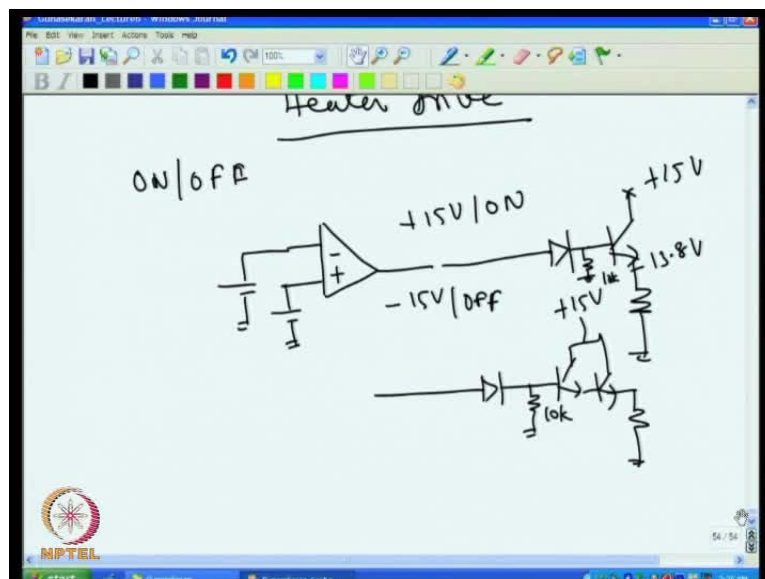


Circuits for Analog System Design
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Lecture No. # 12
Heater Drive for Various Temperature Controllers

Today, we will discuss about how to design a heater drive for various controllers, because we had seen already how to use on-off temperature controller and then proportional and PID temperature controllers, but we have not discussed in detail about how to design the heater drive. So, for 2 minutes, I will explain for on-off controller, how it is to be done? And then I will explain how we have to do for proportional or PI or PID temperature controllers - the heater drive part.

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So, we will discuss about heater drive part. For on-off controller - first I can briefly explain for on-off controller - what is to be done? For on-off controller the heater either should be switched on or off.

So, we can that we can easily do - for example, if I have the final stage of controller - you know - one is given to the v reference and the other one is sensed voltage. So, you

have a comparator, I will pick up the threat from the comparator output; so, if the heater to be on, it will be plus 15 volt and if it is in minus 15 volt, it should be off. So, we pick up from this point.

So, for on-off temperature controller, if it is plus 15, heater to be on; it is minus 15, heater to be off. Now, for low power - of course - the easiest thing would be I can connect this through a driver like this, so I can have this and then I give plus 15 volt and if the power level is high, then I can do the improved version of this (Refer Slide Time: 00:50); for example, I can have a so plus 15 volt, then we have put a Darlington pair.

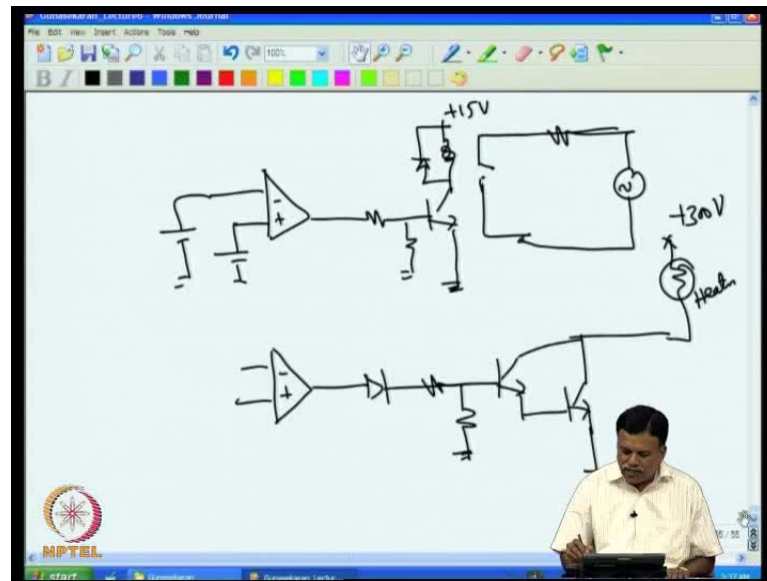
So, when it is goes plus 15, this will be 14.4 and that will be 13.8 volt, so heater will be on; then it comes minus 15, than you get 0 volt here and heater will be off to make it - you know - to discharge the storage charge we can have one resistance - may be around 10 k - to discharge storage charge that serves the purpose here; so put this, that becomes all right.

So, the Darlington pair can be used for high power current, because the current here current in the base cannot be more than 10 milliamperere, because most of the op amp rated for 10 milliamperere output current.

So, in this case, if the H F E of this is say 100, then - 10 milliamperere - 1 ampere current can go through this and the transistor withstands that much power, that much heat, because anyway it is on time about 1 volt is there and 1 watt heat dissipation will be there when 1 ampere current is flowing; in this case, for a high current, then we can have a Darlington, for example, this can be 3 0 5 5 and this can be 3 0 1 9 (Refer Slide Time 00:50).

So, 10 milliamperere here can become 1 ampere here per H F E of 100 and high power transistor H F E is low - that is 20 - thereafter 20 ampere current can go through this and we put a heat sink for this transistor. We had discussed about the heat sink design in our earlier lecture, the same thing can be used here.

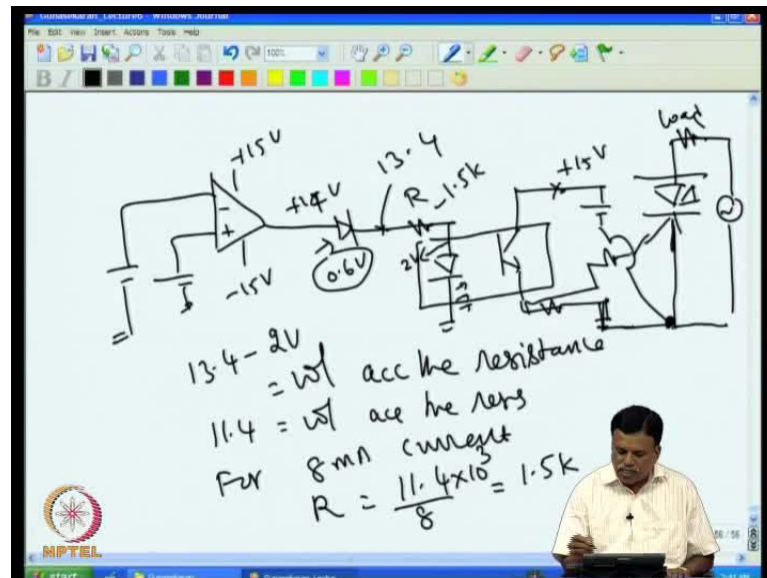
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Now, other possibility of on-off temperature controller drive would be - **we can have the same** - for example, I pick up one of the comparator, so you have this (Refer Slide Time 03:50); now, I can have a relay for switching on and off, this also we had discussed earlier; so, I have plus 15 volt and then you have the relay here and then the relay can give power for whatever circuit you want, either AC or DC can be used; but as we said **you know** the relay - **life you know** - is a mechanical object, so what happens? Whenever contact is made or broken then the some part of metal is lost here and then the number of time it can be operated get reduced; so, for very frequent on-off, **on off** this is not suitable, but this can operate either AC or DC or high power - **it can be used**.

