DC Microgrid and Control System

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Lecture - 11
Modeling of Converters in Microgrid Power System (AC/DC and DC/AC Converters Modeling)

Welcome to our NPTEL lectures on the DC Microgrid and Control. We shall discuss today about the modeling of the converter that is a very important topic till now we have discussed, modeling of the converter in the microgrid power system. So, we will you have both the converter required to be designed that is actually AC to DC as well as DC to AC in the subsequent class we shall do that DC to DC also. So, we shall discuss about this will be our presentation layout today.

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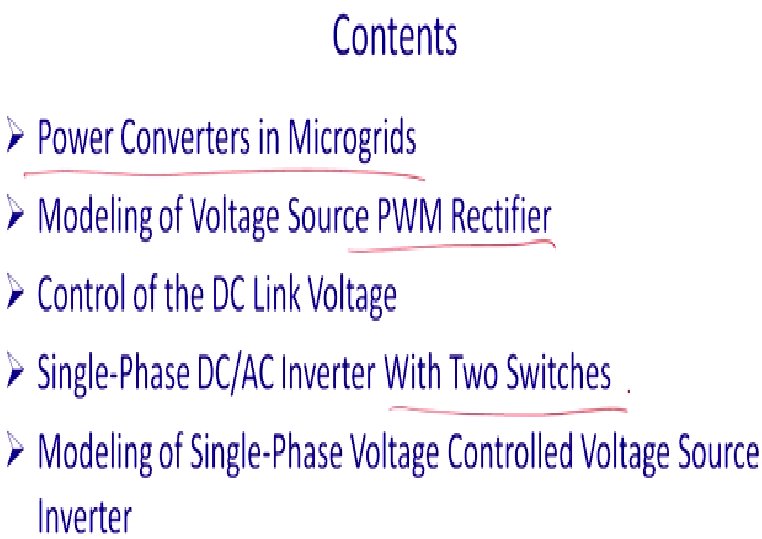

Power converter in Microgrids, modeling of voltage source PWM rectifier followed by the control of the DC link voltage, single-phase AC/DC inverter with 2 switches and modeling of single-phase voltage controlled voltage source inverter. These all we will see together.

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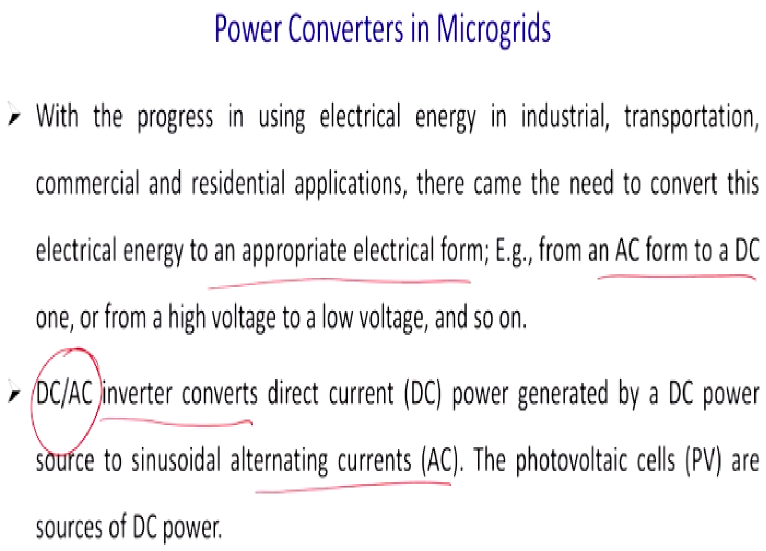

As we know that you know with the progress of using electrical energy in industry, transportation, commercial and residential application, there came the need to convert this energy for appropriate voltage level. For example, we generate the generator around thousands around 1000 to 11 KV voltages and it has been transported based on the transmission line level and for this reason and thereafter what happened you are rectifying it and you are running a different kind of converter.

If you have a local railway locomotive, then you required to rectify for the 11KV line. So, for this reason, you would know you may have from AC to DC or from high voltage to the low voltage and so on. Similarly, we may have adjustable speed drive since we have a constant frequency supply and rise are most of the cases at constant frequency runs have the constant speed.

For this reason, inverter converts direct current or DC power generated by the DC to the sinusoidal alternating current and it should be you know it should be required to be some time required to be variable power. The photovoltaic cells PVs are different kind of DC sources since it required to be connected to the grid or battery it required to be or UPS required to be converted into DC to AC apart from adjustable speed drive.

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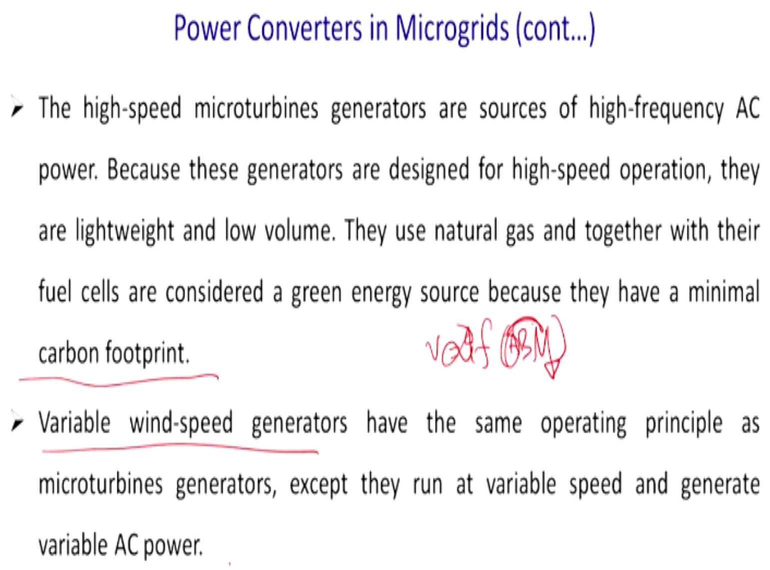

The high-speed micro turbine generator are the source of high frequency AC power because these generator are designed for the high-speed operation, they are lightweight and low volume since you know that is essentially V is is proportional to if you write proportional to f more the frequency is other part that is basically comes and the picture is A B and N can we reduced mainly A is area, B is the flux density that depends on the material and N is the number of ton.

