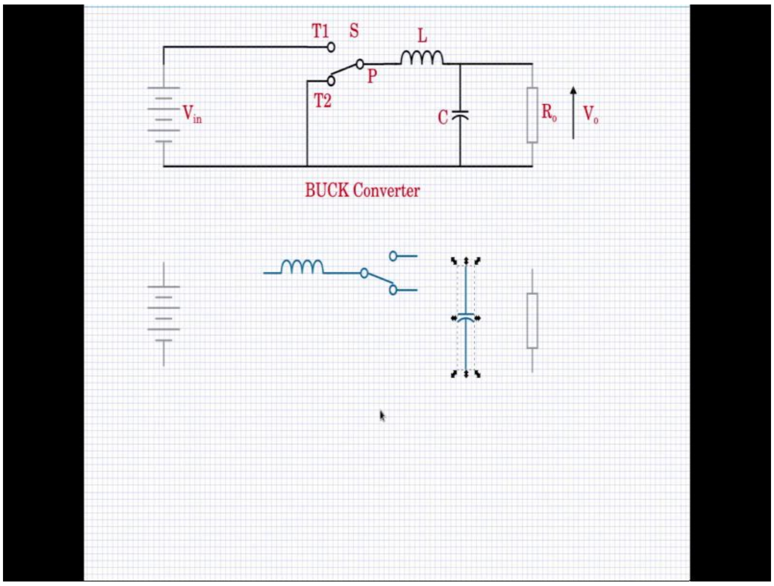
Design and Simulation of DC-DC converters using open source tools
Prof. L. Umanand
Department of Electronics System Engineering
Indian Institute of Science, Bangalore

Lecture – 08
Buck, Boost and Buck-Boost Converters

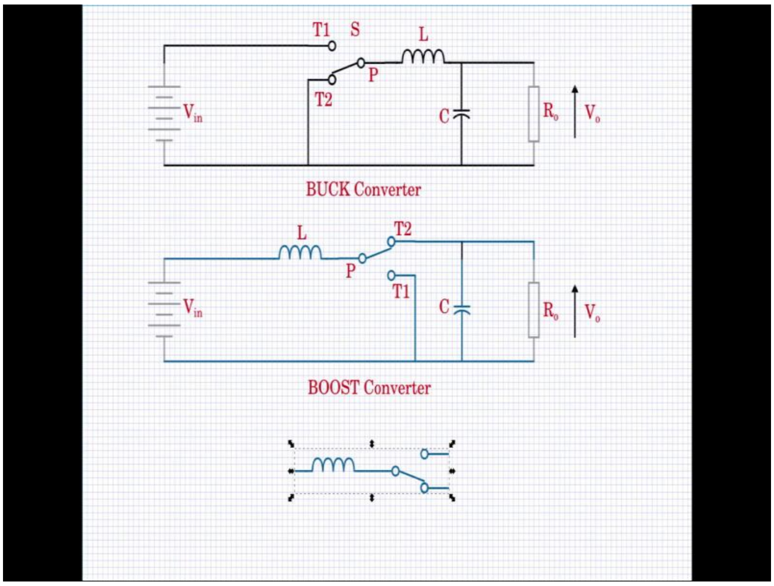
(Refer Slide Time: 00:17)



Coming to this BUCK converter here, we see that the energies flowing from the V in side to the V naught side. V in side is the higher voltage side and V naught side is the lower voltage side, now if we look at it in reverse from V naught side to V in side then the operation would look like a boost action, such a converter will be a boost converter.

Now, let us redraw the circuit in that perspective and see how a boost converter comes into being. It consists of input supply there is no change there, we need to have an output load there is no change there, and the major change is here the inductor and the switch combination. In the case of the buck converter the inductor is in the output side and the inductor which is connected to the pole and the throws are on the input side. In the case of the boost converter as we are seeing in this direction from the buck converters output side to the buck converters input side we have the inductor now on to the input side and the throws on the output side. Of course, we have a capacitance at the output as usual because we need to filter the output voltage. Now these are the main constituent components of the boost converter.

(Refer Slide Time: 01:57)



Now, let us interconnect them and then observe how it is compared with the converter. The circuit connections are made here and you see this is the circuit of the boost converter. The inductance is on the input side connected to V in other side is connected to the pole, the two throws of the switch single pole double throw switch are connected as shown here; throw 1 is connected to the ground, throw 2 is connected to the output capacitor and the loop; this is a boost converter. The operation is very straight forward.

