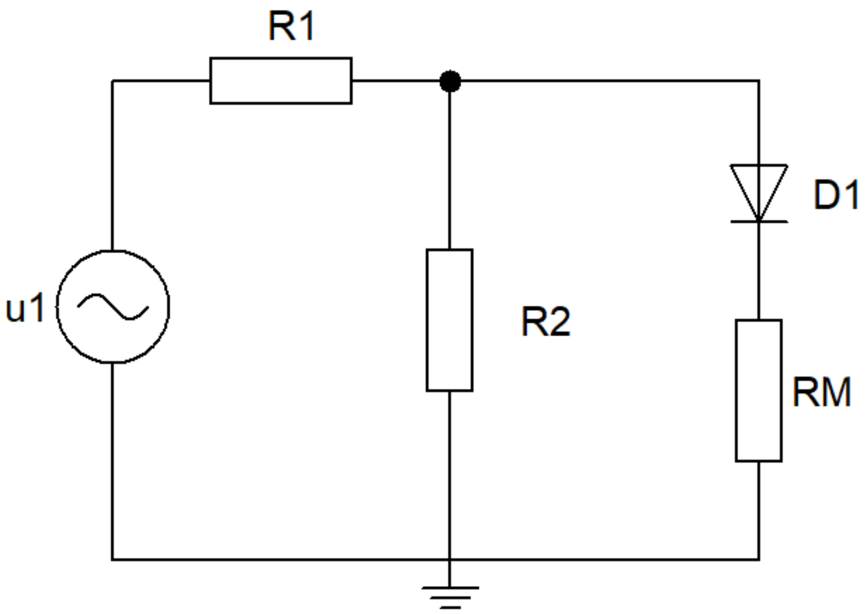
## TASK 1

To power the stepper motor **35H20HM0404A**, we need to convert the alternating voltage from the mains into constant voltage. Could we do this with the simplified circuit in the picture? What are the mean and RMS values of the voltage across the resistor $R_M$ representing the motor?

The motor works at a voltage of $U_M = 6.4\ V$, the nominal value of the current in 1 phase of the motor is $I_M = 0.4\ A$, the resistance of 1 phase of the motor is $R_M = 16\ \Omega$. The diode is silicon with $U_K = 0.7\ V$.

*Circuit:*




*Data:*

$u_1(t) = 330\sin(\omega t)\ V$

$f = 1\ kHz$

$R_1 = R_2 = 820\ \Omega$

$U_M = 6.4\ V, \qquad I_M = 0.4\ A, \qquad R_M = 16\ \Omega$

---

$U_{RM\ AVG}, U_{RM\ RMS} = ?$

*Solution:*

Stepper motors require a constant magnetic field or constant current to generate torque. Although they can also be powered by alternating current, this can cause numerous problems:

- variable torque
- loss of steps

- inability to maintain precise motor positioning
- more difficult control (sequential excitation of windings in a specific direction to achieve motor rotation)
- greater heating → greater thermal losses → lower efficiency
- at higher voltage values:
    - increased stress on materials
    - increase power factor
    - reduced efficiency
    - shortened lifespan
- at lower voltage values:
    - lower rotation speed
    - reduced torque → the motor might not turn at all

To convert AC voltage from the grid to a constant voltage, it is proposed to use a circuit with a diode. The voltage from the grid first goes to a voltage divider with two equal resistors, and part of the input voltage is then directed through the diode. The diode acts as a rectifier. Generally, a diode conducts electrical current in only one direction, which is the direction indicated by the triangle in the diode symbol. This direction is called the forward direction, while the opposite direction is referred to as the reverse direction of the diode.

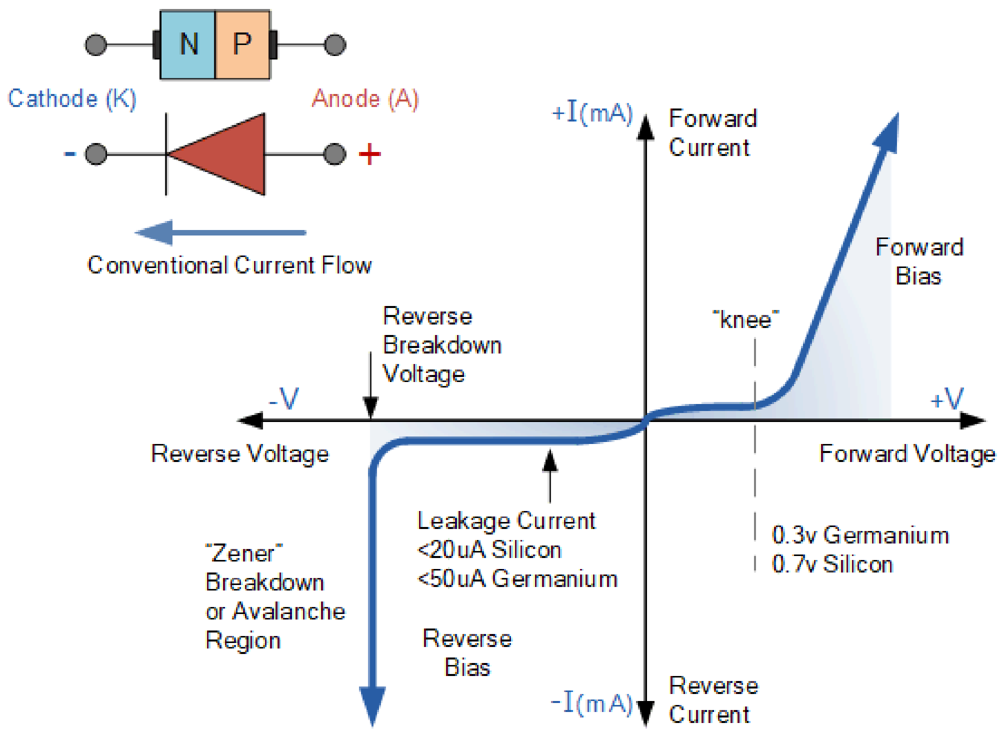
For a diode to conduct current in the forward direction, the voltage across the diode must be greater than its threshold voltage $U_K$. This threshold voltage depends on the semiconductor material from which the diode is made; for silicon, $U_K$ is 0.7 V. Up to this voltage, only a negligible current flows through the diode, but when the voltage across the diode increases to UKUK or more, the diode "opens."

In the reverse direction of operation, the diode is "closed," except if the voltage is set to a very high negative value. At a few hundred volts of negative voltage, Zener breakdown occurs, and the diode starts to conduct even in the reverse direction.

