

CHARGING INFRASTRUCTURE

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Week-05

Lecture-23

Lec 23: Three Phase AC-DC Converter

Hello everyone, welcome to lecture number 23 of this NPTEL lecture series on charging infrastructure. In today's lecture, we will discuss three-phase AC to DC converters for high-power chargers. So far, we have studied single-phase AC-DC converters, which act as an AC-DC conversion stage for the EV charging system. If you recall our EV charging system, the power conversion unit of our EV charger consists of the grid, followed by an AC to DC converter, then an isolated DC to DC converter. For low-power applications or low-power chargers (up to 7 kilowatts), these are generally handled using onboard chargers. Sometimes, even if it is off-board, the power is less (up to seven kilowatts), so this can be done using a single-phase grid. That means you require a single-phase AC to DC power converter at the first stage, followed by an isolated DC to DC converter. However, when we discuss high-power chargers (up to 30 kilowatts or, in the case of DC chargers, where power levels start from 15 kilowatts and exceed 30 kilowatts), we require a three-phase input. Since we require a three-phase input, we need a three-phase AC to DC power converter. There, we cannot use a single-phase converter. One possibility is to use three single-phase AC to DC power converters. Another possibility is to use just one converter that can directly convert the three-phase AC into DC. In this lecture, we will explore the commonly used three-phase AC to DC power converters. Before understanding the three-phase AC-DC converter, we have seen the concept of PWM, where we know that by varying the turn-on time of S1 and S2 switches in the half-bridges, we can obtain different values of average pole voltage variation over a carrier cycle.

Since there is no phase angle between the $v_{s,phasor}$ and $i_{s,phasor}$. So, our i_s will also be in this direction. Same 0 phase angle. because to have the unity power factor operation. So, we can write to have the unity power factor operation.

Now, we have another term which is $j\omega L i_{s,phasor}$. So, now the $i_{s,phasor}$ is in this direction So, if my $i_{s,phasor}$ is in this direction. So, what will be my I_s phasor which is $j\omega L i_s$ and since if you see it is 'j' that means it is 90° shifted and since it is 90° phase shifted and having the (-) sign. So, what we will get is we will get a phasor which is $j\omega L i_{s,phasor}$ this corresponds to $j\omega L i_s$.

Now, let us try to see how we can use this concept of PWM or pulse width modulation and apply it in a three-phase AC to DC converter. Now, before that, let us see what is the most commonly used three-phase AC to DC converter. It is sometimes also called the front-end AC to DC converter. Or you can say front-end converter (abbreviated FEC). It is a kind of active rectifier, so actively you can apply voltage at the output of the bridge. Now, if you look very carefully, the circuit for this particular converter will look like this: you have three identical half-bridges. And having a DC capacitor, which is supplying to load R_L , plus V_o output voltage we are getting. And in this half-bridge, if I draw it more, and in this half-bridge, what we have is we have a three-phase input signal coming in, and then we have one inductor, second phase, and then the third phase. And let us define this as A, B, C, and we'll define all three phases as having the same value of inductances. And this one is then the other side of the phases are connected in a star fashion. Let us define this as small n, and this we can say this particular thing is nothing but $v_{an}(t)$ which is nothing but $v_{s,pk} \sin\omega t$. Here we have $v_{bn}(t)$ and here we have $v_{cn}(t)$, and we can write down $V_{an}(t)$ as nothing but $V_{s,pk} \sin\omega t$, $v_{bn}(t)$ as $v_{s,pk} \sin(\omega t - 120^\circ)$, and $v_{cn}(t)$, as nothing but $v_{s,pk} \sin(\omega t - 240^\circ)$, Three-phase input, and then we have three inductors, and we have currents i_{sa} , i_{sb} , i_{sc} —three currents. And here, we have capacitance C at the output, and again, the same thing which we have done previously. Here, we have i_{conv} coming out, here we have i_c , and here the average value is coming out, which is i_L . Now, if you look very carefully at this particular circuit, this is also called a front-end because power can flow from this side to this side or, by the operation of this, we can

ensure—by using the same converter—that power can also go from the DC side to the AC side. And if we operate in a certain manner, the power can flow from the AC side to the DC side. So, this way also power can go, and the other way around also the power can go.

And here we have six set of switches. Let us say S1, S2, S3, S4, S5, S6. And these are all active switches. Mostly the same switches which we use in our half bridges. That means it has to block the voltage of V_o .