So A and N can be reduced by increasing the value of f. So they use natural gas all together with their fuel cells are considered to be the green energy source because they have a minimal carbon footprint. So that can be used for many micro hydel for fuel cell waste generation system. Apart from that, we have a variable win-speed generators have the same operating principle as that of the microturbine except they run at a variable speed and generate variable frequency AC power as well as voltage.

So, for this for this reason you know we require to have a processed energy and this process has been done by the different type of AC to DC or DC to AC type of converter.

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Power Converters in Microgrids (cont...)

- To utilize the variable frequency AC power sources, the generated power is rectified to DC power using an AC/DC rectifier, DC/AC inverters are used to convert the generator DC power output to AC power at the system operating frequency as illustrated in Fig.1

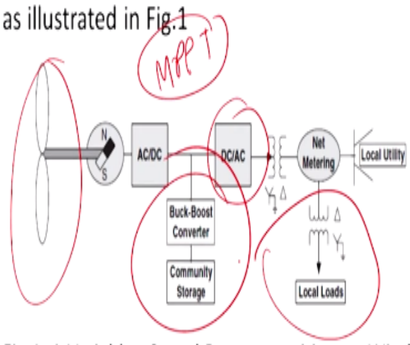

Fig.1: A Variable - Speed Permanent Magnet Wind Generator System

Power Converters in Microgrids, to utilize a variable frequency AC power sources, the generator power is rectifier rectified to the DC power using a AC to DC rectifier that is a simple rectifier and thereafter DC to AC inverter are also used to convert the generator DC power to the AC power at a system operating frequency as illustrated in the system. So, you have a wind turbine of the variable speed permanent magnet motor generator and then it will be converted to the AC to DC and here you require to track also maximum power point.

So far this reason, you have a buck boost converter that will help you to actually extract the maximum power from this wind or hydel setup mostly the wind setup. Thereafter you may have community storage for the local usage also controlling the pick power management. Thereafter it can be converted into the DC to AC and required to be connected the grid to the to send it to the and this is for the microgrid this is you may have a local load and you can send to the local utility or you can dispatch power to the active converter.

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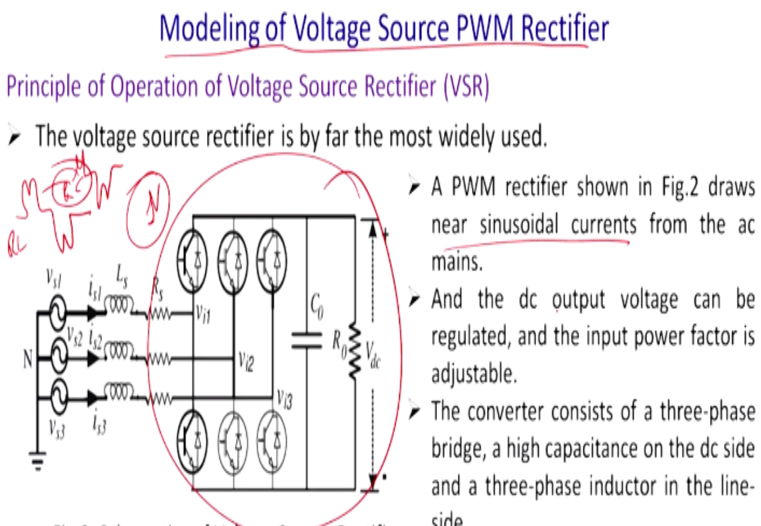

Fig.2: Schematics of Voltage Source Rectifier

Now principle of modeling that is something we require to investigate time on it, modeling of voltage source PWM rectifier. The voltage source rectifier is widely used for this purpose because you know, please understand why we require this active rectifier, we may use in case also founded converter converting AC to DC with the unity power factor also having a low distortion into the and all the power quality issues into the exit site. So it is one of the main part instead of the diode boost rectifier, you will use this this PWM rectifier.

Another issue is actually the power rating of the diode. So once the high current flows through the diode then if it is and this power diode will drop around one volt so in that case this drop is quite huge and some time to negative drop also, we use synchronous rectifier that is most paired base that is generally used for the low power application, but for the high power application, we requires control rectifier and we require different kind of peto power quality issues and for this reason PWM rectifier is preferred.

A PWM rectifier shown in the figure 2 draws near sinusoidal current from the AC mains. Otherwise you know that you have three-phase 3 wire system if you fit to the diode boost rectifier current will be like this for the RL kind of load and for the RC kind of load when it is quite bad this will be the thing for RL and this is for the RC for diode boost rectifier and you don't want that, you want a sinusoidal voltage and for this reason we required to incorporate this PWM rectifier.