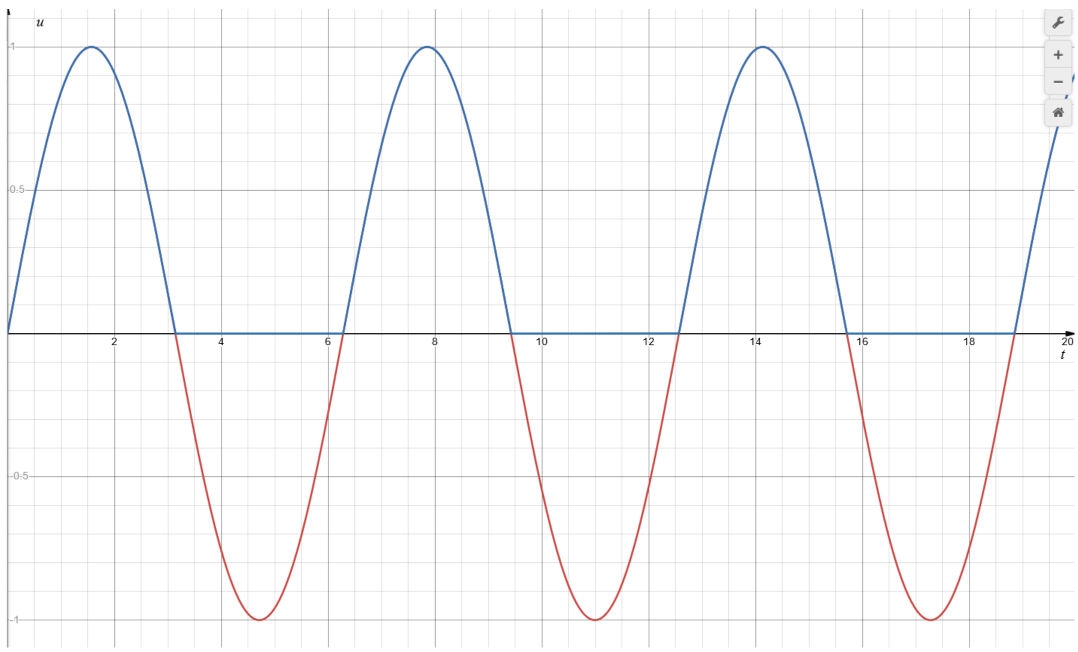
Let us examine the effect of the diode on the rectification of alternating voltage. Given the size of the grid voltage (UV=330 VUV=330 V), the voltage drop across the diode when it is open and conducting current can be neglected. Therefore, for the forward direction of the diode's operation, we can write:

$$U_{RM} = U_{R2}$$

Since the breakdown voltage of the diode in the reverse direction is 400 V, Zener breakdown will never occur. Therefore, in the reverse direction (when there is a negative voltage on the diode), the diode will not conduct electrical current.




The diode thus acts as a half-wave rectifier. During the portion of the input signal when the voltage is positive and the voltage across the diode is greater than its threshold voltage, the diode will conduct electrical current. This current will also flow through the motor windings, providing the motor with energy for rotation. During the portion of the input signal when the voltage across the diode is less than the threshold voltage or even negative, the diode does not conduct current (it is closed), and the motor will not receive energy for operation, causing it to stop. Since the circuit with the diode provides power to the motor only half of the time, this approach of rectifying AC voltage from the grid to a constant voltage is not suitable.



Nevertheless, let us calculate the voltage across the motor during the half-cycle of the input (grid) signal when the diode is forward-biased and conducting current. If we simplify by assuming we have a diode with ideal resistance $R_D = 0\ \Omega$, we can determine that resistors $R_2$ and $R_M$ are connected in parallel. Since we are interested in the voltage across the motor, we use the voltage divider equation:

$$U_{RMP} = U_{R2P} = U_{1V} \frac{R_2||R_M}{R_1 + R_2||R_M} = 6.2\ V$$

The current through the motor is then:

$$I_{RMP} = \frac{U_{RMP}}{R_M} = \frac{6.2\ V}{16\ \Omega} = 0.387\ A$$

At a positive value of the grid voltage, the voltage and current on the motor are very close to the nominal values, so the motor would rotate with such power supply. However, there remains a problem with the negative values of the grid voltage, as the diode is then reverse-biased and prevents electrical current from flowing through the motor windings.

## TASK 2

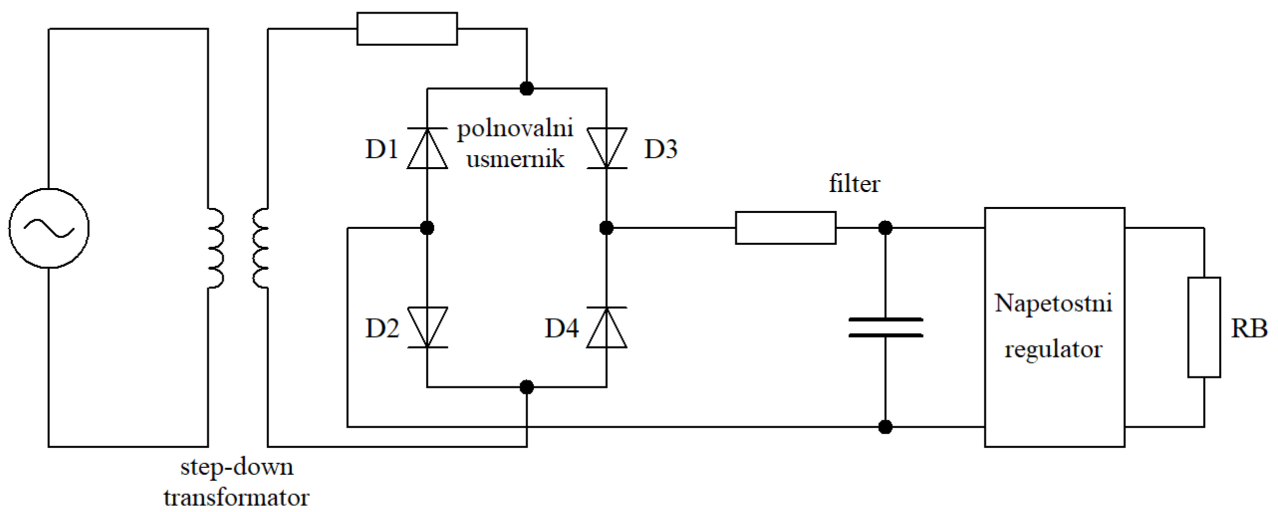
Using diodes, construct an AC voltage converter with an RMS value of $U_{RMS} = 230\ V$ to a constant voltage $U = 12\ V$. The converter must produce a constant signal that will be resistant to fluctuations in the input voltage and changes in the load.

