SWITCHING ELEMENTS USED IN POWER ELECTRONICS

1. Purpose Of The Experiment

Analyzing the behavior of the switching elements which are widely used in power electronics circuit.

2. Introduction

2.1. Diodes

Diodes, which are shown in the Figure 1, are the elements, which are generally composed of one p-type and one n-type semi-conductor material. The **anode** terminal of the material is the p-type side and the **cathode** terminal of the material is the n-type side.

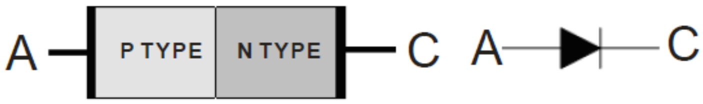


Figure 1. Structure of diode

Diode conducts when a positive voltage is applied to anode with respect to cathode and a voltage drop occurs. This voltage drop differs according to the material of the diode, but generally it is not much more than the 1V level. This voltage value is also called as the **threshold voltage**. Unless there is a voltage much more than this value over the diode, diode does not conduct and remains in the rectification phase.

If a reverse voltage is applied to the diode, namely a positive voltage is applied to cathode with respect to anode, diode does not conduct and a small negative current passes through it in the negative direction. This current is called as the **leakage current** of the diode. This current is at the level of a few microamperes or milliamperes. If this reverse voltage increases over a specific value, the diode turns into the breakdown region. This value is defined as **breakdown voltage** by the diode producers and it is given in datasheets. The breakdown region is dangerous for the diode, because in this situation, a high current with a high voltage passes through the diode. This situation can cause the diode to burn out completely. We have explained the behaviors of the diodes according to the voltages applied on them. The graphical representation of this explanation is shown in the Figure 2.

One of the most important characteristics of the diode is its **delay time**. When the diode passes to the breakdown region, it is required that the carriers in the p-n junction are annihilated for the diode to be conducting. Therefore, the current passing through the diode does not drop to zero immediately due to these excessive carriers and a negative current flows during that era. This time of conducting in reverse direction while the diode is passing to the breakdown region is called as the **delay time of the diode**. This situation is shown in the Figure 3.

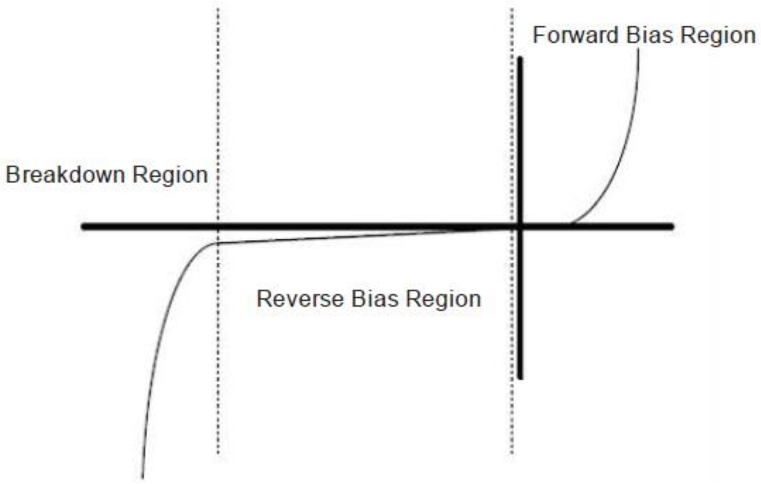


Figure 2. Diode characteristic

The delay time is not very important in the network applications, because the frequency is at the value of 50/60 Hz. Therefore, it is very slow according to the delay time. But, the delay time can be important in dc-dc conversion or in applications where high frequency switching is necessary.

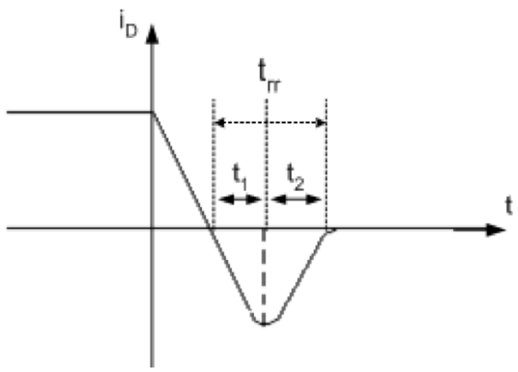


Figure 3. Cutoff conversion time of the diode

The diodes can be classified according to the needs of the applications where they are used.

* *Standard Diodes*: These diodes are general-purpose and used in the network applications which have acceptable scale of delay time.

* *Schottky Diodes*: The forward voltages of these diodes are small compared to the other diode types. They do not have p-n junction. Therefore, their delay time is small compared to the standard diodes.

* *Fast Diodes*: These diodes are used in the applications with high switching frequencies because of their very low delay times.

2.2. Thyristors

The thyristor is the semiconductor switching element which has 4-stratified PNPN regions. As shown in the Figure 4, it has 3 p-n junctions (J1, J2 and J3).

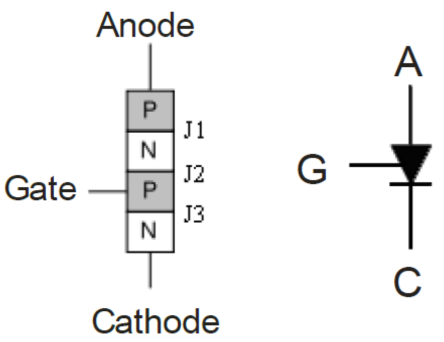


Figure 4. The structure of thyristor and its electrical symbol

As shown in the figure 4, if a forward voltage is applied on the thyristor, J1 and J3 junctions will be polarized on the forward direction; but J2 junction will be polarized on the reverse direction. Therefore, if there is no gate current, thyristor will be at the forward blocking mode and will not conduct any current through itself. If the voltage, which is applied between anode and cathode terminals, is increased, after a specific value the thyristor will start conducting. This voltage value when thyristor turned into the forward conducting mode is called "**forward breakdown voltage**".

Thyristor starts conducting when a positive voltage is applied to the gate terminal and there is no control of the gate terminal over the thyristor. Only when a reversely polarized voltage is applied, the thyristor can be off.

We said that, thyristor starts conducting when a positive voltage is applied to the gate terminal. If this gate current is not applied up until the current passing through the thyristor comes to a specific value, thyristor may not be open and it may turn into the forward blocking mode. This minimum current, which is necessary in order thyristor to conduct and stay in conduction, is called as "**latching current**". Similarly, in order thyristor to turn into blocking mode from conducting mode, the current passing through the thyristor must drop under of a specific value. Unless the current passing through the thyristor drops under this value and even if there is a negative voltage over it, the thyristor will protect its conducting mode. This current is called as "**holding current**". The value of the latching current is smaller than the holding current.

Similar to diodes, thyristors does not conduct when a negative voltage is applied between anode and cathode terminals, but only a reverse leakage current is observed. But, if this reverse voltage is over a specific value, thyristor conducts in the reverse direction. This value at which thyristor starts conducting in the reverse direction is called as "**reverse breakdown voltage**". When thyristor is goes further the reverse breakdown voltage, it burns out and should be replaced with a new one.

All situations of the thyristor defined above are given graphically in the figure 5.