However, allow current in either direction to flow depending upon if we require the non-empty power factor current drawn from the source or if we want to pump the power backwards into the source. So now if you look this particular converter, it has a very symmetrical structure. Three same kind of inductor it requires, six set of identical switches it requires and that's why this converter is very commonly used in case of three phase AC to DC converter. Now let us understand the operation of this three phase AC to DC converter. now if we look very carefully at the output if we have let's say fictitious o point at the output let's say the output voltage is divided into $V_o/2$ and $V_o/2$ and it has the fictitious assume it has point like you know here we have a fictitious point one c is there another c is there this kind of thing is there here that as you have this is v naught and this is $V_o/2$ this is minus $V_o/2$. Now if you look is the same thing if you see the voltage across V_{ao} then what we will see is that we have you know by changing the duty ratio of this S1 and S2 switch or the turn on time of S1 and S2 switch we can on an carrier cycle period or on a switching cycle period the average value we can vary across this v_{ao} so we can have the average pole voltage over the carrier cycle which can be vary depending upon the modulating signal. So if we take the three modulating signal which are varying sinusoidally and have 120° phase difference between each other then we can ensure that we are applying the sinusoidal 120° phase difference pole voltage variation at the output and that's when we can see that from ABC point the voltage we can apply between A to O and then you can say between A to N the same I mean this the DC can be dropped across that N to O this point between this neutral point and the O point we will have the constant potential and thus we can say that we can have the average pole voltage variation which is also varying in a i mean same as that of the modulating signal and if that modulating signal is varying with the same frequency as that of the line frequency then we can ensure that we are also having one more ac source at point a so we

are applying at the output of the half bridge or you can say at the pole of the half bridge we can apply the voltage proportional to that of the amplitude of the modulating wave. And thus we can ensure that the average pole voltage variation at the pole of the half bridge here we can have that average pole voltage variation having the same fundamental frequency 50 Hz at that of the line frequency, and if we can ensure that that from the pole A from the pole point B and from the pole point C the average pole voltage variation is having the sinusoidal variation with frequency same as that of the line frequency and the three pole voltage variations are 120 degree apart. Then we can say that there are two AC voltage sources separated by the inductance L. So, thus we can draw this single-phase equivalent circuit for the let us say for the fundamental frequency let us understand for the fundamental frequency how the single-phase equivalent circuit how it looks like so fundamental. For the fundamental frequency fundamental frequency means my f_m is nothing but equal to f_s which is nothing but equal to 50 Hz or the line frequency 50 Hz or 60 Hz whatever you wanted to take let us take 50 Hz so that is the line frequency now the single phase equivalent will be we have the ac source and let us define that as $v_s(t)$ that is the supply voltage we are applying and this is the v_{an} , v_{bn} , v_{cn} , and we have the inductor L. So, for the fundamental frequency our impedance of that inductor will be $j\omega L$, where $\omega = 2\pi f_s$ is and then we have another voltage source which is nothing but v_{conv} or the pole voltage of the half bridge. Let us define that as a v_{conv} . And if we see very carefully, depending upon the voltage difference between this point and this point, because we have the two voltage source separated by impedance, there will be current which is being drawn from one side to another side or from the v_{conv} side to v_s side or from v_s side to the v_{conv} side between the two AC source depending upon the instantaneous value of voltages applied or you can say depending upon the voltage differences.

then let us try to draw in this ac circuit let us try to draw the phasor diagram so let us try to draw the phasor diagram for this converter phasor diagram to draw the phasor diagram what we have is we have we know that our $v_s(t)$ if let's say if we are having the current in this direction so we can write using the kvl $v_s(t)$ is nothing but $v_s(t) = v_{conv}(t) + j\omega L$ write, so we can easily write $v_s(t)$ equal to this thing using KVL, so that we can write down $v_{conv}(t) = v_s(t) - j\omega L$,

and this if we try to write in phasor form, from this if we can derive that phasor form, we can write v_{conv} phasor is nothing but $v_{s,phasor} - j\omega Li_s$. That means if we assume our phasor diagram to be our phasor of v_s to be like this. This is $v_{s,phasor}$ and its amplitude is nothing but we can write here the amplitude of $v_{s,phasor}$ is nothing but peak value of the supply voltage which is nothing but $v_{s,pk}$.

