CHARGING INFRASTRUCTURE

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Week-02

Lecture-7

Lec 07: Revisiting Diode Bridge Rectifier with Capacitive Filter - I

Hello everyone, welcome to this lecture number seven of the NPTEL lecture on charging infrastructure. In this lecture, let us discuss the diode bridge rectifier with a capacitive filter. In the previous lecture, we studied the single-phase full-bridge rectifier, which is also called the full-bridge uncontrolled rectifier. Now, if we look carefully, some of the inferences we obtained were that the output voltage is uncontrolled, meaning it only depends on the input AC voltage. The output voltage is solely dependent on the applied AC voltage, and there is no controlled variable to adjust the output voltage to the desired value. We also observed that since this rectifier supplies a resistive load, the input current is sinusoidal in nature.

In this rectifier, during the positive half-cycle, D1 and D4 conduct, while in the negative half-cycle, D2 and D3 conduct. In both half-cycles, power is delivered to the output resistive load. This means current is drawn from the AC source in both cycles. We also saw that the output voltage is a rectified DC voltage, meaning it is not constant but continuously varies between 0 and the peak value before returning to 0. This is problematic because the output voltage fluctuates significantly. To restrict or address this problem, capacitive filters are generally used. Let us revisit the concept of the single-phase full-bridge rectifier with capacitive filters. Let us revisit some concepts of this circuit, as it will help us logically develop the converters useful in the AC-DC power conversion unit of an EV charger.

So, let us draw the circuit. It again has the same four diodes connected in a full-bridge manner. It has an input AC voltage applied, denoted as omega t, with diodes D1 and D2. At the output, it is not directly connected to the resistance; instead, a capacitive filter is connected, and this is then connected to the lower resistive load. ‘RL’. Let us define some of the currents: this is the ‘IL’ current, which is the output current of the diode bridge converter.

And then after this you will have there will be a current which is some current will be going through this capacitor bank and the remaining current will be going through this load resistance which is ‘RL’. Let us define this capacitance value as C and the current which is going through this as ‘RL’. ‘ic’ so in this particular manner the current will be going through this and the voltage let us define this particular voltages ‘vd’ as we have mentioned in the previous converter as well now let us draw the critical voltages and current some critical waveform in this circuit to understand the functionality of the circuit so let me draw this Let us first draw the input ‘vs’ input voltage. So, it has the sinusoidal variation cosine respect to t. Now, this is my ‘vs’ and this value peak value is ‘Vs’,peak value.

Now, let us see how the output voltage will be or wheelie voltage which will look like because you know in this particular thing since we have a capacitor which can store or which can hold the voltage across it so this let us see what will be my or what will be the wheelie look like how the wheelie will look like so for that let us draw the ‘vd’ how it looks like to understand. In ‘vd’ what happens is that assume the capacitor was holding a certain voltage and this one since this they were holding the voltage and this voltage of the capacitor is greater than the voltage which is been applied which is been there from the vs which is greater than the input voltage so what will happen is that the diode d1 here diode D1 D4 D3 D2 all will be reverse bias since all the four will be reverse bias this load ‘RL’ will be actually getting or will be getting current from the capacitor because capacitor as capacitor will be discharging as a result of a capacitor voltage will be falling down. Because since there is no diode which is forward biased, all the four diodes are reverse biased. So, the entire power which this resistive load demands or the current which the resistive load demand is being taken by the capacitor and as a result of which capacitor voltage get discharged. So, that is why it discharge from a certain value to its value at the point where this ‘vs’ will become equal to this voltage ‘vd’ at that point after that point the this ‘vs’ will be greater than at this point ‘vs’ will be greater than ‘vd’ and at that point where the ‘vs’ is greater than ‘vd’ this D1 will be forward biased because here you have a ‘vd’ if you take this circuit this particular circuit in this particular circuit this ‘vd’ will be the anode will have more voltage as compared to this point as compared to the cathode as a result of which D1 is followed by it similarly here if you take the entire KVL D4 will be the one which will be followed by as a result of which this D1 and D4 starts conducting and there will be current drawn from this source so as there is since there is a current drawn from the source the capacitor will get charged up and as a result of which capacitor gets charged up your wheel voltage will rise further it will rise and it will rise until This ‘vd’ voltage will again become greater than this ‘vs’ sine omega t, ‘vs’ peak sine w t and again at that point D1 and D4 get reverse bias and D2 and D3 is already reverse bias as a result of which the load will get power from this capacitor by and I mean the capacitor will get discharged and it will supply the required current or the power to the load. Hence, you will see that the capacitor will be discharging and it will discharge until the next point where again this ‘vs’ will become greater than ‘vd’ and at that point this D2 and D3 will get forward bias and thus again the capacitor will get charged. And again at that point, which is nearly at the peak, which is at the peak, at that point of time, the capacitor will be again discharging, goes till this point.

