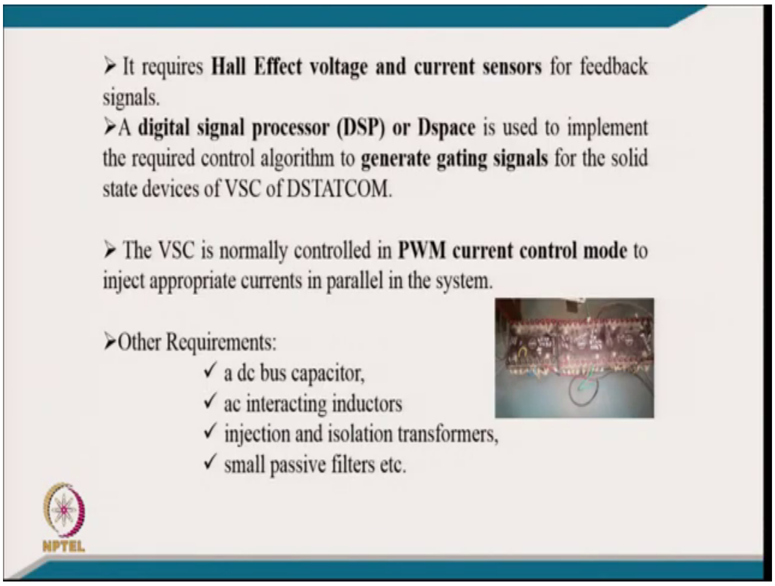


[FL], well it DSTATCOM implementation or the circuit require, the hall effect voltage and current sensor for feedback signal for the control of this. And digital signal processor or maybe you can call it Dspace is a one platform; there may be any platform I mean like or microcontroller is used to implement the required control algorithm to generate gating pulses for the solid state devices for voltage source converter of DSTATCOM.

And the voltage source converter is normally controlled in PWM current control mode to inject the appropriate currents in parallel in the system. And other requirement is a dc bus capacitor, the ac inductor; we already discussed it and injection an isolation transformer, and a small passive ripple filter like I mean.

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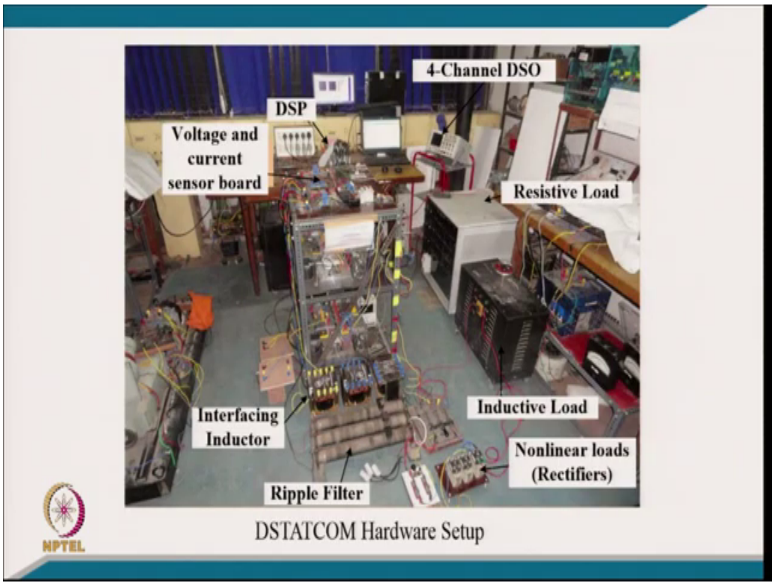

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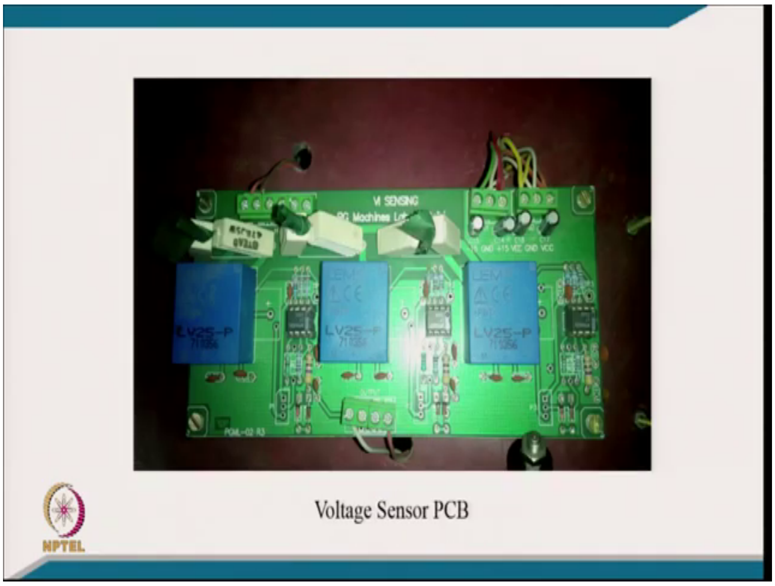

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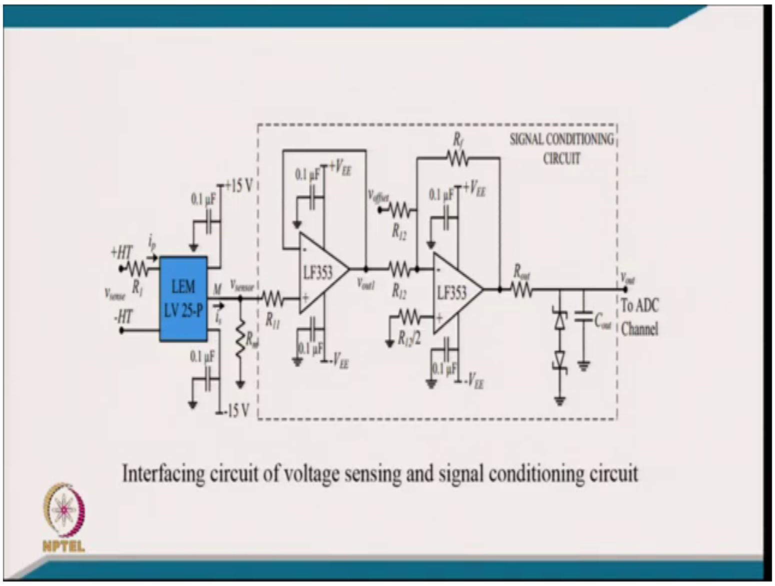


The typical photograph of DSTATCOM, which we have in the our implemented in the our student have implemented in the laboratory and this is the sensor voltage sensor board which we have used in implementation.

This is the circuit of typically of sensing circuit of this voltage source, I mean Hall Effect voltage resource in, Hall Effect voltage sensor and this provide the isolation from high voltage to low voltage and this after that low voltage, virtually we have to scale up and filter it the noise out of it.

And then put appropriate voltage which are accepted by DSP; because some DSP accept only typically your 3.3 volts, some accept plus minus 10 volt, [FL] accordingly you have to scale up with the e scaling. But you have to keep in this mind, you have to use the operational amplifier which are in a fast flow rate.

You are not going to use the slow amplifier; [FL] LF 353 have a very fast flow rate compared to the normal operational wire of your typically of 741 or so. [FL] 741 cannot be used in this case like just has a feedback like.