Why I have written this $v_s(t)$ just like that because $v_s(t)$ will be $v_{s,pk} \sin\omega t$ or $v_{s,pk} \sin(\omega t - 120^\circ)$, $v_{s,pk} \sin(\omega t - 240^\circ)$. Similarly, we can also write our $i_s(t)$ we as since we are assuming that it is a having the unity power factor current drawn because we want in the three-phase system to have the unity power factor current drawn so we can say $i_s \sin\omega t$ that will be our this thing so we can say modulus of is phasor is nothing but is peak maximum value of or the amplitude of the current this one similarly if we recall our v converter v_{conv} is

$$v_{conv}(t) = \frac{mv_{dc}}{2} = \frac{mV_0}{2} \sin\omega t$$

where m is nothing but v_m/v_c where the ratio of the amplitude of the modulating signal and the maximum value of the carrier signal. So, we can write then $|v_{conv}(t)|$ phasor is nothing but or you can say the magnitude of \vec{v}_{conv} is,

$$\vec{v}_{conv} = mV_0/2,.$$

So, this is the these are the things we obtain. Now, let us try to draw the phasor diagram. So, what we have we have let us say this one is a phasor which is let us define this phasor as $v_{s,phasor}$. Now, this $v_{s,phasor}$ now our requirement is we want our current to be having the unity power factor that means whatever the phase angle between the current drawn from the source and the source should be zero that means if in case of 'a' phase current should be $i_{s,pk} \sin\omega t$ and if the 'b' phase is $i_{s,pk} \sin(\omega t - 120^\circ)$, then current of the 'b' phase should be is

$i_{s,pk} \sin(\omega t - 120^\circ)$, and if the 'c' phase it is $v_{s,pk} \sin(\omega t - 120^\circ)$, so current should also be $i_{s,pk} \sin(\omega t - 240^\circ)$ and here since we are considering the balanced three phase system all the three phase currents are having the same magnitudes. So, we can say that we have the unity power factor current drawn from the source so in all the phases one must have the unity power factor current that means The phase angle between the voltage source and the current source in each phase should be having 0° . So, our $v_{s,phasor}$ is shown over here. Now, let us try to draw the current phasor.

Since there is no phase angle between the $v_{s,phasor}$ and $i_{s,phasor}$. So, our \vec{i}_s will also be in this direction. Same 0 phase angle. because to have the unity power factor operation. So, we can write to have the unity power factor operation.

Now, we have another term which is $j\omega L i_{s,phasor}$. So, now the $i_{s,phasor}$ is in this direction So, if my $i_{s,phasor}$ is in this direction. So, what will be my Is phasor which is $j\omega L i_s$ and since if you see it is 'j' that means it is 90° shifted and since it is 90° phase shifted and having the (-) sign. So, what we will get is we will get a phasor which is $j\omega L i_{s,phasor}$ this corresponds to $j\omega L \vec{i}_s$.

And the summation of these two is nothing but our v_{conv} . Let us take the angle between them. Let us say some delta angle what we have. Now, if you look very carefully at any given instance of time, if I can ensure that my v_s or the phasor corresponding to the supply voltage is leading the phasor corresponding to the v_{conv} , then I can ensure that there is a current drawn from the $v_s(t)$ or you can say from the source to the v_{conv} and that current is having the unity power factor.

Similarly, let us take if you consider the current direction to be in this direction, that means going from the v_{conv} side to the grid side. So, for backward power flow, backward power flow means from DC to AC. That means from converter to source. To have that, I mean, we can write in phasor form $v_{conv,phasor}$ to be nothing but v_{phasor} , minus of minus is phasor, which is nothing but $+ j\omega L$ is phasor, because if we assume the current direction to be in this way, in

this direction, then our v_{conv} , if we do the KVL, this is for DC to AC. Power flow, so we can write this using the KVL, and in the phasor form, we can write in that way, and that will correspond to if this is $-j\omega L$, we can say this is $j\omega L$ is phasor, and that we will have the phasor nothing but slightly adjust the size of these things so that we can put in this phasor and then. This is nothing but a v_{conv} , so we can say that this particular part says the backward power flow, backward power flow that means going from DC to AC, and this and when we are operating the system in this side, we can ensure the forward. Power flow, that means power going from AC to DC side, and thus just by changing the phase angle between the \vec{v}_{conv} and \vec{v}_s , we can ensure the power flows from either AC to DC or DC to AC. So with this, we can obtain the bidirectional power flow, and that's why the power can flow from the front to the end or end to the front. That's why it is called as a front-end converter. Because the power flow can be made bidirectional.

So, here we can see that by just changing the phase angle in the positive direction or negative direction, we can allow the power to flow from the other direction. Also, by changing the magnitude of this phase angle, by changing the magnitude of this δ , we can actually change the size of the visor, which corresponds to the voltage drop across the. Inductor because inductor, we cannot change ω , we cannot change because our AC supply voltage is constant, but one thing we can change is the value of this delta. If we can ensure, if we can somehow make sure our δ is smaller, if we make this kind of arrangement, then the current laser corresponds to this one will be smaller as compared to here, and this way we can also control the. Magnitude of current which is flowing from the source to the converter or from the converter to the source. So by changing the sign of, so we can say that by changing the sign of δ , we can change.