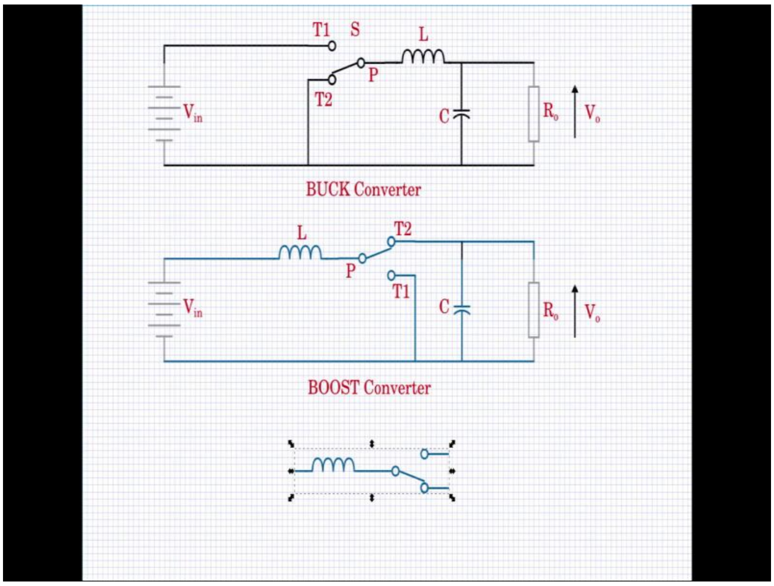
When the pole is connected to T1 the inductor charges up the current flows in this path as pointed by the arrow, being charges of the inductor magnetically the pole is at 0 potential. Then when the pole is switched to T2 the inductor current cannot go to 0, so it has to go through the pole T2 and then the output capacitance and the load and flow back. So, the inductor will discharge the magnetic energy to the output. In this way it will boost the input potential with respect to the output potential by virtue of the L d I by dt generating force which it will force pump the current through the T2 path into the output. So, this is how the boost converter operates.

Later we will use the volt second balance across inductor to find out the input output relationship. Observe that the inductor is always connected to the pole, both here in the boost converter and also here in the buck converter the inductor is connected to the pole. This is because the inductor current cannot change suddenly. Now the Ld I by dt will cause a very large voltage across the inductor if the current changes suddenly and that very large voltage will get imposed on the switch element of the capacitor element and something will glow.

Therefore, one has to keep the inductor current continuous. If you keep it in either of the throws either here or in this converter the throw current will break, it will the switches switch from one throw to the other and therefore the inductor current would break if it was placed either in the T1 throw R bar and the T2 throw R. Therefore, the only place would be to place it along in series with the pole, because the pole will always see a current either of T1 or of T2. So, in this primary converters it is always required that the inductor is placed in series with the pole.

So, we have seen one action in the buck converter where the inductor and the pole are placed towards the output side and here the inductor is placed towards the input side, where the pole is on the input side. Now we have one more such possible position that is we could have the pole in between that is the place it in this fashion where the pole is in between we have input on this side and the output on this side. Let us see how we can construct a circuit like this. This will result in a buck-boost converter.

(Refer Slide Time: 05:58)



Now, we still did keep the buck converter as a reference, the buck-boost converter which we are trying to draw will also have the input d c voltage, the output load and there will be the output capacitance and of course the inductor connected to the single pole double throw switch connected to the pole of the single pole double throw switch. Now these would again form the primary constituents of the boost converter, we have the single pole double throw switch the inductor and the capacitance and they need to be connected, this side to the input this side to the output.