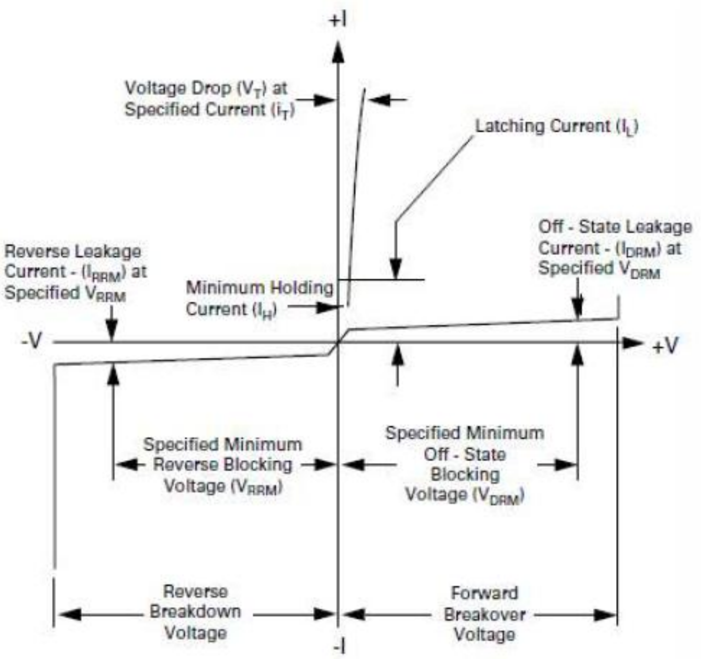


Figure 5. Thyristor characteristic

The necessary conditions for thyristors to be conducting are summarized below:

** By Applying Current To Gate Terminal:*

This is the main method for thyristor to be conducting. When the gate current is increased, the voltage on the thyristor decreases and the current passing through the thyristor increases, namely the thyristor starts conducting. Also, by applying higher gate current, a thyristor can be conducting at lower anode-cathode voltages.

** By Applying High Voltage between Anode-Cathode:*

As defined above, if a voltage higher than forward breakdown voltage is applied between anode-cathode terminals, the thyristor conducts on the forward direction. But this is not a preferable method. To start thyristor conducting by this way may be harmful.

** With dv/dt:*

If a voltage which is increasing rapidly is applied to a thyristor, the thyristor can start conducting. This is also not a preferable method.

** With light:*

When the photons reach the junction of the thyristor, the hole-electron pairs increase and start the thyristor conducting. There are special-produced thyristors which can be activated with light.

** With heat:*

Similarly to light effect, heat effect also creates hole-electron pairs increase and start thyristor conducting.

2.3. Power BJT’s and Power MOSFET’s

2.3.1. Power BJT’ S (Bipolar Junction Transistor)

BJT’s are similar to diodes in terms of structure. These are transistors which have 2 pn junctions and are produced by putting one n alloyed layer between two p alloyed layer (pnp) or by putting one p alloyed layer between two alloyed layer (npn). The symbols of the elements are shown in the figure 6.

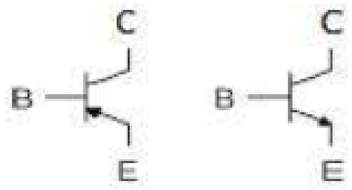


Figure 6. BJT electrical symbol

There are three terminals of BJT; these are called as **base**, **emitter** and **collector**. BJT transistors, which are current controlled elements, conduct with the current given to their base and to stay at this mode, they always need the base current. At this situation, for a specific base current, the output characteristic of the BJT transistors is the change of the collector current with respect to collector-emitter voltage. The variation is shown in the figure 7.

There is a pn junction between the base and the emitter of the BJTs. Therefore, like in diodes, there is also an approximately 0.7V voltage drop here when the transistor is conducting and the transistor will be at the cut-off region in the base voltages under this voltage value. Also, during the mode of conducting, the voltage drop over them is quite low. Therefore, the power loss during the mode of conduction is also low. However, the rise-fall times may be long because of the features of the minority carriers.

BJTs are in the cut-off region unless a current is applied to the base and at this situation; there is the maximum collector-emitter voltage, which the transistor can carry without being damaged. This is called as **breakdown voltage**.

In addition, because of the negative temperature coefficient which is peculiar to the elements with minority current carriers, BJTs have secondary breakdown points and these type of distortions are observed much more than primary breakdowns.

The operations of the BJTs are analyzed in 3 regions. In the cut-off region, due to the zero or inadequate base current, transistor does not conduct and collector current does not flow. Linear region is generally the region which is used at amplifiers and voltage-current relation is linear in that region. The last region is the saturation region. At this point, for a specific base current, the maximum current which can pass over the transistor is passing and the increase of the collector-emitter voltage will not change the collector current so much.

As we have said above, in general, the linear regions of the BJTs are used in amplifier applications and the cut-off and saturation regions are used in switching applications.

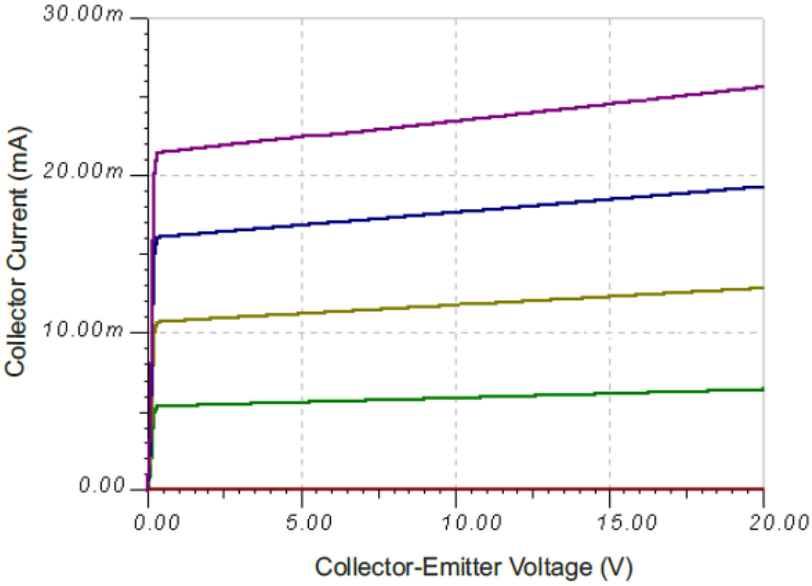


Figure 7. BJT characteristic

2.3.2. Power MOSFET'S (Metal-Oxide Semiconductor Area Effective Transistor)

Together with their occurrence, power MOSFETs becomes more preferable than BJTs. With respect to BJTs, they have higher voltage drop, but, they have not minority carriers so they can be used in higher switching frequencies and they have less losses at total.

MOSFETs have 3 terminals and these are called as **gate**, **drain** and **source**. The gate terminal is isolated from the other parts of the switch with the help of a silicon dioxide layer. Therefore, there is no minority carrier current from gate terminal to MOSFET. This means that unlike BJTs there is no secondary breakdown voltage in MOSFETs. In addition, because of this reason, there is no the blocking conversion which is required for the discharge of the minority carriers from the channel. This reflects on the rise-fall time of the MOSFETs. This is the reason for MOSFETs to be used in faster applications.

In the figure below, the symbols of n-channel and p-channel MOSFETs are shown.

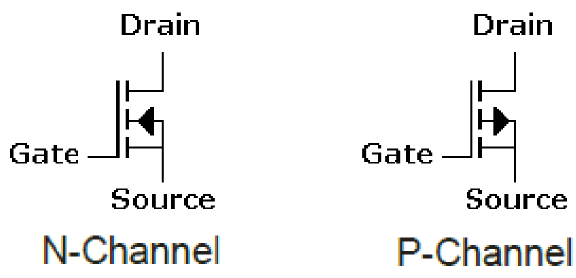


Figure 8. MOSFET electrical symbol

MOSFET is a voltage controlled switching element and has two types which are called as depletion type and enhancement type. Enhancement type is commonly used. To make MOSFET conduct, a voltage must be applied between the gate and source. If MOSFET is n-channel, this voltage will be positive but, if it is p-channel, it will be negative.