Suppose, if you have a DC of high voltage then the on-off controller also can be used like this. So, you have this controller part leaving, then for example, I can have the **on off** on-off part **can be** like this, then if I want I can also have a Darlington and then here it can be even connected to high voltage - say, 100 volt or 300 volt or whatever it is - DC and then I can have this (Refer Slide Time 03:50); so, this can be a heater and this can be high voltage and high power, because **now the even** 15 volt which is coming here can switch on this; and this voltage can be even 300 volt or even any amount of voltage, only the condition is that this transistor and this transistor - this and this - should withstand Avco breakdown then only this can work.

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So, this is easier to handle or we can also use, **for example**, thyristor. So, in case of thyristor what we can do from this? We can have a drive and then we have to fire the thyristor; now, thyristor has to be isolated; the easiest way of doing this would be using an opto-isolator; for example, **I can have the so** whenever this is plus 15, then it will allow plus 15 **to come**

So, you will **come** have 14.4 and then optocoupler needs around 2 volt - is LED of the optocoupler - **so the right close**, so we have to limit the current by 8 milliamperes. So, most of the LEDs take 8 milliamperes current; so the resistance R required will be **if you have** around 4, this normally if you are operating plus 15 minus 15 **minus 15** volt, you may get around 14 volt, then here around **13.4** volt and 2 volt gone.

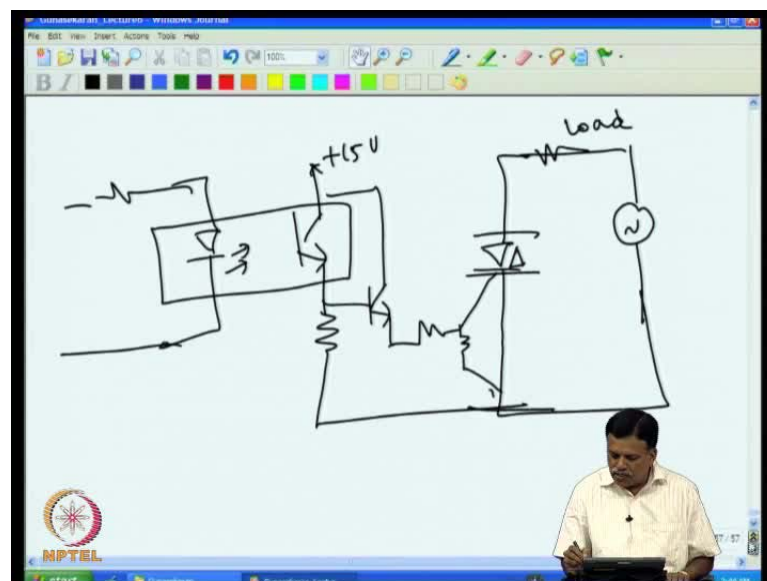
So, 13.4 minus 2 volt is the voltage across the resistance, because taking this as 14 volt and this as 0.6 volt (Refer Slide Time 05:54), voltage across this 0.6 and 14 that arrive at 13.4, this point arrive at roughly 2; so that comes 11.4 volt across resistance, that is the voltage across the resistance.

So, for 8 milliamperes current, R will be 11.4 divided by 8 milliamperes that will be this, so that is roughly about 1.5 k. So, 1.5 k resistance put here will see that whenever the **suppose** heater on this will go plus 15 volt and the LED will go with 8 milliamperes current; now, other side we can have the optocoupler; basically, this is the optocoupler with transistor one side and the LED in the other side; so, **this optocoupler** whenever it is

high, the optocoupler will be conducting. So, I can have a resistance here and this ground will be different ground, so I can have the thyristor here - a triac for that matter - if it is AC I can have a triac; whenever this is high, the triac can fire this; so we have AC current here and then the load connected here and that is connected this point, so that is the load, so AC **you have on the** current goes through this; so, whenever the LED closed, this is supposed to have isolated supply plus 15 and that current **the 0 of the** plus 15 supposed to be here, so this supply is connected here between this point and this point.

So, essentially, when the LED glow this conducts and this voltage goes high, and that fires the gate of the triac, so the gate conducts and whenever the LED off, this will become 0 and the triac will not fire this one. Now, this is a very elementary circuit; this can be improved by putting a Darlington pair, because the current required to be seen.

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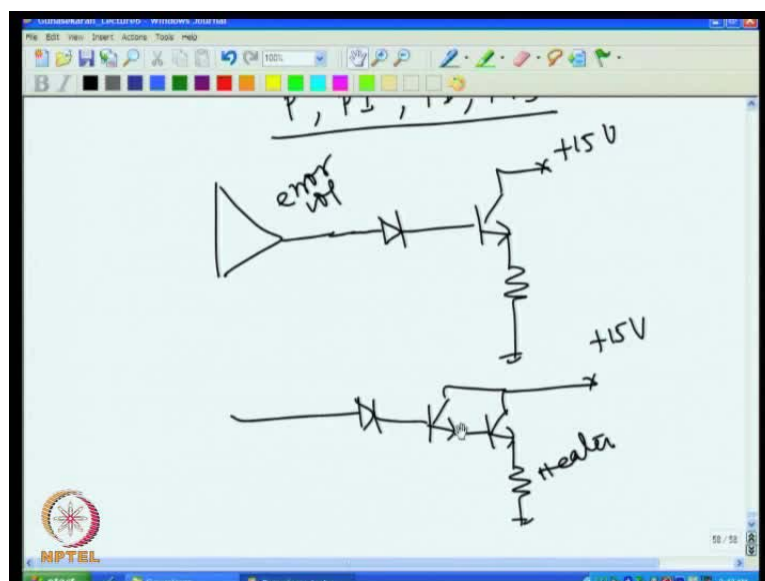
So, if I redraw the drive path of the triac, **that you have this** and then you have the load and then you have the triac; so, if this is plus 15 volt and I have this, I can improve this by putting a current, because I want to boost the current and **can give this and** then to avoid $d v$ by $d t$ fire I can connect one resistance like this, so that, when this is off, this is not floating and that is connected to the ground and so the $d v$ by $d t$ triggering is improvised the noise triggering **will not be there**; so, this is one possibility here, **is the** this is acting as a load and then this side our LED, this is the opto-isolator part, so this

ground is our circuit ground - the op-amp ground - **site ground** and this side is the power ground, this and this are no way connected.