The DC output voltage can be regulated, and the input power factor is just the series can be adjusted. So, you can control the PQ control that we will come little later can be done through the PWM rectifier. The converter consists of three-phase bridge, a high capacitor so that actually voltage (( )) (09:18) in the output side is low, high capacitance of the dc side and the three-phase inductor in the line side, this is called line inductor. Ultimately, this is a boost topology, this LS help us mostly it indicate to the source inductance. If source inductance is not so high, then you have to add the external inductance.

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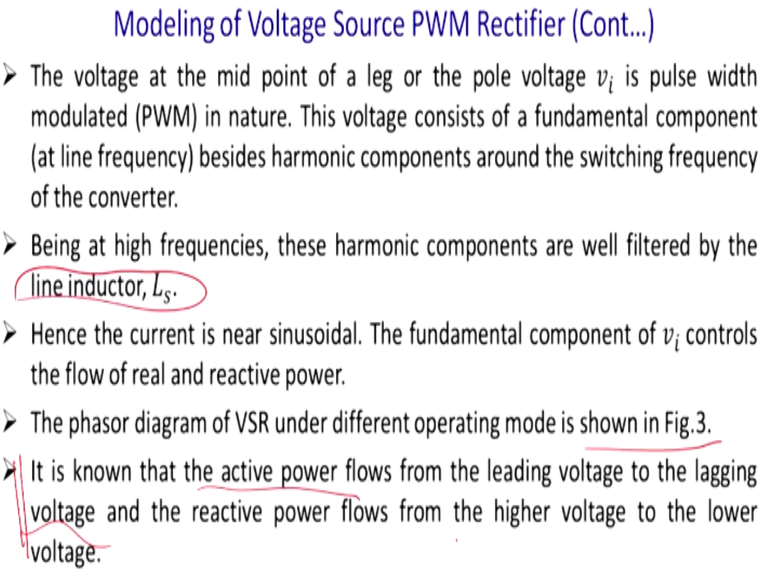

The voltage at the midpoint of the leg of the pole voltage v1 is a pulse width modulation PWM in nature. This voltage consists of the fundamental component of the line frequencies beside the harmonic components around the switching frequency on the convert. So this will have a problem of the voltage to be AC to be higher, but since it has all in-built low pass filter, so current AC will be lower. At high frequencies, these harmonic components will be filtered out by this line inductor, Ls.

Hence inductor current is nearly sinusoidal. The fundamental component Vi controls the flow of the real and reactive power. The phasor diagram of VSR will come with later and the different operating condition is shown in next figure that is figure 3 and is known that the active power flow from the from the leading voltage to the lagging voltage and reactive power flow from higher voltage to the lower voltage.

So please understand that this is one of the important chunk of its operation that the active power flow from leading voltage to the lagging voltage, so you can control the flow of active power by controlling the power factor and reactive power flows from the higher voltage to the lower voltage.

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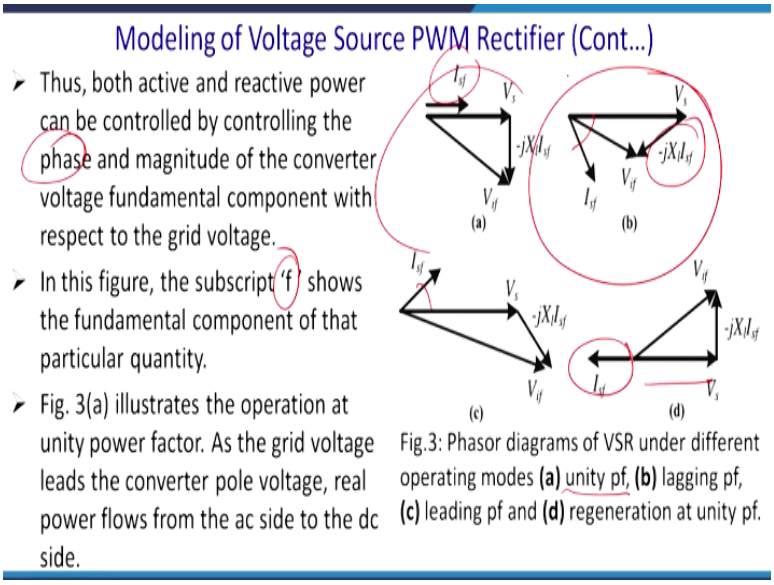

So, this principle will be applied to actively control the PNQ. Thus both the active and reactive power can be controlled by controlling the phase, if you control phase then you can control that active power and if you control the voltage level you can control the reactive power and the magnitude of the converter voltage fundamental component with respect to the grid voltage.

You see that this is a reference, so this is a reference a shows that phasor diagram of the voltage source rectifier under different operating modes, that is unity power factor where voltage and current are at unity power factor and this one is VIF and in b it is lagging power factor, so you have this value of the induction and this current is lagging. Similarly, here in C, current is leading, you got a leading power factor and it is regeneration you fit the current and voltage will be 180 degree phase shifted.

So, power will come back from the dc side to ac side and it will acts as an inverter. In this figure, subscript f shows that fundamental component, so If is input fundamental component. So, figure 3 illustrates the operation at the unity power factor as I described and others are lagging, leading and regenerative way of operation.