Again it will be charging up to the peak and again it will be discharging and again it will be charging and then again it will discharge as it goes along. So, the capacitor voltage will be having a certain ripple. However, this ripple is much smaller than what we have when we don't have the capacitive filter and the capacitor voltage will vary between this ‘vd’, max and this point. which is ‘vd’, min. So, the capacitor will be varying between ‘vd’, max and ‘vd’, min.

And because of this, let us draw the current which will be drawn from the or let us first draw the ‘id’ current. and then we will draw the current which is been drawn from the input source and the current which is been taken from this diode so let us draw what will be the ‘id’ current Now ‘id’ current as we see from this point to this point it is the place where capacitor is discharging so there will not be any ‘id’ current only this capacitor will be actually be meeting this value ‘iL’ however during this point to this point it is that time when there will be a current which will be drawn from this source and that will be we can let us draw that particular current it will be of the shape something like it suddenly goes up and then it will die down. Like this.

And then again. It will start again at this point. Then take it up again. And then it goes down. So it will have some peak value.

And then again. In the next cycle, it will go up. And comes down. Similarly, here also it goes up. And comes down.

Why does it come down? Because after this point, the diodes—all four diodes—get reverse-biased, and then this capacitor will be supplying this 'IL' current. That's when the current drawn—I mean, that's when this 'id' current becomes zero. And if you see, the 'IL' current—the 'IL' current will be—so it is having this current which is being drawn is not a pure DC, I mean, it is not a constant DC current. There will be—there is some portion of the time where the peak current kind of thing—the peak current is being drawn, while in other portions, it is zero. So that's why this particular current will have the average value, and that average value is defined as 'IL', which is been going.

into the load. Now, if you look very carefully this particular current has the peak value. Let us define this peak value as 'Is',peak and this will have some non-zero value or this you can say that some current which is been drawn from this source. Let us say the time from which is start is let's say 'ta' and the time it again goes down let's say 'tb'. Similarly, if we see our 'is' current which is drawn from the source, if we try to see the 'is' current which is drawn from the source,

is again the same goes here in positive half cycle the value is nothing but 'is',peak . And in the negative half cycle, if you see in the negative half cycle, this D2 and D3 will be in conduction for this period of time. And as a result of this, this will have a current of the same shape in the negative direction. And similarly, in the next positive cycle, have the current going like this. In negative cycle, it will have the current going like this.

And if we see, the amplitude of this one is nothing but So, what we see is that we are imposing this AC voltage 'vs' which is a sinusoidal wave. However, the current which has been drawn from the source because of this capacitive filter is of a peaky nature and it draws current near to the peak of the sine wave in the form of peaky nature in the form of peaky nature. Now let us see some of the things what we see from here. From 'ta' to 'tb' period the capacitor C is charging while in the remaining period

Let us define this time from here to here as 'T' that's one from here to hear it will be $T/2$ where we can write T is nothing but 1 by fs which is nothing but 50 hertz and we can also write 'ω' which is 2πfs which implies our ωt is nothing but 2π that we can write the same thing we have also written in the last class so from ta to tb the capacitor c is charging while in the remaining portion of we can say that in the remaining portion of $T/2$ meaning portion of $T/2$ the capacitor is discharging while giving a current to the load R_L. So, thus we can see that in this particular system the capacitor is charging for some time and it is charging for the remaining portion of time and the capacitor voltage is varying between 'vd',max and 'vd',min and generally Most of the converters we have some tolerance where we can allow this ripple across the capacitor or this voltage variation across the capacitor.