When this voltage is applied, a channel on which a current can pass occurs between drain and source. Bigger the gate-source voltage, bigger the current which can pass through the MOSFET. In this case, for a specific gate-source voltage, the output characteristic of the MOSFET is the change of drain current with respect to drain-source voltage. In the figure 9, this change is shown graphically.

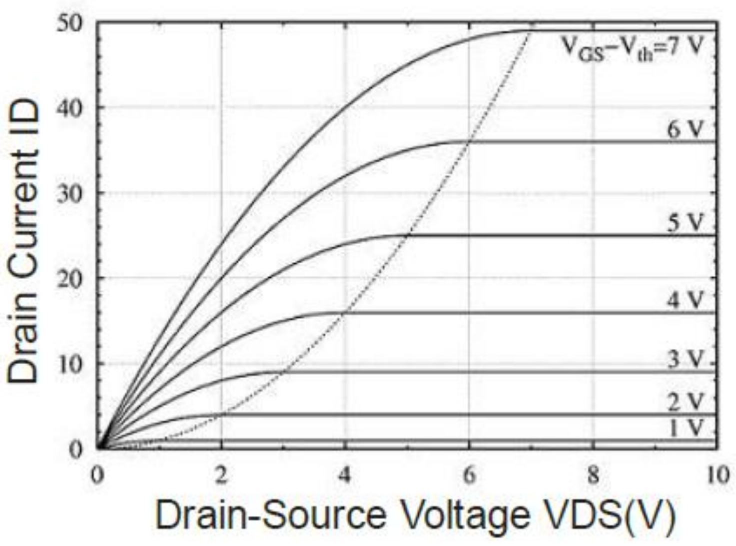


Figure 9. MOSFET characteristic

In the MOSFETs, which start conducting with the voltage which is applied between gate-source, there is no conduction up to a specific value of this voltage. Namely, MOSFET is not ON up to a specific gate-source value. This value is called as the **threshold voltage** value of the MOSFET and shown in manufacturer's data sheets as Vth.

One of the most important features of the MOSFET is the capacitance between the terminals as a result of their physical structure. The MOSFET is actually modeled as it is shown in the figure 10.

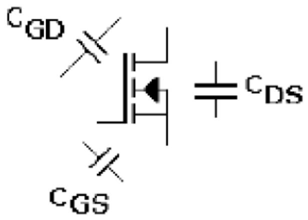


Figure 10. MOSFET's capacities between terminals

These capacitors are very important for the switching characteristic of the MOSFET. Because the rise time and fall time of the transistor is related with these capacitors and so the losses at high switching frequencies is directly related with this. One of the most important effects of these capacitors is the effect observed between gate-drain and this effect is called as "**Miller**" capacitance. As Miller capacitance is located between input and output, it is also multiplied with the gain of the amplifier and its effect is more dominant than the others. In the figure 11, this case is shown with the switching characteristic of the MOSFET.

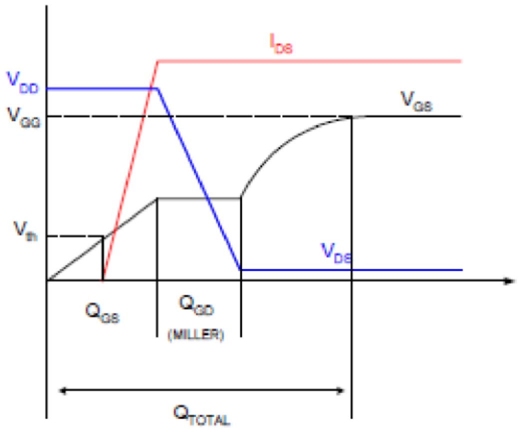


Figure 11. MOSFET's switching characteristic and miller effect

2.4. IGBT's

IGBTs are the switching elements which have some of the advantages of MOSFETs and BJTs. Similar to MOSFET, they have high gate impedance and this provides convenience for switching. Similar to BJTs, IGBTs have quite low conduction voltage drops and quite high breakdown voltages. Because there is no minority carrier injection from gate into the channel, unlike BJTs they have not secondary breakdown voltage problems. They have higher switching frequencies than BJTs have but, they can not be as fast as MOSFETs. After all,
their switching characteristics are almost the same as MOSFETs.

IGBTs have 3 terminals and these are called as gate, emitter and collector. For a specific gate-emitter voltage, the output characteristic is the variation of collector current with respect to collector-emitter voltage. The symbol of IGBT and its output characteristic is shown in the figure 12.

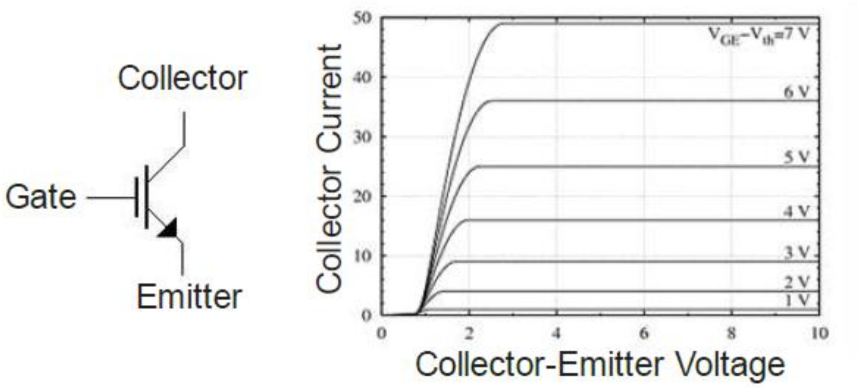


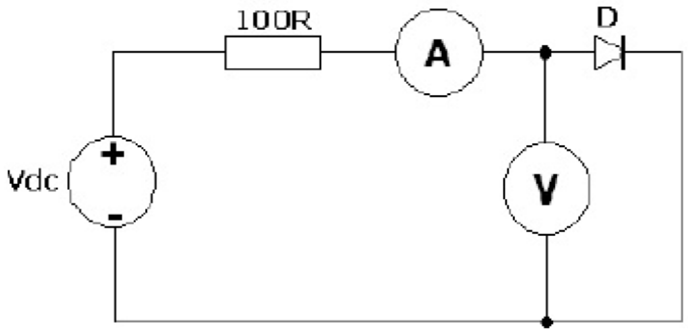
Figure 12. IGBT electrical symbol and characteristic