So, you get the totalization because this ground is different from this ground; so, there is no shock hazard for the user of the instrument and this 15 volt supply is different from the 15 volt supply used in the analog side, that should be different, otherwise you will not get the isolation, so this plus 15 is different from this. Now, the circuit also further improved, in the sense that, we can make the triac to fire only at 0 crossing that is also possible, that we will discuss probably in the other part that is - when we are using a drive power proportional controller.

For on-off controllers these are the different possibilities of driving the heater voltage; this is mainly to practice the formation of different circuits, because one have to acquire the circuit design skills only in a smaller steps by seeing how each step is followed? Now, let us see how to design the heater drive for proportional controller?

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Next, we see heater drive for P or PI or PD or PID; these all are same because output voltage has to be linearly varying with error; so, it start over on-off, because what you have discussed so far are on-off, you had either switch on or off that was quite easy; but now the same thing **whatever** we had seen there to be implemented for proportional action, that is, we see for example, in simpler case where smaller power like crystal ovens are there, they need only 1 or 2 watts of power, mostly they are operated at 15

volt. If I want to design a PID temperature controller for a crystal oven, then I will as I discussed you may have or you have a PI stage or PID stage or whatever it is and then the output of that will give you analog voltage proportional to the error. So, that error voltage assume that I am getting it here, so that is the error voltage that you are getting which we are discussed in earlier classes. So, the error voltage must drive a heater, the error voltage must be proportional to the heater voltage.

In this case, when positive is there it is supposed to go I can have diode to block this and then I can have this and this can be connected to plus 15 volt, so that whatever voltage is here this point the same voltage minus 0.6 - suppose, if it is 10 volt then you will get 9.4 here - so when error voltage increases, this voltage also increases.

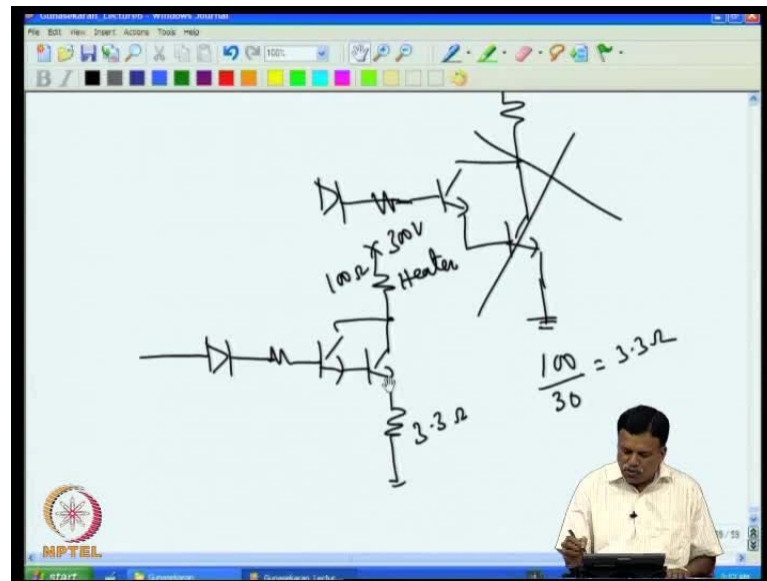
So, heater voltage increases linearly, so this system works, of course, this current can be maximum upto 10 milliamperes, so this current cannot be more than if it is HFE is 100, this cannot be more than 1 ampere; but here unlike on-off temperature controller the voltage drop is very small; you know only the that device is either on or off, but here it is neither on nor off; so, if it is 5 volt then this will be 4.4; so voltage across this will be 10.6 volt; so, this 1 ampere current goes, then there will be a 10 watt heat dissipation which will be enormous, so this transistor should withstand all the high power.

One improvement that can be done is we can instead of having the simple thing, we can have high power device at the output, so I can have the same thing with Darlington - I can have a Darlington - and the heater, so here this current is multiplied by 100 times beta of this. Suppose, here it can be maximum 10 milliamperes current, that means up to 100, 1 milliamperes current can come and this can withstand up to 20 ampere current, because HFE of this high power transistor is only 20 that range, for example, 3055 if we take HFE is only 20.

So, we can have a heater drive like this (Refer Slide Time 12:05), which can give high power and then this also can dissipate high amount of heat and the heat sink can be utilized for this purpose.

Now, this kind of heater drive works only for very low voltage - that is, up to 15 volt - because if this is 15 volt, then this can go only 15 - here 15.4, 14.4 minus 0.6 will be 13.8 minus 0.6, it will come to the 13.2 - so heater voltage cannot go more than 13.2.

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For example, I cannot have heater drive like this to drive a high voltage; for example, I cannot have this like what we have done in the on-off controller, so I can put this drive and I put this, for example, here plus 300 volt I put and then put this and then put this, this will not work, because what will happen is that if this voltage increases linearly.

This voltage across this will not increase linearly, this is the a major problem because we want you know if this is increases, this 15 voltage across the error voltage increases, the voltage across this heater should increase linearly, that will not happen in this circuit; so, if you want that to happen then we have to modify this circuit.

Now, one simplest way of modifying this would be **we can have** - I pick up threat from the output of the error amplifier; then for example, one simplest way could be - I can have this, I can have this, have a resistance here, then have a heater here. In this circuit, we had used this resistance, assume this base current is negligible; if the base current is negligible, then I can assume there is no voltage drop here and for example, if 14 volt is present at this point.

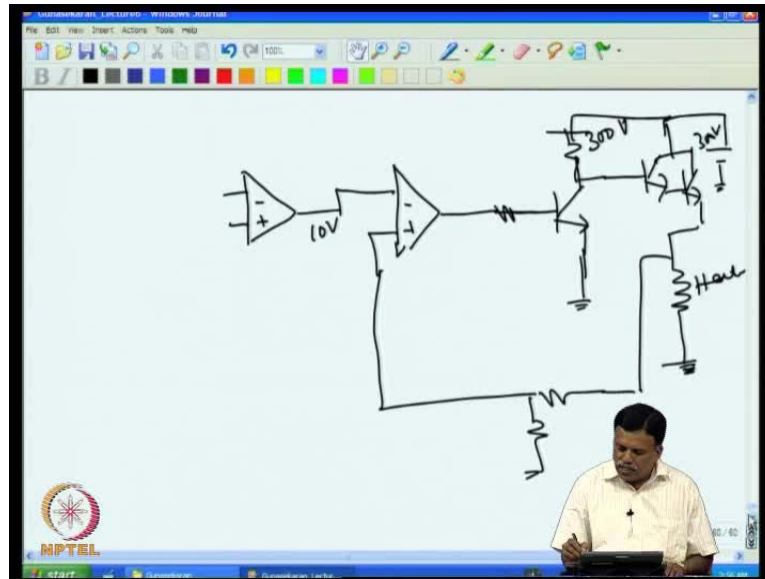
We know at this point you will have 14 minus 1.2, that will be 12.8; so, current through this now determined by this 12.8 divided by this resistance; now, this current is same as this current; assuming this current negligible, I can take this and this are essentially same; so in that case, even the voltage increases here; this voltage increases (Refer Slide

Time 16:03); this current increases; this current also will increase (Refer Slide Time 16:03).