So, thus if we want to make sure this ripple or the difference between the maximum 'vd', maximum 'vd' means to be within a certain limit, we need to size our capacitor such that we will be in a position to satisfy some of the requirements of the I mean some of the load requirements that the voltages should be between within a certain limit so we need to make sure we cannot avoid the charging and discharging so we need to make sure that charging and discharging happen in such a manner that the voltages of the capacitor is maintained between 'vd',max and 'vd', min and we can define that we that ripple or the difference between this 'vd', max and 'vd', min as one of the specification of the converter and that's when we can we can able to calculate the value of capacitor so let us see how we can design or we can evaluate this capacitance value so we can say that to in order to maintain the volt maintain the voltage between 'vd',max and 'vd', min energy gained during energy gained during charging must be equal to energy lost during discharging why because if you draw if your voltages if you draw the i mean the voltages of this capacitor goes up that means you are charging the capacitor when it is going down you are discharging capacitor so if the amount of energy which goes in which gets gained during charging

If it is equal to energy loss during discharging, then we can make sure the capacitor voltage is maintained between 'vd',max and 'vd',min. So, let us see to maintain the voltage between 'vd',max and 'vd',min, how a capacitor can be sized. So, we have to evaluate the energies during charging and discharging. So, the energy gain during charging that means the voltage goes from 'vd',min to 'vd',max is nothing but is equals to half.

Let us define C capacitance value ‘vd’,max minus ‘vd’,min. So, half C ‘vd’,min square is the energy before the charging and half C ‘vd’, square max is the energy after charging. So, this is the energy gain during the charging.

$$E_c = \frac{1}{2}C\left(v_{d,max}^2 - v_{d,min}^2\right) \tag{1}$$

Let us define this as the equation number 1, and let ‘PL’ be the load power or you can say that power delivered to the load. So, generally we define the power of the load in terms of kilowatt as well.

So, let us define PL be the load power or the power which is been delivered to the load. So, we can say that energy delivered to the load from capacitor again during $T/2$ period from this point to this point so which is during $T/2$. We can say that let us define this as ‘vd’ is nothing but ‘PL’ times $T/2$times since the if you look very carefully since the energy or within this $T/2$ period it is within this period and within this period the capacitor is discharging that means delivering power to the load so that's why we have to also take the average value of that particular thing so this is a time between between $T/2$ minus this period, which is the difference between ‘ta’ and ‘tb’.

So, we can also define one term called as a ‘tc’. We can also define a term ‘tc’. Let ‘tc’ be ‘tb’ minus ‘ta’ which is nothing but the time of time during which the capacitor is charging. Let us define this as a ‘tc’.

$$t_c = t_b - t_a,$$

So, we can write the energy delivered to the load during $T/2$ time as nothing but the time period during which the energy is charging, which is $T/2$ minus ‘tc’. in the whole T by 2 period. So, we can write this as PL into $T/2$ multiplied by 1 minus ‘tc’ by $T/2$.

$$E_d = P_L \times T/2 \times \left[\frac{T/2 - t_c}{T/2}\right],$$

$$E_d = P_L \times T/2 \times \left[1 - \frac{t_c}{T/2}\right] \tag{2}$$

This is my ‘Ed’ value, and this I can define as equation number 2. So, thus in order to maintain the voltage between ‘vd’,max and ‘vd’,min, we need to make sure this Ec is equal to ‘Ed’. So, that is why we can make sure ‘Ed’.is equal to ‘Ec’.

$$E_d = E_c = \frac{1}{2}C\left(v_{d,max}^2 - v_{d,min}^2\right) = P_L \times T/2 \times \left[1 - \frac{t_c}{T/2}\right]$$

$$E_d = \left[1 - \frac{t_c}{T/2}\right] \times \frac{P_L \times T}{\left(v_{d,max}^2 - v_{d,min}^2\right)} \qquad (3)$$

$$\left(v_{d,max}^2 - v_{d,min}^2\right) = \left(v_{d,max} - v_{d,min}\right)\left(v_{d,max} + v_{d,min}\right) \qquad (4)$$