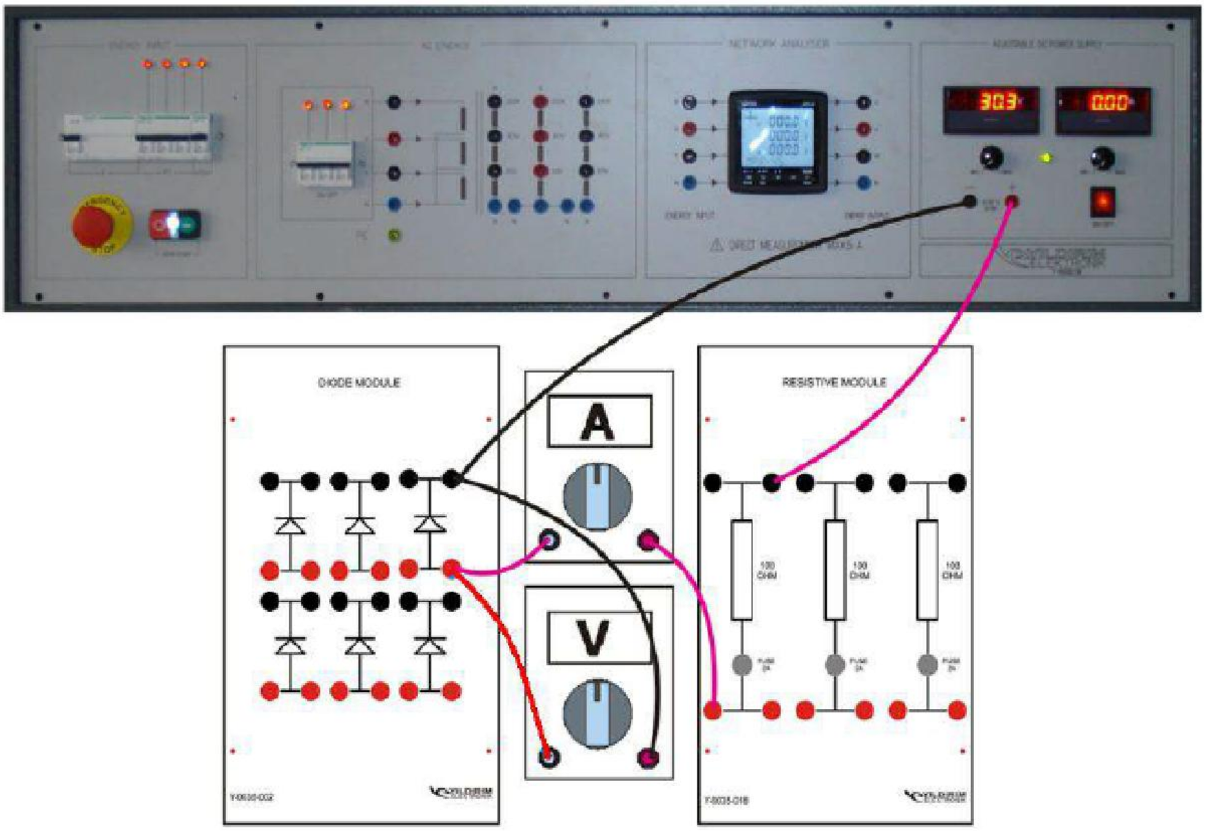
3. Conduct of Experiments

3.1. Analyzing the Diode Experiment

3.1.1. Correct polarization of the Diode

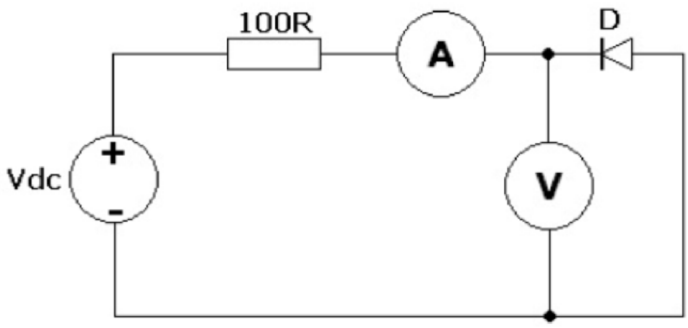
1. Make the circuit connections as in the figure. An extra multimeter will be used for this experiment.
2. Turn the voltage potentiometer of the regulated power supply in the energy unit to the minimum (left) and the current potentiometer to the maximum (right). Energize the circuit. In this case, the diode is correctly polarized.
3. Adjust the adjusted power supply voltage in order to obtain the current values given in Table 1. Record the voltages corresponding to each current value from the voltmeter at the diode ends in the table.
4. De-energize the circuit.
5. Calculate the diode resistance in each step from the formula ($R_D = \frac{E_D}{I_D}$). Save it in the table.
6. Draw the correct bias characteristic curve of the diode by plotting the obtained I_D and E_D values on the graph given Figure 1.

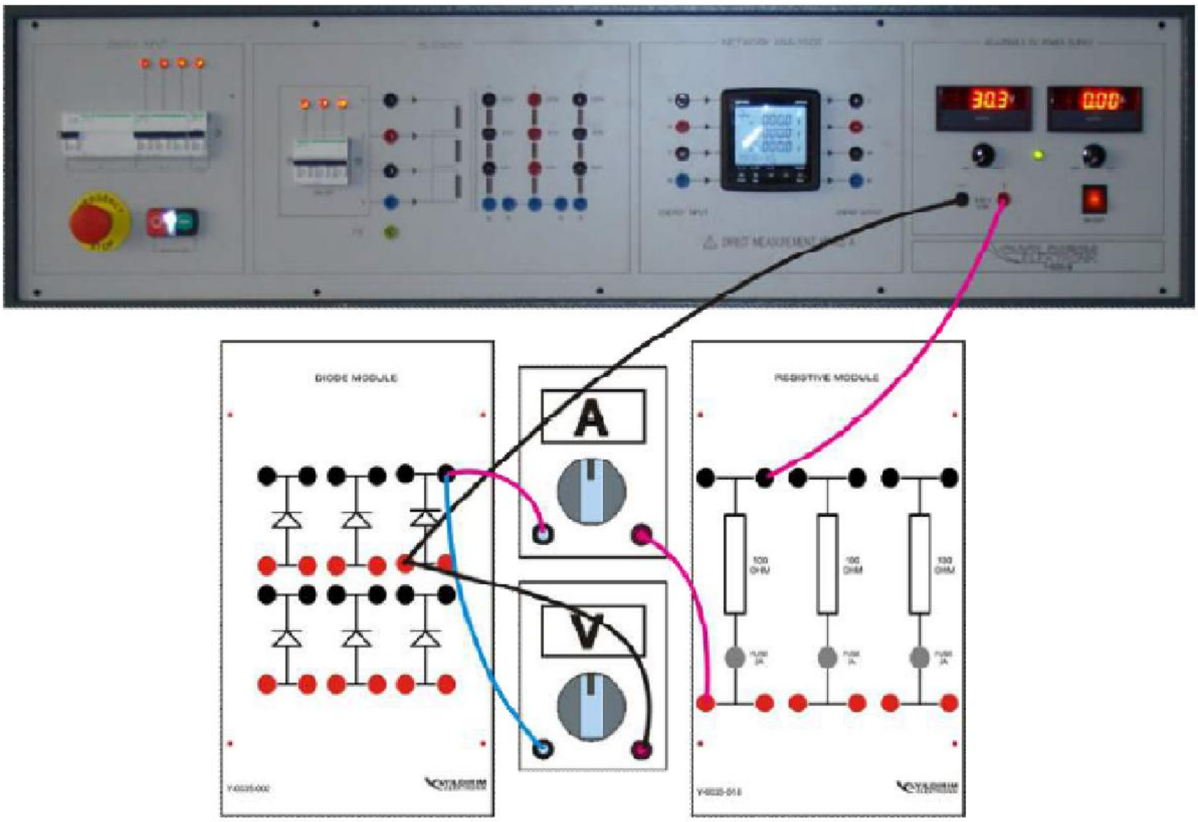




3.1.2. Diode Reverse Polarization

1. Make the circuit connection as follows.
2. Turn the voltage potentiometer of the regulated power supply in the energy unit to the minimum (left) and the current potentiometer to the maximum (right). Energize the circuit. In this case the diode is reverse biased.
3. This time, obtain the voltage values at the diode terminals given in Table 2, respectively, by adjusting the regulated power supply. Record the I_D value obtained at each step in the table.
4. De-energize the circuit.
5. Draw the reverse bias characteristic curve of the diode by plotting the obtained I_D and E_D values on the graph given in Figure 2.

