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Maciej Pawłowski

ALTERNATIVE DRIVE SYSTEMS

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1. INTRODUCTION

The automobile's electrical consumption has grown year by year. Coinciding with the establishment of the 12 V battery as a supply standard in order to satisfy the increasing exigencies of comfort and security. An aspect to consider in the historical evolution of the automobile is the minimal penetration of the power electronics in the automobile field until a few years ago. However, in the immediate future a massive presence of power electronic in the automobile is an fact.

There are two aspects what will be important in the very near future. One of the axes of change is increase a electrical consumption to be able to elevate the level of comfort and security. Another point of improvement is the diminution of fuel consumption per kilometer. It is necessary to say that very important inherent problem is and will be fact that conventional system of supply in automobile is the battery between 8 V and 16 V. However for the future solutions this level must be changed.

Conventional gasoline-and diesel fuel internal combustion engines will remain practical over the long term especially with anticipated enhancements and future innovations. Even with all of the innovations it will not be possible to reach emissions regulated targets without further improvements to fuel economy. The hybrid electrical power train (Hybrid Electrical Vehicle HEV) is now accepted as the low cost near-term solution. Hybridization provides the following power train features [1]:

- Idle stop
- Torque augmentation
- Regenerative braking

A hybrid electric vehicle (HEV) has two types of energy storage units, electricity and fuel. Electricity means that a battery (sometimes assisted by ultracaps) is used to store the energy, and that an electromotor (from now on called motor) will be used as traction motor. Fuel means that a tank is required, and that an Internal Combustion Engine (ICE, from now on called engine) is used to generate mechanical power, *or* that a fuel cell will be used to convert fuel to electrical energy. In our case the vehicle will have both an engine and a motor as mechanical power source. Depending on the drive train structure (how motor and engine are connected), we can distinguish between parallel, series or combined HEVs. Depending on the share of the electromotor to the traction power, we can distinguish between mild (=micro) hybrid, power assist hybrid and strong (=full) hybrid. Depending on the nature of the non-electric energy source, we can distinguish between combustion (ICE), fuel cell, hydraulic or pneumatic power, and human power.

Series hybrid system, the combustion engine drives an electric generator (usually a three-phase alternator plus rectifier) instead of directly driving the wheels. The electric motor is the only means of providing power to the wheels [1],[29],[35]. The generator both charges a battery and powers an electric motor that moves the vehicle. When large amounts of power are required, the motor draws electricity from both the batteries and the generator. To say again the series hybrid architecture has yet to catch on gasoline or diesel electric power plants. Certainly, the fuel cell hybrid is a series hybrid architecture, but for now focus on the more conventional vehicles [1],[29],[35].

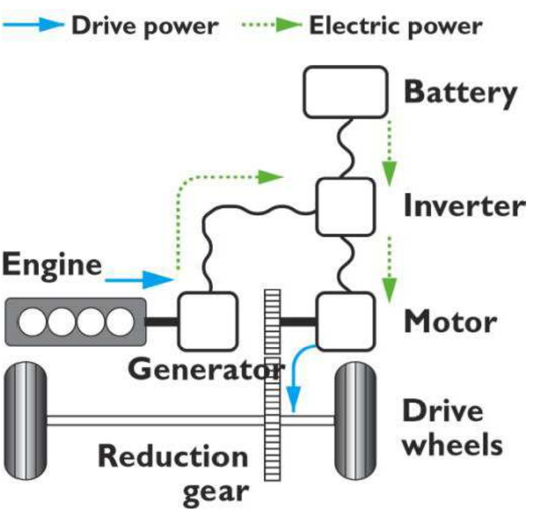


Figure1 .1. Structure of a series hybrid vehicle [1],[8],[29],[35].

Series architecture means that power from the heat engine is delivered via an electric-only transmission path to the driven wheels. Some vehicle designs have separate electric motors for each wheel.

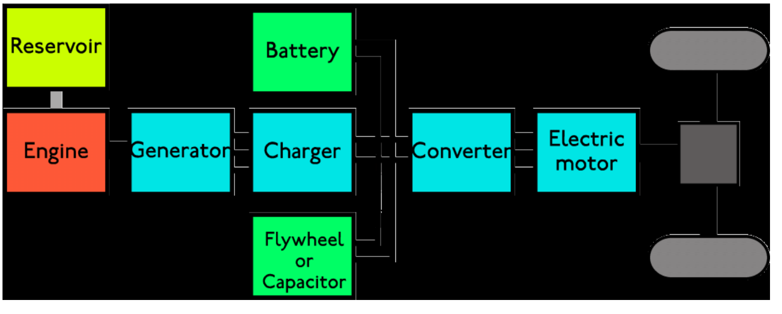


Figure 1.2. Structure of a series hybrid vehicle with flywheel or ultracaps as peak power unit [1],[8],[29],[35].

A fuel cell hybrid electric always has a series configuration: the engine-generator combination is replaced by a fuel cell. In the figure 1.3 this schematic structure is given.

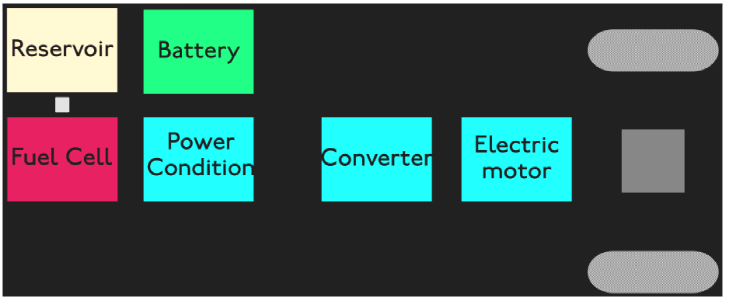


Figure 1.3. Structure of a fuel cell hybrid electric vehicle [1],[8],[29],[35].

Parallel configuration have most common hybrid propulsion shown schematically in figure 1.4.

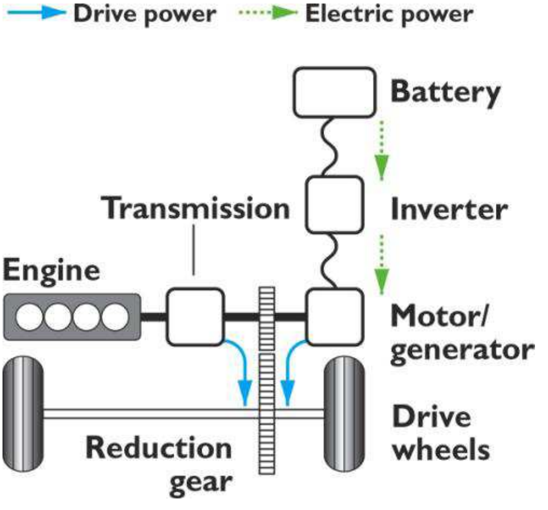


Figure 1.4. Structure of a parallel hybrid electric vehicle [1],[8],[29],[35].

In this configuration the motor is added to the existing power train in either a side –mounted or in-line package. Side –mounted motor configuration are known as belt-ISGs, for Integrated Starter Generators. This is the most economical of the hybridization approach [1],[29],[35].

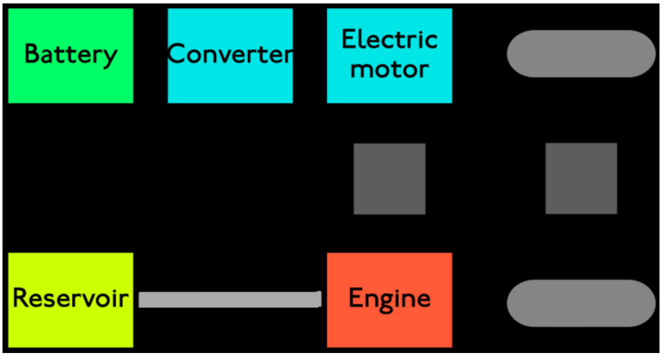


Figure 1.5. Parallel hybrid electric vehicle [1],[8],[29],[35].

In fact parallel hybrid systems have both an internal combustion engine (ICE) and an electric motor in parallel connected to a mechanical transmission. The parallel hybrid architecture is widely used because the vehicle propulsion architecture is not that different from a conventional vehicle. In this case most designs combine a large electrical generator and a motor into one unit, often located between the combustion engine and the transmission, replacing both the conventional starter motor and the alternator. Sometimes, an extra generator is used to charge the battery, but this give an increased weight and price to the HEV. [1],[29],[35].

The combination of parallel and series hybrid architectures into a single package is quickly becoming the standard in passenger vehicle hybridization. In the figure 1.6 is shown the structure of combination architecture.

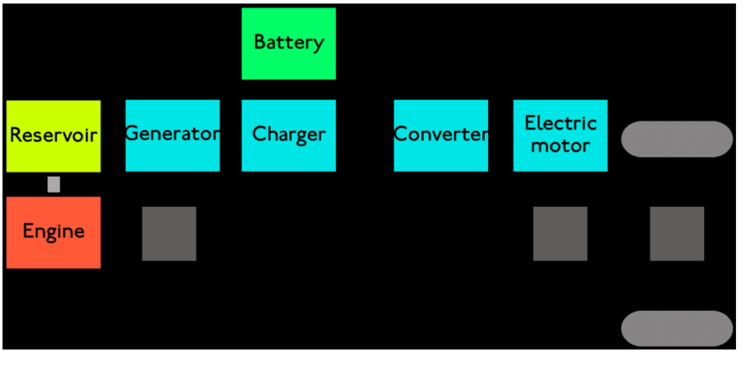


Figure 1.6. Simplified structure of a combined hybrid electric vehicle [1],[8],[29],[35].

In the consequence of upper description we should say that to explain of modern alternative drives is necessary to present :

1.Sources of electrical energy in automobile
- Batteries
- Ultracapacitors

2.Power electronics
- Elements
- Rectifiers (convertere AC-DC)
- Choppers (converters DC-DC)
- Inverters (converters AC-DC-AC)

3.Electrical machines
- Conventional (DC,AC motors)
- Brushless (BLDC,PWSM)

4.Implementation.

2. SOURCES OF ELECTRICAL ENERGY IN AUTOMOBILE

2.1. Batteries

The batteries are base of sources of electrical energy in conventional, but in modern automobiles also. In electrical vehicles specially ,but also in hybrid vehicles it is the main source of electrical power. The larges hurdle holding back battery-powered electric vehicle commercialization is the battery [1]. Batteries typically account for one third of vehicle weight and one fourth of life-cycle cost of EVs. Major improvements in batteries are expected because we can say little effort has been put into designing and building batteries of size needed for vehicles. Electrical energy storage is an essential component of Electrical Vehicles (EVs), but it is still the weakest component. Although a few electric cars with advanced batteries have been introduced, no current battery technology has demonstrated an economically acceptable combination of power, energy efficiency, and life cycle for high-volume production [1],[16],[17], [18].