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Modeling of Voltage Source PWM Rectifier (Cont…)

- Fig. 3(b) shows lagging power factor operation. The real power flows from the ac to the dc side. Since V_s is greater than V_i, the reactive power flows from the mains to the converter side.
- In Fig. 3(c) (leading power factor), the real power flows from the ac to the dc side, while the reactive power flows from the converter to the grid. Fig. 3 (d) shows the operation under regenerative mode with the real power flowing from the dc to the ac side and at unity power factor.
- As shown in Fig.2, the VSR is fed from ac main. The rms value of phase to neutral voltage of the main ac supply can be defined as:

$$v_{s1} = \sqrt{2}V_s cos\omega t$$
$$v_{s2} = \sqrt{2}V_s \cos(\omega t - 120) \quad (1)$$
$$v_{s3} = \sqrt{2}V_s \cos(\omega t - 240)$$

Figure 3b, please recall this figure, figure 3b this one, shows that lagging power factor operation. The real power flows from ac to the dc side since Vs is greater than Vi, the reactive power flows from the mains to the converter side. So, this is the mode of operations in case of the lagging power factor. Similarly, in 3c, the leading power factor the real power flow from ac to dc is same while the reactive power flow of flow from the converter to the grid and just reverse happened.

In case of the 3d that this the regenerative mode of operation shows the operation under regeneration mode with the real power flow from the dc to the ac side at unity power factor. Figure 2 shows that figure 2 we have seen that actually VSR is fed from the ac mains the rms value of the phase to the neutral voltage to the mains ac supply can be defined as these 3 are unity power factor at 120 degree phase shift balance three-phase load.

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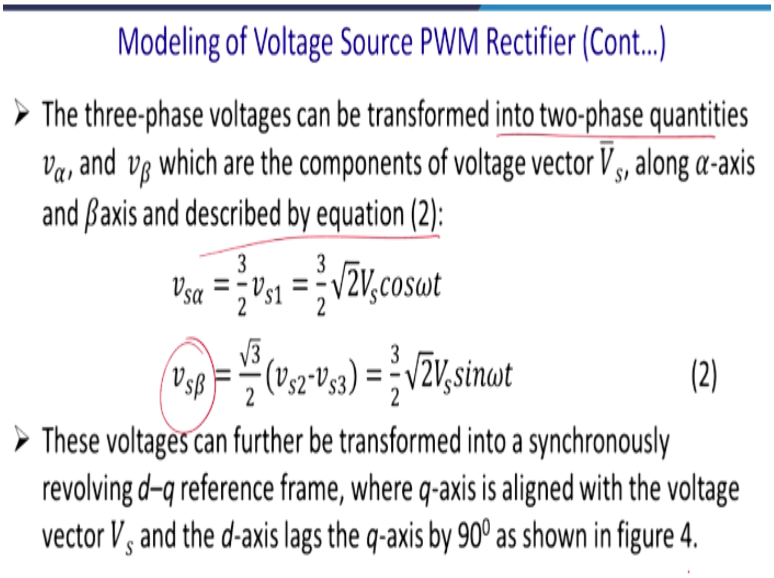

Modeling of Voltage Source PWM Rectifier (Cont...)

- The three-phase voltages can be transformed into two-phase quantities v_α, and v_β which are the components of voltage vector $\overline{V}_s$, along α-axis and βaxis and described by equation (2):

$$v_{s\alpha} = \frac{3}{2}v_{s1} = \frac{3}{2}\sqrt{2}V_s cos\omega t$$

$$v_{s\beta} = \frac{\sqrt{3}}{2}(v_{s2}\text{-}v_{s3}) = \frac{3}{2}\sqrt{2}V_s sin\omega t \qquad (2)$$

- These voltages can further be transformed into a synchronously revolving d–q reference frame, where q-axis is aligned with the voltage vector V_s and the d-axis lags the q-axis by 90^0 as shown in figure 4.

Now we shall continue to model this thing in stationery reference frame in alpha beta frame. So the three-phase voltage can be transformed into two-phase electrical quantities that is called stationary alphabet A frame, V alpha and V beta which are the component of the voltage vector Vs along alpha axis and the beta axis and described by the equation 2 that is V alpha = 3/2 Vs1 = root 3/2 2Vs cos Omega T.

Same way Vs beta = root 3/2 Vs2-Vs3 = 3/2 root 2 Vs sine Omega T. This voltage can further be transformed into asynchronously revolving d-1 reference frame where d-q axis is aligned with the voltage vector Vs and d-axis lags the q-axis by 90 degree as shown in the figure 4.

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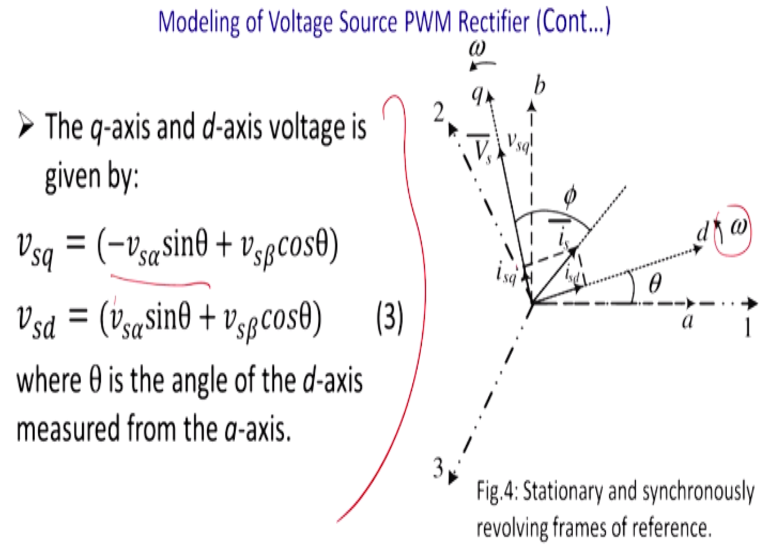

So this is the representations or transformation to the alpha beta to ABC to the alpha beta which is not a very difficult thing, you have studied the resolution force in class 12 that is actually three forces are 120 degree apart, they are made to the they have been put in to the x and y axis. So, x axis is alpha axis and y axis is the beta axis, same transformation has been used here as simple as that. So, q now we shall once we rotate this alpha beta frame into a synchronous speed.