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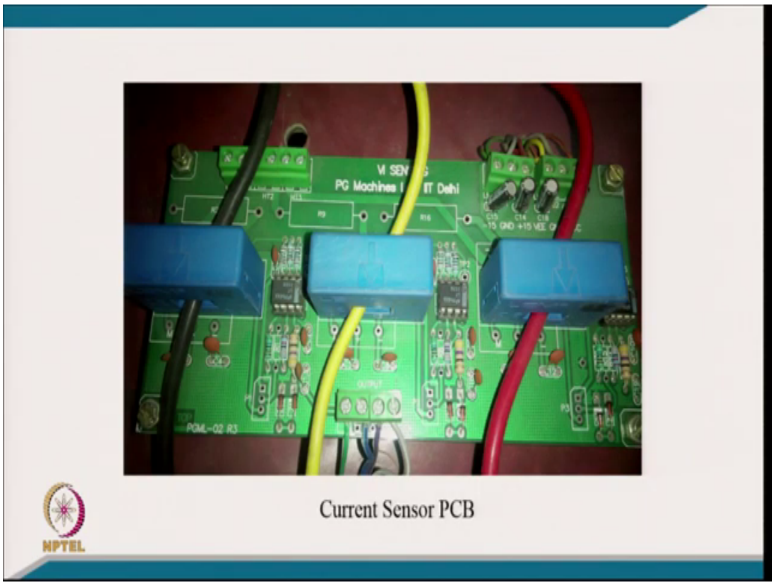


This is the current sense hall effect current sensor PCB, there are lot of kind of current sensor; this is maybe a PCB mounted up to 25 Ampere, they typically like a 50 Ampere current sensor, but you might have a 300 or 3 kilo Ampere depends on the rating and they are the thick wire which are going through it, it is power circuit.

And on secondary side of course, we have a complete circuit which give a same signal to us like I mean. [FL] Here also you have a LEM current sensor and secondary side we get the signal across this R m we get the voltage when current flows, secondary current flow through this.

And this current signal which is converted into voltage signal, now we have to scale up, which can be given to a dc analogue to digital channel of the processor; whichever processor you are using whether DSP or Dspace or any other processor you are using. So, this is like a sensor circuit like I mean.

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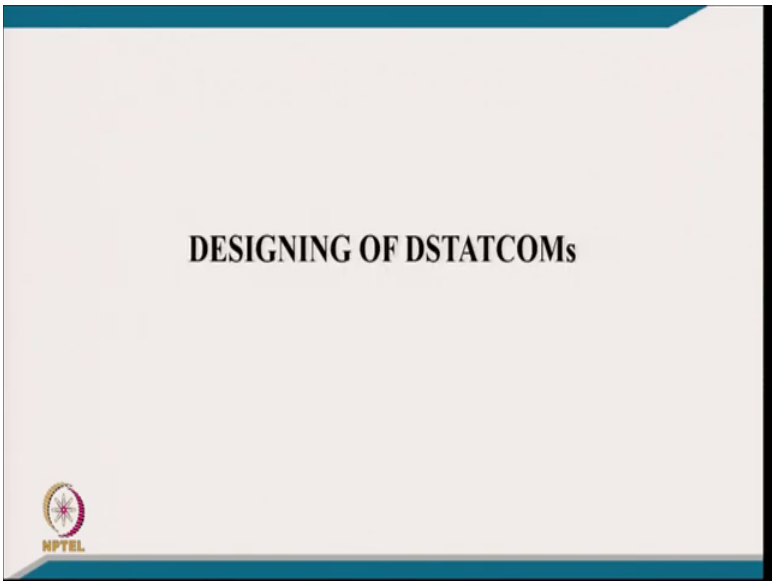

The design of distribution static compensator in short we call a DSTATCOM.

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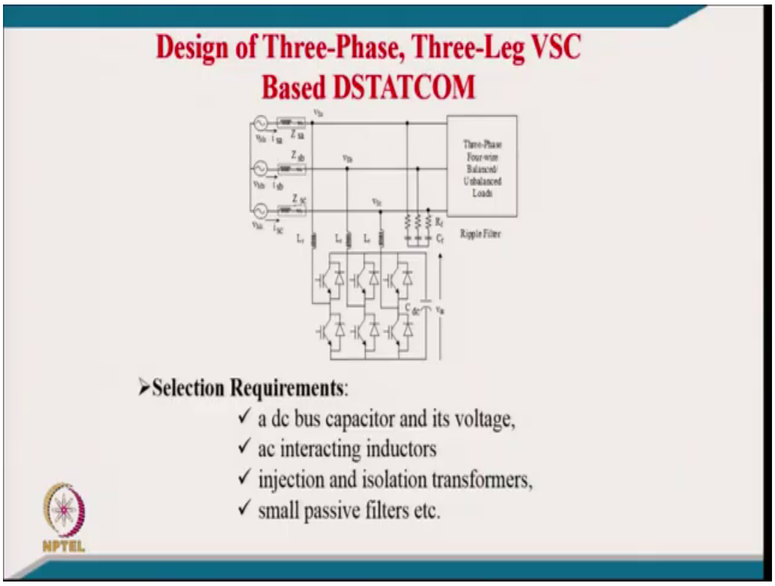


Well, to start with, we will like to discuss the design of three phase three leg voltage source converter based DSTATCOM. And we already discussed the circuit that it consists of three phase supply system and the typically three phase load, may be unbalanced load, may be balanced load I mean this load have to be like a three wire.

[FL] You can and then we have a typically a DSTATCOM with the three leg voltage source converter and we have the dc link capacitor and ripple filter, which we discuss earlier.

The very role of typically of dc link capacitor is to provide the self-supporting bus with the proper control and it if dc link voltage is maintained appropriate, which should be peak of more than the peak of the line, we will just discuss with the design formula. Then to maintain this then only it will work with the proper PWM control to inject the current at the point of common coupling through this inductors like I mean.

[FL], the purpose of inductor is because on the inverter side, you have a PWM voltage, on the grid side you have a typically balanced sinusoidal voltage [FL]; it should absorb the difference between the PWM voltage and your typically the point of common coupling sinusoidal voltage.

The very purpose of ripple filter we discussed this R f and C f, it to improve the voltage profile at the point of common coupling; because the voltage at the inverter output is PWM voltage and we do not know the source impedance.

If source impedance is higher, the this inductance interfacing inductance L r will not be able to absorb the all the ripple between the different between PWM voltage and typically on sinusoidal voltage. [FL] You will find a kind of high frequency com of around of switching frequency at the point of common coupling.

To reduce this, I mean switching ripple voltage at the point of common coupling, we use this R c filter. The value of R c filter we will discuss it at high frequency; this impedance of this will be almost closer to resistance, which is we normally select order of 3 to 5 Ohm, [FL] it should be order of that. [FL] It makes it and it will provide the short circuit for high frequency switching harmonies.

And the capacitor value normally we have order of 5 micro farad; at switching frequency it offers very low impedance, order of very close duration. But at fundamental frequency it offers very high impedance order of 300 Ohm and the current even with the few 100 volts at the point of common coupling of the at the point of common coupling, it does not draw the current more than 3 milli Amperes at typically at fundamental frequency.

[FL] The losses in this hardly may be less than 1 volt irrespective of the rating, I mean typically in this ripple filter like on. Of course, the load can be your balance load, unbalanced load, reactive load, maybe capacitive or inductive nature, [FL] variety of load which we are going to compensate.

[FL] After compensation from the DSTATCOM, we expect the supply current or grid current should sinusoidal balance and preferably either at (Refer Time: 36:01) power factor or we can use it for; if we are using a this DSTATCOM for power factor current, so those current should be in phase with the point of common coupling voltage.