Energy density: the amount of energy that can be stored in one kg of battery (Wh/kg)

Power density: the amount of power that one kg of battery can deliver on demand (W/kg).

Specific energy: the amount of energy that can be stored in one volume-unit of battery (Wh/m3)

Specific power: the amount of power that one volume-unit of battery can deliver on demand (W/m3).

Charge / Discharge efficiency**:** As the chemical reactions cause dissipative losses, the electrical energy provided to a load is of course less than the energy consumed at the charging process. The rate of available energy in relation to the energy delivered by the charger is called Charge/Discharge efficiency. Another name often used is coulombic efficiency or cell efficiency.

Capacity C**:** the rated (nominal) capacity = charge a new battery can deliver, expressed in Ah or mAh, for a given total discharge time. Thus batteries are usually specified at an "hour" rate, for instance 100Ah at 20 hours, or 90Ah at 10 hours.

State of Charge (SOC): The actual available battery capacity = charge expressed as a percentage of its rated (nominal) capacity. Knowing the amount of energy left in a battery compared with the energy it had when it was new gives the user an indication of how much longer a battery will continue to perform before it needs recharging. Using the analogy of a fuel tank in a car, SOC estimation is often called the "Gas Gauge" or "Fuel Gauge" function.

Discharge Curves: Graphs of the cell voltage as function of the delivered charge (which is often expressed in terms of the Capacity C). Parameter is the level of the discharge current. This current is often also expressed as a factor of C (where C is expressed in Ah).

Depth of discharge (DOD): The delivered charge expressed as a percentage of its max. charge (fully loaded in the actual state, not in the new state).

State of Health (SOH): There is no absolute definition of the SOH. The SOH reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery. It is a subjective measure in that different people derive it from a variety of different measurable battery performance parameters which they interpret according to their own set of rules. It is an estimation rather than a measurement. Battery manufacturers do not specify the SOH because they only supply new batteries. The SOH only applies to batteries after they have started their ageing process either on the shelf or once they have entered service.

Cycle life: The cycle life is defined as the number of full charge - full discharge cycles a cell can perform before its capacity drops to 80% of its specified capacity.

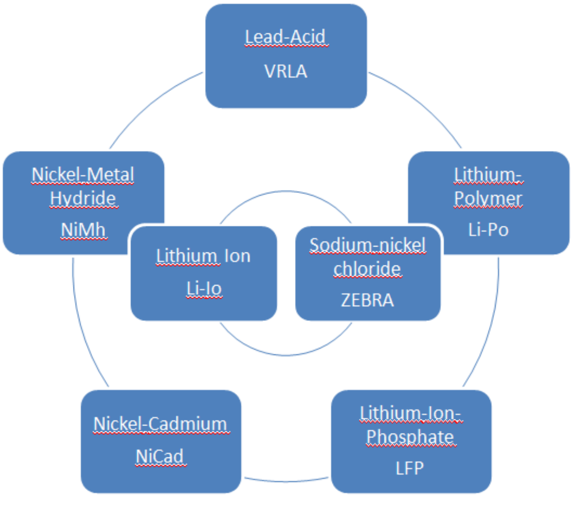


Figure 2.1.1.The main properties of these batteries.

Most of the batteries used today are Lead-Acid type. However we are using in the last years different types also. In the figure 2.1.1 is shown another types rechargeable batteries. The differences between types of batteries are not in construction only, but in number of cycles, time of charges, voltages, time and conditions of discharging etc. More technical data we can find in the internet (e.g. Wikipedia) or descriptions of battery producers [36],[37].

Each batteries have some electrical value what are not the parameters given by producers, but are necessary to switch another equipment to the batteries. In fact this is the electrical model of batteries [1],[16],[17], [18].

1. R_m is the resistance of the metallic path through the cell including the terminals, electrodes and inter-connections.
2. R_a is the resistance of the electrochemical path including the electrolyte and the separator.
3. C_b is the capacitance of the parallel plates which form the electrodes of the cell.
4. R_i is the non-linear contact resistance between the plate or electrode and the electrolyte.

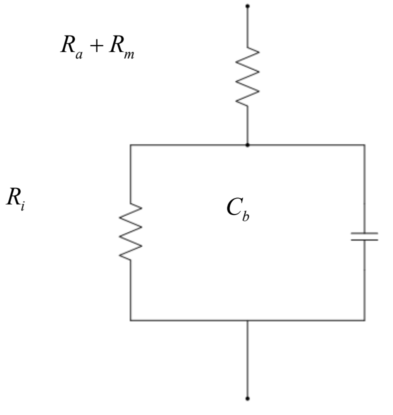


Figure 2.1.2. The equivalent circuit for an energy cell [1],[36],[37].

Generally it can be said that all of resistances of the batteries are internal resistance of batteries. This resistance is very important parameter because it is responsible for all losses of electrical power. The internal resistance is decreasing as the temperature rises due to the increase in electron mobility.

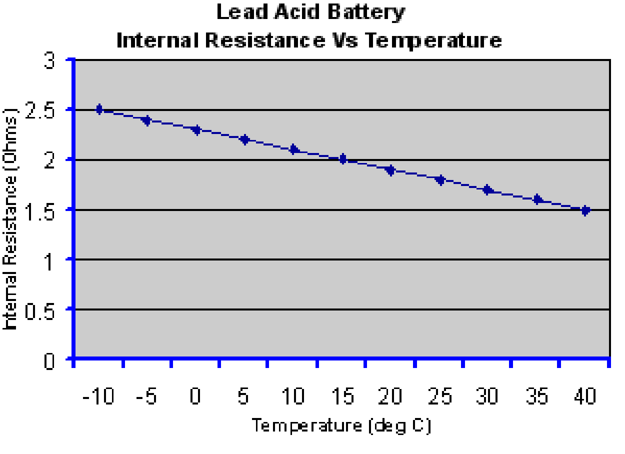
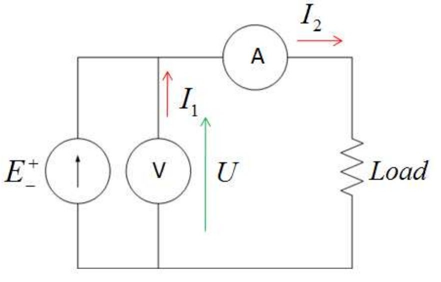


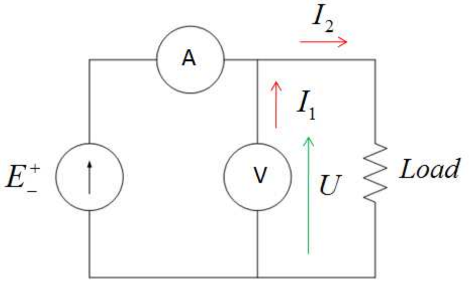
Figure 2.1.3.The influence of temperature on internal resistance of battery[1],[8],[36],[37]. .

The low temperatures improves the lower internal impedance, but also to the increased rate of the chemical reactions. However the lower internal resistance unfortunately also causes the self discharge rate to increase. Furthermore, cycle life deteriorates at high temperatures.

Knowing the internal resistance is a reliable measure of its ability to deliver current. A simple measurement with an ohmmeter is not possible because the current generated by the cell itself interferes with the measurement. To determine the internal resistance, first it is necessary to measure the open circuit voltage of the cell. This case is presented on the figure 2.14.



Accurate measurement of current value



Accurate measurement of voltage value

Figure 2.1.3.The methodology of measuring of internal resistance of batteries.

The internal resistance reduces the effective capacity of a cell: the higher the internal resistance means the higher the losses while charging and discharging, especially at higher currents. This means that a high discharge rate lowers the effective available capacity of the cell. This is called the capacity offset. The discharge rate is the voltage drop as function of the delivered capacity or charge [1],[16],[17], [18].

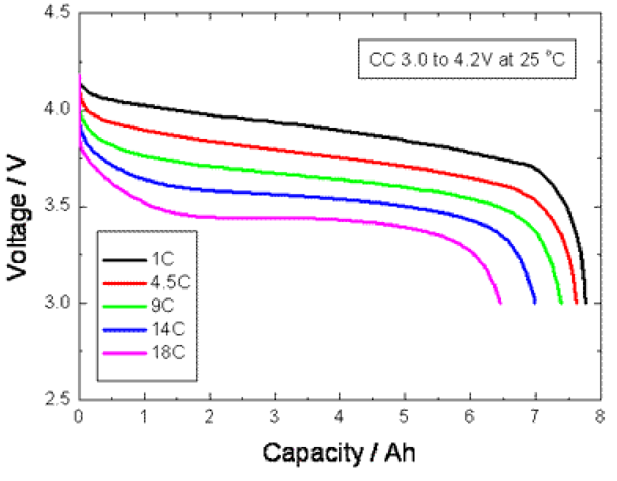


Figure 2.1.4.Discharge curves for a Lithium-ion cell for different temperatures [1],[8],[36],[37].

In the figure 2.1.4 are shown curves of discharge of battery for different temperatures [1],[36],[37] .

In the end it is necessary to say shortly about cell protection. The purpose of cell protection is to provide the necessary monitoring and control to protect the cells from out of tolerance ambient or operating conditions. It must also protect the user from the consequences of battery failures, and isolate the battery from the system. The main points of cell protection are [1],[16],[17], [18]:

1. Excessive current during charging or discharging
2. Over voltage-overcharging
3. Under voltage
4. Short circuit current
5. Overheating
6. Pressure build up inside the cell

2.2. Ultracapacitors

Ultracapacitors behave like very high-power, low-capacity batteries but store electric energy by accumulating and separating unlike-charges physically, as opposed to batteries, which store energy chemically in reversible chemical reaction. The fact that ultracapacitors can provide high power for acceleration and can accept high power during regenerative braking makes them ideally suited for the load leveling required in a hybrid electric vehicle [1],[8]. Conventional capacitors can store energy as well, but their volume increases spectacularly if they must compete with a battery. With the ultracap or supercap, a new generation of capacitors is emerging. They are electrochemical systems that store energy in a polarized liquid layer at the interface between an ionically conducting electrolyte and a conducting electrode. This component can deliver and take back energy in a very short period of time, and can repeat this cycle a million times. This capacitor keeps on functioning, when batteries would have died after some hundreds of cycles [1],[8].