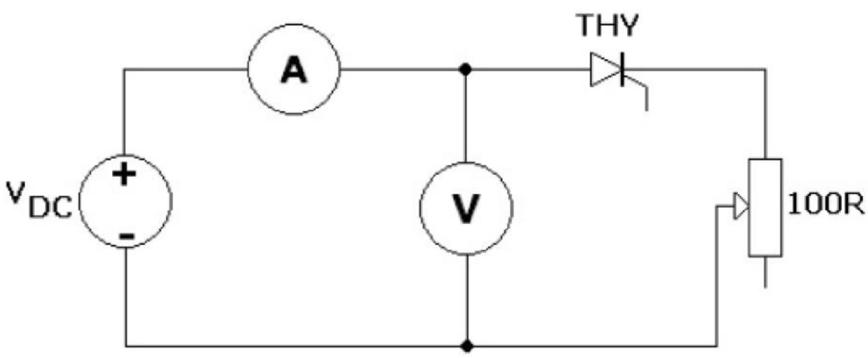


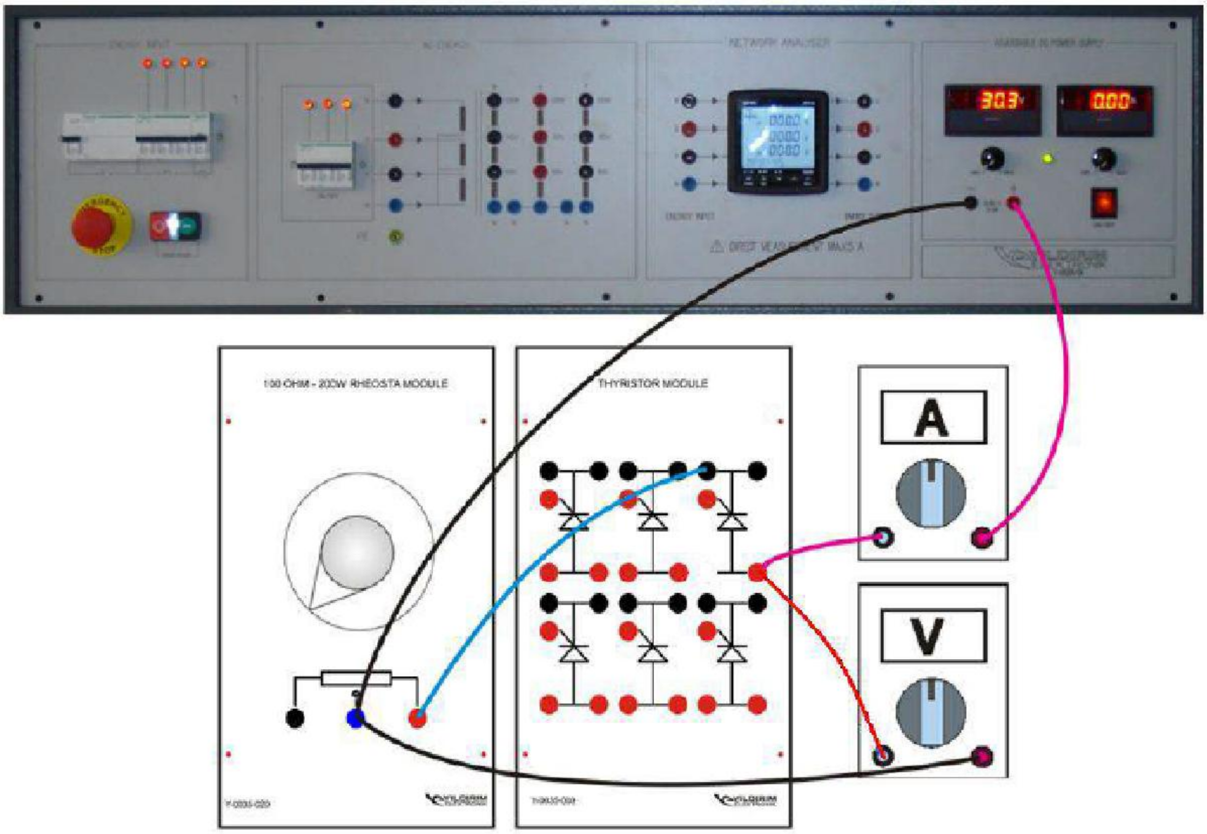


3.2. Analyzing The Thyristor Experiment

3.2.1. Forward Blocking Mode Tests

1. Affix Y-0030-003 THYRISTOR MODULE modulus to its place. Do the circuit connections as shown in the figure.

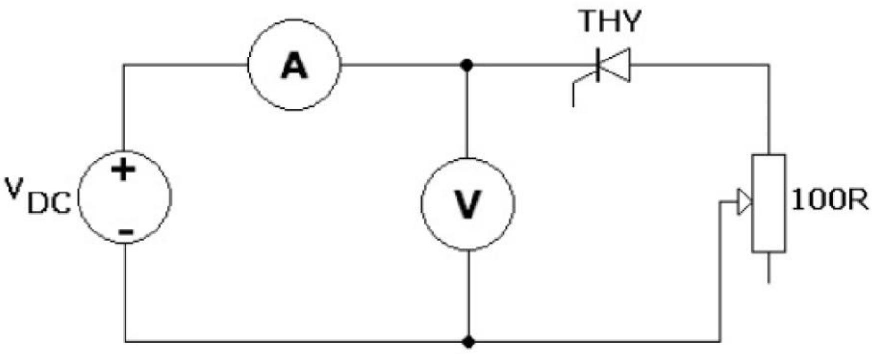


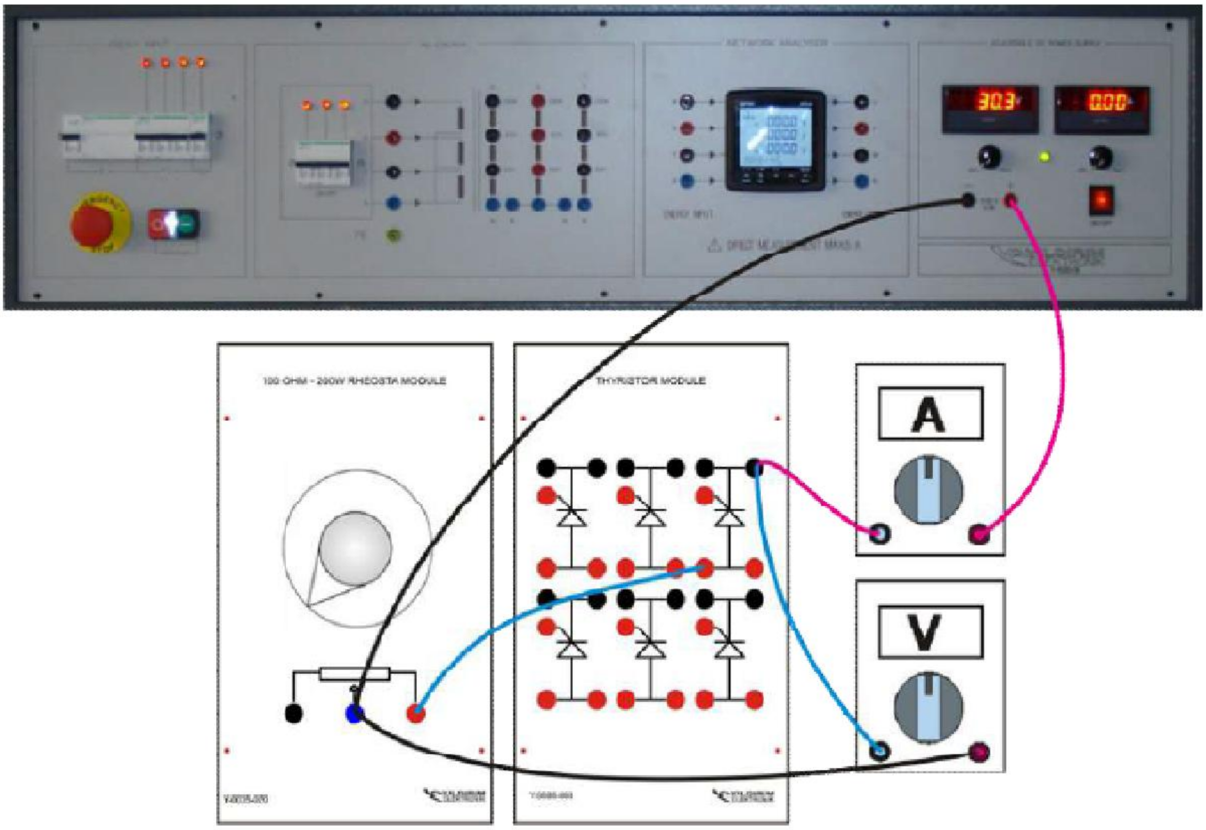


2. Set DC adjustable power supply to minimum its minimum position. After connecting the circuit above, apply the energy.
3. Change the voltage between $0 - 30\ V$ and fill in the table.
4. De-energize the circuit

3.2.2. Reverse Blocking Mode Test

1. Do the circuit connections as shown in the figure.





2. Set DC adjustable power supply to its minimum position. After connecting the circuit above, apply energy.
3. Change the voltage between $0 - 30\ V$ and fill in the table.
4. De-energize the circuit.