*Solution:*

We encountered a similar problem in the first year in the course Electrical Engineering and Electronics when we measured the load characteristic of voltage sources during one of the laboratory exercises. For an unregulated voltage source (AC-DC adapter), we set the voltage to 6 V, but the voltage at the source output or on the load resistor was highly dependent on the value of the resistor used. With open terminals (no load), the voltage was around 9 V. However, as we connected progressively smaller load resistors, the voltage dropped and could end up being less than 5 V. This issue did not occur with the regulated laboratory power supply, and regardless of the connected load, the voltage source provided 6 V at the output terminals. How can this be achieved?

These types of converters from alternating current to direct current (rectifiers) are composed of several parts:

- transformer to step down the voltage
- rectifier
- filter to smooth the voltage
- voltage regulator

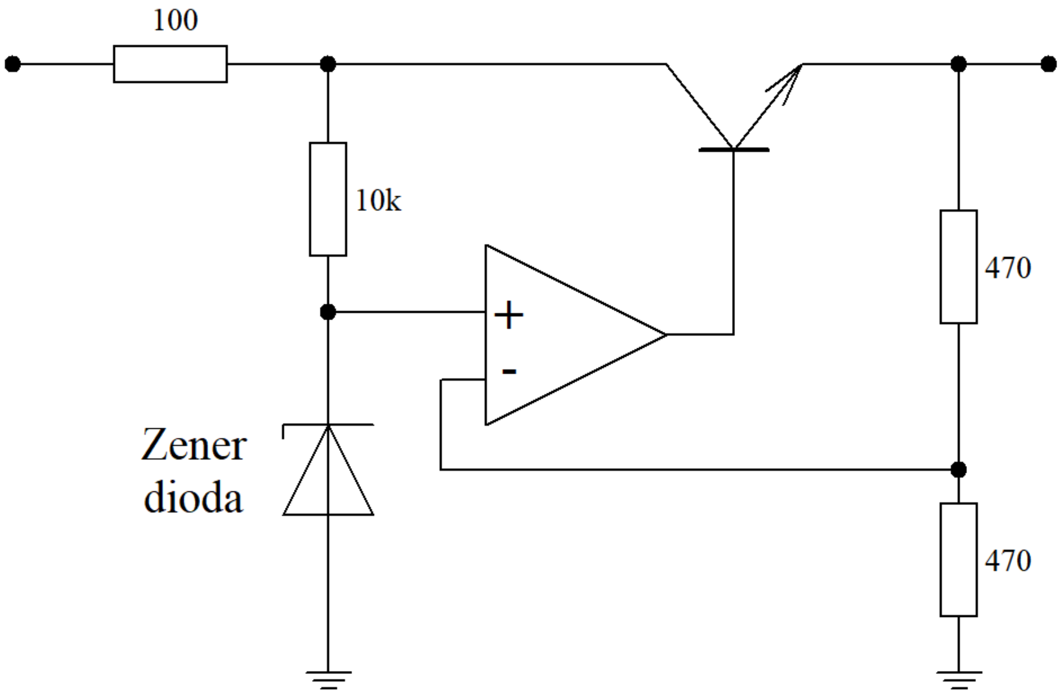



The first component is usually a step-down transformer. The grid voltage is high (approximately 330 V amplitude), so we need to adjust and reduce it by at least one order of magnitude for the next steps of the converter. For example, using a transformer with a turns ratio of 10:1, we can reduce the voltage to 33 V.

The rectifier is implemented as a bridge rectifier using four diodes in a Wheatstone bridge configuration, with the diodes appropriately oriented. The centre terminals of the bridge are the output terminals, and they provide a full-wave rectified signal. This signal is practically the same as the input signal (reduced by the diode threshold voltages) during the positive half-cycle, and during the negative half-cycle, the output signal is almost the same shape but with the opposite polarity.

The output from the bridge is already rectified (its polarity does not change), but its shape is quite unsuitable due to significant variations over time (sinusoidal oscillations). Since the output signal of the converter needs to be as constant as possible, the output from the bridge must be smoothed. We use a low-pass RC filter, where R and C are in a voltage divider configuration. R is connected to the output signal from the bridge, and C is connected in parallel with the load resistor. R affects the time constant of the filter, influencing the charging and discharging rate of the capacitor. When the voltage rises, the capacitor charges. When the voltage starts to fall, the capacitor discharges, driving current through the load resistor and reducing the voltage drop across the load.

The output from the RC filter is a smoothed and rectified signal. The remaining requirement is that the output voltage of the AC to DC converter must be resistant to changes in the connected load resistance. For this purpose, we use a voltage regulator. Its key role is to maintain the output voltage at a specific (selected) level. This is a linear regulator (step-down regulator).



One possible implementation of a voltage regulator (shown in the image above) includes:

- An operational amplifier that acts as a comparator between the voltage of the Zener diode and the voltage across the load resistor.
- An adjustable Zener diode, which is deliberately used in the reverse direction.
- A bipolar transistor, whose input current (base current) is regulated by the output current of the operational amplifier.

The Zener diode plays a very important role. We select a diode with an adjustable breakdown voltage and connect it in the reverse-bias direction. This means that if the voltage on the upper side of the diode is greater than the breakdown (Zener) voltage, the diode will conduct in the reverse direction, maintaining a constant voltage across it. The Zener diode is connected to the positive input of the operational amplifier, while the negative input of the amplifier is connected to a portion of the signal from the output (load) side. The operational amplifier amplifies the difference between the two signals, and its output is connected to the base of the bipolar transistor.

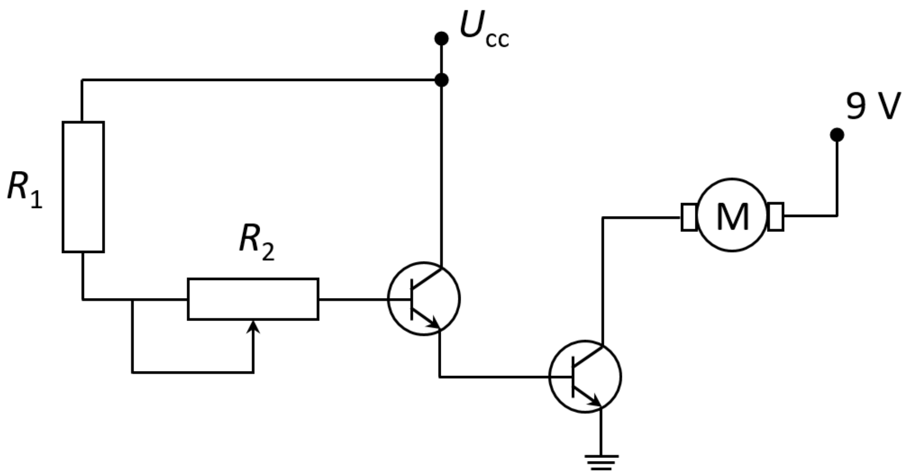
The bipolar transistor (BT) is a current-controlled component; the base current controls the current flowing through the transistor from the collector to the emitter. This setup functions similarly to a control loop with automatic regulation. If the load resistance changes, it causes a change in the voltage across the load and subsequently the voltage at the negative input of the operational amplifier. This voltage is compared to the Zener diode's voltage, and if there is any difference between them, the amplifier amplifies this difference, increases the base current of the bipolar transistor, and indirectly increases the current through the load. With negative feedback, the circuit converges towards the Zener diode's voltage. Therefore, regardless of changes in the load resistance, the voltage across the load will always match the Zener diode's voltage. The same principle applies to fluctuations in the input (grid) voltage, which cause changes in the amplitude of the rectified signal. If the Zener diode is adjustable, this type of regulator allows us to select and regulate different voltage levels.