Then it becomes d-q and that what happened at this stage this electrical signals which was a stationary and since you are stationery, you look like that this is rotating at 50 hurtz. Once you rotate in a synchronous speed, those entities are even stationary with respect to you. So, transforming alpha beta to d-q frame, so sq can be written as –Vs alpha sine theta + Vs beta cos theta and sd = Vs sine alpha sine theta + Vs beta cos theta where theta is the angle of the d-axis measured from the alpha axis.

So this is the uh when it is rotated in a synchronous frame and this is the initial reference with that we may angle theta, so this this becomes d and perpendicular to it, it should be q and ultimately this is this become will become sd and at perpendi this is basically is you will have it has been spread into sd and sq into components.

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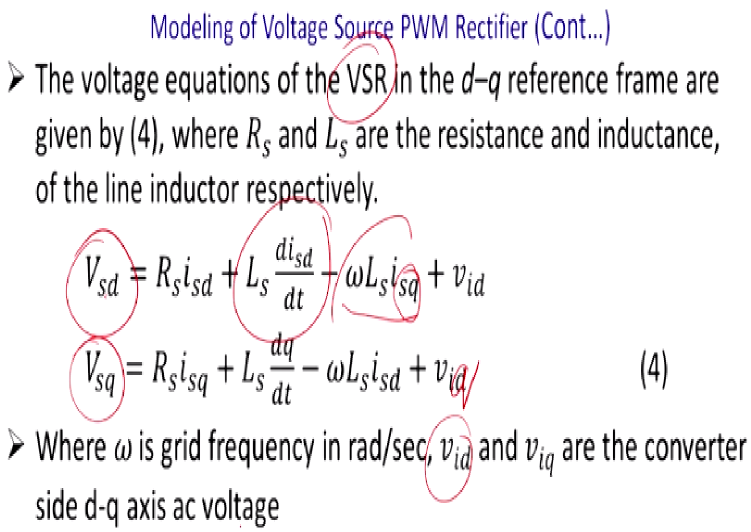

Now similarly so we can write the voltage equations of the VSR in the d-q reference frame are being represented here where Rs and Ls are the inductive resistance of the source inductance and the sources resistance that we can talk about. Now microgrid has a problem you know that actually predominantly it is resistive generally in case of the normal grid we neglect the value of resistance and it is predominantly inductive, but we shall take care of these things at later stage.

So Vsd equal to then it can be represented by Rsisd + Lsisdt. Please understand I was telling it looks like dc but it is not d for this is this time will survive and similarly omega Ls x iq, omega Lsisq + Vid. Similarly, you got Vsq Rsisq + Ls dqdt – omega Lsisd, these are the cross term here with isd you will get this isq and here with vsq you will get isd + Vid. While omega d is a grid frequent radiant per second and Vid and Viq, so Viq are the convertor sites voltages.

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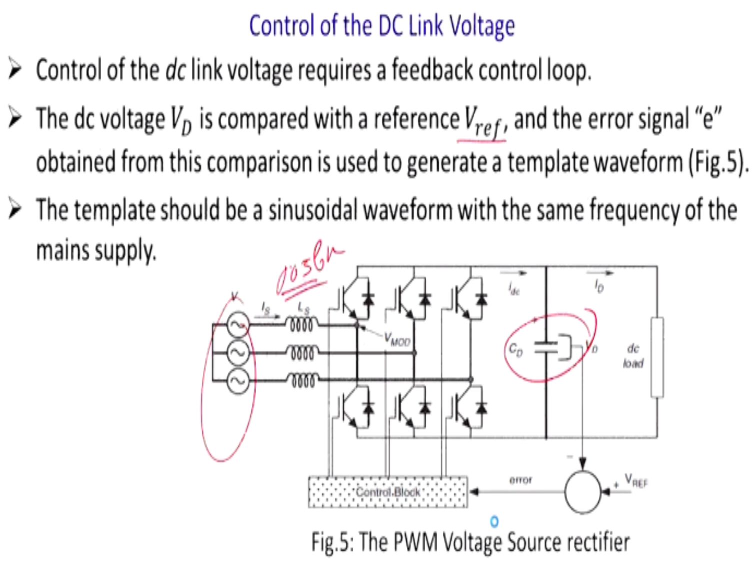

Control of the dc link voltage, it is quite the important aspect of controlling the active rectifier or PQM rectifier. Control of the dc link voltage require of feedback loop that dc voltage VD is compared with the reference Vref and the error signal e obtained from the comparison is used to generate the template waveform. The template should be a sinusoidal waveform with the same frequency of the main supply.

So you have to generate the unit template from the voltage sensor and look this is the voltage supply, there it is Is here was source inductance generally you have to put extra sources inductance, you generally require this value of Ls to 0.05 per unit, accordingly you can generally if it is voltage is quite higher then you may require to use the multilevel converter, I was for sake of simplicity, we are looking 2 level converter, now ultimately you got a Vdc and that has to be compared with the Vref and you got an error signal.

This error signal will multiply, will be fed into the PI controller then whatever reference will come out to be multiplied by the unit voltage template then the reference for this converter will be generated.