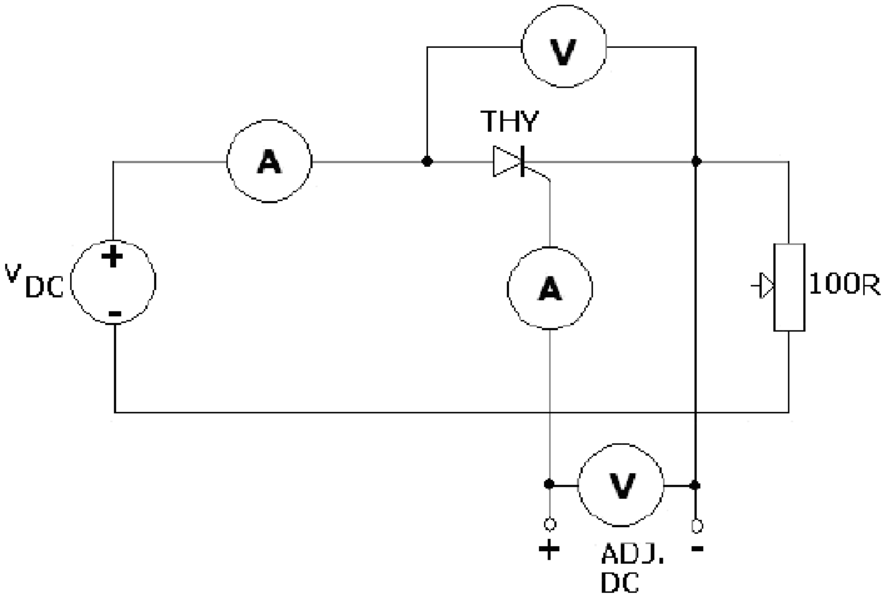
3.2.3. Forward Breakdown Voltage Of The Thyristor

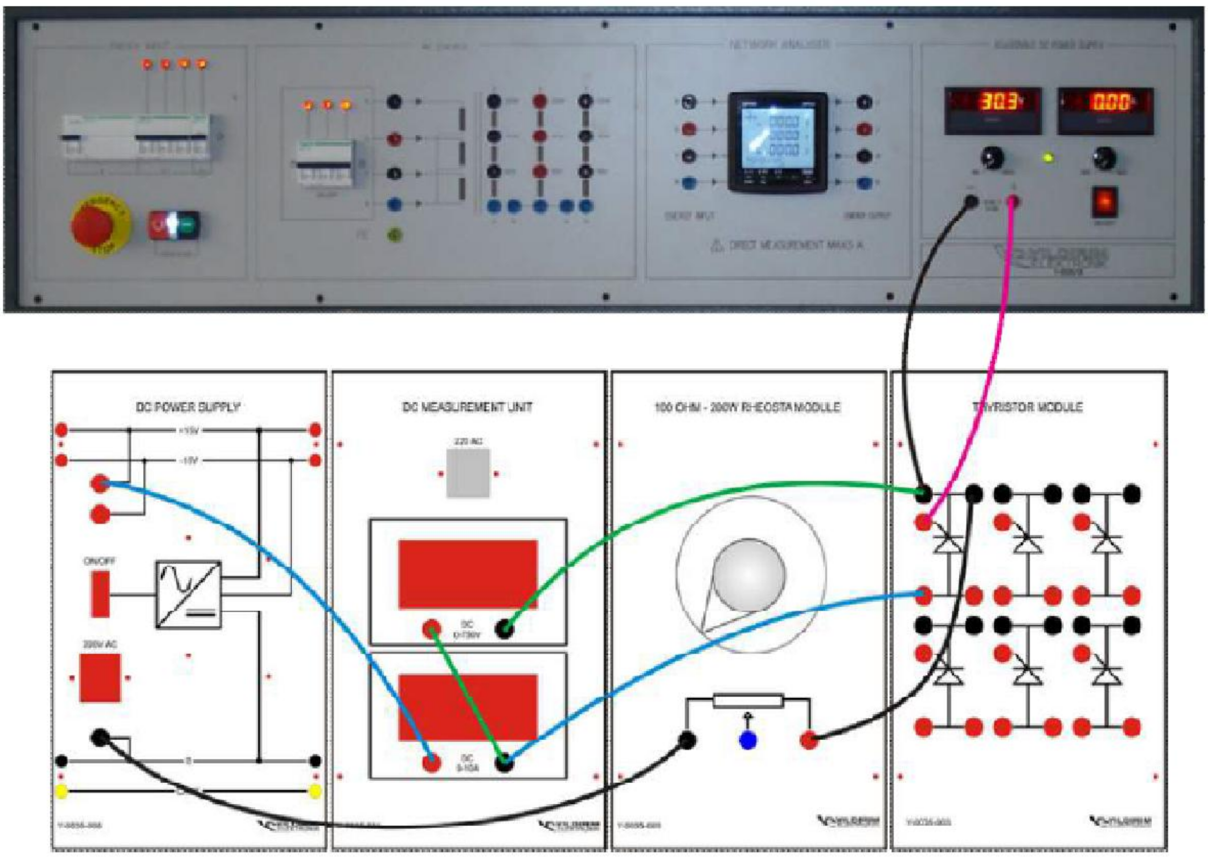
1. Do the circuit connections as shown in the figure.
2. Connect the gate terminal of the thyristor as shown. Adjust the adjustable source in the gate circuit of the thyristor to "0" as shown in the Figure. Then, increase the adjusted source voltage in the gate circuit gradually and increase the gate current. Meanwhile, observe the voltage on the thyristor.

Note: When the thyristor is in cutoff, the voltage at the input will be observed between the anode-cathode terminals of the thyristor. When the thyristor turns on, the applied voltage will be transferred to the load and forward conduction voltage will be observed on the thyristor. The gate current that turns the thyristor on under these conditions is the maximum gate current. The thyristor can also be turned on with gate currents lower than this. The input voltage at which the thyristor conducts under this constant gate current is the forward breakdown voltage (V_{BO}) corresponding to the current gate current of the thyristor.