[FL] Whatever the requirement of the load is there, whether it is reactive power or negative sequence current or unbalanced current ok it is taken care by the typically of by this DSTATCOM. And the selection requirement we like to discuss here, a dc link capacitors and its voltage rating and interfacing inductance value, injection and isolation transformer if it is there at all, and then we like to discuss a small ripple filter like.

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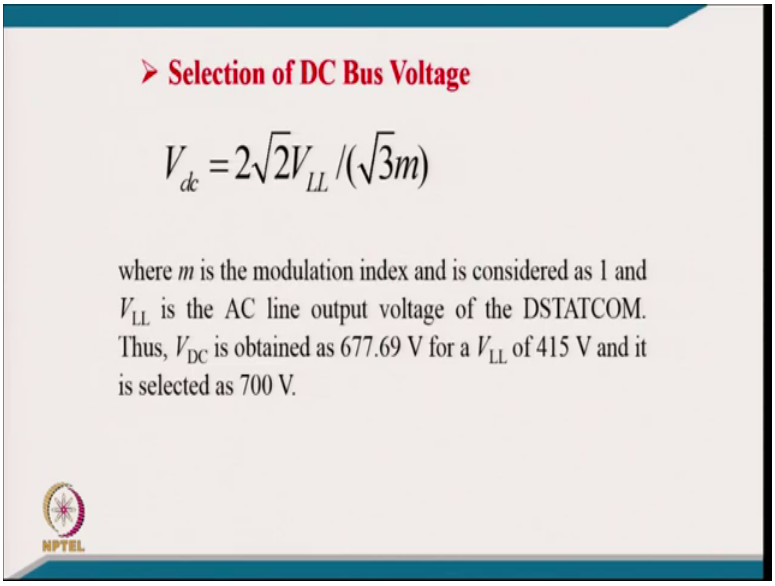

Well to select the DC link voltage, I mean in this the relation is from really from voltage source inverter you may find in many of the textbooks this relation, I mean which is where m is the typically where m is the modulation index of the inverter and is considered 1, I mean like you can take accordingly the safety factor. And V LL is the line voltage in RMS at the AC line voltage at the point of common coupling. And thus this DC link voltage is obtained from this relation if you keep the value of typically of V LL 415, it comes around 677.99.

[FL] Well to round off little higher as we have taken a modulation index 1, then it can be rounded off to 700 standard voltage, like of 700 like I mean or also. [FL] That is about the selection of DC link voltage, I mean it should be greater than the typically of the peak, peak of 415 is around like typically 586 [FL] it is on 700 side is slightly.

Because it what it is supposed to take care, it is supposed to take care the drop of the both the inductor of the line which are interfacing inductor, we discussed last time from the circuit or just your slide we have discuss it.

And of course, it had to take care of the modulation index and it had to take care of even the there is a variation in supply voltage in fourth place of 415 80 and go even a 440 also is still the inverter or voltage source converter should operate satisfactory like I mean or so.

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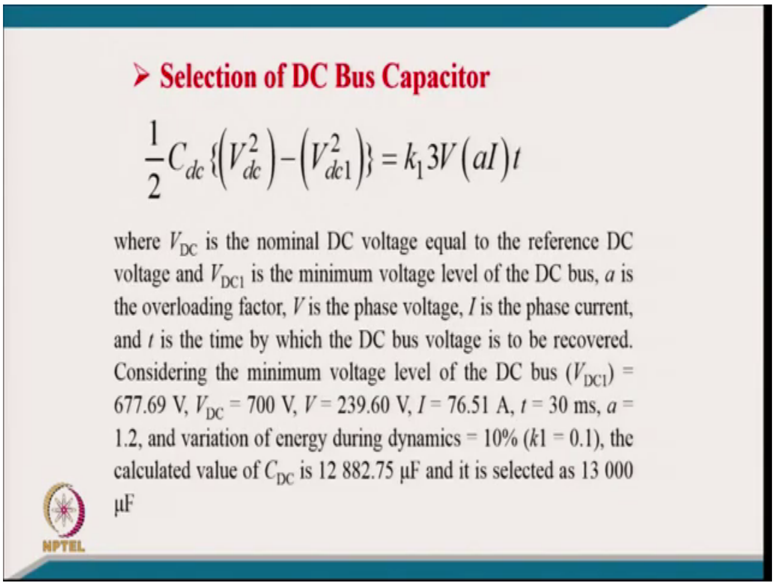


Well, the as far as selection is of capacitor is there, there may be there are many criteria; I mean these are the virtually the design guideline we consider it, [FL] one of the criteria is that you must not have a ripple voltage, I mean corresponding to the harmonics I mean the you might have a lower second harmonic [FL] that is one criteria.

The [FL] corresponding to that there will be a ripple voltage, we will discuss that also; but the very important stringent requirement is the dynamic variation of the voltage; the relation which is given here it is a half C dc's I mean into V dc square minus V dc 1 equal to k 1 into 3 V that is the phase voltage and a I, a I is the coefficient we will discuss that I and t, t is the time period in which we want to recover the voltage back at the nominal value of V DC, I mean if it is deviated from let us say from V DC to V DC 1; this V DC 1 may be the lower voltage or it can be higher voltage accordingly we can select it.

[FL] Based on this relation of energy you can call it energy storing and energy conservation formula, I mean we just decide the value of capacitor. [FL] Here the V DC the nominal DC link voltage to the reference DC voltage and V DC 1 is the minimum voltage level at the DC bus and a is the overloading factor and V is the phase voltage, I is the phase current and t is the time by which the DC link voltage is to be recovered.

[FL] Considering the minimum voltage level of the DC bus, that is typically it is a 677.69 and V DC 700 and considering phase voltage RMS 239.6, [FL] I, I mean like correspond to the rating let us say it comes 76.51 and t 30 millisecond we want to recover the, and a safety factor maximum allow current let us say 1.2 20 percent more mean 1.2.

The variation of energy dynamics will be 10 percent correspond to k 1 equal to 0.1; then the calculated value of this DC links capacitor comes around typically 12852 and we can select around 13000 micro Farad little higher than that for a typical gearing rating. So, that is the way how we can design, I mean design the value of the capacitor from this relation like I mean or so.

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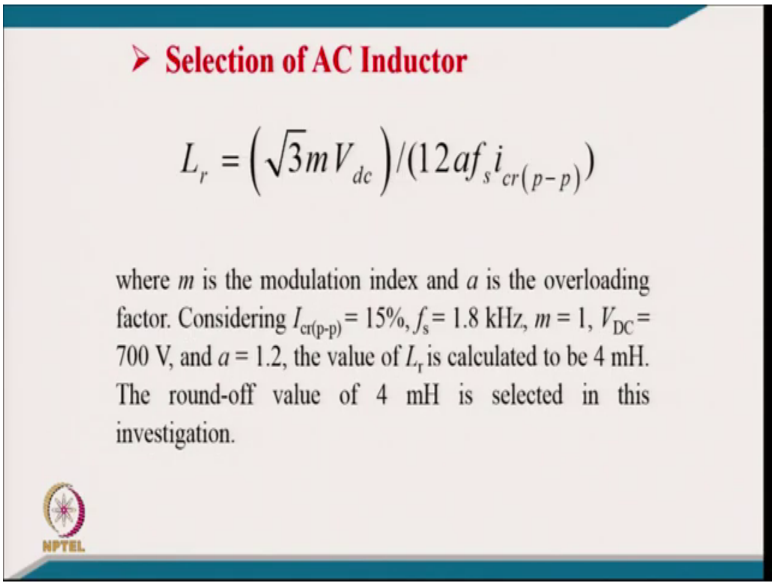


Well, the interfacing inductance, I mean like this is L r what we already discussed it; I mean this is corresponding to the ripple current, how much ripple we want to allow virtually from the inverter to go in the inductor. [FL] This is the relation derived for three phase, I mean where the root 3 is the corresponding to typically the line voltage and I mean the modulation type and V DC is the DC link voltage and 12 is the factor corresponding to 3 into 4 virtually.