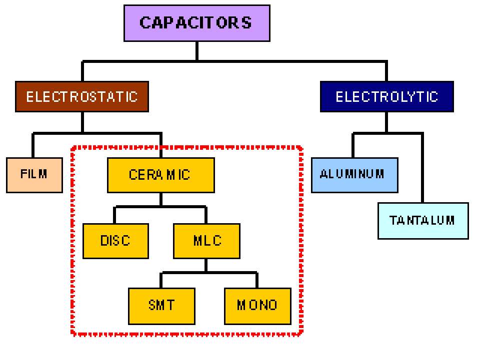
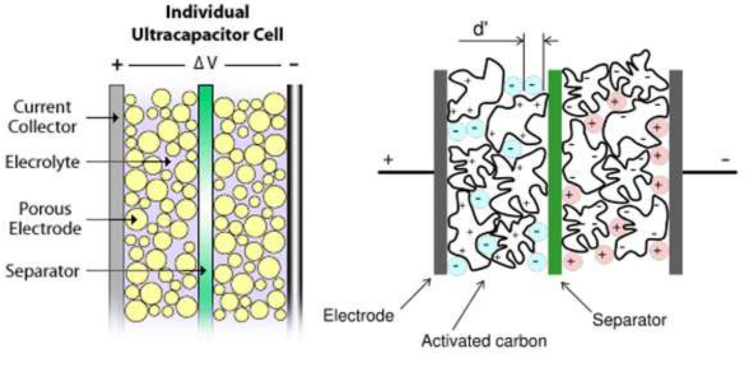


Figure 2.2.1Classification of conventional capacitors [8],[19],[20].

Electronic **D**ouble **L**ayer **C**apacitor (EDLC) represent a particular subclasses of electrolytic. The EDLC effect is shown in the figure 2.2.2 and is focused on asset of carbon electrodes in a nonaqueous solvent. The capacitance value in a EDLC system is depend on the surface properties of the activated carbon used for electrodes in terms of specific area. Adding to the capacitance value is the electrolyte's ionic accessibility to all pores available in the activated carbon and to the electrolyte properties themselves.



THE ULTRACAP=supercap=Electrochemical Double Layer Capacitor EDLC

Figure 2.2.2.Ultracap simplified (left) and realistic (right) cutaway [8],[19],[20].

To make a summary the functioning of the ultracapacitor is based on the Electrochemical Double Layer principle. An ultracap consists of two electrodes, which are immersed into a common electrolyte, and a perforated separator that prevents physical contact between the electrodes, but allows ion transfer between them. The best way to realize high capacitance is to use activated carbon as the electrode material [38],[39],[40].An ultracap (Electrochemical Double Layer Capacitor) contains two capacitors in series.

In the figure 2.2.3 is shown comparison between an ultracap and a conventional capacitor. Like an ELCO, an ultracapacitor relies on an electrostatic effect, purely physical and highly reversible. Charge and discharge performs upon movement of ions within the electrolyte. There are no chemical reactions like in a battery. We can say that an electrostatic capacitor has a constant field; an ELCO also has a linear voltage drop over the oxide; an ultracap is built with several layers.

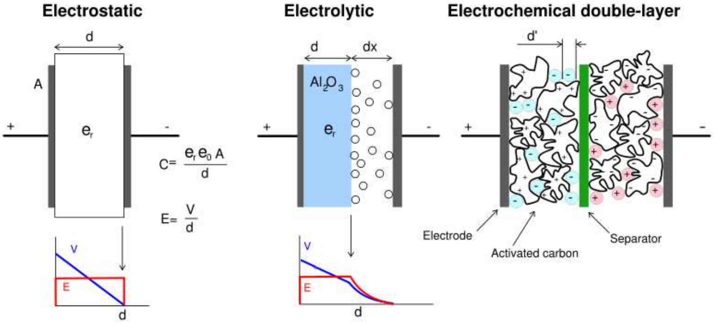


Figure 2.2.3.Conventional capacitor (left),ELCO (middle),and Ultracap (right) [8],[19],[20].

In the figure 2.2.4 is presented a equivalent circuit of an ultracap. If we agreed that [8]:

R_{cel} :ESR,equivalent series resistor
$C = C_{cel}$:Ultracap-capacity
C_{dl} :Capacity of one layer
R_F :Leak resistance of the ultracap
$\varepsilon, \varepsilon_0$:coefficient of electrical penetration
A : electrode surface
$R_{rxn1...}$:equivalent resistance of one layer

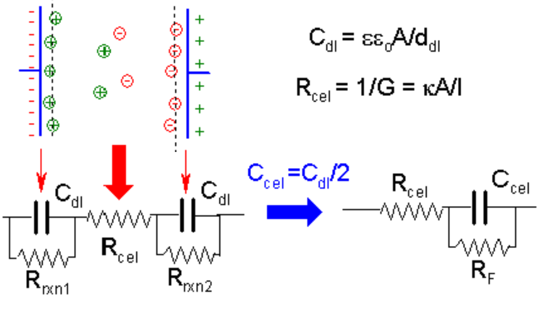


Figure 2.2.4. Ultracapacitor equivalent circuit [1],[8].

In the summary it can be said (figure 2.2.3) that the great difference with a conventional capacitor is the extremely high electrode surface (A), which is the surface area of the activated carbon, and the extremely small dielectric thickness (d), which is the diameter of one electrolyte ion. Very interested is comparison between ultracaps and batteries what is given in table 2.2.1.

Table 2.2.1. Comparison between a capacitor, ultracap and lead acid battery

	Electrostatic capacitor	**Ultracapacitor**	**Lead-acid battery**
Discharge time	10-6 to 10-3 s	1 to 30 s	0,3 to 3 hrs
Charge time	10-6 to 10-3 s	1 to 30 s	1 to 5 hrs
Energy Density Wh/kg	less 0,1	1 to 10	20 to 100
Power Density W/kg	less 10000	10000	50 to 200
Charge /Discharge Efficiency	Ca. 1	Ca.1	0,7 to 0,85
Cycle life	infinite	more 500000	500 to 2000

Ultracapacitors are supplying circuits with power electronic converters different types and electrical machines conventional and brushless. It means that very important process to discus is cell balancing. Voltage distribution in a series stack of ultracaps is initially a function of capacitance: initial charge and initial voltage will depend on the capacitance of each cell. But after the stack has been held at voltage for a period of time, voltage distribution then becomes a function of internal parallel resistance: the sustained voltage will depend on the leakage currents of each cell. This is because each cell conducts the same current, and the voltage is the product of current and capacitance. The average voltage will still be 2.5 volts (50 volts /20 cells).

In the figure 2.2.5 is given process of charge and discharge of ultracap with two cells [1],[8].

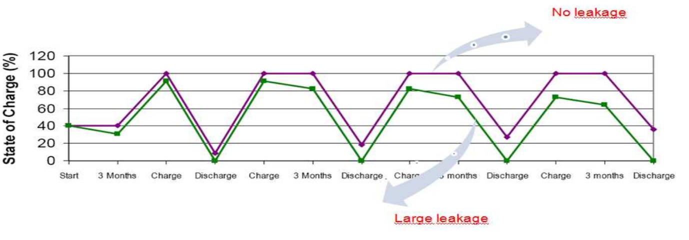


Figure 2.2.5.Capacitor pack with two cells [1],[8],[19],[20].

Constant charging current is stopped when one of the cells has reached 100% state of charge , than discharging is stopped when the U_C -voltage is zero. Each cell are discharges through an internal “parallel resistance”. This leakage current has the effect of self-discharging the cell.

After some time the voltages on the individual cells will vary based on the differences in leakage current, rather than on the differences in capacitance value. The cell to cell voltage should be balanced (made equal). If no, after several charge cycles, a large unbalance can occur between cells: initially equally charged cells gradually diverse to contain different amounts of charge. In the figure 2.2.6 is shown process of charging and discharging two cells ultracap applying a high current to cell 2 provide full capacity for cell 2 .

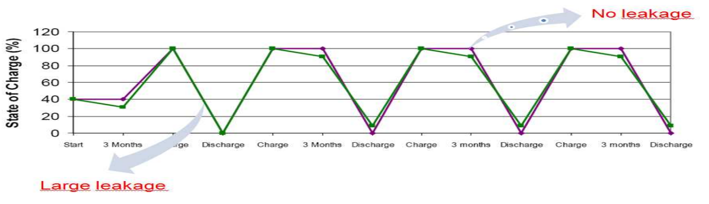


Figure 2.2.6.Capacitor pack with two cells with high current [1],[8],[19],[20].

That are several methods of balancing using by different ultracap producers. For the work of ultracap without any problems it have to be solved with save and accuracy ,because charging and discharging process take place many times it can be said to the end of using of automobile. In the figure 2.2.7 are given most important methods of techniques of balancing.

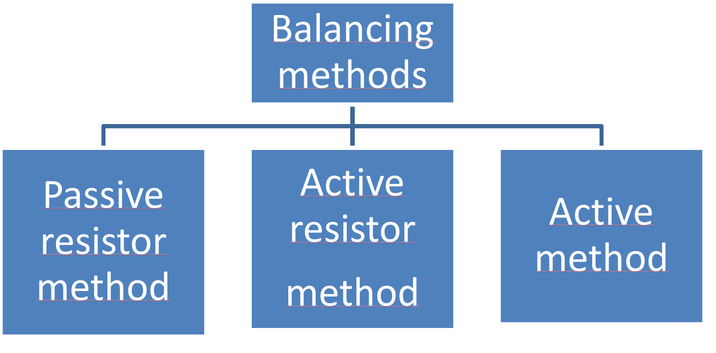


Figure 2.2.7.Methods of balancing of ultracap.

Passive resistor method [8]:

A simple technique to compensate for variations in leakage current is to place a bypass resistor in parallel with each cell, sized to dominate the total cell leakage current. This effectively reduces the variation of equivalent parallel resistance between the cells.

Active resistor method [8]

An individual cells are monitored to allow active cell balancing. When cell-to-cell voltages variations are larger than fixed limits (e.g. whenever the cell voltage is above or equal to 2.73 volts), a balancing routine will gradually match the voltages of the cells. Typical a power semiconductor and a resistor are used to shunt the cells.

Active method [8]:

An even better solution is a balancing circuit that redistributes charges, without dissipation. Ideally, charges are transported from the weakest cells to the strongest cells. In the following circuit, balancing is done by applying a voltage pulse train to each cell. The current will depend on the cell voltage.

Finally is necessary to describe process of charging of ultracap. Ultracaps rely on an electrostatic effect, which is purely physical and highly reversible. Charge and discharge occurs upon movement of ions within the electrolyte. This mode of energy storage is in contrast to all battery technologies, since they are based on the formation and dissolution of chemical compounds on the battery electrodes (Faraday reactions). In comparison it is not necessary to reach a certain state of charge (output voltage) in order to use an ultracap [1],[8].