## TASK 3

With the bipolar transistor in the diagram, we want to control the $9\ V$ electric motor. The maximum current of the motor is $340\ mA$, and the minimum current for the motor to start rotating is $20\ mA$.

Determine the resistance values $R_1$ and $R_2$ for proper operation of the motor controller. Why do we use two transistors?

*Circuit:*




*Data:*

$U_{cc} = 12\ V$
$\beta = 40\ \Omega$

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$R_1, R_2 = ?$

*Solution:*

Bipolar transistor has two main functions:

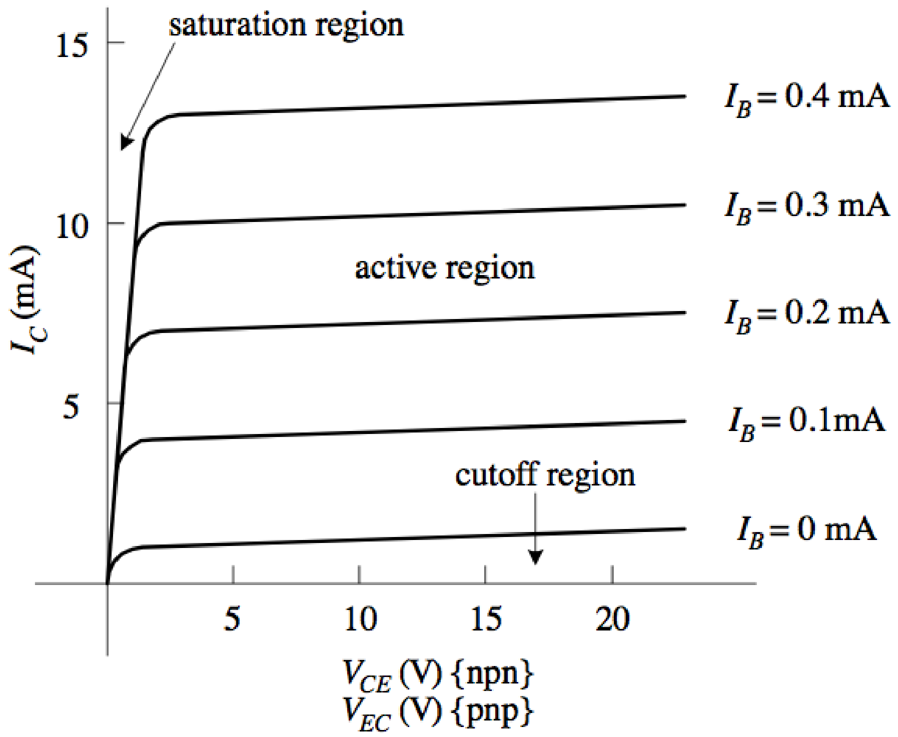
- Current amplifier
- Switch

The characteristic output curve of a bipolar transistor is shown in the figure below. The bipolar transistor has three regions of operation:

- linear region: In this region, the transistor operates as a current amplifier. The current flowing from the collector to the emitter is controlled by the base current, and the transistor can amplify small input signals to produce larger output signals.
- saturation region: In this region, the transistor operates as a closed switch. Both the base-emitter and collector-emitter junctions are forward-biased, allowing

maximum current to flow through the transistor with minimal voltage drop across the collector-emitter junction.

- cut-off region: In this region, the transistor operates as an open switch. The base-emitter junction is not forward-biased, so no significant current flows from the collector to the emitter. The transistor does not conduct in this state, acting effectively as an open circuit.




In the cut-off region, no current flows through the transistor, so it functions as an open switch. This state is achieved when the voltage between the base and emitter (V_BE) is lower than the diode's forward voltage drop. The junction between the base and emitter acts like a diode, requiring a sufficiently high voltage to conduct current. For silicon-based transistors, this voltage is approximately 0.7 V.

In the linear region, current flows through the transistor, meaning it is operating in its active mode. A sufficiently large voltage is applied between the base and emitter junction to allow current flow. In this region, the collector current is linearly proportional to the base current. For transistors in common-emitter configuration, where the base terminal is the input and the collector terminal is the output, this relationship is described by the equation:

$$\beta = \frac{I_C}{I_B}$$

$\beta$ is the DC current gain of a bipolar transistor. This equation applies only in the linear region of the output characteristics. In the characteristics, we observe this dependence by comparing the change in collector current when we change the base current – meaning we move from one curve to another.

In the saturation region, current still flows through the transistor, but increasing the base current no longer increases the collector current. This occurs when the junction BC is also conductively biased. In this region, the transistor operates almost like a short circuit or a closed switch. The equation for $\beta$ no longer applies in the linear region here; instead, the value of $\beta$ is always smaller.

Using a bipolar transistor, we can control a significantly larger collector current with a very small base current. If the input signal is digital and the base current alternates between 0 A (transistor is open) and a value that places the transistor in saturation (transistor is closed), we can use the transistor as a switching element.

In this task, we use a pair of bipolar transistors to control the current to a DC electric motor. Thus, the transistor is used as a current amplifier. Two conditions are necessary to adjust the transistor to operate in the appropriate part of the output characteristics:

- setting input parameters (base current)
- setting output parameters (voltage at the CE junction)

Why are there two transistors in the circuit? To ensure greater current amplification. In some situations, the input current to the transistor is very small, so the transistor cannot provide the output current demanded by the load. By connecting two transistors in series, we achieve current amplification that is approximately equal:

$$\beta \doteq \beta_1 \beta_2$$

where $\beta_1$ and $\beta_2$ are the current gains of the individual transistors. Such a Darlington transistor typically has a combined gain of 1000 or more. An additional advantage of this configuration is high input impedance and low output impedance. The Darlington transistor is used, among other things, in the output stages of power amplifiers and in linear power supplies. However, it also has some disadvantages:

- the voltage required to turn on the transistor (to start current flow through it) is approximately equal to twice the knee voltage of the BE junction,
- the saturation voltage drop is higher (instead of 0.2 V, it is approximately 0.9 V),

- switching speed is higher; when the transistor is used as a switch, there is a greater phase delay at high frequencies.