And f is the switching frequency is again the overloading factor and i c r is the ripple current like percentage, actual ripple current like how much as a percentage of the your DSTATCOM current. So, m is the modulation index and a is the overloading factor. Considering the ripple current of 15 maybe 15 to 25 percent is the standard ripple current and switching frequency maybe even; if we are doing only the compensation for reactive power and negative sequence, we can take low frequency at around of 1.8 kilo Hertz.

But if we are doing harmonic compensation, then certainly the switching frequency should be at least double the lowest harmonic we want to compensate; that we will talk about somewhere little later in active shunt filter again. And V DC equal to 700 and a equal to 1.2, the value of this L r is calculated of 4 milli Henry, the round off value of I mean it comes typically 3 point something and then rounded to value can be taken up as a 4 milli Henry can be selected for this I mean typically designed.

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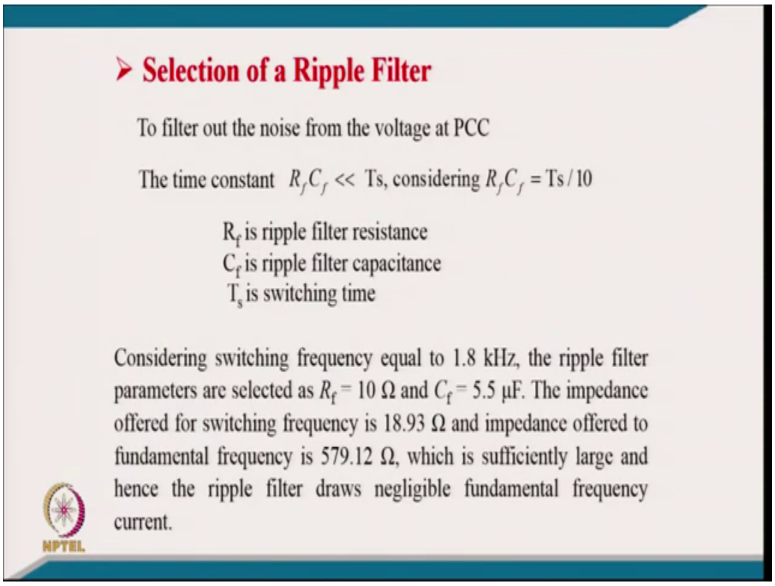


Well, selection of a ripple filter, to filter out the noise from the voltage at PCC. The time constant RCC is less than let us say T s, where T s is the time period for the typically you can call it for the switching corresponding switching frequency. To considering R f C f equal to T s by 10 [FL], R f is the ripple filter resistance, and C f is the ripple filter capacitance, and T s is the switching time [FL] corresponding to switching frequency.

[FL] Considering the switching frequency 1.8 kilo Hertz, the ripple parameters are selected R f equal to 10 Ohm and C f equal to 5.5. And impedance offered of switching frequency is 18.92 Ohm and impedance offered to fundamental frequency 579.12, which is sufficiently large. Hence, the ripple filter draws a negligible fundamental current and certainly the losses in the ripple filter also quite low, because high frequency current also will be quite low.

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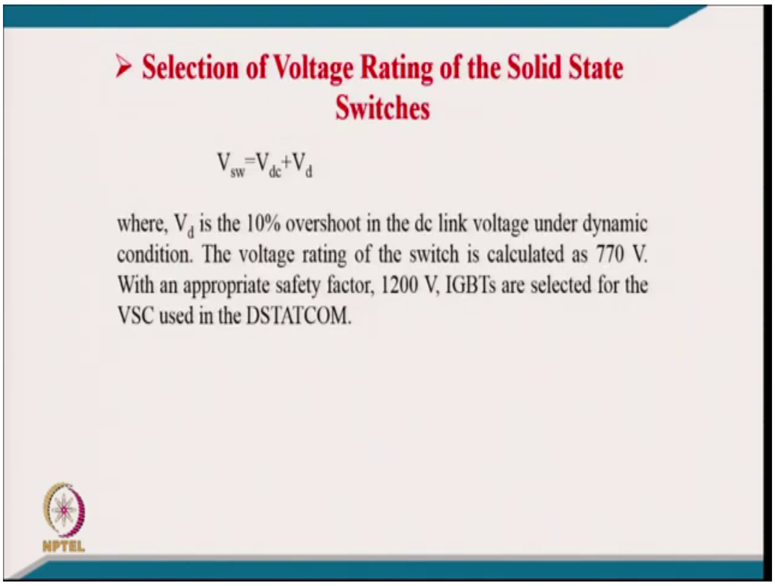


So, selection of this voltage rating of the solid state devices IGBT of the volt DSTATCOM, I mean that we take V d, that will be equal to V s w [FL]; it will be some of the dc link voltage plus V d, the 10 percent overshoot in the DC link voltage under the dynamic condition. And the voltage rating of the switch is calculated as typically 770 volt with appropriate safety factor normally for this voltage range of 415 volt line; we consider 1200 volt IGBT, we selected for the voltage source converter used in this DSTATCOM.

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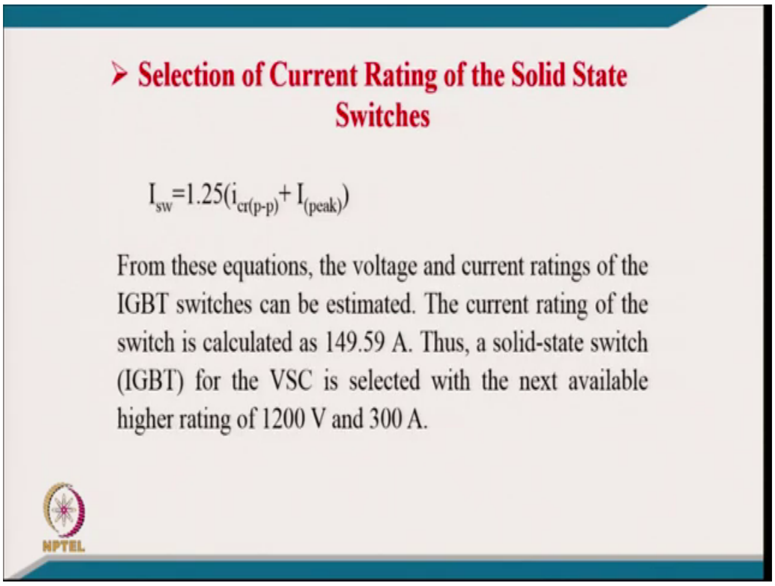


Similarly, the current rating of the switches, I mean we consider around with the safety factor about 25 percent 1.25, where we consider the peak current which is going to DSTATCOM current plus the ripple current, I mean like peak of ripple current. [FL] From this equation the voltage and current rating of the IGBT can be estimated and the current rating of switch is calculated 149.59. Thus a solid state switch of VSC selected with respect to next available rating that is 1200 volt and 300 Ampere like I mean.