The ultracap characteristics show a simple linear relationship between voltage level and charging condition what is given in figure 2.2.8.

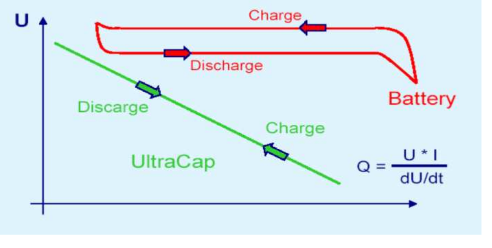


Figure 2.2.8. Charging and discharging curves of Battery and Ultracap [1],[8].

3. POWER ELECTRONICS

3.1. Semiconductors

Power electronic components include all power converters and PCUs. These components control power flows between the power sources (described in chapter 2), loads and power buses according to control of the PMC. For understanding of this chapter is necessary to have basic knowledge about semiconductors. In the figure 3.1.1 are given the basic types of different semiconductors.

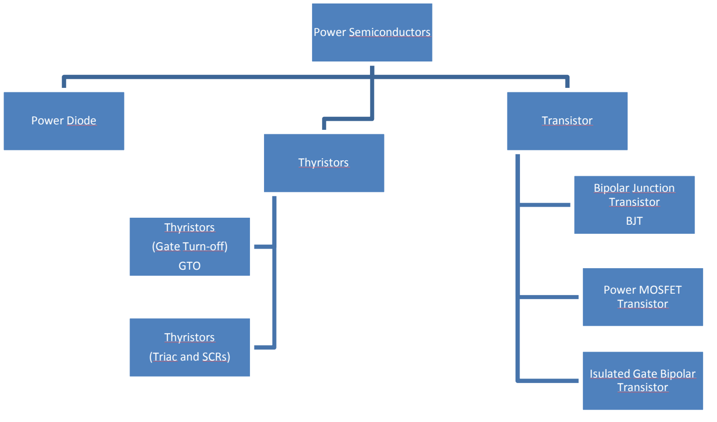


Figure 3.1.1.The semiconductors typically used in power electronics.

Currently, the main types of power semiconductors are: the Power Diode (PD), the power Bipolar JunctionTransistor (BJT), the Thyristor (Triacs and SCRs), the Gate Turn-off Thyristor (GTO), the Power MOSFET, and the Insulated Gate Bipolar Transistor (IGBT).An ideal power semiconductor switch should have following characteristics:

1. Block large forward and reverse voltages in off mode
2. Conduct large current in on mode
3. Switch between on and off instantaneously without incurring switching losses
4. Easy control
5. Rugged and reliable
6. Low loss power during switching
7. Low cost

Short describing of some semiconductors will be done with this criteria.

Power diodes

Diodes are the simplest semiconductor device. Diodes are used in application that require current to flow in one direction only. The characteristic of power diode is presented in figure 3.1.2.

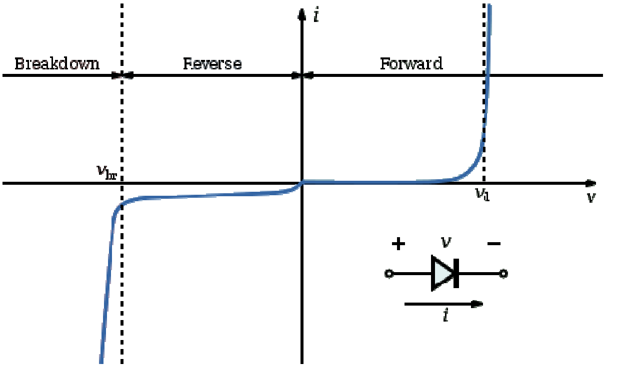


Figure 3.1.2.The characteristics of a P-N junction diode (not to scale) [3],[5],[8].

In automotive applications , diodes are mainly used to perform the following functions:

1. Rectify AC current from alternator to DC also to charge batteries.
2. Allow load current freewiling as anti-parallel diodes for IGBTs or MOSFET.
3. Suppress voltage transient when being reverse biased.

Very important processes are dynamic behavior of semiconductors specially under the switch off process. There is a reverse diode current flowing, until the minority carriers have vanished. The duration of this reverse current is called reverse recovery time t_{rr} . It is usually between 0,1 and 10 µs. Only after this time, when all minority carriers have disappeared, the diode blocks with a high current slope. Thus stray inductances can produce overvoltage In the figure 3.1.3 is shown this process [21],[22],[23].

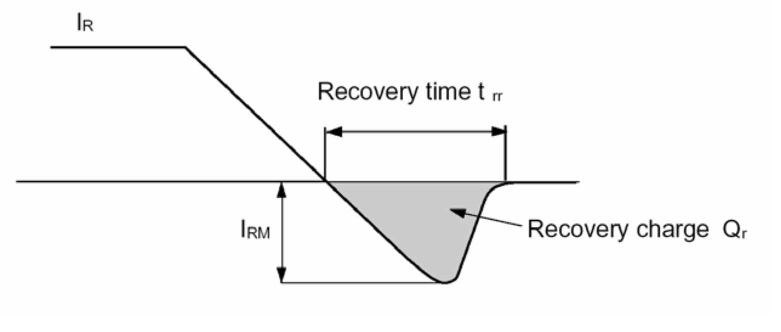


Figure 3.1.3.Current during blocking of a power diode [3],[5],[8].

Recovery time t_{rr} is very important parameter because it determines the frequency of switching diodes in electrical circuits.

That are many different types of diode sometimes used in automotive ,but it will be not describes here. In the figure 3.1.4. is given symbols and names of the most popular diodes.

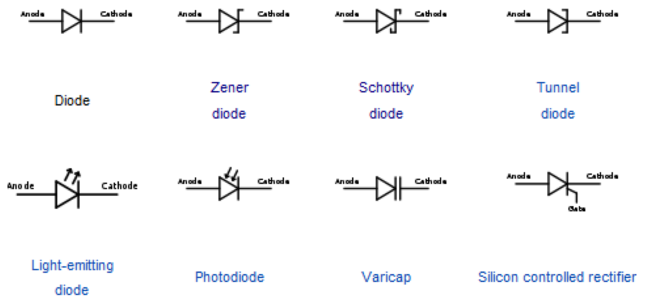


Figure 3.1.3. The symbols and names of most popular diodes.

Bipolar Junction Transistor (BJT)

A bipolar (junction) transistor (BJT) is a three-terminal electronic device constructed of doped semiconductor material and may be used in amplifying or switching applications. Bipolar transistors are so named because their operation involves both electrons and holes. In the figure 3.2.4. is presented output characteristic of BJT.

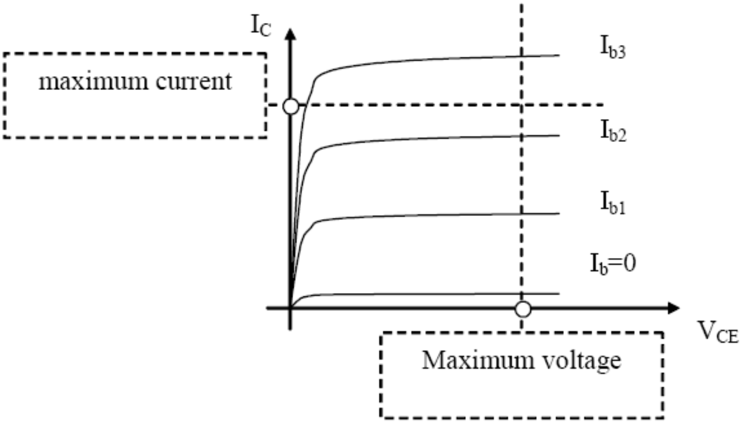


Figure 3.1.4.Output characteristic of a BJT [3],[5],[8].

The process of amplifying is good presented with very low base current value control high current of collector. It is necessary to control the temperature of BJT because of a breakdown hazard in some cases. So for save of BJT it has to work in triangle I_C - V_{CE} - I_{CEO} what is indicated in figure 3.1.5.

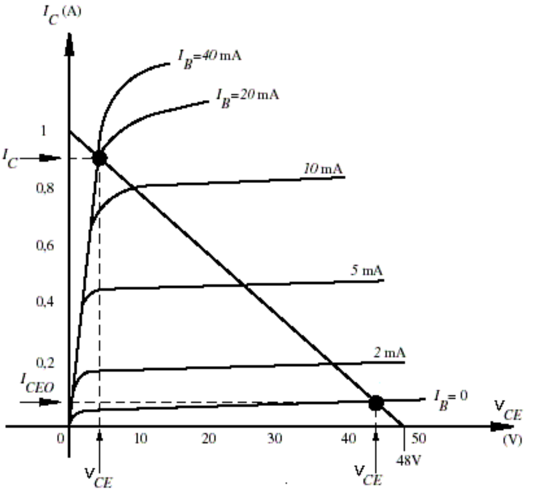


Figure 3.1.5.Output characteristic of a BJT with triangle of save power [3],[5],[8].

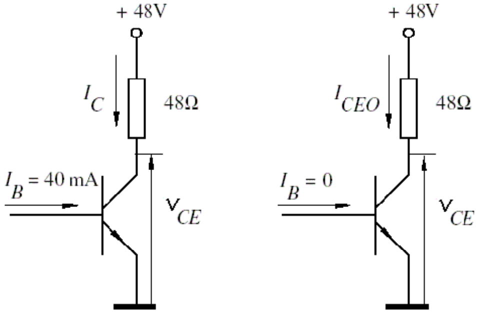


Figure 3.1.6. BJT switched on (left) and switched off (right)

Metal Oxyde Semiconductor Field Effect Transistor (MOSFET)

Presently in the applications with a voltage rating below 200V , power MOSFETs are the device of choice and have replaced traditional power bipolar junction transistor BJT, because of their low on-state resistance, high switching speed, easy control, and superior safe operating area. In the figure 3.1.7 is presented structure and symbols of it [3],[5],[8].