So, this way when the voltage at this point increases linearly, voltage at this point increases linearly, so the current through this also and then the current through this, that means, voltage across the heater will vary linearly with error voltage; now, of course, this ratio between these two gives you the gain, take for example, I have a heater resistance of 100 ohms, if the heater voltage needed is 300 volt then I know 300 volt and around 3 ampere current is what is needed, that we have to go through this. So, the other way around 300 voltage at come when per say, for example, voltage at this point is 10 volt, so 10 volt has to become 300 volt, that means, you need a gain of thirty; that means, this resistance or this resistance should have ratio of 30, that means 100 by 30, this is 100 ohms and gain requirement is 30, so we need 3.3 ohms.

For example, I put 3.3 ohms 3.3 ohms, if I keep this because when the voltage at this point changes by 10 volt, I want this heater voltage changed by 300 volt, that is why we are calling gain of 330, so 10 voltage changes we have to produce a 300 volt change here; so, that can be achieved by keeping this resistance ratio as this is 100 ohms, so I put 3.3, that is the ratio of this resistance 300; so when the voltage across this is 1 volt obviously voltage across this will be 30 volt; so, like that when the voltage increases here, this voltages increases and voltage across this also increases; so, that it linearly goes up; but this will not work when the error voltage is very small, for example, the error voltage is 1 volt then this voltage is almost negligible and almost 0 current flows, so there will be a non-linearity issue in this case; in addition to that there will be a large power dissipation across this when 300 volt is there and if only about 100 volt is present here, remaining 200 volt will be across this and that will produce a very large heat.

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Nevertheless if it can also be used or if you want to avoid this small problem that you are facing this, still this circuit can be improved in the following manner, what I can do is I can take the error voltage from here and then what can I do this? The error voltage can be further compared with another comparator and that can act like a voltage regulator, like for example, I can have **the here** 300 volt fatigue, this is like a high voltage power supply, so I can have this; this can be utilized to drive the high power; so, we can have the output voltage coming here and this can be fed back to with a division 1 is to 30, for example, I can divide this voltage regulator and give it to this.

So, idea is, **if I know that if the input voltage this is say if this if I have a 10 volt**, so it produce a 300 volt, this is the heater; so, the 10 volts should produce the 300 volt across the heater; if it is 1 volt I want 30 volt across this; if it is 2 volts I want 60 volts across.

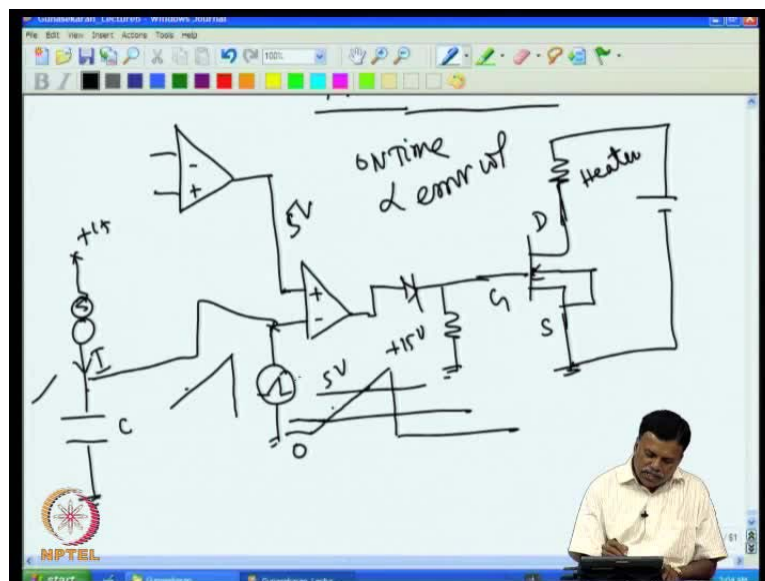
This now here what it does? We had given this 300 volt here between this and this what we had given is this 300 volt is given here, so what is done? Is this 300 volt whatever is coming I divide this using a voltage divider and give this as a reference; so, if this is 10 volt and if this is less than 10, then output will be almost 0 or minus, then this will be off; if this is off, if this is 300 this also will be 300 and then you will get almost 300 volt and heater will be getting 300 volt. Because of that **you know** the heater voltage is high. Now, this voltage also will go high and if this goes high, automatically this will come down; suppose, if this is 10 and if this goes more than 10 **if more than 10 means** this

assume that this is as a division of 1 is to 30, that is at 300, you will get 10 here; so if I give 10 and if it is **more goes** more than 10 then this will go high and then this will conduct heavily and this voltage will produce current, because the current flowing through this produce a voltage drop.

Then voltage across this will be reducing; so, when this is high then voltage across this reducing and output also reducing **in that automatically reduce this**; in case if this goes below 10 then automatically this will go minus and it will be the other way around it will go reduced and this will go high and this will go high, so whatever voltage is here, 10 volt means this also come to 10 volt; if this is 1 volt this also come to 1 volt; 2 volt comes means this also will come to 2 volts and then correspondingly this also increases, if it is 1 volt then this will be 30 volt; 2 volt means 60 volt; now, this will linearly increase of course the loop will oscillate and we had to put the loop civilization network to stop the oscillation, but nevertheless this can be achieved by doing like this.

But this will solve the problem what I told you in the earlier case that is at lower voltages, that is why the error voltage is small, you may not get the output voltage, that problem is solved but still there will be a large heat dissipation and this transistor that problem is not solved, we can solve that by using a PWM control for this.

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What I can do is that, if this is the error voltage, if this the error amplifier's output, so here you get a voltage corresponding to the error; now **this can be this is to be** this

voltage your drive heater proportional to this voltage, at the same time we do not want the transistor, that the transistor which is driving to heat it up too much, because it happens in high power cases; so, we can go for pulse **width** modulation technique.

So, using pulse **width**, let us see pulse **width** modulation technique, how to reduce the heat dissipation? So, what you do is, in this case what I do I will take - say, MOSFET as a switch in general - MOSFET, I had taken and then source will be grounded and then I get the gate **the gate I here there here drain gate, so I put the load here, then I supply high power supply, I connect it here.**

So, idea is that **this is coming is as a** this is the heater actually, **so what you do is this is heater**; so, what is required - is the power dissipated across this heater must be proportional to the error voltage here, that is what we want, we do not want switch on-off like what we had done in the on-off controller, but we want you to know this voltage and the heater voltage must be **or other way around** power dissipated on this must be proportional to the heater voltage.

So, what we do is, if I switch on, it will be fully on and 300 volt will be across this and only very small voltage across the MOSFET; then if I off then all voltage across this and no current is flowing through this, that way the MOSFET will not get heated up, because during on time only small voltage is there, during off time there is no current.

So, heat dissipation will be less if I go for on-off mode, only problem is that we have to convert this voltage into pulse **width**, that is the thing - that is to be done - that we can do using a simple circuit, like for example, **I can have I can compare example I produce 1 triangle all right** or saw tooth wave at this point, then I can connect this to the other one; so, this point is given to the saw tooth wave generator, we will see how to generate saw tooth wave? We can have this and that is what it is I have given here.