The direction of power flow, and we can say that by changing the value of the phase angle delta, we can change the amplitude of the phasor corresponds to this drop across the inductor. That means we can say the magnitude of current, and since our voltages are constant, we can actually control the amount of power flow from AC to DC or DC to AC. Thus, it is important to ensure the operation of this v_{conv} or the value of voltage which will appear at the output of the half-bridge or, you can say, the pole of the half-bridge. It is very important to ensure that the

average pole voltage variation should be such that we can ensure the right amount of power as well as the direction of power is obtained.

We must ensure that the $v_{conv}(t)$, which is the output of the half-bridge, should be generated in an appropriate manner. Now, if you look very carefully, the size of this inductor is one of the critical things because this inductor size is responsible for the amount of power flow, and also, we are controlling the current through the inductor by applying the voltages across it. One side voltage is constant, which is defined by the grid; on the other side, we have the flexibility to apply the variable voltage on this side, obviously over the carrier cycle, and in this way, we can ensure that it is controlled. Now, let us try to find out how we can calculate the value of the inductor, so the inductor. Now, what we can do is, if we just try to find the phasor, we know this phasor is v_{phasor} , this is $-j\omega L \vec{i}_s$. Assume the power is going from AC to DC, and we have $v_{conv,phasor}$. Now, we can write that the modulus of v_{conv} is

$$v_{conv}^{\rightarrow} = \sqrt{(-j\omega L \vec{i}_s)^2 + |v_s|^2} = \sqrt{\omega^2 L^2 |\vec{i}_s|^2 + |v_s|^2}$$

$$\frac{mv_o}{2} = \sqrt{\omega^2 L^2 (i_{s,pk})^2 + v_{s,pk}^2}$$

$$L^2 = \left(\frac{mv_o}{2}\right)^2 - \frac{v_{s,pk}^2}{\omega (i_{s,pk})^2}$$

$$L = \sqrt{\left(\frac{mV_o}{2}\right)^2 - \frac{v_{s,pk}^2}{\omega (i_{s,pk})^2}}$$

Here, our m is the modulation index, which is in our control, and we can vary this modulation index from generally it is being kept between 0.8 to 0.9 generally in normal operation, and we know our f_s is nothing but equal to f_m , which is nothing but equal to 50 Hz, and our $i_{s,pk}$ is nothing but the peak of the phase current. V_o is the DC link voltage, which is again a given specification? We can obtain it from the specification by doing the power balance and knowing the power level of the load. V_o is a DC link. $V_{s,pk}$ is the peak of the phase voltage.

Accordingly, we can calculate our inductance value. Finally, once we calculate the inductor value, we must ensure that the voltage drop across the inductor must be within 10% of the supply voltage. Again, this voltage drop is in terms of a fundamental component.

So, this has to be ensured. This has to be ensured. So, what we do is we can define these values and then calculate L. Then, one can cross-verify whether this voltage drop across the inductor, obviously in the fundamental frequency sense—for the fundamental frequency—must be within 10 % of the supply voltage. This has to be ensured at last. So, one can define this term because this is again a design freedom which the designer has. This is input. These are the things which you obtain from the specification. All these things from the specification you will obtain, so we can calculate the inductance value L. But then, finally, at last, we must ensure that this L—the voltage drop across L—should be within 10% of the supply voltage. Otherwise, most of the voltage will drop across the inductor, and you can say that DC bus utilization will be lesser.

So, we must ensure that the inductor voltage must be within 10% of the supply voltage. If you look very carefully, this inductor will always be in conduction throughout the line cycle because it is at the front side. So, if you see the RMS current—if we see the RMS current of the inductor—the RMS current of this inductor is nothing but is nothing but equal to $i_{s,pk} / \sqrt{2}$, simply because we can, I mean, we can write this one as root mean square. So, root of mean $1/T$, going from 0 to T, $(i_{s,pk})^2 \sin^2 \omega t$, obviously squared. If we do that, we will finally get $i_{s,pk} / \sqrt{2}$, and thus we can easily size our inductor accordingly.

Now, if we look very carefully in this converter, we have our capacitor also. So, we will design this capacitor in the next lecture. So, in this lecture, we have seen the operation of a front-end three-phase AC-to-DC converter, and we have seen how we can allow the power to flow in either direction by just changing the sign of the phase angle between the $v_{conv,phasor}$ and the $v_{s,phasor}$. We have also seen how we can size the inductor in this particular converter. And now, in the next class, we will see how we can size this capacitance value. Then, we will further improve our understanding of the operation and try to find how we can define the closed-loop control of this particular converter. So, thank you very much for attending this lecture.

We will meet in the next lecture.