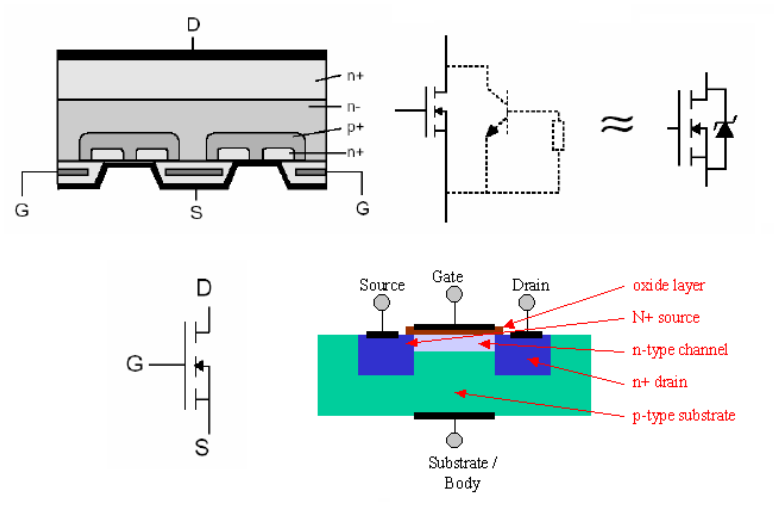


Figure 3.1.7. Simplified structure and circuit symbols of a n-channel MOSFET[3],[5],[8].

A MOSFET is a unipolar transistor. Current flows under the influence of the gate voltage; the current cannot be limited by a "gain phenomenon", which was the case in the BJT. There are two MOSFET types: n-channel and p-channel. It can be said a power MOSFET is a tree-terminal device where the gate controls the main current flow between the two output terminals: drain and source. The source terminal is usually common to the gate and drain terminals. Power MOSFET output characteristics, that is , the drain current i_D as the function of drain-to-source voltage V_{DS} with gate-to-source voltage V_{GS} as a parameter , are shown in figure 3.1.8.

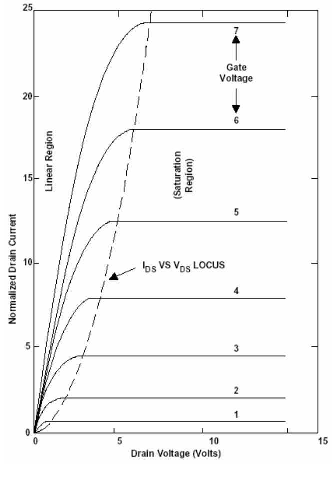


Figure 3.1.8. Output characteristic (current vs voltage) for example [3],[5],[8].

To switch on the MOSFET, the Gate-Source-spanning must surpass the threshold voltage V_{GS}. The V_{GS} value is typical between 2 and 4 volt. For a fully switched-on MOSFET, a V_{GS} between 10 and 15 V is recommended. Switching off is performed by lowering V_{GS} below the threshold voltage V_{GS}, thus to pull V_{GS} down to 0 Volt. The transfer characteristic is the relation between the drain current i_D and the control voltage V_{GS} value.The slope in the nominal current region is called transconductante , and it is several Amps per Volt large. In the figure 3.1.9 is shown transfer characteristic of power MOSFET [3],[5],[8].

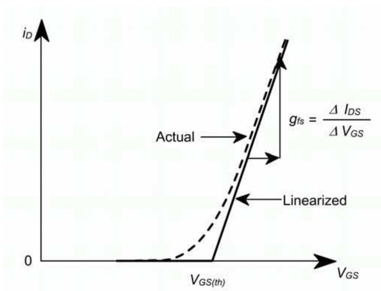


Figure 3.1.9. The transfer characteristic of MOSFET [3],[5],[8].

Insulated Gate Bipolar Transistor (IGBT)

The structure of an IGBT is very similar to presented the power MOSFET. One and main difference between a MOSFET and IGBT is the substrate of the wafer material. An N-channel IGBT is fabricated on a p-type substrate, while an n-channel of MOSFET is made on an n-type substrate. In the figure 3.1.10 is shown a structure and symbols of IGBT transistor. Notice that IGBT has a gate like MOSFET but has an emitter as collector like BJT [3],[5],[8].

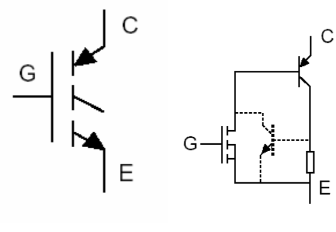


Figure 3.1.10. The symbols of IGBT transistor [3],[5],[8].

For both devices (it means IGBT and MOSFET), an n-epi layer of high resistivity is needed to support the required high breakdown voltage. It is the highly resistive epi-region that is responsible for the high on-state resistance of the MOSFET. However ,the n-epi region is placed on the p+ substrate in the IGBT to form a pn junction. When forward biased , this pn junction injects a large number of holes into the n-epi region, which is flooded with excess electrons and holes. The conductivity of the n-epi region is therefore increased by orders of magnitude. This is referred to as conductivity modulation , the reason why IGBTs offer much higher current conducting capability than MOSFET counterparts [3],[5],[8] .

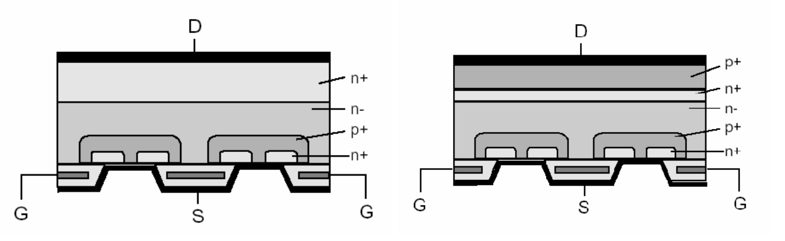


Figure 3.1.11.Comparison of the MOSFET (left) and IGBT (right) device structures [3],[5],[8].

Another way an IGBT can be considered as a pseudo-darlington with a MOSFET as driver and a bipolar transistor as the power stage. It combines the best properties of the MOSFET (simple drive circuit) and of the BJT (low conduction losses), which gives this new transistor a significant benefit. It means that the structure of an IGBT is a vertical MOSFET with an extra p-doped layer (now called collector) at the drain. In the figure 3.1.12 is shown the structure of IGBT and the current flow [3],[5],[8].

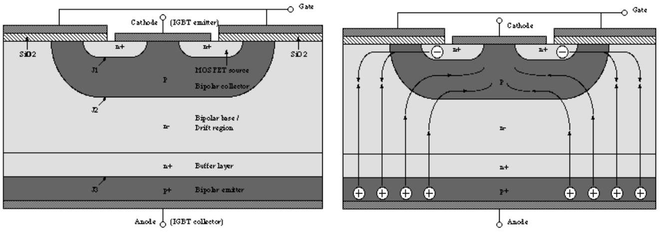


Figure 3.1.12. The structure of IGBT (left) and the current flow (right) [3],[5],[8].

In the figure 3.1.13 is presented characteristics of transistors MOSFET in the comparison to IGBT.

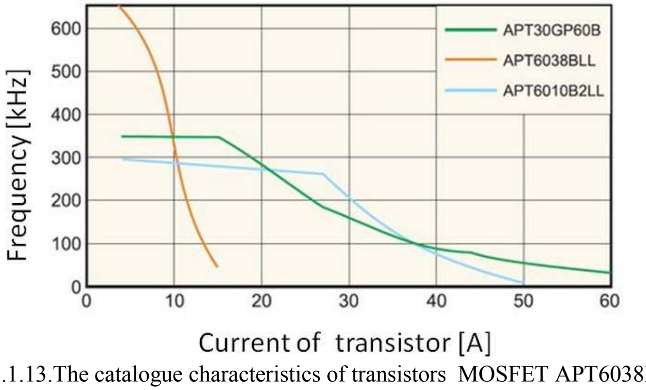


Figure 3.1.13.The catalogue characteristics of transistors MOSFET APT6038BLL , APT6010B2LL and IGBT APT30GP60B

There are two kinds of IGBTs , PT (punch through) and NPT (non punch through). A PT switches off fast, but cannot be connected in parallel. They are used in SMPSs and *cos φ* – correctors. From another hand a NPT can be connected in parallel, has an excellent SOA [3],[5],[8].

An IGBT is characterized by very small control power consumption, a good switching behavior, and a small voltage drop during conduction. This transistor is currently available for voltages of 600V, 1200V and 1600V, but also 6,5 kV.

Thyristor

The thyristor is a four-layer, three terminal semiconducting device, with each layer consisting of alternately n-type or p-type material, (p-n-p-n).Very often it is used another name SCR (silicon controlled rectifier) because of the most popular function of thyristor. The main terminals, labeled anode and cathode, are across the full four layers, and the control terminal, called the gate, is attached to p-type material near to the cathode. In the figure 3.1.14 is presented symbol and double transistor model of the thyristor.

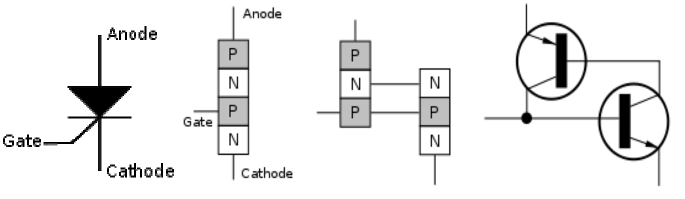


Figure 3.1.14.The symbol and double transistor model of the thyristor [3],[5],[8].

The thyristor can be turned on or off. It can also regulate power using something called phase angle control α . This allows the amount of power output to be controlled by adjusting the angle of the current input.

The thyristors indicate significant advantage of using phase angle control and handling large amounts of power. However they are not as suitable for low power applications. This is because they can only be turned off by switching the direction of the current flow. For this reason, a thyristor may take longer to turn on or off with compare other semiconductors. Also, the thyristors can only conduct current in one direction. It makes them poor in applications that require current to be conducted to and from each device. In facts, it can be said , that thyristors have three states:

1. Reverse blocking mode — Voltage is applied in the direction that would be blocked by a diode
2. Forward blocking mode — Voltage is applied in the direction that would cause a diode to conduct, but the thyristor has not yet been triggered into conduction
3. Forward conducting mode — The thyristor has been triggered into conduction and will remain conduction until the forward current value drops below a threshold known as the "holding current"

In the figure 3.1.15 is presented the characteristic of work of thyristor describes in three states up.

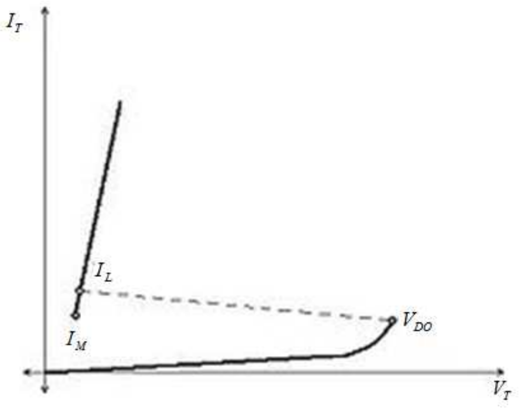


Figure 3.1.15.The characteristics of work of thyristor. [3],[5],[8].