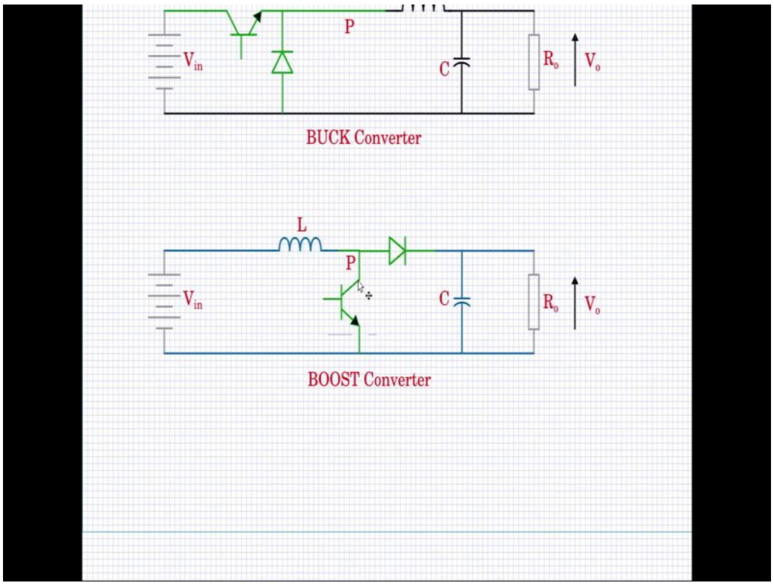
Let us now make the connection. After having done the connection the circuit looks like this. This is the buck-boost converter we shall name it so, the various parts are also named here, this is V in, this is the single pole double throw switch the pole connected to T1 as shown here T1 is connected to V in, T2 is connected to the output side and this is the inductor L the capacitor is like (Refer Time: 06:57) shown.

Now, the operation of the buck-boost converter is also pretty straightforward. Now let us say that the pole is connected to T1, so V in is connected to L through the pole and charges up the inductance magnetically. And then when the pole is connected to T2 the current in the inductor is going in this direction going down will not change path and it has to follow in this direction to continue to have the current flow in the same direction in the L. So, the inductor will charge up to this capacitance in this way through the capacitor and the load and then flow from T2 to P.

So, which means that the capacitor will be positive on this side as shown here, this will be the positive so therefore I will it will be better to connect the capacitor inverted like this with this side positive. In the case of the buck-boost converter the output will be inverted, if the input is positive the output will be negative, the input is negative the output will be positive. So, this is how the buck-boost converter operates the input output relationship of the buck-boost converter is also obtained in the same manner using the volt second balance across the inductor. Shortly we will also look into that how to obtain the input output relationship of the buck-boost converter.

The next important thing that we need to now identify is, what is this single pole double throw switch? A single pole double throw switch is a symbolic switch here that we have shown, but this has to be replaced with the relays of new components. So, we have to replace with power electronic devices, so to do that we use two power semiconductor devices.

(Refer Slide Time: 09:15)



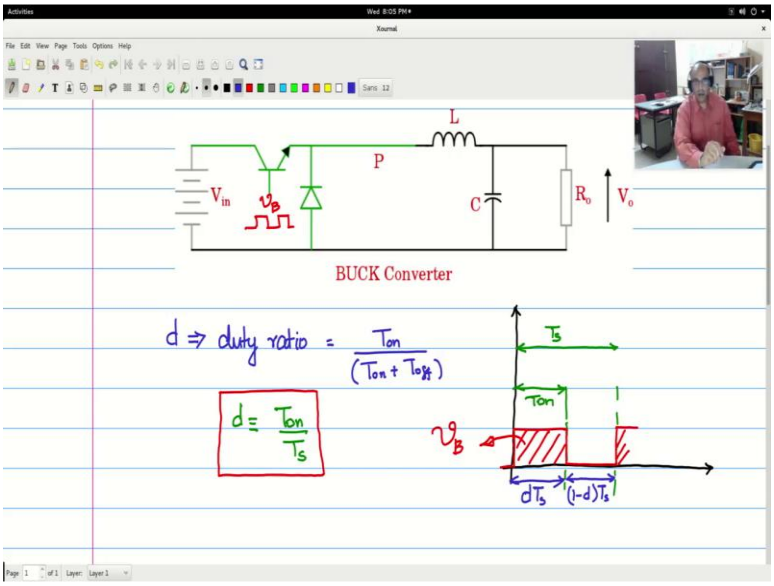
Now, this is a BJT. This BJT is one controlled switch likewise one could us a IGBT or a MOSFET controlled switches instead of a BJT. There is no problem in that any controlled switch for that matter will do. And another device is a diode. Now these two devices can be used to make up this single pole double throw switch. So, we can place the BJT in this fashion and series that with throw T1 and the diode can come along through T2.