Now, to switch on the MOSFET, I have to give plus 15 and switch off, I should discharge the gate-source capacitor then the MOSFET will go off; so, first let us see how to switch on? I can do this switch on and I put one resistance discharge the gate-source capacitor here; so, if this is plus 15 then MOSFET will get 14.4 at the gate and that is much more than the threshold voltage required for the MOSFET, so the MOSFET will turn on.

Initially, for example, if this voltage is small, for example, if it is only 1 volt, then the saw tooth is rising; so, when it is below 1 **that is the saw tooth voltage is** when it is goes more than 1 and because you have a saw tooth voltage going from this is 0 this is plus 15, then if the error voltage whatever we have here, if it is more than - say if it is - 1 volt, **the 1 volt is here**; if this voltage is below 1, this is high, because this is say it starts from 0; once it goes above 1 then this will go high or I can do other way around then I can change the polarity of this that would be easier, I do one thing, I remove this plus and minus I put the minus here and plus here.

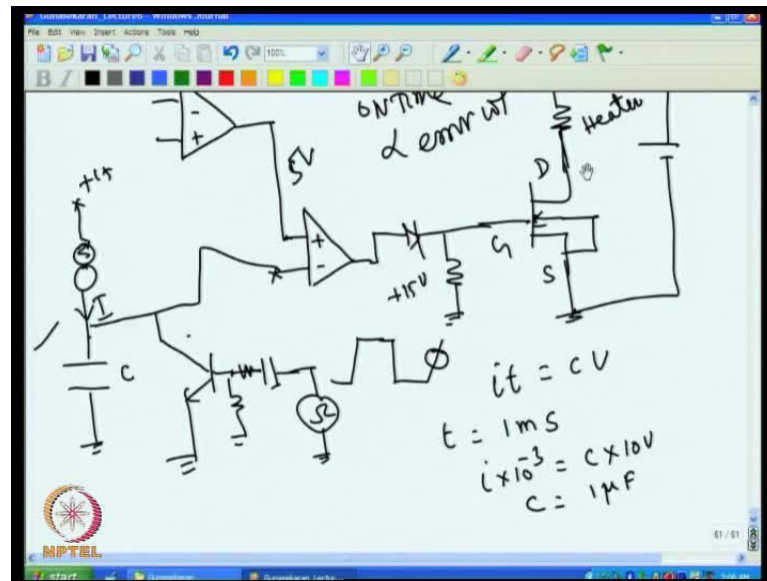
In this case, initially when this voltage is 1 volt and when saw tooth starts at 0, so up to this saw tooth reaching 1 volt output will be high then heater will be on. Suppose, if this error voltage is 5 volt, then saw tooth takes time to reach 5; but only when the saw tooth reaches 5, output will turn negative, so till saw tooth reaching 5.

You know saw tooth has go to 5 volt, this is 5 volt; so, saw tooth slowly rises and reaches 5 volt so up to saw tooth reaching 5 this will be plus, so output it will be on; that means, it will be on for more time, suppose if the error voltage is 10 then saw tooth the output will be minus till saw tooth reaches 10 volt; that means, output will have more voltage, that is output will be initially plus, because this is higher 5 volt and this starts from 0; only when this point curve goes more than 5, output will turn negative and it will switch off. Now, the on time was proportional to error voltage.

So, what is happening is on time is proportional to error voltage in this arrangement; so, error voltage is given at this point and a fixed saw tooth is given, so that why the heater is either on or off; so, it is on proportional to the this voltage and remaining time it is off, that remaining time actually depends on saw tooth period.

Now, how to generate this saw tooth wave? That **that** is to be seen now; the remaining ways we can design the saw tooth wave, for example, one is we already seen the current source, I can have a constant current source put the capacitor here, so this is plus 15.

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So, this current I always flowing constant; so, if I have a capacitor C , so voltage at this point will linearly raise this I can give it to this point; so, whatever voltage, for example, I this I want to reach this true 10 volt and repeat for example I can stop this one should reaches 10 volt, so I can do 2 ways even without sensing this, for example, I can have a discharge circuit; here I can have a square wave generator and **it will be when the** here one pulse comes, it will be discharging what it can be done is during the life time is discharge.

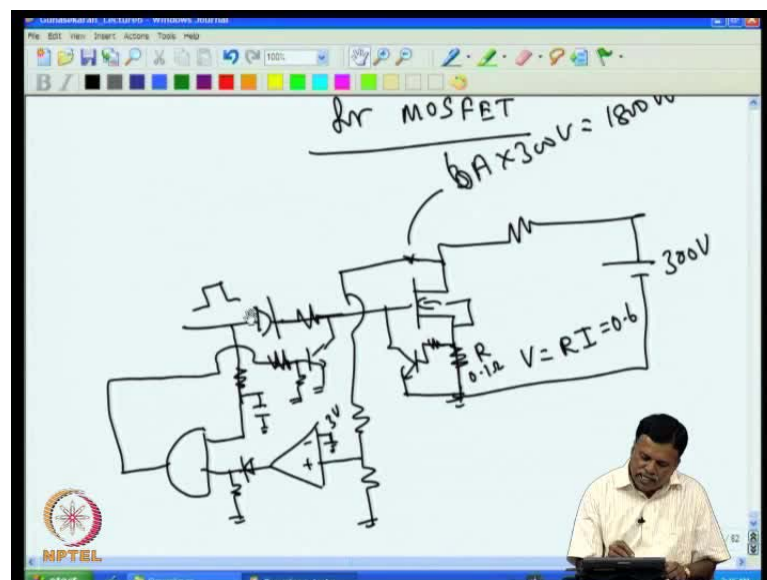
So, I can do one thing, I can input one resistance limit the base current; so, whenever this raising wave comes, so you will have plus voltage coming here and till discharge the rest of the time it will keep charging; the next pulse comes here again, the raise time this will discharge ones and again will be slowly raising.

So, this way the heater voltage can be all on-off time can be controlled. So, we can the frequency of the saw tooth is determine by this; frequency of the saw tooth is same as frequency of this square wave generator and then this is C and current source to be selected, such that, with in that 1 period 1 cycle, you know before the next squaring comes, this is this current source charge with C to appropriate voltage and that actually can be found by this formula i into t is equal to C into V ; so, t is the time period of this square wave generator.

So, **if** for example, if I want 1 mill second t is equal to say 1 mill second; if time period of this channel is 1 mill second, square wave channel is 1 mill second, then I can select i into 1 mill second, then C and if I want 10 volt as peak here for saw tooth, then I take 10 I can select i and C .

So, for example, if fix C automatically I can be selected; for example, C I can take 1 micro farad and then automatically i you get it and **you** automatic constant current source off that i value that will give you the saw tooth wave here and saw tooth wave will be compared with the reference that will drive the heater on-off on-off.