Finally it can be said that all of describes power electronics elements are used in rectifier, choppers, converters and another applications. It is difficult to say which are the best or the most popular. Its depend to our needs and parameter of circuits. However we can say that the most important indicators determine of using of power electronics elements are max current, voltage (power) and frequency. The most commonly used transistors are the MOSFET and IGBT. The major determinant parameter used as a criteries for selection between the MOSFET and IGBT is the voltage value to withstand. Below voltages of 200V, MOSFETs are preferable due to almost ideal switching performance. At higher rated (max) voltages, the resistance value at conduction increases dramatically. Between 400 end 4000 Volt, the IGBT is the best choice as far as energy efficiency is concerned. In the figure 3.1.16 are presented ranges of max. current, voltage and switching frequency of the most often used power components for comparison.

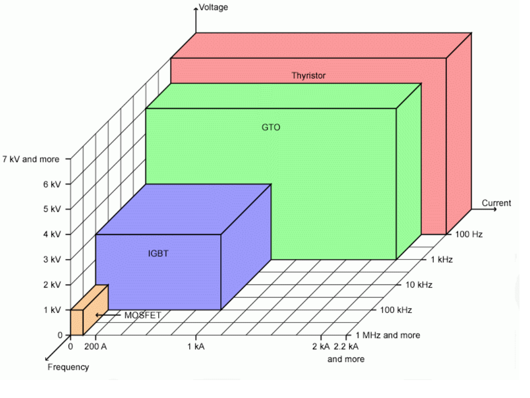


Figure 3.1.16. Max. current, voltage and frequency values for the most popular power electronics elements [3],[5],[8].

3.2. Power electronics converters

There are many definitions of power electronics converters. For our needs it can be said that a power electronic converter is a machine for converting and controlling electric energy (current, voltage, frequency). The converters employ one or more switching power semiconductor, magnetic components, capacitors, control electronics and other essential supplementary components. The essential characteristic of these types of circuits is that the switches are operated only at one of two states -either fully ON or fully OFF - unlike other types of electrical circuits where the control elements are operated in a (near) linear active region. Figure 3.2.1 presents a categorization of power electronic converters into families according to their type of electrical conversion. Of these families, converters that change energy to or from alternating current (AC) involve much more complex processes than those that solely involve direct current (DC). The purpose of this chapter is to explore the converter modulation issue in detail as it relates to high power DC/AC (inverting) and AC/DC (rectifying) converters, with particular emphasis on the process of open-loop pulse width modulation (PWM) applied to these types of converters.

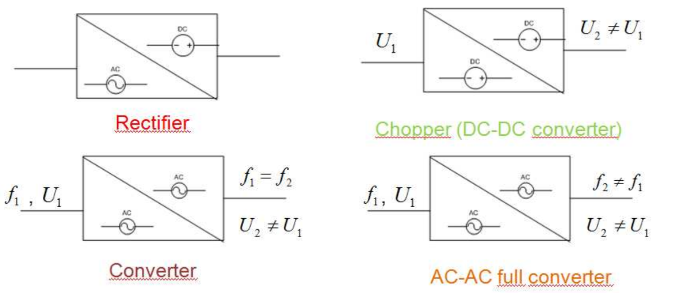


Figure 3.2.1..Family of solid state power converters categorized according to their function.

Rectifiers

Power electronics converters which convert alternative voltage (AC) to direct one (DC) are known as rectifiers. Usually they are supplied which the sinusoidal voltage of one or three phase circuits. The name of rectifier one, two, three, six or more respectively orientates from number of pulse on the DC side. The rectifiers can transform electrical energy from AC to DC side and its called as rectifier function while if energy is transferred from DC to AC side it performs the inverter function (there is break process under control). The one pulse rectifier is used in the circuits of less than 1 kW power. The waveforms , equitation's, and parameters of rectifier depend of type of loading of rectifiers. In the figure 3.2.2 is shown base circuit of one pulse rectifier with (R) resistive type load.

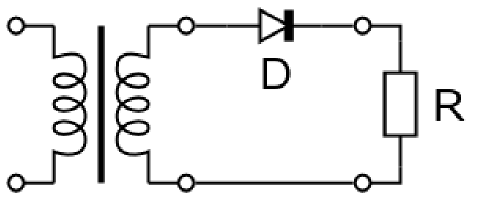


Figure 3.2.2.Diagram of one pulse rectifier [3],[5],[8].

There are some important parameters to be explained to understand the performance of rectifiers. They are presented in the figure 3.2.3.

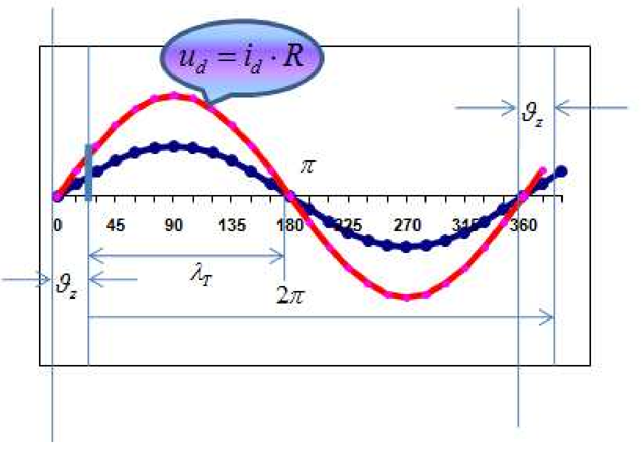


Figure 3.2.3.Explanation of angle of ignition ϑ_z and angle of conduction λ_T.

The angle of ignition ϑ_Z present an electrical angle at which the pulse is provided to the gate of thyristor. The thyristor begins to conduct the current (angle on). This angle can be controlled within the range $0 \le \vartheta_Z \le \pi$. For the angle equal to π the load current is equal to 0 (ϑ_W -angle off). In this case :

$$\lambda_T = \pi - \vartheta_z \tag{3.2.1}$$

Figure 3.2.4 presents the waveform of DC voltage, current and gate impulse as an example. These waveforms of voltage and current are the same for the R-load.

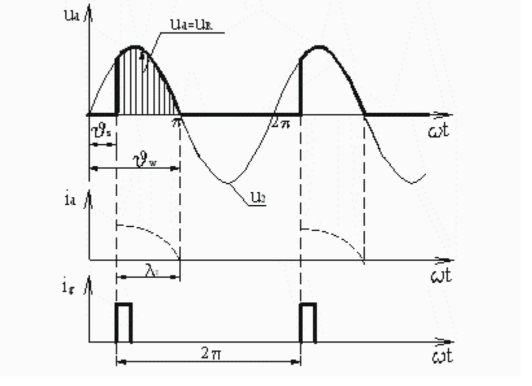


Figure 3.2.3.The waveform of DC voltage, current and gate pulse for R-load [3],[4],[5],[11].

The value of DC voltage in the case of R-load is describes by below equitation 3.2.2

$$U_d = \frac{1}{2\pi}\int_{\vartheta_z}^{\pi} U_{\max} \sin \omega t \cdot d\omega t = \frac{1}{2\pi} U_{\max}(1+\cos\vartheta_z) \qquad (3.2.2)$$

where: $U_{\max}$ -amplitude of supplying voltage

The highest value of voltage U_d appears for the diode state of operation (in this case $\vartheta_Z = 0$) and thus:

$$U_{d_0} = \frac{U_{\max}}{\pi} \approx 0{,}45 U_{RMS} \qquad (3.2.3)$$

The current value can be estimated from:

$$I_d = \frac{U_d}{R} \qquad (3.2.4)$$

where: *R* is a resistance of load.

If the load of different character (like containing the resistance *R* and inductance L) of voltage and current have the waveform as indicated in the figure 3.2.4.

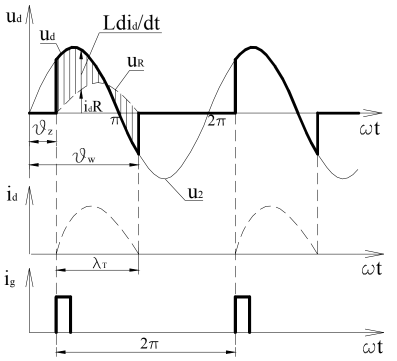


Figure 3.2.4. The waveform of DC voltage, current and gate impulse for RL-load [3],[4],[5],[11].

In this case the current prolongs flow within the ($\vartheta_w - \pi$) period also. It results from the stored electromagnetic energy in the magnetic field of the inductance *L* and after the angle π the thyristor is in forward conducting mode. Of course this phenomena is reached influences the value DC voltage negatively. This status of circuit can be written as:

$$\sqrt{2}U_{RMS}\sin\omega t = R\cdot i_d + L\frac{di_d}{dt} \qquad (3.2.5)$$

if: $\quad i_d(\vartheta_z) = 0$

The pulse current i_d will be describes by equation (3.2.6)

$$i_d = \frac{\sqrt{2}U_{RMS}}{Z}\sin(\omega t - \varphi) - \frac{\sqrt{2}U_{RMS}}{Z}\sin(\vartheta_z - \varphi)e^{-(\omega t - \vartheta_z)ctg\varphi} \qquad (3.2.6)$$

where : $Z = \sqrt{R^2 + (\omega L)^2}$ is impedance of circuit and $\varphi = arctg\frac{\omega L}{R}$ is angle of phase transferring.

Under above conditions DC output voltage is given as:

$$U_d = \frac{1}{2\pi}\int_{\vartheta_z}^{\vartheta_w} U_{\max}\sin\omega t\cdot d\omega t = \frac{1}{2\pi}U_{\max}(\cos\vartheta_z - \cos\vartheta_w) \qquad (3.2.7)$$

Finally, for active load with additionally source of energy like EMF the waveform of voltage and current have plats as in the figure 3.2.5.

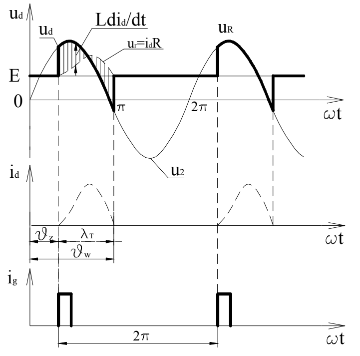


Figure 3.2.5. The waveform of DC voltage, current and gate impulse for RLE-load [3],[4],[5],[11].

This status is suitable for control of the DC parallel motor where *R* and *L* are resistance and inductance of rotor and *E* is electromotive force of motor. The silicon rectifier control (SRC) can be control if $U_{\max}\sin\vartheta_z \geq E$ what means that:

$$\arcsin\varepsilon \leq \vartheta_z \leq \pi - \arcsin\varepsilon \qquad (3.2.8)$$

where : $$\varepsilon = \frac{E}{U_{\max}} \qquad (3.2.9)$$

The angle ϑ_Z the thyristor is off and depend of $tg\varphi$ of circuit and ε value.