Let us write down the equations for each transistor and determine the exact value of the total current gain. Since we want to use the transistors to amplify current, we assume they are in the linear operating region. The current in the motor is the output current of the second transistor, which is linearly dependent on the input current of this transistor:

$$I_M = I_{C2} = \beta_2 I_{B2}$$

According to the connection of both transistors, we can also write:

$$I_{B2} = I_{E1}$$

The current flowing through the second transistor is the emitter current of the first transistor. We are also interested in how the emitter current $I_{E1}$ depends on the base current $I_{B1}$ of the first transistor. For the transistor, the equation (from Kirchhoff's current law) holds:

$$I_{E1} = I_{B1} + I_{C1}$$

If we consider that the transistor is in the linear region, we can write:

$$I_{E1} = I_{B1} + I_{C1} = I_{B1} + \beta_1 I_{B1} = (1 + \beta_1) I_{B1}$$

Inserting this result into the previous equations, we get:

$$I_{B2} = I_{E1} = (1 + \beta_1) I_{B1}$$

$$I_M = I_{C2} = \beta_2 (1 + \beta_1) I_{B1}$$

If we take the total current gain $\beta$ of the Darlington transistor as the ratio of the collector current of the second transistor to the base current of the first transistor, we find:

$$\beta = \frac{I_{C2}}{I_{B1}} = \beta_2 (1 + \beta_1)$$

This is the exact equation for the total current gain.

The task requires us to control the current to the DC motor within the range of 20 mA to 340 mA. Since the motor current is the collector current of the second transistor and using a pair of bipolar transistors controlled by current, we need to determine the appropriate range of base current for the first transistor. The base current of the bipolar transistor can be adjusted in two ways:

- by changing the battery voltage
- by changing the resistance in the base branch

In our case, the first method is less suitable since we use a common battery to power both the base and collector. It is more practical to implement a variable resistor. In the circuit, we have two resistors: one fixed ($R_1$) and one adjustable from 0 to its maximum value ($R_2$).

We will determine the lower limit value of the motor current with a smaller base current for the first transistor. This will be achieved by setting the variable resistor $R_2$ to its maximum value. The base current will then be:

$$I_{B1\,min} = \frac{U_{CC} - 2U_{BE}}{R_1 + R_2}$$

In the above equation, we subtract twice the voltage of the BE junction from the battery voltage $U_{CC}$ because we have two transistors in the circuit. Since both resistors are unknown in the equation, we cannot solve them, so we will focus on the upper limit of the current range on the motor. To achieve the maximum current at the output of the second transistor, we must also provide the maximum allowable current at the input to the first transistor. This will be achieved by setting the variable resistor $R_2$ to $0\ \Omega$. The base current is in this case:

$$I_{B1\,max} = \frac{U_{CC} - 2U_{BE}}{R_1}$$

Since we know that:

$$I_{C2} = \beta_2(1 + \beta_1)I_{B1}$$

we can determine the resistance $R_1$:

$$I_{C2\,max} = \beta_2(1 + \beta_1)I_{B1\,max} = \beta_2(1 + \beta_1)\frac{U_{CC} - 2U_{BE}}{R_1}$$

$$R_1 = \frac{\beta_2(1 + \beta_1)(U_{CC} - 2U_{BE})}{I_{C2\,max}} = \frac{40(1 + 40)(12\,V - 2 \cdot 0.7\,V)}{0.34\,A} = 51.1\,k\Omega$$

Now we can go back to the equation for currents at the lower limit of the allowed range and determine the resistance $R_2$:

$$I_{B1\,min} = \frac{U_{CC} - 2U_{BE}}{R_1 + R_2}$$

$$I_{C2\,min} = \beta_2(1+\beta_1)I_{B1\,min} = \beta_2(1+\beta_1)\frac{U_{CC} - 2U_{BE}}{R_1 + R_2}$$

$$R_1 + R_2 = \frac{\beta_2(1+\beta_1)(U_{CC} - 2U_{BE})}{I_{C2\,min}} = \frac{40(1+40)(12\,V - 2\cdot 0.7\,V)}{0.02\,A} = 869.2\,k\Omega$$

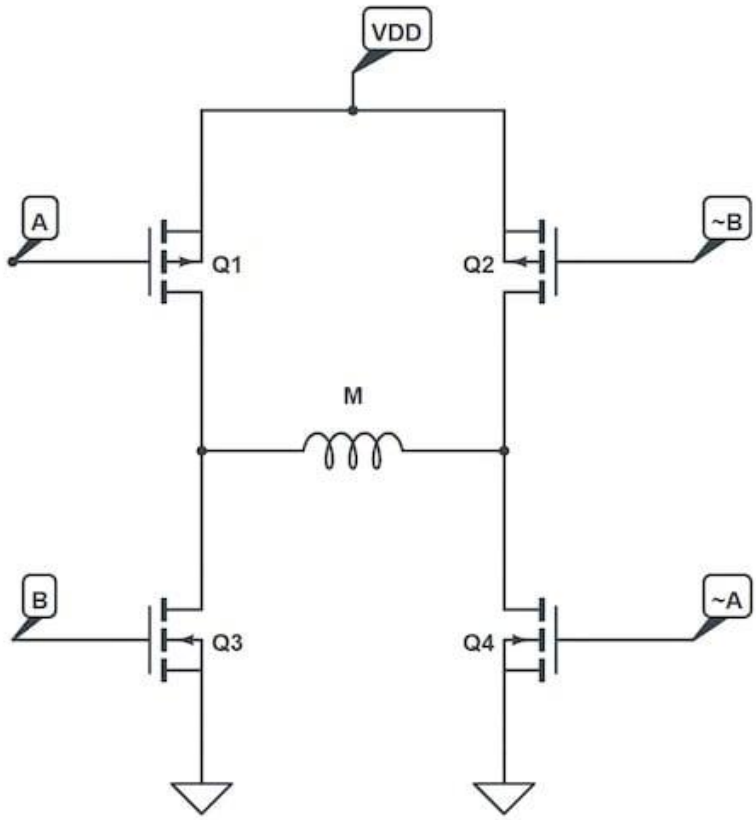
$$R_2 = 869.2\,k\Omega - 51.1\,k\Omega = 818.1\,k\Omega$$

## TASK 4

How can we control the rotation of the motor in both directions? One effective method is using an H-bridge, typically built with MOSFET transistors as shown in the diagram below.