Now, let us remove this switch and redraw the connections. This is the buck converter circuit a practical buck converter circuit, this is V in the positive is connected to the collector of the BJT the emitter of the BJT goes to the pole the diode connected the cathode connected to the pole. The reason why the diode is connected in this way is, when this switch is on you will be using this base drive to turn on the BJT and this is on the current flows through like this the diode is reversed by as it is or current flows through the inductor charges of the inductor and flows in this fashion. When this BJT is switched off in that case the current in the inductor cannot be broken so it keeps flowing in this path freewheeling through this diode. So, in this way both the throw 1 and throw 2 are emulated using this power semiconductor device couplet.

Remember that this BJT can be replaced by a MOSFET or an IGBT2 any controlled power semiconductor switch. So, boost converter circuit is shown here, in the case of the boost converter two we need to replace the single pole double throw switch with power semiconductor switches. So, here at the throw T1 we will put the controlled power semiconductor device BJT or a MOSFET or an IGBT and along throw 2 we will put the diode.

Let us now remove this single pole double throw switch and reconnect the circuit. BJT is connected like this, the pole end is the collector and then you have the base drive here and the emitter connected to the ground and at the pole end is the anode of the diode cathode is connected to the output. The operation is pretty simple. When the base drive is given to this BJT this transistor is formed and you have the current flowing in this path and this charges up the inductor. When the base drive is removed this switch is off and the current in the inductor flows through this path in terms of forward biases this diode and flows in this path (Refer Time: 12:53). So, this will give you the boost action. So, this is the boost converter circuit with practical realizable semiconductor devices.

(Refer Slide Time: 13:08)



Now, for the buck-boost converter; this is the buck-boost circuit which we saw here again we will replace the single pole double throw switch with 1 BJT and 1 diode. So, 1 BJT which is the controlled switch will connect here, the uncontrolled switch of the diode will be placed here. Now let us remove this switch and reconnect the circuit using these power semiconductor devices. After having made the reconnection you see that the circuit is like this, the BJT is connected to the pole point in this fashion emitter is connected to the pole point the diode is connected in this direction to the pole point.

So, when the BJT is on we give the base drive BJT is on the current flows through V in BJT inductor charging up the inductor in this path. When the BJT is switched off the current in the inductor cannot change direction so instead it flows in this path through the capacitor load and diode duct, capacitor load diode and buck. So, this is how the buck-boost converter works and charges up the capacitor with a reverse polarity.

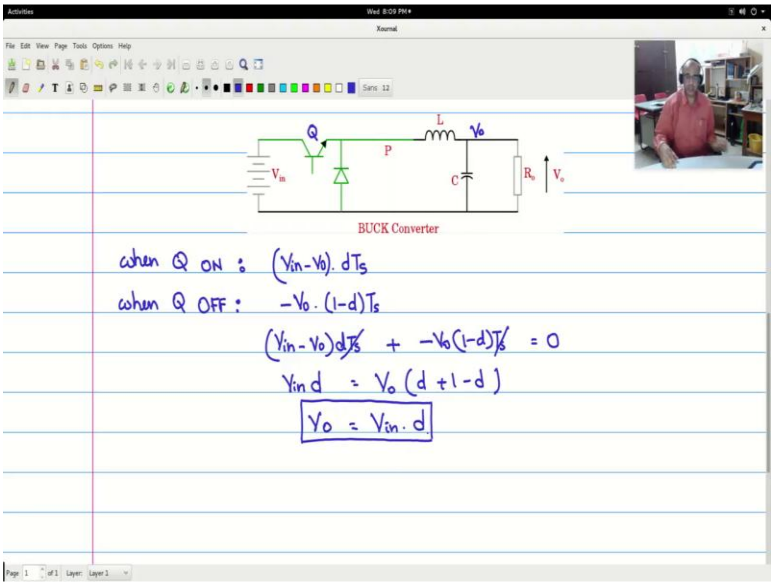
So, in this way the buck, the boost and the buck-boost are now replaced with practical realizable power semiconductor switches which can now be simulated and even implemented in hardware. This is the buck converter circuit we shall now go to the writing pad and see the input output relationship with (Refer Time: 14:57) the parameter d or the duty ratio.

Let us now define the parameter d. Now d is called the duty ratio. Now what is the duty ratio? This is the ratio of the on time by the total switching period. So, if I say that we have the y axis and our x axis and let us say the switching period is divided into two parts where thing is switching period Ts and this period is the on-time T on, then duty ratio d equals T on by Ts this is by definition. So, this is a very important ratio which we will be using throughout in switch mode or converters.