3. De-energize the circuit.

4. Plot the change in $I_g - V_{BO}$ in figure 3.

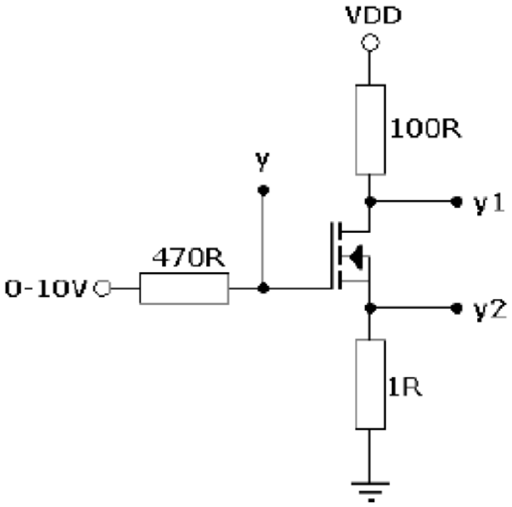


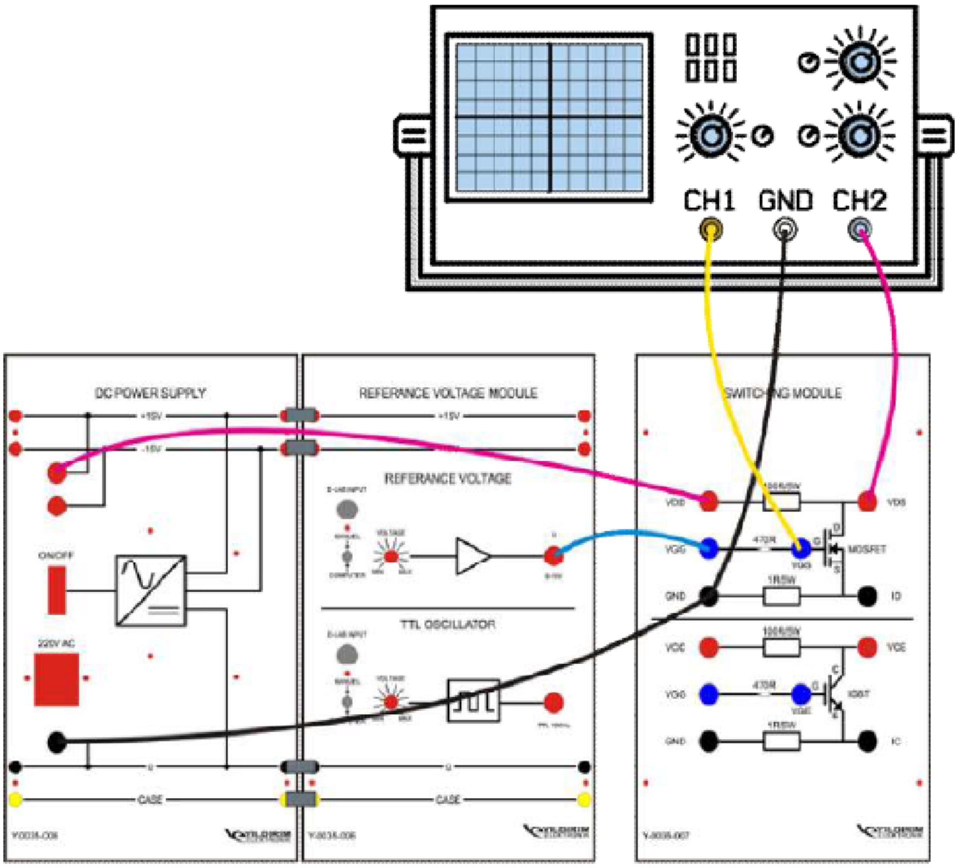


3.3. MOSFET Experiments

3.3.1. MOSFET ON-OFF Test

1. Do the circuit connections as shown in the figure.
2. After doing necessary connections, apply voltage to the circuit.

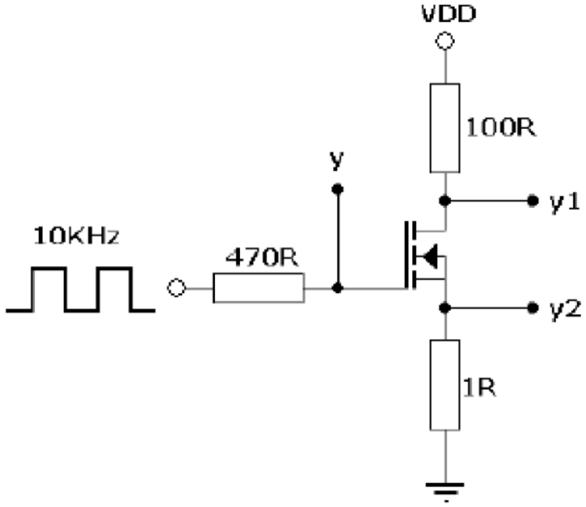


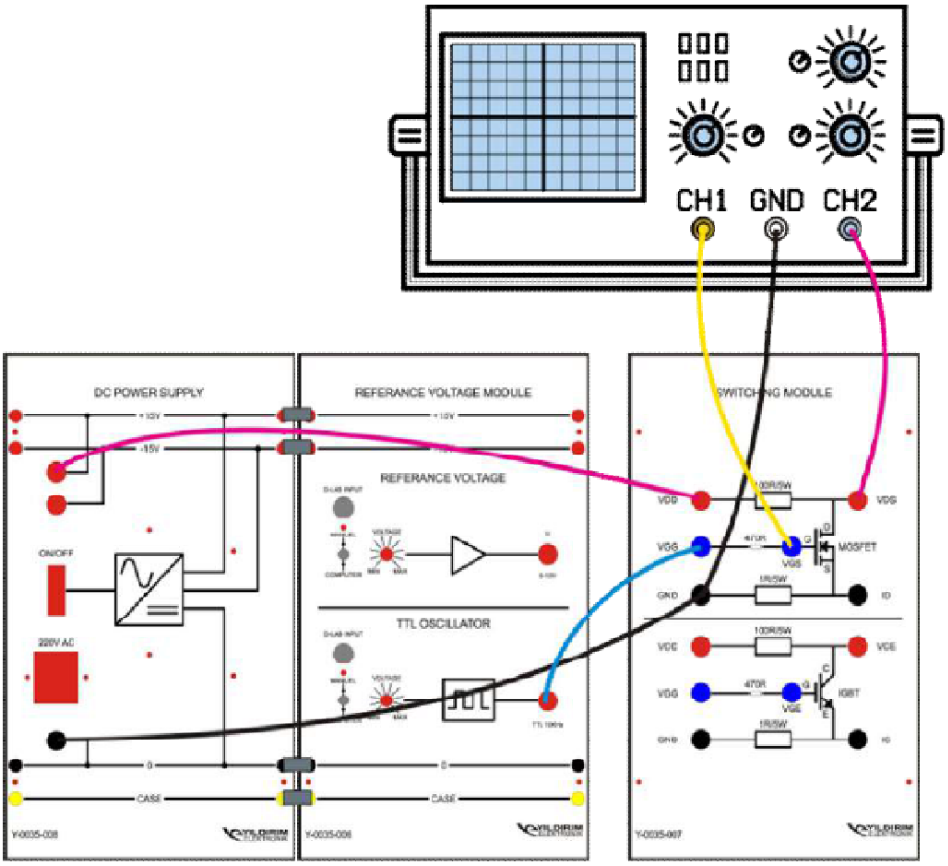


3. Observe the output voltage from the oscilloscope while increasing the gate voltage slowly. At this moment, the output voltage must be 15V which is the supply voltage.
4. When the gate voltage becomes approximately 3V, the output voltage will start decreasing slowly. Record the gate voltage at this moment. (MOSFET has started conducting)
5. Continue to increase gate voltage. The output voltage will be at the least level after a short time and then it will not decrease. (MOSFET is conducting) This voltage value is approximately 5 V.
6. Sketch the output with respect to the gate voltage.