Explain how the bridge operates, all possible conditions, and how to prevent motor control issues.

*Circuit:*

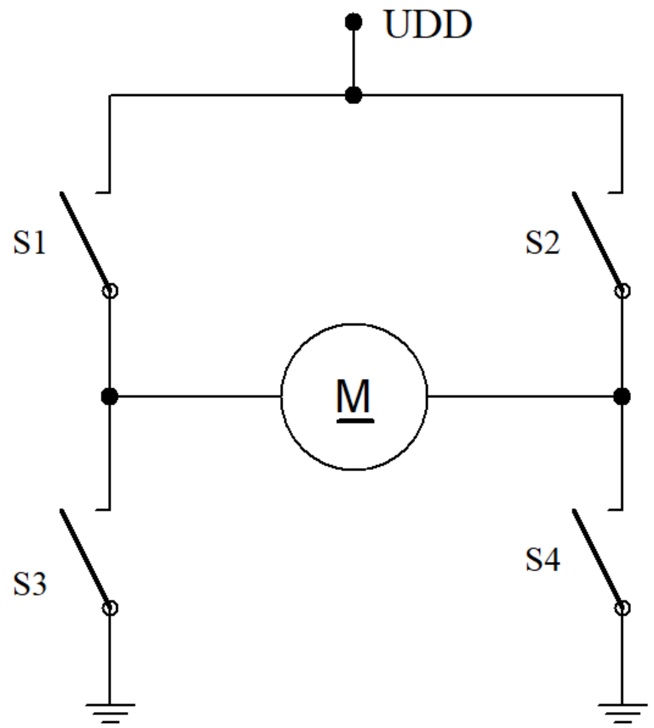



*Solution:*

In motors, there is often a need to rotate in both directions. Typical examples include raising and lowering garage doors, operating conveyor belts, electric vehicles, etc. The question arises of how to reverse the motor's direction. To find the answer, we start from the basics of motor operation. Applying voltage to the motor induces electric current. The current flows through the stator winding, establishing a magnetic field. The stator's magnetic field and the rotor's magnetic field create torque, which rotates the motor. The direction of rotation depends on the direction of torque, which is determined by the direction of the magnetic field lines (flux density). The direction of the magnetic field is influenced by the direction of the electric current through the stator winding. Therefore, to change the motor's direction of rotation, we need to change the current direction through the motor or swap the connections of the voltage source. Some options for implementing this functionality include:

- Relays: Change the voltage polarity with relays. This method is suitable for applications where speed and efficiency are not critical due to the mechanical switching speed of relays.
- Electronic speed controller (ESC): Circuit for controlling the speed, direction, and sometimes torque of brushless DC motors. It allows electronic switching and adjustment of phase voltages.
- Dual motor driver IC: Integrated circuit that controls motor direction, speed, braking, and provides protection against overcurrent and overheating.
- H-bridge: Configuration of four switches that allow electric current to flow through the motor in both directions.

H-bridge is one of the most common choices due to its advantages. It can be implemented with bipolar or FET transistors, with MOSFET transistors being popular for their fast switching capability (as fast as a few nanoseconds). MOSFET transistors have very high input impedance, making them suitable for voltage control.




From the simplified diagram, it is evident that to achieve the desired motor rotation or specific current direction through the motor, we need to close two of the four switches (transistors) and open the other two. For current flow from left to right, we close switches 1 and 4; for current flow from right to left, we close switches 2 and 3. The battery $U_{DD}$ provides the voltage across the switches, and activation or deactivation of transistors is controlled accordingly. Control signals are typically generated using microcontrollers (Arduino, ESP32, PIC, etc.), often involving PWM signals.

Using four transistors, each with two possible states (on or off), provides 16 possible combinations. For motor rotation in either direction, only two of these combinations are required, while the others can offer additional functionalities, potentially introducing complexities as well.

| S1 | S2 | S3 | S4 | function |
|---|---|---|---|---|
| 1 | 0 | 0 | 1 | forward motor rotation |
| 0 | 1 | 1 | 0 | backward motor rotation |
| 1 | 1 | 0 | 0 | braking |
| 0 | 0 | 1 | 1 | braking |
| 0 | 0 | 0 | 0 | free running |
| 1 | 0 | 0 | 0 | free running |
| 0 | 1 | 0 | 0 | free running |
| 0 | 0 | 1 | 0 | free running |
| 0 | 0 | 0 | 1 | free running |
| 1 | X | 1 | X | short circuit! |
| X | 1 | X | 1 | short circuit! |

Closing switches 1 and 2 while opening switches 3 and 4 shorts the motor terminals. Consequently, the voltage across the motor is 0V. However, due to inertia, the motor cannot immediately stop and continues to spin. The rotor windings still detect changes in the magnetic field, inducing a voltage in the windings that generates a current opposing the changes in the magnetic field. This state results in braking. A similar situation occurs when switches 3 and 4 are closed while switches 1 and 2 are open.

Another group of switch combinations occurs when only one switch is closed or none is closed out of the four. In this case, no current flows through the motor as no circuit is completed. The motor will slowly come to a stop due to friction in bearings, air resistance, etc.

A situation of high danger occurs when either switches 1 and 3, or switches 2 and 4, are closed simultaneously. This creates a direct connection from the voltage source to ground, resulting in a large current flow limited only by the resistance of the transistors. Since this resistance is low (from a few mΩ to at most a few Ω), the current can be very high and potentially damage the transistors. These switch combinations should be avoided.

## TASK 5

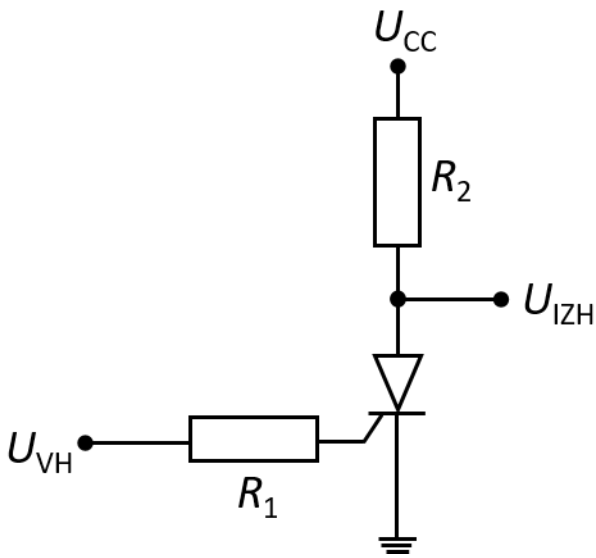
A **diode with a control electrode (*Silicon Controlled Rectifier, SCR*)** is used in the circuit in the picture. The triggering voltage of the diode $U_T$ is $0.7\ V$, the triggering current $I_T$ is $7\ mA$, and the holding current $I_H$ pa is $6\ mA$.