For active resistive-inductive (*RLE*) load the medium DC output voltage can be derived from:

$$U_{d(medium)} = \frac{1}{2\pi}U_{\max}(\cos\vartheta_z - \cos\vartheta_w) + E\frac{2\pi - \lambda_T}{2\pi} \qquad (3.2.10)$$

where : $$\lambda_T = \vartheta_W - \vartheta_Z$$

The equation (3.2.10) is similar to (3.2.7) and is verified by the last form that includes *E*. For this type of circuit one can be write:

$$U_{\max}\sin\omega t - E = Ri_d + L\frac{di_d}{dt} \qquad (3.2.11)$$

When solve equation (3.2.11) using condition $i_d(\vartheta_z) = 0$ the respective formula (3.2.12) for pulse current i_d is obtained :

$$i_d = \frac{U_{\max}}{R}\{[\cos\varphi\sin(\omega t - \varphi) - \varepsilon] + [\varepsilon - \cos\varphi\sin(\vartheta_z - \varphi)]e^{-(\omega t - \vartheta_z)ctg\varphi}\} \qquad (3.2.12)$$

Therefore medium output current I_d is described from equ. (3.2.13)

$$I_d = \frac{U_{\max}}{2\pi \cdot R}[\cos\vartheta_z - \cos\vartheta_w - \varepsilon(\vartheta_z - \vartheta_w)] \qquad (3.2.13)$$

If the rectifier works as the inverter the electromotor force *E* has to be put negative value, but the equation posses the same form as for rectifier status.

The most popular rectifier type used in the many applications is the two pulse one. There are two types circuit of the two pulse rectifier using usually –bridge or Graetz rectifier. In the figure 3.2.6 there are both of these circuits. For the further analyze the bridge circuit will be taken into account. The equation for current and voltages values of the bridge are similar to that for the one pulse rectifier. The only change is the limitation of integrals and the results are increate by 2. Both types of rectifier can work with supplying transformator or without them. This is high advantage of this circuits.

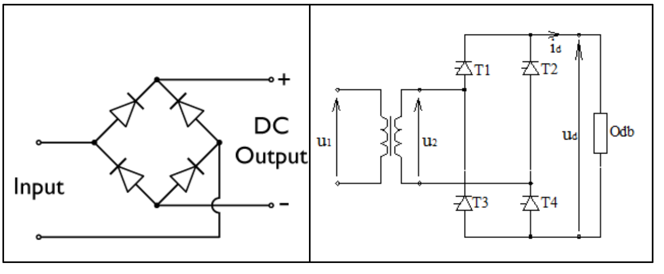


Figure 3.2.6. The two pulse rectifier Graetz (left) and bridge (right) circuits. [3],[5],[8].

In the figure 3.2.7 is presented the waveforms of DC voltage, current and gate impulse for the two pulse rectifier . The waveforms of voltage and current are the same as for the R-load.

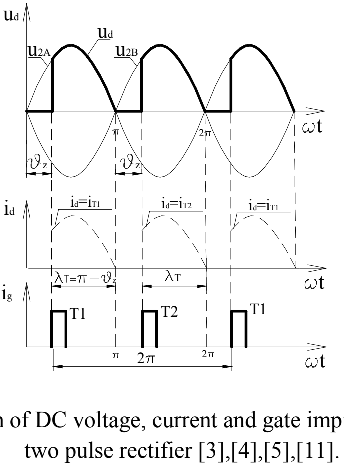


Figure 3.2.7. The waveform of DC voltage, current and gate impulse for R-load when used the two pulse rectifier [3],[4],[5],[11].

Value of the DC voltage in the case of R-load is described by equation as follows:

$$U_d = \frac{1}{2\pi} \cdot 2 \int_{\vartheta_z}^{\vartheta_w} U_{\max} \sin \omega t dt = \frac{U_{\max}}{\pi}(1 + \cos \vartheta_z) \tag{3.2.14}$$

This value is the highest for diodes bridge because in this case $\vartheta_z = 0$ and

$$U_{d_0} = \frac{\sqrt{2} \cdot 2 \cdot U_{RMS}}{\pi} \approx 0{,}9 U_{RMS} \tag{3.2.15}$$

However current value for both cases is calculated as:

$$I_d = \frac{U_d}{R} \tag{3.2.16}$$

If the load indicates *RL* character the waveform of voltage and current can be equivalent to both of two operations conditions. They are called the pulse and continuous status of operation. In the figure 3.2.8 are presented both types of the rectifier operation.

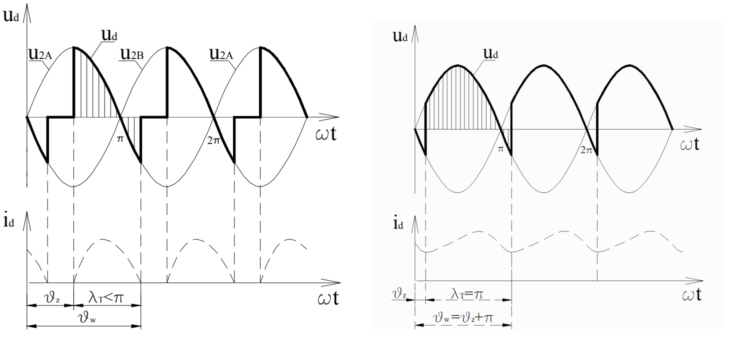


Figure 3.2.8.The waveform of DC voltage and current for RL-load for two pulse rectifier the impulse status (left) and continues one (right) respectively[3],[4],[5],[11].

The equitation describing the DC output voltage will have different form for impulse (3.2.17) and continuous (3.2.18) status respectively:

$$U_d = \frac{1}{2\pi} \cdot 2 \int_{\vartheta_z}^{\vartheta_w} U_{\max} \sin \omega t d\omega t = \frac{U_{\max}}{\pi}(\cos \vartheta_z - \cos \vartheta_w) \tag{3.2.17}$$

$$U_d = \frac{1}{2\pi} \cdot 2 \int_{\vartheta_z}^{\pi + \vartheta_z} U_{\max} \sin \omega t d\omega t = \frac{2 \cdot U_{\max}}{\pi} \cos \vartheta_z \tag{3.2.18}$$

In the case of continuous current flow the angle of conducting is $\lambda_T = \pi$. For the active load and additional electromotive force *E* equitation describing waveform of voltage are the same like formula (3.2.17) and (3.2.18) but the DC output current is calculated using formulas:

$$I_d = \frac{2 \cdot U_{max}}{\pi \cdot R}[\cos \vartheta_z - \cos \vartheta_w - \varepsilon(\vartheta_w - \vartheta_z)] \quad (3.2.19)$$

for pulse status and

$$I_d = \frac{U_d - E}{R} \quad (3.2.20)$$

for continues status.

In the practice are uses characteristics of control of the bridge. They depend on type of load and are presented in the figure (3.2.9).For the multipulse rectifier there is used the angle of control α instead of the angle ignition (on) ϑ_Z .

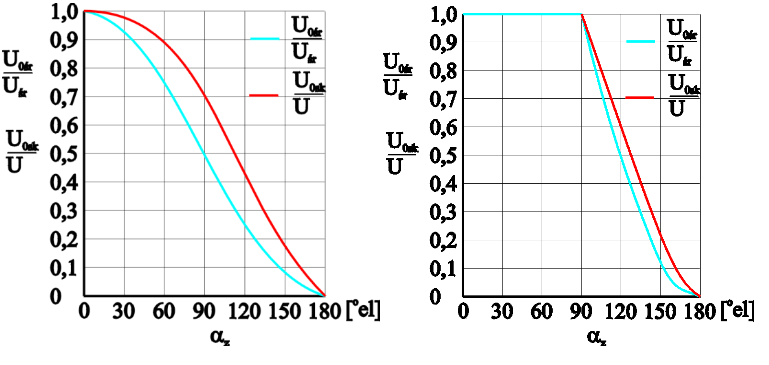


Figure 3.2.9.Characteristics of control of two pulse rectifier for R-load (left) and RL-load (right) [3],[4],[5],[11].

The most popular in use are three phase rectifiers due to convenient supply and high quality of the DC voltage. In the figure (3.2.10) there is shown the circuit of such rectifier in the bridge variant. This type of rectifier can work with the neutral (null) point only. The equitation for current and voltages values of the bridge are close to the one pulse rectifier with only the changes the limitation value of integrals and the results are increate by 3. Under the analyze of the multipulse rectifiers it is necessary to include the process of commutation of thyristors. The reason of this phenomena is because commutation take time and it can be overlap of current two or more thyristors what in the consequence canmake shortcircuits. The commutation process is describes by commutation angle μ as it is shown in the figure (3.2.11).

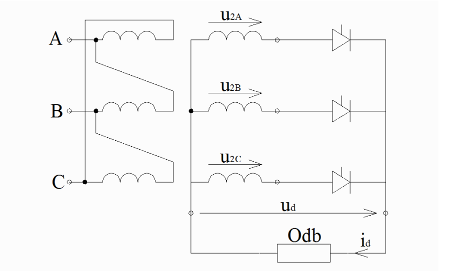


Figure 3.2.10. The three pulse rectifier as the bridge variant [3],[4],[5],[11].

In figure 3.2.11 is presented the waveform of DC voltage, current of the three pulse rectifier . The waveform of voltage and current are the same as for the R-load.

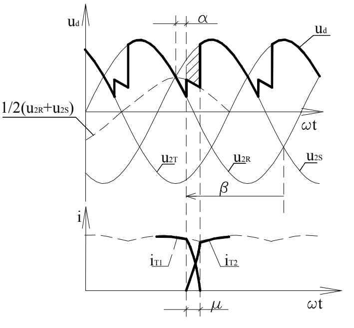


Figure 3.2.11. The waveforms of DC voltage and current for R-load when include of the commutation process [3],[4],[5],[11].