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Table

Comparison of three-phase three-wire DSTATCOM.

| S. No | DSTATCOM Parameter | Three single-phase VSCs | 3-leg VSC | 2-leg VSC |
|---|---|---|---|---|
| 1 | DC bus voltage (V) | 350 | 700 | 1400 |
| 2 | DC bus capacitance (uF) | 5000 | 3000 | 3300 |
| 3 | AC Inductance (mH) | 1 | 2.5 | 6 |
| 4 | Voltage Rating of Switch(V) | 600 | 1200 | 1800 |
| 5 | Current rating of Switch (I) | 100 | 100 | 100 |

This is the typical I mean you can call it the design calculated data, I mean for a given rating; I mean for three leg VSC and two leg VSC. [FL], DC link voltage I mean we can have three single phase.

If we take all three topology corresponding to the design, [FL] I mean considering even a unity race of the transformer in case of three single phase VSC, the DC link will be here only 350 Volt, where the three leg VSC it will be 700 volt and two leg VSC; because each half should be greater than the line, so it comes around 1400 volt like. [FL], that is another drawback of course of your two leg VSC.

So, voltage rating virtually is almost the double like and that causes the typically the rating of the devices also affected. And DC bus capacitance we already calculated that for being a lower voltage, of course in three single phase here the capacitor value comes, I mean like a 5000 micro Farad and here it is come 3000 in three leg VSC and two leg it come 3300.

And the interfacing inductance of course, in single phase it come milli Henry and it can be 2.5 milli Henry for three leg VSC and 6 milli Henry for two leg VSC. And voltage rating of the switch for single phase it comes only 600 Volt; of course it comes like a 1200 volt for the case of three leg and for two leg it comes 1800. And current rating of switch is 100 Ampere, I mean for typically for all the rating like.

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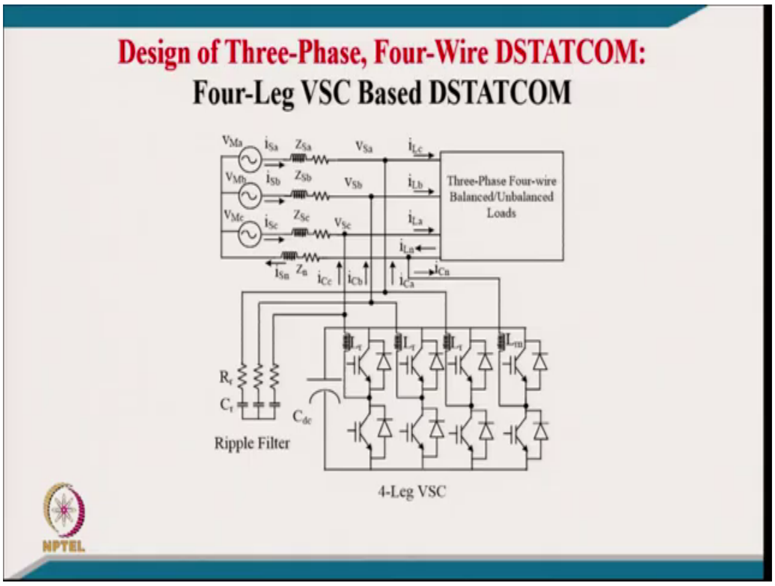


Then we like to go of course, the design of four wire system, four leg VSC based DSTATCOM, where we have a three leg for three phases and the fourth additional leg we consider for the neutral [FL]. Here is the three phase, four wire supply system with the three phase voltage and the neutral.

And at the after the source impedance, we have a point of common coupling, where we are connecting the three phase, four wire load. It can be balanced load, it can be unbalanced load.

Well, unbalanced load even can be even a single phase or two phase, we can have a load even on single phase also or all the three phases and there may be unbalance in the balance three phase or balance three phase load also there, may be there like; I mean it can be reactive load or capacitive load or even a pure resistive load may be unbalanced load, like I mean as we discussed in the previous chapter like when we were discussing passive compensation.

[FL] Here we have again typically the three interfacing inductor for three phases and then fourth leg we have another interfacing inductance the value may be little different; because here the ripple current is no decide with similar formula. Of course, the DC link capacitor is again for self-supporting DC bus and we will use the four leg VSC, because of the fourth leg requirement here. And then we have a R C filter, I mean here with the R f and C r like I mean or so.

Well, this is the basic circuit, here also you can understand; I mean we will discuss in control we have to regulate the DC link voltage, so that is PWM I mean it is quite effective to operate separately to, you can call it the control the this compensating current I mean which are i C a, i C b, i C c also or as well as i C n like I mean or so. So, i C n is very straightforward, the reference for this will be i L n.

Because you have to compensate that current with the opposite phase, so that i S n is 0. So, that is for other typically we like to discuss with the control how we are going to have a reference supply current or reference compensator current, so there are many concept of as far as any control is concerned like. So, we will talk about the after the design about the control of the.

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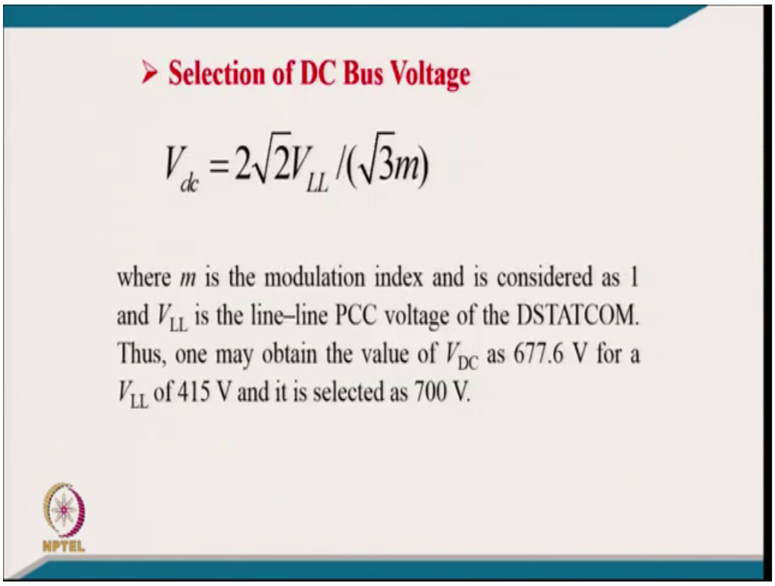


[FL] Here also the DC link voltage you can call it like is again 2 root 2 into V LL upon root 3 m where again modulation index and can be considered 1 or 0.9. And VLL is the line PCC voltage with. Thus, only one may obtain the value of V DC as 677 and we can select for this 400 voltage can be selected as a 700 volt after the round off value like I mean or so.