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So, this work find for DC supply. In case, if want heater drive for the from heater drive from 230 volt AC, like if you want to use the triac and then control the heater particularly that is the very often use in i power over sense so on; so then using of this kind of triac this this kind of MOSFET or IGBT is not good, because you need DC voltage, of course, one can rectify the AC and give this.

Nevertheless, if it is triac, it is good; and then there is one more issued to be a handle in this, for example, when I use somebody uses this, in case if the heater is short circuited; for example, some reason the user may unknowingly short this, in that case whenever the i pulse comes here, the MOSFET will be switched on and then MOSFET will be go back.

So, we at give some sort of short circuit production for this, then only the circuit is use full. We will see how to produce the short circuit production for the MOSFET.

So, **we see how to give...** we are seen earlier how to give a short circuit production for linear power supply; the same trig can be used here; of course, with needs small one modifications like, for example, **if this is the...** I will look only the MOSFET part alone known, so if I take the MOSFET here.

So, we have this and then we had the heater there and then this - **so** - one easiest thing that can be done is that, if this is high coming here, I put 1 resistance here; so, this is on-off on-off signal coming from the pulse PWM - says pulse with modulation says; so, if the current goes high, we know that **the** whatever resistance is kept that will develop voltage across this; then I put the transistor across this and then this collected I terminate it here; so, **when the**, suppose, if the normal case on the heater is on, this voltage across this will not be 0.6, it will be 0.2 or 0.3; so that, this chances not activated and is not doing any part and not playing any part and the heater works normally, that is whenever it is on, this is on; whenever this is minus or 0 volt, this is off, that will be taking place.

In case, if the short circuiting take place here, then the load current is very small, then the voltage at this point will increases go more than 0.6 volts; once it is go more than 0.6, this chance will conduct heavily; of course, to product the **from** spike and so on can have one small serialization here; it assume base current is small that this resistance places actually no part, but when high voltage spike comes it should not extra this.

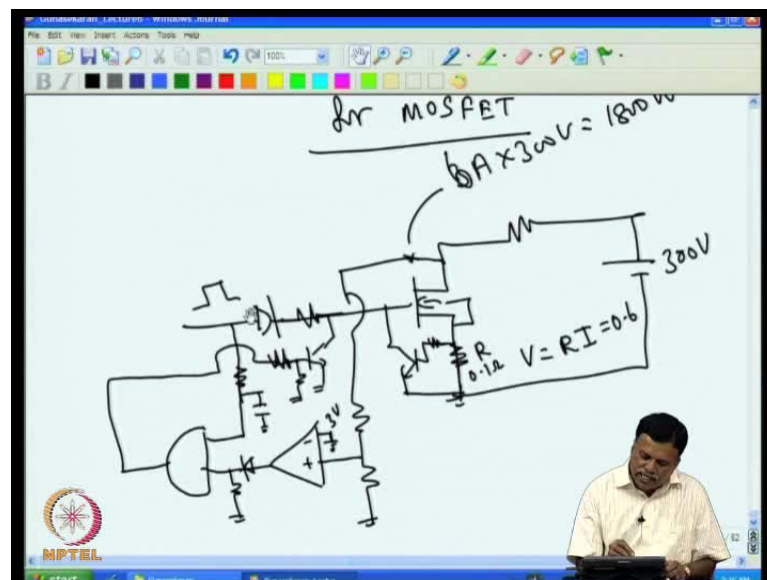
So, we put one limiting resistance that is all. Nevertheless, once it goes more than 0.6, this will conduct and then the current whatever is coming, the voltage whatever there it actually divide at now if conduct. So, the voltage of this on the gate voltage will come down; once gate voltage comes down, the MOSFET will enter into the linear region; that is, if it neither fully on or off but nevertheless current will be limited by this, because you have here it is R.

So, voltage across this will R into I . So, that has to be only 0.6, because this voltage cannot go more than 0.6, so depending upon this resistance value, the current **that much current will go on the MOSFET resistance adjusted took make sure that that much current only flow**, so MOSFET quickly drawn into a linear region, but still law the current, suppose, if I put in this case say 0.1 ohms, then 6 ampere current will flow 6, but

6 ampere; and this is already shorted as, I can this going for current will not be more than 6 amps, but 6 amps and then about say if this voltage is 300 volt, the 300 volt and 6 amps will give 1800 watt heat dissipation; so, that is 3 ampere 6 ampere into 300 volt will be 1800 watt of heat dissipation that will be high.

So, in few micro seconds, this MOSFET will go in to vapor state; so, it will get and it also exports with (()); So, one should not... if you once use this activated once you short then it is find this is and purpose of the production is lost; but what we at do is, this is acting as current limiter as soon as this is activated; we see that, this voltage, this is shorted that is why you know the entire voltage is coming here; so, this point voltage will go up, once this point voltage goes up, we should shut down the MOSFET; so otherwise the MOSFET will going into the vapor state; so, one should this is acting as a current limiter; once current is limiter then this voltage must be sends because normally when the MOSFET it is on and the when the heater is not short circuited, the voltage across the MOSFET is very small, maximum 2 volt or 1.5 volt at the maximum 3 volt not more than that; but if it is short circuited and if the current is limited then you will see almost all the voltage is across the MOSFET.

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So, we should sends this and then switch of the drive itself, then only the MOSFET can be protected; so, what we do is, we at sense this one this one, so what we do is, next stage is you will sense this; this voltage, I can sense this by having a divider and see that

what is the voltage if this is high compare to my reference, I put the reference here; for example, normally, if this will not be more than 3 volt circuit, so I keep here 3 volt, so the voltage goes more than 3 output will go high.

Now, what I do is, this high voltage should pull down, that should pull down only when the gate is on, what I do is, I just one more trig at this point, for example, I can have 1 gate here; for example, I can compare this gate also apply only the plus here, then I have another input that I apply from output of the pulse here; if this is high, then what I do this if this high, I put one small divided here RC network, then once this the... I just complete the circuit then I pull down this completely.

So, in this case, what is happening is, one pulse comes, once pulse comes high here, this will come high and then this will switch on; in case, if the heater is short circuited already, the heater is short circuited already, then this voltage will go high and then this voltage will pull down 5 volt, because if it puts 0 completely, this voltage will disappear; so, it will not normally pull down, this will be sitting around 5 volt and this will be conducting that 6 ampere current what I discuss earlier, because that is depends upon 0.1 into say 0.1 ohms I put.

So, 0.1 into 6 ampere will be 0.6 volt; so, at 6 ampere current will be flowing and that will make this voltage go high; and that if this voltage is high, this will go higher than 3 volt, that will come high, that will come high.

Now, since this is high, this also already high and this will go here, I had switched, I had that resistance here to product the waves; so, once this this output goes high, then this transistor will conduct, that will make this one goes to 0, that will make this one to go 0 the MOSFET will go off; once it is goes off, that is no problem, this is still high and then this is still high and then this will be still high and then we know that this also comment is there this will high and then it will be completely latched.