What is the output voltage $U_{OUT}$ when the diode is not conducting current?

What input voltage $U_{IN}$ initiates diode conduction?

If we reduce the voltage $U_{CC}$, at what value does the diode open?

*Circuit:*




*Data:*
$U_{CC} = 15\ V$
$R_1 = 1\ k\Omega$
$R_2 = 100\ \Omega$
$U_T = 0,7\ V$
$I_T = 7\ mA, \quad I_H = 6\ mA$

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$U_{OUT-OFF}, U_{IN-ON}, U_{CC-ON} = ?$

*Solution:*

A diode with a control electrode or a thyristor is a semiconductor device consisting of four layers of semiconductor (P-N-P-N), which creates three sequentially connected semiconductor junctions. Functionally, it resembles both a diode and a transistor. A thyristor has three terminals:

- anode: input terminal
- cathode: output terminal
- gate: control electrode

It is a unipolar device, meaning it can only conduct current in one direction (similar to a diode or an FET transistor). Unlike a diode, which acts solely as a rectifier, a thyristor can function as a rectifying diode or as an open switch.

A thyristor is controlled by current at the control electrode. This current must exceed the triggering current $I_T$. When a sufficient current is applied to the control electrode, the thyristor turns on (starts conducting current) and remains on even if the control electrode current decreases below the triggering level. In this sense, a thyristor can also be understood as a latching device. The current through the thyristor can only be interrupted in two ways:

- disconnecting the power supply
- reverse biasing the diode

For the second method, additional elements can be used to reduce the current through the thyristor's anode below the holding current or to ensure a higher voltage on the cathode than on the anode. However, a thyristor cannot be turned off by adjusting the current at the control electrode.

Thyristors have several significant advantages and limitations compared to other semiconductor devices used for control:

- they can control very high powers (high voltages, high currents).
- they have very low switching losses and thus high efficiency.
- the control signal needs to be applied only once and not continuously.
- they only conduct current in one direction.
- the switching speed is approximately one switch per one microsecond, making them suitable for low-frequency applications.

Thyristors are primarily used for

- controlling DC and AC motors
- welding
- battery charging
- UPS power supplies

- semiconductor relays

Let us calculate the required values. When the thyristor is closed, meaning it does not conduct current, the voltage across the thyristor is 0 V. Since no current flows through the thyristor, there is also no voltage drop across resistor $R_2$, so the voltage at the output is:

$$U_{OUT-OFF} = U_{CC} = 15\ V$$

To turn on the thyristor and start conducting current, we need to exceed the triggering level. In the borderline case when the thyristor just turns on, the voltage across it is 0.7 V. To achieve this, we must supply a current of 7 mA at the control terminal. This means the input voltage should be:

$$U_{IN-ON} = U_T + I_T R_1 = 0.7\ V + 0.007\ A\ \cdot 1000\ \Omega = 7.7\ V$$

The diode will be reverse biased if it is to be closed. This means the voltage at the cathode is higher than the voltage at the anode. Since the cathode is connected to ground, the only option is to set the battery voltage $U_{CC}$ to $U_{CC-ON} = 0\ V$ or disconnect the battery from the circuit.

## TASK 6

**An insulated-gate bipolar transistor (IGBT) i**s a power transistor employed as a switch in electric motor control systems.

To determine the total power losses for the circuit shown in the diagram, we need to consider the following components:

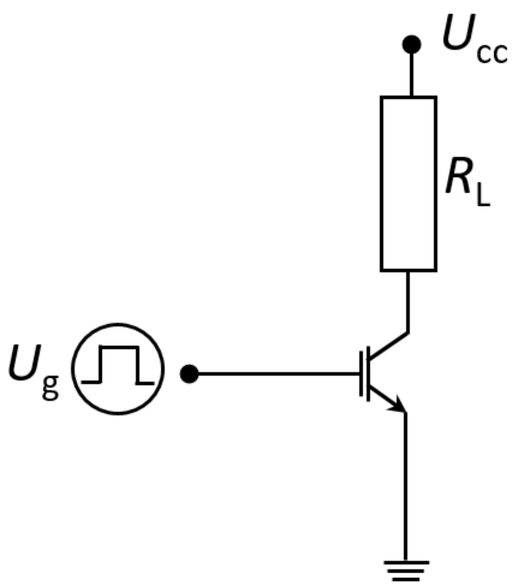
• turn-on losses,

• turn-off losses,

• resistive load losses.

We control the transistor using a PWM signal with a frequency of $f = 1\ kHz$ and a duty cycle of 0.7.

*Circuit:*




*Data:*

$U_{CC} = 200\ V$
$R_L = 10\ \Omega$
$U_{CE-sat} = 2\ V$
$t_{ON} = 3\ \mu s, \quad t_{OFF} = 1.2\ \mu s$
$f_S = 1\ kHz$
$\delta = 0.7$

---

$P_{ON}, P_{OFF}, P_{RL} = ?$

*Solution:*

An Insulated-Gate Bipolar Transistor (IGBT) is a semiconductor device combining the characteristics of a bipolar transistor and an n-channel MOSFET. It consists of four semiconductor layers and has three terminals. From this perspective, it resembles a thyristor but operates not as a rectifying diode but as a transistor. It is widely used as a switch in power applications.

The input stage of an IGBT is structured like an MOSFET transistor, giving it similar input characteristics:

- it is voltage-controlled
- it has high input impedance
- the input current is minimal
- it conducts current in only one direction

The output stage of an IGBT is structured like a bipolar transistor, providing it with similar output characteristics:

- it is used for controlling high powers (high voltages, large currents)
- it exhibits similar high switching losses

IGBT transistors allow for extremely high switching speeds (similar to MOSFETs), capable of transitioning between ON and OFF states every nanosecond. Therefore, they are highly suitable for high-frequency applications.