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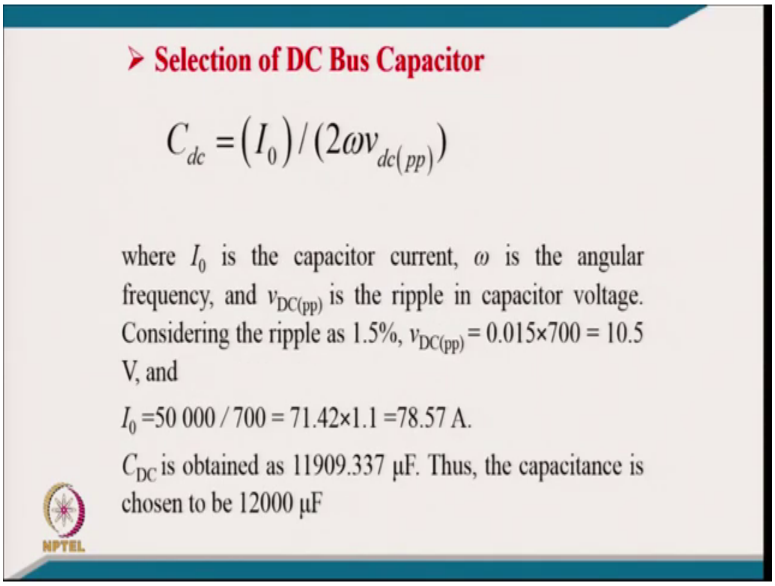


Well, the DC link capacitor here usually it is a different formula than what we discussed earlier. The reason being here, I mean typically the second harmonics will get reflected typically on the DC link. And because of presence of DC second harmonics on the DC link; I mean we have to have a twice of the frequency similar to like a single phase inverter circuit that is the relation go. [FL] Where I 0 is the capacitor current, and omega 0 is the angular frequency and V DC is the ripple voltage in the capacitor.

And considering the ripple 1.5 percent, V DC ripple of 0.0 700, [FL] it is a 10.5 Volt. And we can find out typical value of I 0 for a given of 50 kVA rating and it comes to be like a 78.57. So, C DC can be calculated 11909.337 micro and this can be selected as 1200, 12000 micro Farad like or so.

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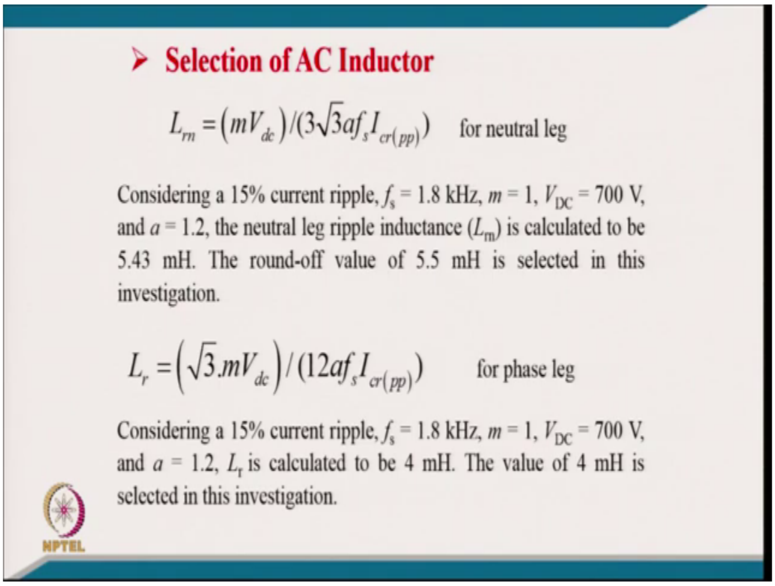


Well, selection of AC inductor, [FL] the inductor for neutral leg we can select; here typically in this case only the DC link voltage will be responsible and 3 root, 3 is corresponding to the neutral because supplier will be there and a f I c r. Considering the 15 percent ripple and switching frequency 1.8 kilo Hertz and modulation index 1 and DC link voltage of 700 volt and a equal to 1.2, the neutral leg inductance is calculated to be 5.43 milli Henry, and round off value can be taken 5.5 can be selected for this like I mean.

[FL] The of course, for other three leg, the formula remain same as we have discussed in typically three, where DSTATCOM that is root 3 m V dc by 12 a f I ripple. And considering 15 percent again ripple 1.8 kilo Hertz, and m equal to 1, and V DC 700, a can be 1.2, and L r can be calculated 4 milli Henry. It comes around 3 point something, so we can select 4 milli Henry as a value for after the round off like.

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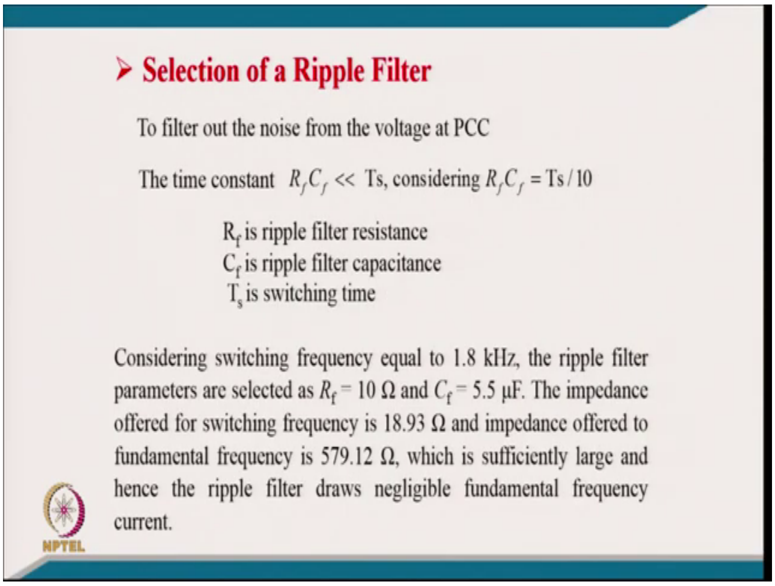


[FL] To find out the noise from typically the voltage at PCC, because of switching of this voltage source inverter. So, again we can say that, this time constant for R C filter should be much less than the switching frequency. [FL] Considering this typically the value corresponding to that, [FL] we can think about R f equal to filter resistance, C f is the filter capacitance and T s is the switching.

And considering the switching frequency 1.8 kilo Hertz and considering typically resistance of R f equal to 10 and C f 5.5. The impedance again for fundamental for the switching frequency is 18.92 and impedance offered at fundamental frequency is 579.12, which is sufficiently large and hence the ripple filter draws a negligible fundamental current.

And that is the reason the loss is, because it is will be very milli Ampere current; you can think about like even a, I mean like a you take a typically phase voltage 239 or 240 divided by

579, it is hardly a you can call it a I mean 400 milli Ampere. And 400 milli Ampere you can consider the square of that will become a (Refer Time: 49:52), you will have losses hardly less than a Watt or so. Even in all three phases, this will be summing all will not be more than 1 or 2 Watt like or so.

So, irrespective of the rating, because these concepts are irrespective of rating whether your DSTATCOM is 50 kV or 100 kV or 200 kV like I mean.

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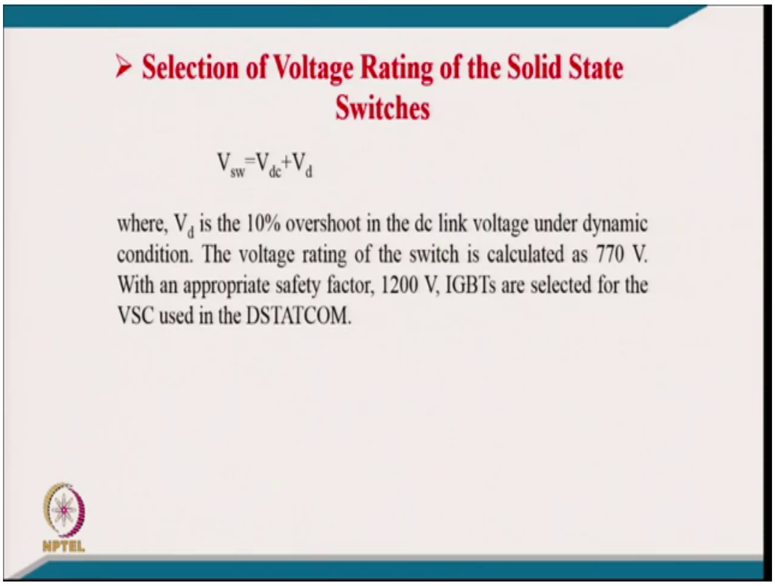


Well, selection of the voltage rating of the switches here; [FL] again switch voltage rating should be dc link voltage plus the overshoot in the dc link. [FL] That is the highest voltage we have selected it, but there will be a some overshoot; I mean because of the controller action, around 8 to 10 percent overshoot is there.