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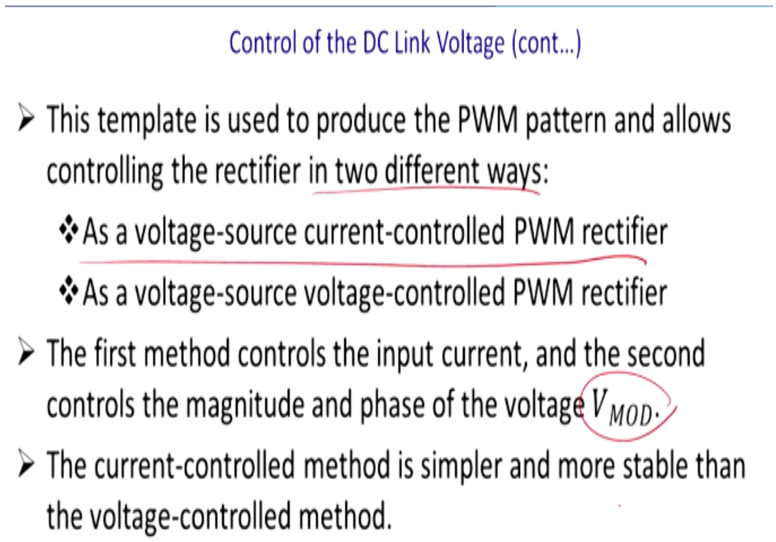

This template is used to produce the PWM pattern and allows the controlling of the rectifier in 2 different ways. One is the voltage-source current-controlled PWM rectifier for this size of the inductor required to be higher and the voltage-source voltage-controlled PWM rectifier. In first method, we shall see that this is quite familiar.

The first method controls the input current and the second controls the magnitude and the phase of voltages of VMOD and it is abbreviation magnitude and phase of the voltages. The current-controlled method is simpler and more stable than the voltage-controlled method and it has it is inherently protected forest short circuit.

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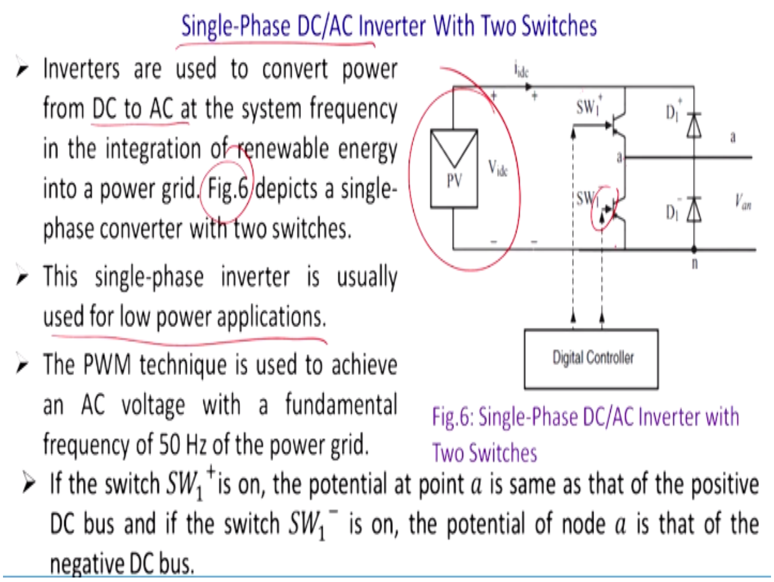

Now let us come to the AC to uh we have talked about AC to DC converter that is rectifier, now we will talk about DC to AC inverter. You may find that its application in where we have you have a dc and you have to connect the local AC grid and this reason you requited to have rectifier. In in IIT or IIT Roorkee we have a DC microgrid, we have AC microgrid, we have DC microgrid test bench and we have genuine AC microgrid because everybody has donated that battery setup.

So we have a solar power installation at the rooftop and excess power is being sent to the battery to store and ultimately you have AC to DC converter, then it is bidirectional AC to DC converter, then we have a battery charging that is also bidirectional AC to DC converter. So, you have whole system in our campus. So, inverters let us come to the our studies. Inverters are used to convert power from DC to AC at the system frequency in the integration of the renewable energy, mostly solar because it is DC, into the power grid.

It is can be shown in figure 6, depicts the single-phase converter with 2 switches for simplified discussion. The single-phase inverter is usually used for the low power application. Mostly you have root of system of sub less than 5-6 kilowatt, then you can go for this kind of topologies. The PWM technique is used to achieve an AC voltage of the fundamental frequency 50 or 60 Hertz depending on the what kind of country you live in.

If the switch S1 is on the potential at a point a is same as that of the positive DC bus and if the switch SW1 is on the potential of the anode a is that of the negative DC bus because once the switch is on so this point will go to here if this switch is on it will go to the lower DC bus.

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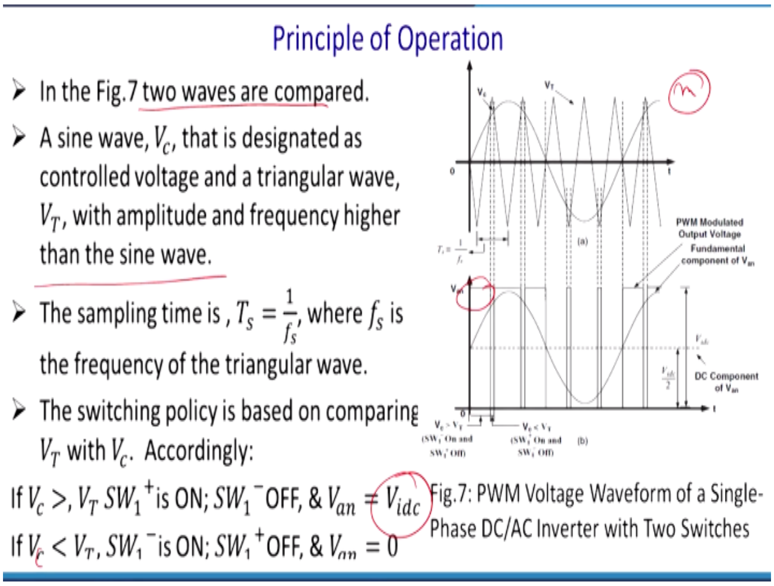