Now, during the period T on that information let us say we have which goes high during the period T on. And during the period T off it is low and again during the T on it is high. Now this wave shape will be the base drive pulse, this will be the base drive pulse V B and this V B is what will be given here in the form of a pulse shape and there will appropriate circuitry which will make the transistor on and off. So, when V B is high transistor will be on, V B is low transistor will be off. This is how the buck converter will operate.

Now, let us this d which is equal to T on by Ts for obtaining the input output relationship. Just remember that this part of time T on is now dTs from this equation which you see here this is equal to Tm by Ts. And this part of the time we will hence forth be calling it as 1 minus d times Ts. So, total overall dTs plus 1 minus dTs will be Ts and d is always less than 1; 0 to 1. So, using this parameter d we shall now figure out what are the input output relationships of all the three converters. Now first let us look at the buck converter.

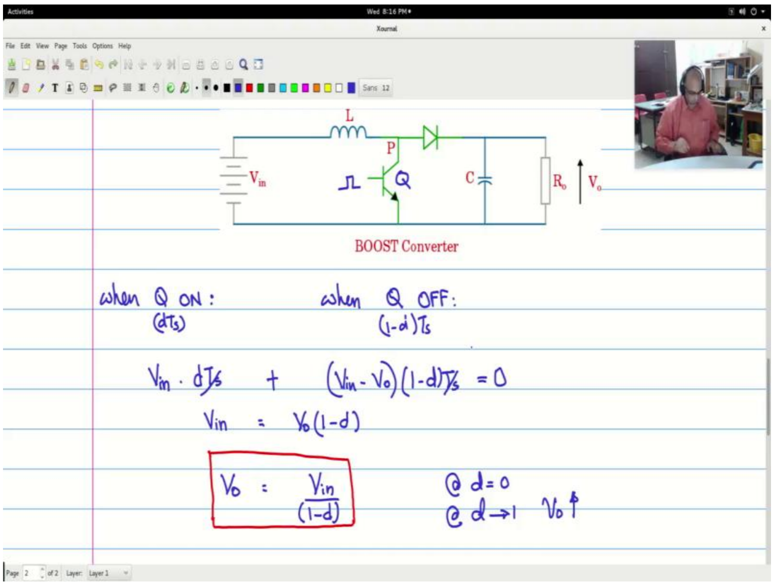
(Refer Slide Time: 18:51)



Now, let me call this transistor as Q. When Q is on, V in is appearing at this point this will be V in and this will be V naught V B that the pole voltage will be V in plus V B naught and therefore as we saw earlier we have V in minus V naught. This is occurring during the period when Q is on as we saw earlier that was a period T on time of dTs. And when Q is off the voltage across the inductor is minus V naught this is connected to the ground because of the freewheeling path of the diode and the period is dt into Ts assuming the diode drop is 0.

Now, these two should be balanced for the inductor to operate properly and therefore you have V in minus V naught into dTs plus minus V naught 1 minus dTs is equal to 0, be careful with the signs. Now V in d that is now you can cancel out Ts is equal to V naught d plus 1 minus d. So, V naught will be equal to V in into d this is a very useful relationship in terms of the parameter duty ratio.

(Refer Slide Time: 21:22)