So, taking a safety factor of around 10 percent in the dc link voltage under dynamic condition, the voltage rating of the switch is calculated 770. The appropriate safety factor, we take a 1200 volt IGBT for the voltage source converter used in DSTATCOM.

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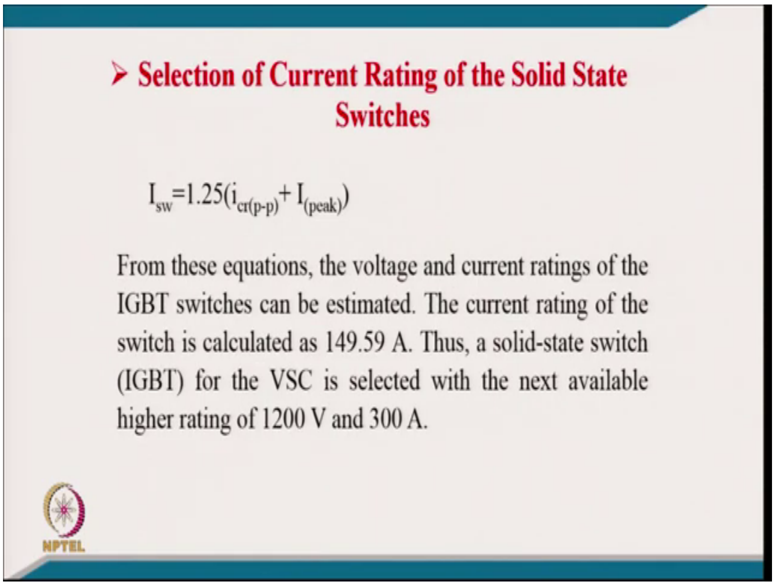


And the this typically the switch current rating we decide again 1.25 is the kind of an I ripple peak and then the peak of DSTATCOM current. From this equation the voltage and current rating of IGBT switches can be estimated and the current rating of the switch is calculated as 149.59. The solid state switch of VSC selected with the next typically available higher rating of 1200 volt and 300 Ampere like I mean or so.

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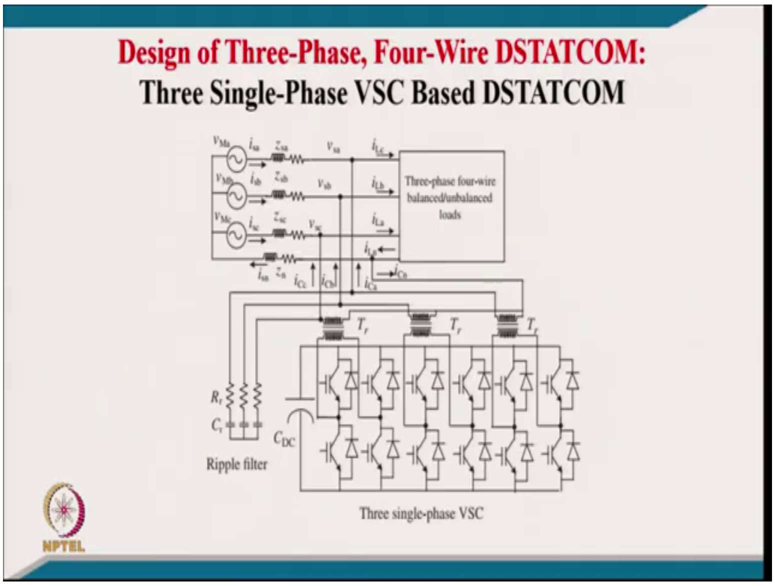


[FL] Coming to the typically another topology designed for four wire , typically four wire system, that is the design of three phase, four wire DSTATCOM.

[FL] We have a three single phase voltage source converter based DSTATCOM here. And what we are using here of course, we are using a transformer; I mean like a for the purpose of isolation and it can be for scaling the voltage level also, that may be the your load and distribution system may be at high voltage, but power electrons you can design at lower voltage.

But when we discuss in principle operation and these three single phase that was one of the major benefits that you can use the unipolar switching. [FL] Ripple current frequency will be double the switching frequency of the devices or other way you can call it switch you can see here it half the switching losses and the devices will be lower in this case.

And the dc link voltage can be maintained much lower, approximately half compared to what you have in previous topology like. And here again the we keep R f and C f for mitigating the switching ripple here typically at the point of common coupling like I mean.

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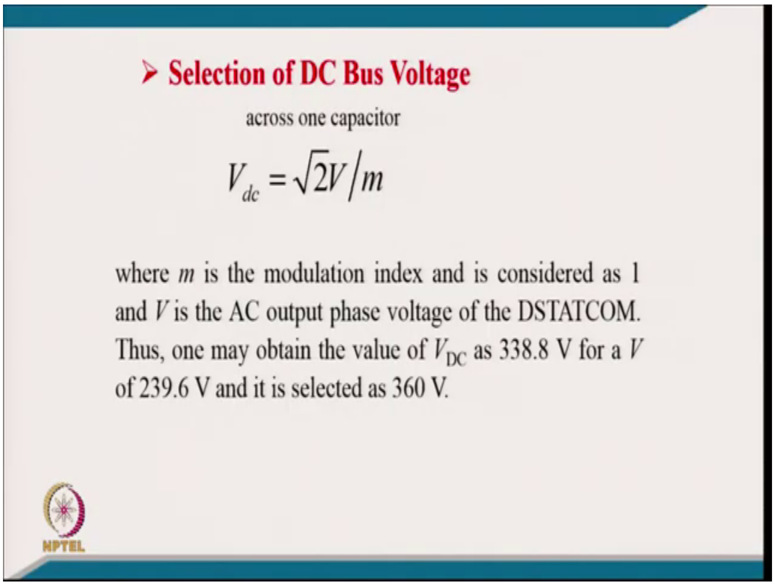


Well, here because the this typically working as a single phase inverter to selection of DC link DC bus capacitor is similar to like V dc into root 2 V upon m. And m is the modulation index and we consider 1 and we the AC RMS voltage of phase voltage of DSTATCOM. So, thus one may obtain the V DC as 338 for a, you can call it V 239.6 and it can be selected like a 360 or 400 like typical order of that like I mean or so.