So for simple operation, you can have a different kind of PWM technique, you can have a bidirectional PWM controller, you can have a unipolar bipolar PWM controller, you can have a unipolar PWM controller, here it is a unipolar PWM controller. For this, you can find that it is switching to plus Vdc to minus Vdc. Figure 7 show uh 2 waves are compared. The since wave Vc that is designated as a controlled voltage and triangular wave VT with the amplitude and the frequency higher than the sine wave.

So this is the so you have modulation index. Please refer your PWM technique in your books or my previous NPTEL lectures in Advanced Power Electronics. So, control voltage and the triangular wave VT, the amplitude and the frequency higher than the since wave. The sampling rate is TS = 1/sf where fs is the frequency of the triangular wave. The switching policy based on the comparing VT with Vc, this is the principle of the bipolar PWM.

So once Vc is greater than VT, SW1 is on and SW1 equal off so you got +Vdc otherwise if Vc is more than VT, then switch SW1 is on minus is on and ultimately you get negative DC bus voltage is it is coupled to the 0 voltage you get 0 voltage.

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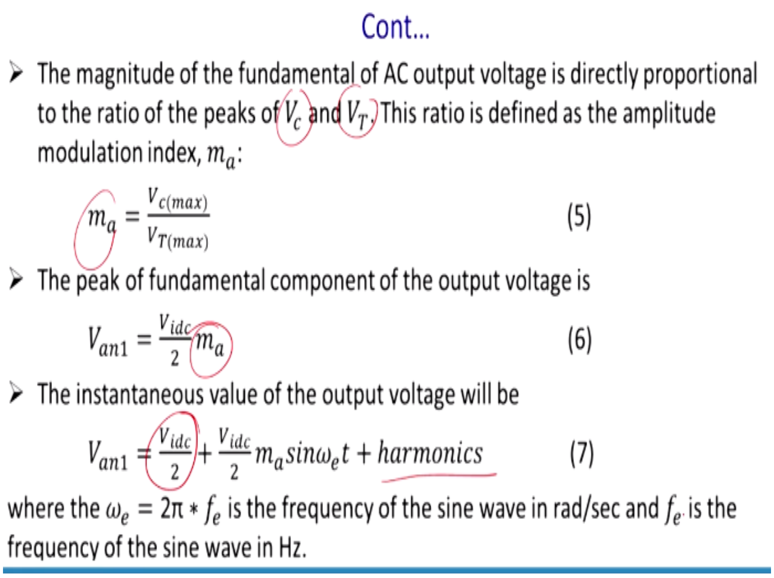

Now the magnitude of the fundamental of the AC output voltage is directly proportional to the ratio of the peaks of Vc and VT and this ratio is defined as the modulation index. So modulation index ma is essentially ratio of Vc max by the carrier wave or rectangular wave. The peak of the fundamental component of the voltage is Van1 = idc/2 x ma.

The instantaneous value of this output voltage will be given by an1 = Vdc/2 Vdc/2ma since fundamental omega t and the harmonics, while omega e is 2 pi x, 2 pi x fe is the frequency of the since wave in radiant per second.

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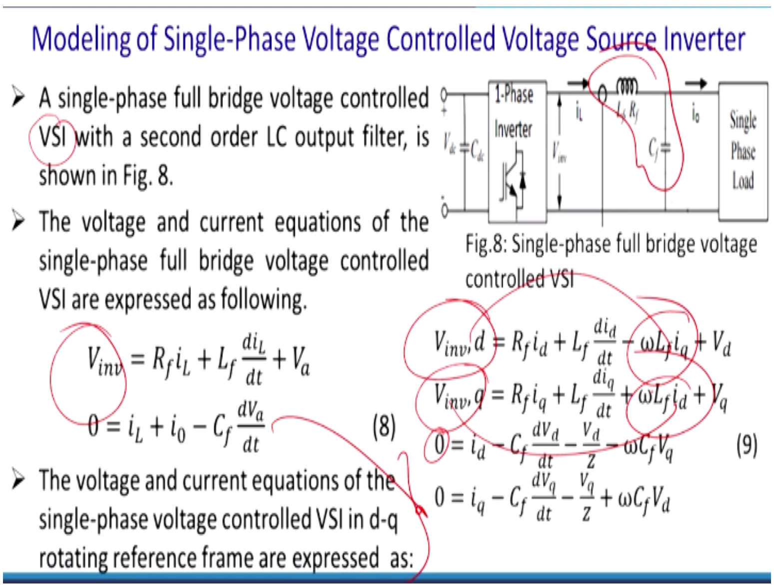

Now we can come to the modeling. The single-phase voltage controlled VSI with a second order LC filter because you got a because you generate PWM and that is not allowed to connect and ultimately there is a limitation of the voltage THD and the current THD is very imposed, for this reason we require to have a filter for grid connector invertor also if it is a single-phase load that also require to fit with a filter to make this current sinusoidal.