Typical applications of IGBT transistors include:

- high-power motor drives
- power inverters
- induction heating
- high-frequency welding
- solar inverters
- electric vehicle charging

In our task, we are interested in the losses in the switch. The IGBT transistor is treated as a real switch. For an ideal switch in the ON state:

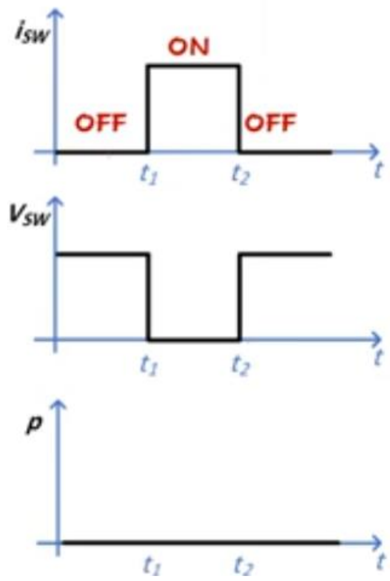
- the voltage drop across the switch is 0 V
- the electric current is maximum, theoretically up to $\infty$ A

In the OFF state:

- the electric current through the switch is 0 A

- the voltage drop across the switch is maximum according to the circuit, theoretically up to ∞ V

In an ideal switch, the transition between the closed and open states is infinitely fast. This means the switch switches between a state where the voltage across the switch is 0 V and a state where the current through the switch is 0 A. In both cases, the power dissipated in the switch (losses) is equal to 0 W.




Losses can be divided into three types:

- switching losses (turn-on losses)
- switching losses (turn-off losses)
- conduction losses

In real switches, transitions between the on and off states are not infinitely fast but rather take a few microseconds. This real-time transition is influenced by several factors:

- turn-on delay time: The time it takes for the voltage at the transistor's gate to exceed the threshold voltage ($U_{th}$ in the case of a MOSFET transistor).
- rise or fall time of current or voltage: This refers to the time it takes for the current or voltage to rise or fall, which is related to the effective width of the base connection.
- saturation time: This is the time required for the transistor to transition into its linear region from saturation.

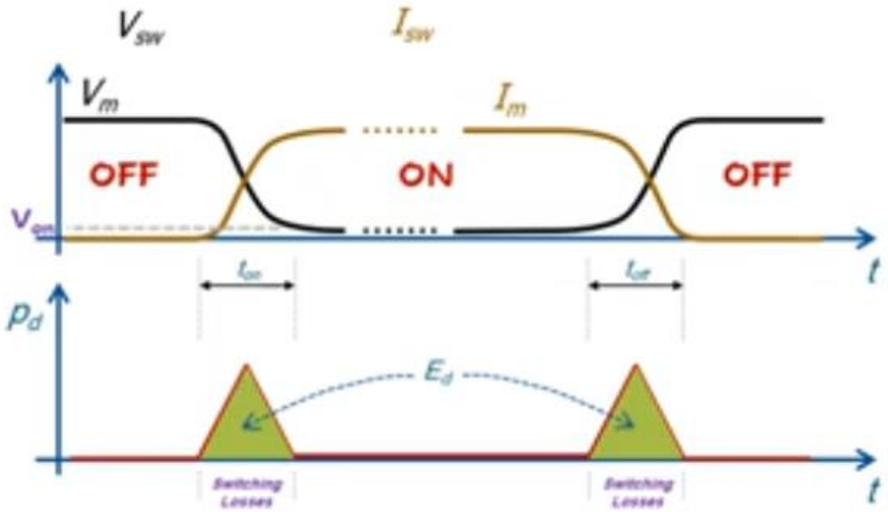
Combining all these factors that affect the transition time, we define:

- $t_{ON}$: the transition time of the switch from OFF to ON

- $t_{OFF}$: the transition time of the switch from ON to OFF

The time-varying signal of voltage or current during the switch transition has an approximately sigmoidal shape (S function), but for simplicity in calculating losses, we approximate it as a linear function.

In a real switch, when it is ON, the voltage is not 0 V but rather a saturation voltage $U_{CE-sat}$ on the output side of the bipolar transistor. Recall that a bipolar transistor is in saturation mode when it is in the closed switch state. The electric current through a real switch is limited by the characteristics of the transistor. When the switch is open, the voltage across the transistor is limited, and the current through the transistor is not exactly 0 A but rather a small leakage current flows through it. Regarding power consumption or losses on a real switch, we can assume that the leakage current is so small that no power is consumed on the switch when it is open.




As evident from the above figure, for simplification in calculating the transition between the closed and open states of the switch, we approximate it with a linear form. Consequently, the graph for the power consumption over time exhibits two segments in a triangle and one segment with a constant value.

Let us derive the equation for power losses during the switch transitions. When the switch toggles from the OFF state to the ON state, the voltage across the switch follows this form:

$$u(t) = U_{max} - \frac{U_{max}}{t_{ON}} t$$

where $U_{max}$ is the maximum voltage across the switch (transistor), in our case, it is the supply voltage $U_{CC}$.

$$U_{max} = U_{CC} = 200\ V$$

The current through the switch during the transition from the OFF to ON state follows this form:

$$i(t) = \frac{I_{max}}{t_{ON}} t$$

where $I_{max}$ is the maximum possible current through the transistor, determined as

$$I_{max} = \frac{U_{max} - U_{CE-sat}}{R_L} = 19.8\ A$$

The power consumption profile on the switch during the transition from the OFF state to the ON state is thus:

$$p(t) = u(t)i(t) = U_{max} \cdot I_{max}(\frac{t}{t_{ON}} - \frac{t^2}{t_{ON}^2})$$

To determine the average power loss, we would integrate the above equation and normalize it to one period of the input PWM signal. This gives us the result:

$$P_{avg-ON} = \frac{U_{max} \cdot I_{max} \cdot t_{ON} \cdot f_s}{6} = 1.98\ W$$

For the transition of the switch from the ON state to the OFF state, the derivation would be quite similar. The simplified form of the power function over time is also triangular in this case; hence the result differs only in the different transition time $t_{OFF}$. The average power loss during the transition of the switch from the ON state to the OFF state is thus:

$$P_{avg-OFF} = \frac{U_{max} \cdot I_{max} \cdot t_{OFF} \cdot f_s}{6} = 0.79\ W$$

Let us determine the average power consumed by the switch when it is closed. During this time, the transistor is open and conducting current, with a saturation voltage across it. The magnitude of the current through the switch is determined by the resistor $R_L$, and we must consider the duty cycle of the PWM signal. The average voltage across resistor $R_L$ is:

$$U_{avg} = (U_{CC} - U_{CE-sat})\delta = 138.6\ V$$

The average current through resistor $R_L$ and simultaneously through the switch (transistor) is:

$$I_{avg} = \frac{U_{avg}}{R_L} = 13.86\ A$$

The average power on the switch when it is closed is therefore:

$$P_{avg-cond} = I_{avg} \cdot U_{CE-sat} = 27.78\ W$$