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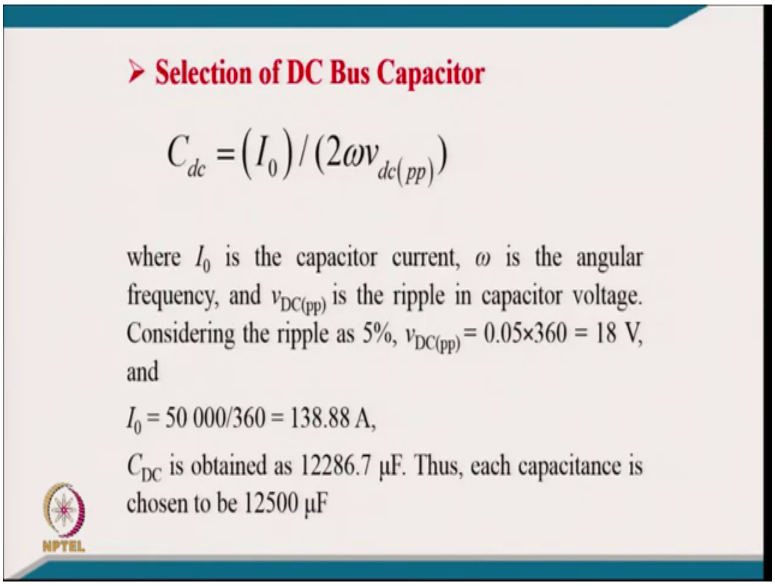


So, that is about the DC link voltage selection here, because it is a similar to single phase. Similarly the capacitance is also corresponding to, because second harmonics again there on the; because of operation of independent phases and you might have a because of unbalanced, the second harmonics appearing at the DC link.

So, the same formula is valid here I 0 upon 2 omega V DC ripple peak and I 0, here the where the I 0 is the capacitor current, omega is the angular frequency, and V DC is the ripple filter. Considering the 5 percent ripple voltage of 360 [FL] 18 volt and I 0 4 50 kV if we are designing; then come 138.88 and C DC obtained is 12286.7. So, it can be selected 1200 12500 micro Farad like I mean or so.

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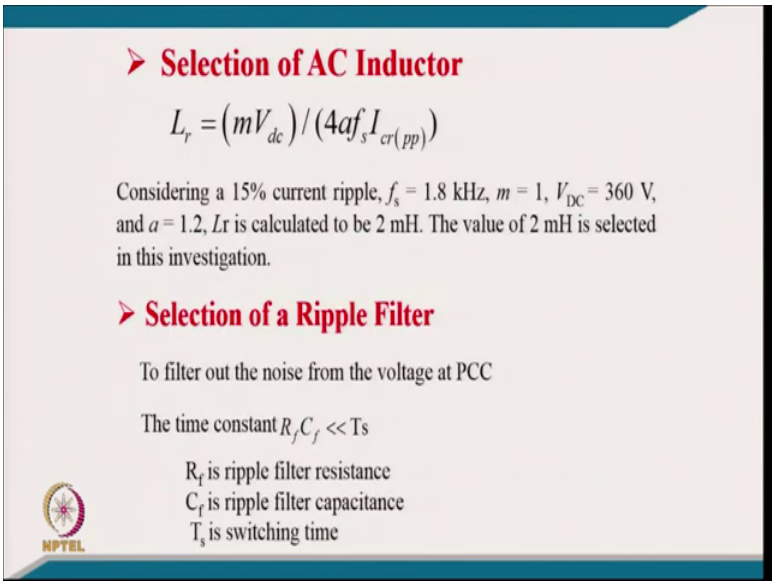


Well, the selection of interfacing inductance here again; because the formula it is a like a single phase inverter, a voltage source inverter, [FL] formula of all ripple current of single phase will be applicable here. [FL] This interfacing inductance for the single phase voltage source converter similar to will be m V dc upon 4 a f s I ripple current, I mean typically of peak to peak.

[FL] Considering 15 percent ripple and switching frequency 1.8 kilo Hertz, modulation index 1, V DC 360, and a equal to 1.2, L r is calculated 2 milli Henry; it comes around less than little 2 milli Henry and we can calculate one point, typically select 1.2 milli Henry for this like.

And coming to the selection of ripple filter, I mean to filter out the noise from the voltage at point of common coupling; time constant is again considered much lesser than RCC R f C f as a time constant of the filter, where the R f is the ripple filter capacitance, C f is the ripple filter typically you can call it capacitance, and T s is the switching, I mean the time period for corresponding to the switching frequency like.

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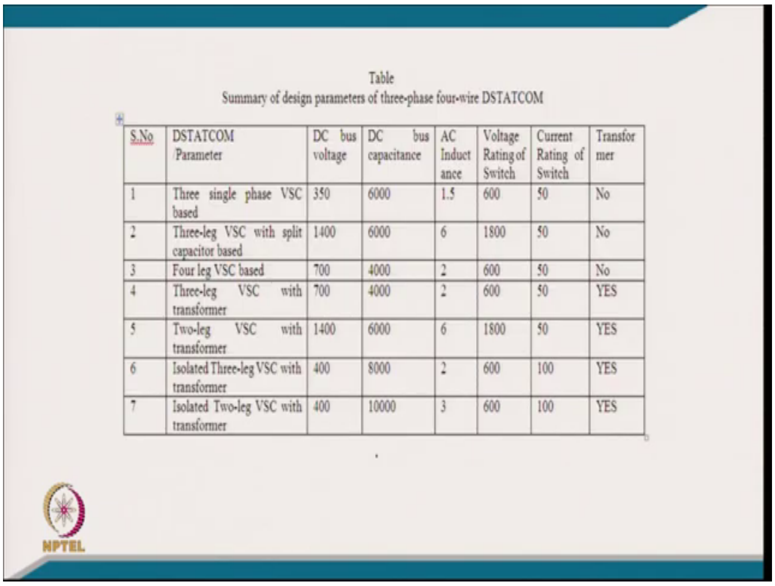
Table
Summary of design parameters of three-phase four-wire DSTATCOM

| S.No | DSTATCOM Parameter | DC bus voltage | DC bus capacitance | AC Inductance | Voltage Rating of Switch | Current Rating of Switch | Transformer |
|---|---|---|---|---|---|---|---|
| 1 | Three single phase VSC based | 350 | 6000 | 1.5 | 600 | 50 | No |
| 2 | Three-leg VSC with split capacitor based | 1400 | 6000 | 6 | 1800 | 50 | No |
| 3 | Four leg VSC based | 700 | 4000 | 2 | 600 | 50 | No |
| 4 | Three-leg VSC with transformer | 700 | 4000 | 2 | 600 | 50 | YES |
| 5 | Two-leg VSC with transformer | 1400 | 6000 | 6 | 1800 | 50 | YES |
| 6 | Isolated Three-leg VSC with transformer | 400 | 8000 | 2 | 600 | 100 | YES |
| 7 | Isolated Two-leg VSC with transformer | 400 | 10000 | 3 | 600 | 100 | YES |



So, this is the table of summary of design for three phase, four wire DSTATCOM; the different topology, I mean seven topology corresponding to the same rating. And you can find out the typically the DC link voltage, here it is around 350 with the DC capacitance 6000 micro Farad and AC inductance of 1.5 milli Henry and this is three single phase based and voltage rating of 650 Ampere current and of course no transformer.

And we talk about like, I mean similarly for other one and similarly three leg VSC with split capacitor or you can call it the four leg VSC, that is important [FL] you have a DC link voltage 700 and you have a capacitance of 4000 micro Farad; that will lose because the voltage is little bit increase compared to the.

And then you have a inductance of 2 milli Henry and voltage rating of 600 volt and typically of 50 volt I mean like and then 50 Ampere. And then if you come out with the transformer isolation, of course here it is we consider the transformer trans ratio 1; but non practice transformation its ratio normally will be higher, because you will be connecting this DSTATCOM at much higher voltage than only the one of the reason that why we you have to use the transformer for the purpose of.

One is of course isolation, another is to interfacing the high voltage distribution system this and you are designing the power electronics at optimum voltage like I mean.

[FL] It is a three leg VSC with the transformer typically and the all the parameters comes around the same with the transformer isolation for all the design like or so.

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[FL] We can have a typically control of this.