So VSI of the second order LC output voltage is shown in figure 8. Voltage and current equations of the single-phase full voltage controller definitely it is given by inv = Rf x iL Lf di/dt x Va that is the terminal voltage at this point or the load of the grid and the current will be given by iL + i0 – Cdv/dt. The voltage and the current equation from the single-phase voltage-controlled VSI in d-q axis we can make it a transformation, so inverted d will be given by Rfid Lf dq/dt – omega Lf iq + Vd.

Similarly, for the q domain to Rfiq Lf diq/dt to omega Lfid + Vq and similarly that the this current will be transformed to this method id and iq. Thus, you can control the flow the current of id and iq depending on the requirement.

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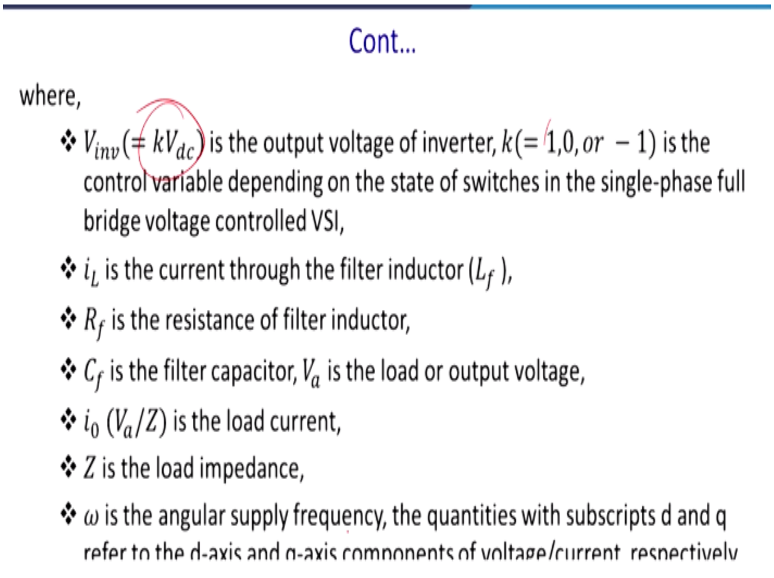

So while please understand that that inverter that is essentially that depends on the modulation index that value will be k x Vdc is output voltage of the inverter and since it is switching on 1 to 0, so it can be 1, 0 or -1 depending on its pole voltage which has been clamped to is a control variable depending on the state of the switches in the single-phase full bridge converter is being controlled in case of the VSI.

Vil is the current through the filter inductor Lf and Rf is the resistance of the filter inductor and Cf is of course the filter inductor for the capacitor, i0 is essentially the load current that is given by Va/Z, Z is the load impedance and Omega is angular frequency. fundamental angular frequency.

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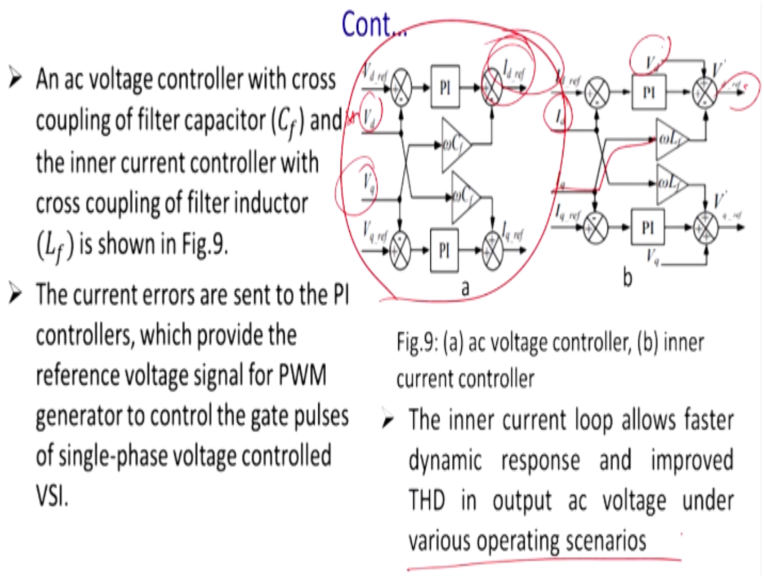

Now we have to control this control loop. An AC voltage controller with cross coupling because you can see that omega terms comes, omega lf comes with the cross coupling, this term is essentially cross coupling, this term, here it is iq and here it is id, that is what I am saying. So that an AC voltage controller with the cross coupling filter cross coupling of filter Cf and the inner current controller with the cross coupling with the Lf as shown in the figure. So, it is Vref – Vd equal that is fed to the PI and thus you generate this id reference.

Similarly what happens you know there is another loop, please come to the picture Vd, thereafter you got a Vq, Vq will be multiplied by Cf x omega and it will be substituted and similarly Vq will be subtracted from the Vref, fed into the PI, and this time Vq will be multiplied with the Cf, this is the inner current loop. Similarly, once you start the inner current loop, you start with the Vd and Vdref, Vq and Vqref for this outer voltage loop, so you will have current as a reference.

So Idref as you generated from here, it will be used here and then for this it is called current-controlled voltage source inverter and you will be compared with id and you have across term that comes from iq and you have multiplied with the omega Lf and you have PI controller Vd, that you will actually subtract Vd which is here and thus you get the Vdf reference. So this Vdf reference will be fed here. Similarly, same for the Vq.

So, this is explanation of the current controlled voltage source inverter and the inner current control loop allow faster dynamic response and improved THD in the output voltage under various operating condition. Thank you for your attention. We shall continue through our discussions in our next class. Thank you.