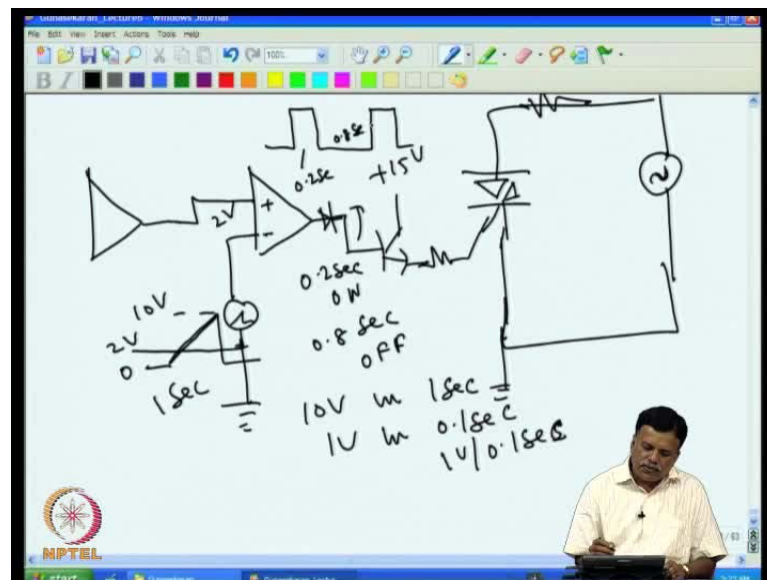
Now, you may ask, what is this I done here with RC; this is actually when this goes high first time, then if it allow this, if know short is there, this we should allow this work; so, whatever if there is no short, this will go high only after some time; for initially, when the MOSFET of this will be high, so anyway this will be high, so this will go high after sometimes only by the time, this will be switched on; and once switched on, this voltage

if the no short, this voltage will be low and this will be 0 and this will not go high, it will be on.

So, this will be launched permanently; that is, this arrangement will protect the MOSFET; once that short occurs and then if once short removable tab to work, so the this information, that latched information should go to the controller; so, that the controller can make sure that, you know, the latch is removed frequently once in a while; so, that arrangement can be done like, for example, we can have this signal switched on-off once in a while.

So that, if the one short removed the current conducts and then it works; so you can think over this issue and see what result can be done or even this circuit can be modified, such that, it automatically recovery also possible, this I leave it as an exercise; so, this way the MOSFET can be protected; we can also design a circuit, such that, we can use thyristor instead of MOSFET and still we can use the thyristor controls; it is a power to the heater linearly with respect to error voltage.

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So, that design can be done like this; so, we can have a AC source and then we can have a load and then we have say a triac or thyristors two things are connected like this; and then is **that** we can have this first, I do without isolation, then I have a optocoupler and connect the rest here, we have to switch on and off the thyristor proportional to error voltage; so, if I have the error voltage, assume that, I get an error voltage from this op

amp, then this I had to compare it with a saw tooth wave; so, I can put a saw tooth wave here, so that is same as what we had done in our earlier case.

So, we will have a minus here; then assume that, I have a saw tooth here generated at this point; for example, in this case, there is no isolation, so I connected this also to ground; we will see how to isolate that. Next, so I can have this, of course, I want fire this, I can have plus 15 here and then the current limiting resistance to the gate of the thyristor; so whenever **this is...** if the error voltage is more, we know that, you know say 2 volt - error voltage 2 volt - only when the saw tooth wave goes more than to output will tend minus; so, still it reaches, still the saw tooth reaches 2 volt, output will be high; if this voltages is 3, then the output will high still this reaches 3 volt; that means, more the voltage, this will be high for more time; so, if this is high, automatically this will be high; and this switched on and the MOSFET will be on, so here the time constant; this saw tooth wave is a very slow wave, for example, it can be once in 0.1 second point or once in 0.2 second in 1 cycle.

So, if it is say R once in 1 second, so it will take, for example, if it is 5 volt and if the saw tooth wave is say 1 second wave; in 1 second, it takes times go 0 to 10 volt, so this is 0, this is 10 volt, assume this take 1 seconds; that means, if the error voltage is say 2 volt, then it will be on; for 0.2 second on and 0.8 second, it will be off, because here is the 2 volt; so to 10 volt, it takes 1 second, so it goes 0.1 volt per second.

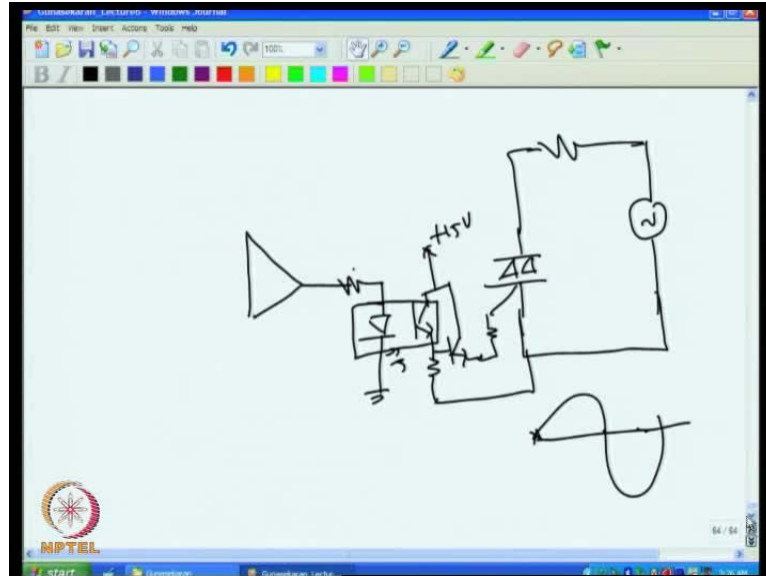
So, rate at which it is rising is 0.1 volt per second; so, rate at 1 volt per second, because it takes 10 volt per second, so 0.1 volt per second that is the rate at which it is rising **sorry**. So it goes 10 volt, then 10 volt in 1 second; so it reaches 1 volt in 0.1 second; **sorry** so it goes 1 volt in 0.1 second; so this rises at the rate of 1 volt per 0.1 second, that means, to reach 2 volt it needs 0.2 second.

So, after 0.2 second only the saw tooth will reach here - 2 volt; so, it takes 0.2 second; so, still up to 0.2 second, it will be on and several AC cycles will be going through that the one AC cycle loss only 20 millisecond; so, 100 millisecond only 5 cycles and 200 millisecond you will have 10 cycles will be conducting, then for remaining period that is remaining 0.8 second it will be off.

So, if we see the pulse at this point, you will have 0.2 second on, 0.8 second off; so, this will be 0.2 second and this will be 0.8 second off; so, if it is if this voltage goes to 3 volt,

then it will be on for 0.3 second, off for 0.7 second; so, if it is 5 volt, it will on; for 0.5 second off for 0.5 second.