$$\Delta V_0 = v_{d,max} - v_{d,min}$$

$$\frac{V_{d\ max} + V_{d\ min}}{2} = V_0'$$

$$\left(v_{d,max}^2 - v_{d,min}^2\right) = 2v_0 \Delta v_0 \qquad (5)$$

To ensure the capacitor voltage between ‘vd’,max and ‘vd’,min, so that implies then write half C ‘vd’,max square minus ‘vd’,min, square is equal to PL times $T/2$ to 1 minus tc by $T/2$.. So, in order to calculate the C value, let us rearrange this expression to obtain this value of C, which we can obtain as C is equal to 1 minus tc by $T/2$.multiplied by PL by ‘vd’,max square minus ‘vd’,min, square times T. So, here we can also define one term, this ‘vd’,max square minus ‘vd’,min, we can write this ‘vd’,max square minus ‘vd’,min, square as ‘vd’,max plus ‘vd’,min, multiplied by ‘vd’,max minus ‘vd’,min. So, let us define this as 3, this is 4. Further, we can also define a term called delta V naught, which is the ripple voltage ripple on the output voltage delta ‘vd’,max minus ‘vd’,min. This is nothing but the output voltage ripple or the ripple on the DC output voltage. Similarly, we can also define the average value of the ripple which is ‘vd’,max plus ‘vd’,min by 2 is nothing but the output voltage. So, this Vo is nothing but the nominal output DC voltage, nominal output DC voltage. and that we can put this expression in equation number 4 and that we will say ‘vd’,max minus ‘vd’,min square is nothing but 2 Vo times delta Vo let us define this 5 .

And substitute 5 in 3 we will get

$$c = \left(1 - \frac{t_c}{T/2}\right) \times \frac{P_L}{2v_0 \Delta v_0} \times \frac{1}{f_S}$$

see nothing but 1 by tc by $T/2$.multiplied by PL divided by 2 Vo delta Vo and T we can define it as 1 by fs. So, this is the value of capacitance one can one need to put for the required ripple delta v naught and if you look very carefully this particular thing this 'PL' will be the value given as one of the parameter defined in the load specification V naught is again the required values or required is a thing which is be given in the specification load specification Delta V naught is again one more specification which will be given generally in the load as one of the load specification which tells that this particular load can sustain or can withstand this much voltage ripple. So, that is why these three things are the values which has been given. However, this fs is nothing but the 50 Hertz value. It is because it is the supply voltage is at 50 Hertz.

If it is 60 Hertz, it will be a 60 Hertz value. $T/2$ is again we can easily calculate by T we can easily calculate as $1/f_S$ and there we can calculate the $T/2$ however is the 'tc' so if we recall the tc which is nothing but our the time during which the capacitor gets charged so if we reduce this tc and to so so if we reduce this 'tc' the capacitance value go up in order to make sure if we reduce this tc in order to make sure to meet that delta v delta v naught value the capacitance value need to increase if we reduce the tc so this is this is one of the understanding we can get from this particular expression this tc is something which you can define and then calculate capacitance according to this that means the time for which you want the capacitor to be charged that you can take as one of the design variable and you can calculate the capacitance value.

Further if you look very carefully we have understood what is the value of capacitance however in order to select the capacitor one need to define three things one obviously the capacitance value.

Which we had derived in the previous section. Second, the voltage rating, which is the maximum voltage the capacitor can withstand. Generally, we will select the capacitor with a slight safety margin, and then we will select the capacitor accordingly. For example, let's say if it has to hold the voltage of 400 volts, then we will definitely choose a certain voltage more than that particular voltage. More importantly, we also need to know what the RMS current through the capacitor is because this RMS current is the one thing that will determine the parallel connection in the capacitor bank. That means each capacitor will be defined with a certain RMS current it can withstand. Obviously, it is determined by the amount of losses happening in the capacitor, I square R losses. So, one also needs to calculate or evaluate the RMS current going through the capacitor. To select the capacitor, you first need to know the capacitance value, you need to know the maximum voltage it will see while the circuit is in operation, and also you need to know how much RMS current will be flowing through the capacitor. Since we already have this capacitance value, as mentioned in this expression, and also the voltage rating, so if you see the voltage rating, this capacitor has to block the voltage going between 'vd',max or it has to withstand the voltage going between 'vd',max and 'vd',min.

So, the maximum voltage it can withstand is nothing but the value 'vd',max or 'vd',max, which is nothing but your nominal output DC voltage plus V naught plus delta V naught by 2.

$$v_{d,max} = V_0 + \frac{\Delta V_o}{2}$$

So, in this way, one can select the capacitor. However, we have known this capacitance value. So, this voltage rating is also defined.

Now, we have to calculate the RMS current. Since we have come up with this capacitance value, we will see how to further select the proper capacitance because we also have to define the RMS current going through this. That we will see in the next lecture. Thank you for patiently listening to this particular lecture. Thank you.