3.3.2. MOSFET Switching Test

1. Do the circuit connections as shown in the figure.



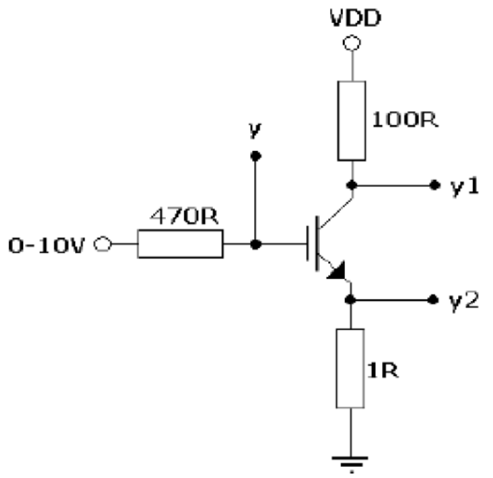


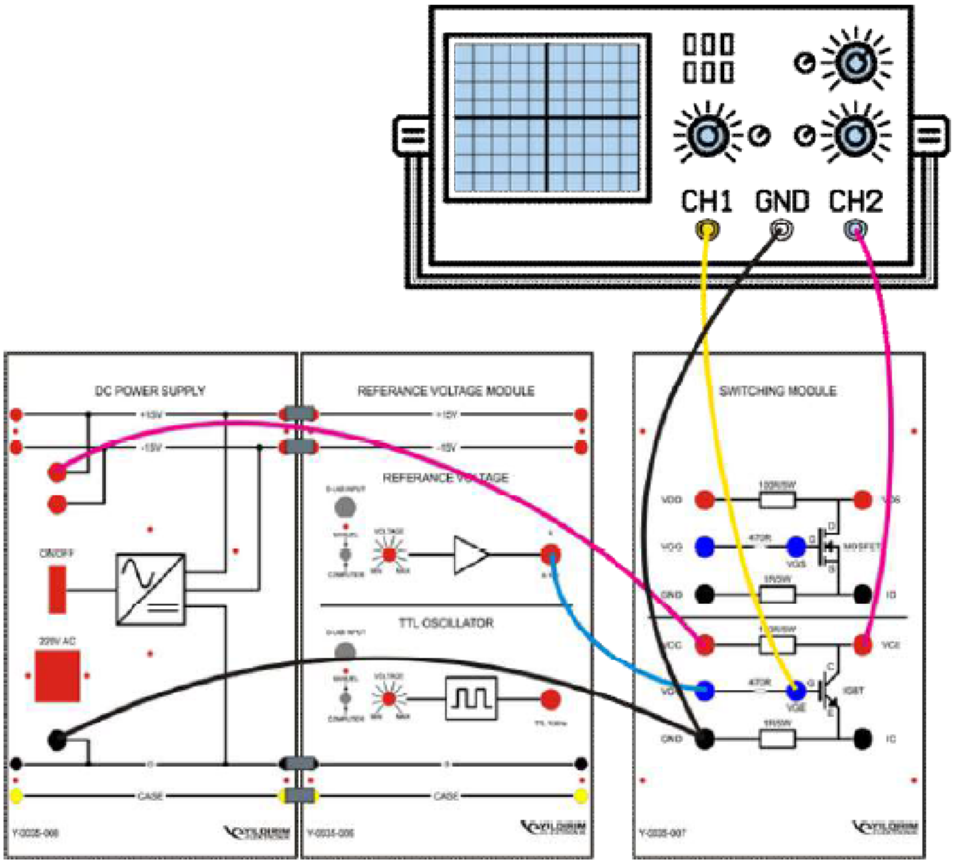
2. Apply a 10 kHz square wave with a 10V peak value at the input and observe and draw the VGS gate source voltage (Y) and VGS gate-source voltage (Y) on the oscilloscope. Plot the change in figure 5.
3. Determine the threshold voltage value required for the MOSFET to turn on by gradually decreasing the peak value of the square wave you applied and plot these changes in Figure 6.

3.4. IGBT Experiments

3.4.1. IGBT ON-OFF Test

1. Do the circuit connections as shown in the figure.



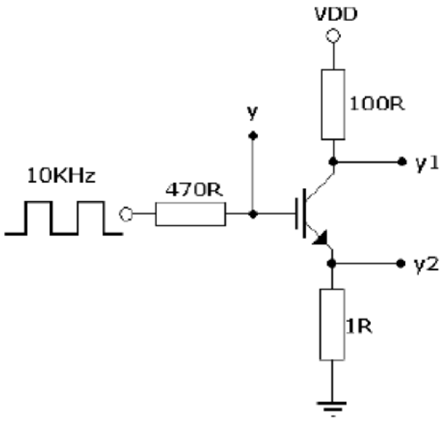


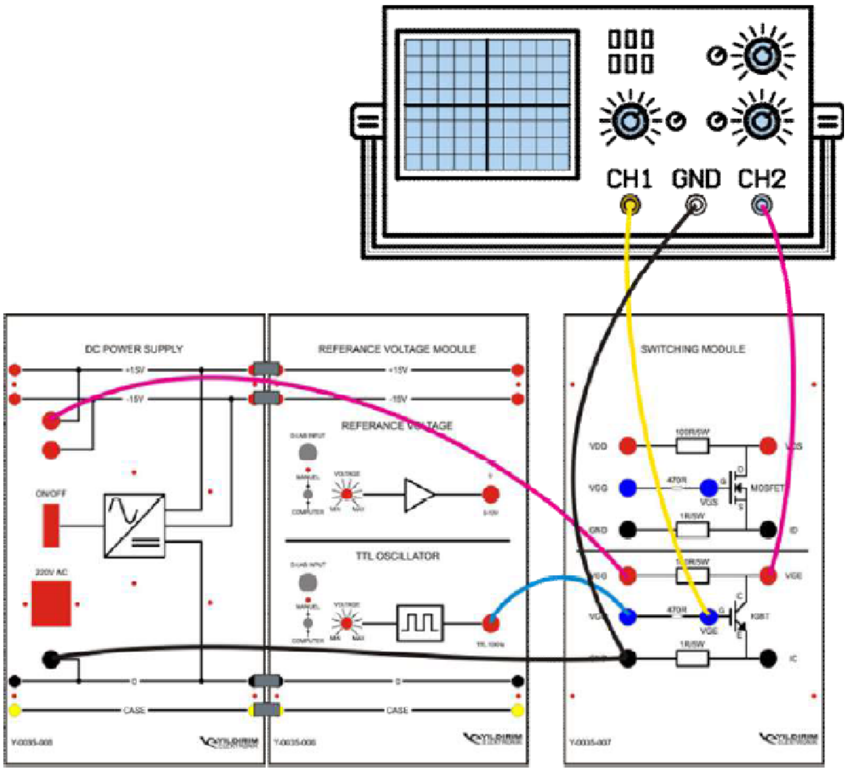
2. After doing necessary connections, apply voltage to the circuit.
3. Observe the output voltage from the oscilloscope while increasing the gate voltage slowly(Table 7). At this moment, the output voltage must be 15V which is the supply voltage.
4. When the gate voltage becomes approximately 6V, the output voltage will start decreasing slowly. Record the gate voltage at this moment. (IGBT has started conducting)

5. Continue to increase gate voltage. The output voltage will be at the least level after a short time and then it will not decrease. (IGBT is conducting) This voltage value is approximately 8V.
6. Sketch the output with respect to the gate voltage.

3.4.2. IGBT Switching Test

1. Do the circuit connections as shown in the figure.
2. Apply a 10 kHz square wave with 10V peak value at the input and observe and draw VGE gate voltage (Y) and VCE gate source voltage (Y1) on the oscilloscope. gate voltage and plot in figure 8.
3. Determine the threshold voltage value required for the IGBT to transmit by gradually decreasing the peak value of the square wave you applied and plot these changes in Figure 9.




CH1
GND
CH2
DC POWER SUPPLY
REFERANCE VOLTAGE MODULE
SWITCHING MODULE
REFERANCE VOLTAGE
TTL OSCILLATOR
ON/OFF
MOSFET
IGBT