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So, as the voltage increases more time it will be on and less time it will be off, that way power that is flowing is proportional to the error voltage; this way you can use the thyristor; only drawback of this circuit is, this ground must be equal to say this ground, then only current will flow through this; if you want to break this, we can add opto-isolator for this circuit to make it such that, there is no shock hazard.

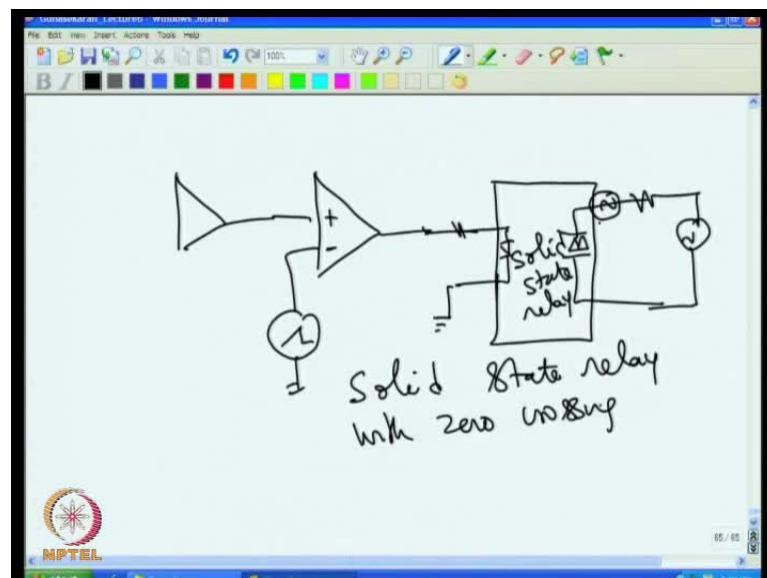
So, the same thing can be modified like this; so, I can have a AC voltage here and then we can have the triac, you can have this, then I can have the output from the PWM stage - that traverse stage, now instead of giving directly, do this, I can connect to the opto-isolator say LED that actually can be connected to the other side, which we had done earlier in the our... and that is the plus 15 volt, whose ground is this, not the ground of this; so, you have isolated plus 15 volt, that actually will drive the opto-isolator; that way the isolation is provided in this case, this ground is different from this ground and this supply ground is same as this, not this, so that way now you get a opto-isolated PWM stage.

There is still improvement possible in this; that is, there are actually... this is called integral cycle control. We can also make a circuit using 0 crossing detector, that also can be included, that is in the sense that, now it is firing randomly that is when it comes high

immediately it is fired; but that I coming can need not to be coinciding with 0 crossing of this AC, because if the AC cycle, if it is like this, if I fire at this point, automatically it goes off at this point; next cycle since voltage is present, it is firing again like this and it goes.

Suppose, if the if the gate signal comes high at this point, then you will be firing, suddenly large current will be flowing, that produce an electromagnetic interference; so, normally, this integral circuit control, it is better the firing voltage given only at 0 crossing point; if that is done, then the noise will be less; so, that circuit can be added by synchronizing with 50 hertz AC again, that I leave it to you as an exercise 0 crossing pulse with modulated firing circuit can be made for high power applications.

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Now, even this is available as solid state relay in commercial market; all that you have to do is that, you know, one need not even buy this, suppose if you have an error voltage here, all that need to be done is, you have to convert into saw tooth wave; you know give this one to the saw tooth that, I told you how to make a saw tooth wave generator, I can have this, sorry this is has to be minus then you will get a saw tooth wave here and that actually can be given; you know, you have a block available as a solid state relay, it is available which contains a thyristor and all that stuff to go with that, that is your then in the other side you have this thyristor connected inside and all that firing circuit; and all the firing circuit also built in all that need to be in connect this.

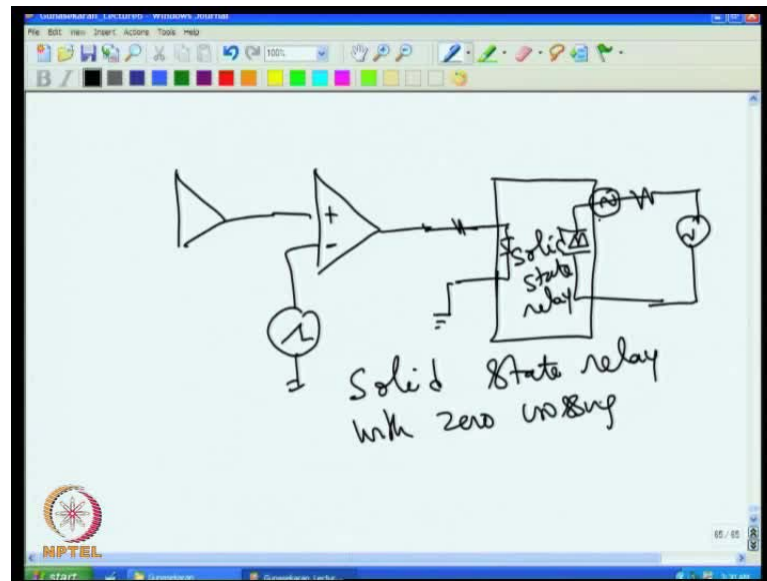
So, life is little to be easier, one need not struggle and you got isolation and firing circuit everything; whenever this is high this will be on and whenever this is 0 this off and also solid state relay with 0 crossing are also available.

So you can buy solid state relay with 0 crossing; so, it is even though, you give high here, even though you give high here; this will be firing only at the next 0 crossing; it will wait still you know the next 0 crossing occurs; so, that kind of solid state relay is also available in the market; basically, they are nothing but opto-coupler combined with triac or 2 thyristors connected back to back; and then of course, the power supply requirement for this also automatically derived inside, you need not so what give a supply for this.

So, **the live** ones live becomes easier nevertheless as analog circuit design here; one should know how to design these circuits, because you may be making solid state relay one day yourself.

So, it is essential to know, how to design this - any kind of analog circuit as it is required; so, here we had seen today that, how to produce a saw tooth wave, how to compare it with error voltage and produce a PWM signal; and once PWM signal is obtained then how to use that to fire a triac with isolation, because we had shown how to use a triac and fire in isolation, also we had shown how to use MOSFET switch on or MOSFET switch on PWM mode and then how to give a protection for MOSFET from the short circuit; because if MOSFET or transistor used in the power stage, they must be protected against short circuit; if they are not protected against short circuit, then what essentially happens is one day or other somebody will be, without their knowledge will be shorting the load and the MOSFET or transistor will get destroyed; so, if it is given to a user, any transistor or MOSFET drive, it must be protected against short circuit.

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That thyristor, one good thing, thyristor can be protected using a fuse; in fact, this is the only device in electronics that can be protected using a fuse, no other device can be protected using a fuse; so, in case of thyristor or triac, one can give a protection with simple fuse added; and when short occurs only fuse goes **not the** thyristor, if the fuse, proper fuse is put, but using fuse you cannot protect a MOSFET or IGBT or transistor always fuse is protected by these devices not the other way around.

So, with this I will stop today. We will see continue this in the next class.

Thank you.