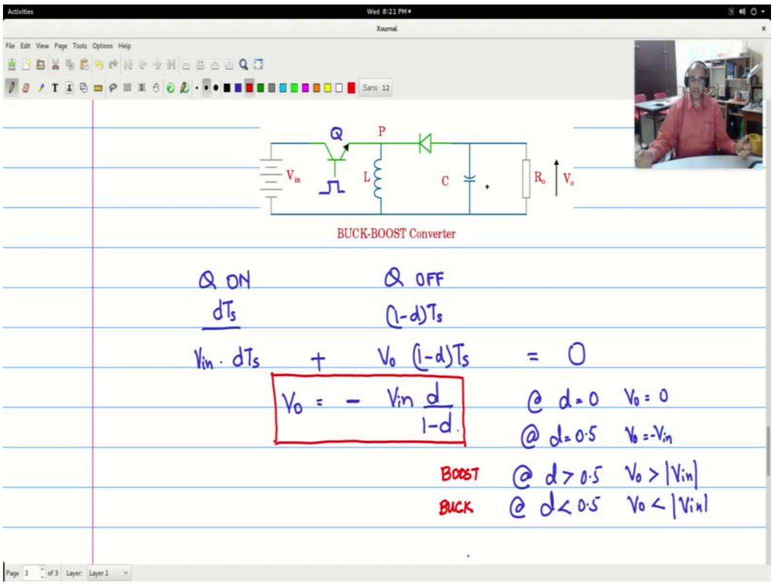
Next we will take up the input output relationship of a boost converter in the similar way. We have here the circuit of the boost converter and like before we will call the BJT the symbol Q and the base drive is given here as pulses. When Q is on the period is called dTs and when the Q is off the period is called 1 minus dTs; like here. During the period when the Q is on this is connected directly to the ground, so potential at P is 0 potential on this side of the inductor is V in, so the voltage across the inductor is V in. So, it is V in into dTs plus and during the time when Q is off the diode is conducting the current is magnetically discharged from the inductor into the capacitance on the output. This is at V naught potential and the diode is conducting and therefore V P is at V naught potential, this is at V in potential. So, you will have during that time voltage across the inductor is V in minus V naught 1 minus dTs is equal to 0.

You should understand that during the time when Q is on the potential across the inductor is V in and for volt second to balance to happen the potential across or voltage across the inductor should change the sign, and as this potential becomes V naught when the diode is conducting for it to change sign V naught should be higher than V in. So, automatically for volt second balance or energy conservation to happen V naught has to be higher than V in which is the boost effect.

So, now coming back to the equation here, we see that V in into V in is equal to now V naught 1 minus d with Ts going out and therefore if I write V naught it is V in by 1 minus d. Now see here that at d is equal to 0 that is the Q is never turned on the inductor eventually becomes short, V in comes directly to the output, V naught will be equal to V in V is 0.When d is closer to hundred percent duty cycle this denominator becomes a very large value when v tends to closer to 1 and V naught will become high a very high value.

But it is important to know that when d is 1, then the transistor is not switching and it is continuously on the diode is off and the capacitors decouple from the circuit and it will eventually discharge to 0. So, you should never go to d is equal to 1 but d closer to 1, approaching 1 that is when the circuit will operate because the switches will have to switch for circuit to operate. However, the input output relationship for the boost converter is like this and at d tending to 1 V naught will shoot up to a large value. Now this is the input output relationship for the boost converter.

(Refer Slide Time: 26:28)



Now, let us look at the input output relationship for a buck-boost converter. The buck-boost converter again we call this as Q and we apply the base drive here, so when the Q is on this is called the dTs period and when the Q is off it is called 1 minus dTs period. So, during the time period when Q is on the voltage across the inductor is directly the battery voltage the input voltage, so V in occurs directly across the input across the inductance. At that time it is V in into dTs plus during the time when it is off Q is removed and the diode is connected because the inductor is freewheeling in this fashion.

So, let me ask you the same direction and evaluate for the voltage across the inductor. When the diode is connected here it is V naught that comes into this picture directly across the inductor and it will be V naught into 1 minus dTs. Now this should be equal to 0. When you solve this you see that V naught is equal to minus V in d by 1 minus d. Observe the minus sign here because I have assumed the direction of measurement of the voltage in the same old wave and this is positive with respect to this, but actually the capacitor charging positive in this way and automatically because the volt second balance equation you will get this minus value which means that this is plus.

So therefore, this is the input output relationship for the buck-boost converter at d is equal to 0, V naught is equal to 0, at d is equal to 0.5, so the numerator is also 0.5 denominator is 0.5, V naught is equal to minus V in and at d tending to 1 or should let us say greater than 0.5 at V naught duty cycle greater than 0.5 the denominator is smaller than the numerator V naught is greater than V in magnitude this is boost operation. At d less than 0.5 the denominator is more than the numerator, therefore V naught is less than the magnitude of V in and this is the buck operation.

So, you see that it will operate as a buck converter for d less than 0.5 and operate as a boost converter for d greater than 0.5. Hence, the name buck-boost converter and this is the relationship for the buck-boost converter. Now we know the input output relationship, we know the circuit of the three primary converters. We are now ready to simulate this circuit and see how it operates and look at the waveforms.

Next what we have to do is open gschem, gEDA gschem put the circuit in it and then use NG (Refer Time: 30:38) to simulate and see the various waveforms, and that is what we will do.