The DC voltage value for the case of the R-load and impulse status of work is calculated from equitation (3.2.21):

$$U_d = I_d \cdot R = \frac{1}{2\pi} \cdot 3 \int_{\vartheta_z}^{\pi} U_{\max} \sin \omega t d\omega t = \frac{3 \cdot U_{\max}}{2\pi}(1 + \cos \vartheta_z) \quad (3.2.21)$$

It was already mentioned for the multipulse rectifiers there is used angle of control. In the case of three pulse rectifier this angle α is equal:

$$\alpha = \vartheta_z - \frac{\pi}{6} \quad (3.2.22)$$

The DC voltage for continues status is independent to character of load and for R , RL have the same form:

$$U_d = \frac{3}{2\pi} \int_{\vartheta_z}^{\vartheta_z + \frac{2\pi}{3}} U_{\max} \sin \omega t d\omega t = \frac{3\sqrt{3}}{2\pi} U_{\max} \cos(\vartheta_z - \frac{\pi}{6}) = \frac{3\sqrt{3}}{2\pi} U_{\max} \cos\alpha \quad (3.2.23)$$

For the *RL* type of load and impulse status of the rectifier operation this equation takes the form:

$$U_d = \frac{3}{2\pi}\int_{\vartheta_z}^{\vartheta_w} U_{\max}\sin\omega t d\omega t = \frac{3U_{\max}}{2\pi}(\cos\vartheta_z - \cos\vartheta_w) \qquad (3.2.24)$$

Finally, for the active load (with electromotive force *E*) the equation describing waveform of voltage is as follows:

$$U_d = \frac{3U_{\max}}{2\pi}[\cos\vartheta_z - \cos\vartheta_w - \varepsilon(\vartheta_w - \vartheta_z)] \qquad (3.2.25)$$

The most important for the automotive engineering is the six pulse rectifier. It is used in all types of the automobiles usually in alternator for transfer of AC to DC voltages, however recently it has became the main part of inverters for controlling of drives in Hybrid and Electrical vehicles. In the figure 3.2.12 is shown the circuit of rectifier for the bridge variant.

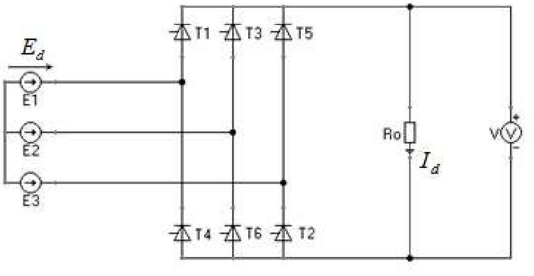


Figure 3.2.12. The six pulse bridge rectifier variant [3],[4],[5],[11].

This rectifier can operate in impulse and continues status as well. Its waveforms of the output DC voltage depend on character of load like for another type of the rectifier. In the figure 3.2.13 is presented waveform the DC voltage, of the current six pulse rectifier for continues mode while in figure 3.2.14 for the impulse mode respectively.

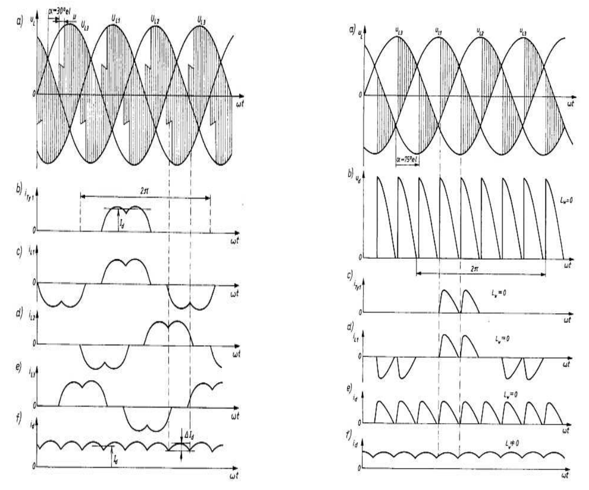


Figure 3.2.13. The waveform of DC voltage and current for continues mode (left) and impulse mode (right) , including commutation process [3], [4], [5], [11].
a) DC voltage output waveform b), c), d),e) phase supplying current of rectifier
f) DC output current waveform

The DC voltage for the R-load and impulse operation is given by equation (3.2.26):

$$U_d = R \cdot I_d = \frac{1}{2\pi} \cdot 6 \int_{\vartheta_z}^{\pi} U_{max} \sin \omega t d\omega t = \frac{3U_{max}}{\pi}(1 + \cos \vartheta_z) \qquad (3.2.26)$$

This value for continues work is independent on type of load and for *R* , *RL* has the same form (like for the three pulse case):

$$U_d = \frac{1}{2\pi} \cdot 6 \int_{\vartheta_z}^{\vartheta_z + \frac{2\pi}{6}} U_{max} \sin \omega t d\omega t + \frac{3U_{max}}{\pi} \cos(\vartheta_z + \frac{\pi}{3}) = \frac{3U_{max}}{\pi} \cos\alpha = U_{d0} \cos\alpha \qquad (3.2.27)$$

where :U_{d0} is the output voltage for $\alpha = 0$.

The characteristic of control of the bridge depends to type of load and is presented in figure (3.2.14).

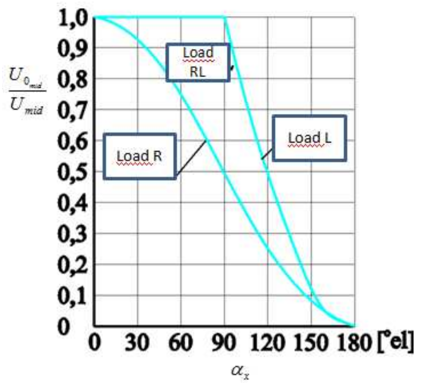


Figure 3.2.14.The characteristics of control of six pulse rectifier [3],[4],[5],[11].

In figure (3.2.15) is presented application of the six pulse diode rectifier for Bosch alternator [31]. It is most popular employment of six pulse rectifier.

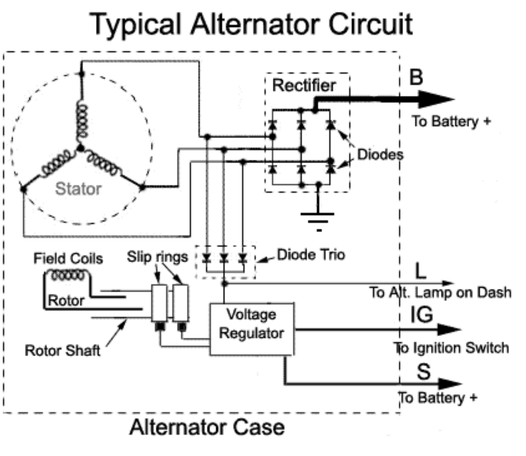


Figure 3.2.15.The six pulse rectifier transfer AC alternator voltage to the DC battery and/or to another units voltage with three pulse rectifier for voltage regulator.

Choppers

One parameter converters of the DC electrical energy into the DC energy of another parameters are usually done by impulse circuits. This circuits are used to create the output signals like a series impulse with modulated width and constants frequency or with control of frequency also. The impulse converters are named choppers and they are used for the power electronic elements as well thyristors GTO, transistors etc. Thyristors SCR are used rather in power electronic drives for EV or Hybrid drives. The frequency of SCR choppers is between 100 to 1000 Hz. The power of choppers is drops down with the frequency. The figure 3.2.1 (green) is presented the idea of operate of choppers. It is of course important how the choppers are construct . While the structure the choppers is shown in the figure 3.2.16

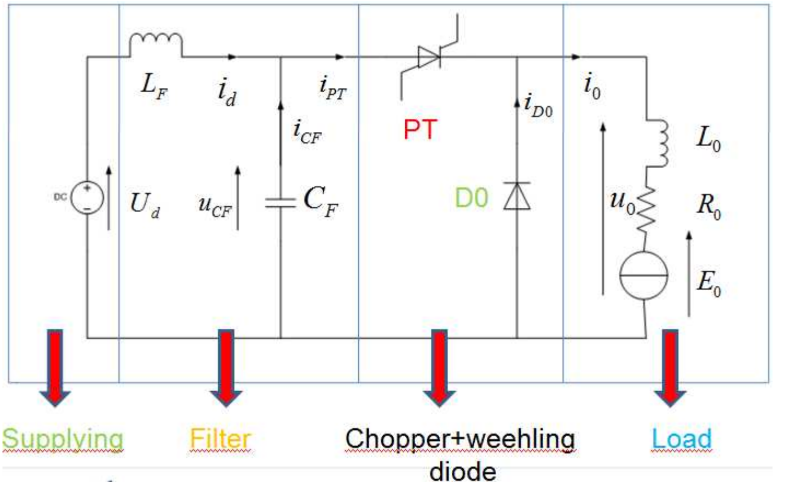


Figure 3.2.16.Basic structure of the SRC choppers [4].

The choppers are composed of four main parts, where each of them represents independent electrical circuits: supplying, filter, chopper, and load. They have to be supplied from dynamic electrical voltage source and for this case it is necessary to employ a low flow filter $L_F\,C_F$ or C_F. For control the output voltage it is used the thyristor chopper with parallel or series circuit of commutation.

The figure 3.2.17 explained an idea of control of output voltage of choppers.

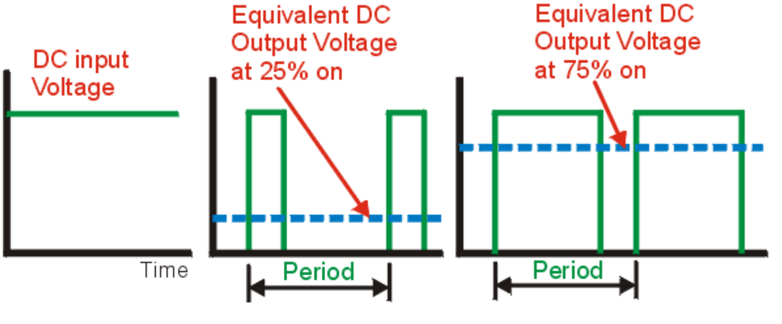


Figure 3.2.17.Principle of controlling of output voltage of choppers [3],[4],[5],[11].

Idea of controlling of voltage used in choppers and presented in figure 3.2.17 is an interpretation of equation (3.2.28) for output (load) voltage

$$U_0 = \frac{1}{T_0}\int_0^{t_p} u_{CF}(t)dt = U_d \frac{t_p}{T_0} = U_d \cdot \gamma \qquad (3.2.28)$$

where :

$$\gamma = \frac{t_p}{T_0} \qquad (3.2.29)$$

is coefficient of duty cycle. By controlling of γ one can be controlled output voltage U_0. This type of control is called the control by means of the frequency modulation. Mostly, the load is inductive .Therefore to avoid a dangerous overvoltages (and thus transistor breakdown) during switching off, a freewheeling diode is required. The diode takes over the load current during the off-phase, keeping the magnetic energy of the load. Under chopping, the current increases and decreases exponentially with a time constant equal to L/R. Therefore if the switching frequency is high enough, and/or the load inductance is large enough, the current will flow continuously. In figure 3.2.18 is presented waveform of voltages and current of choppers under real conditions of application with indication of status on (time t_P) and status off (time t_w) of the choppers. All indicators are like in figure 3.2.16.

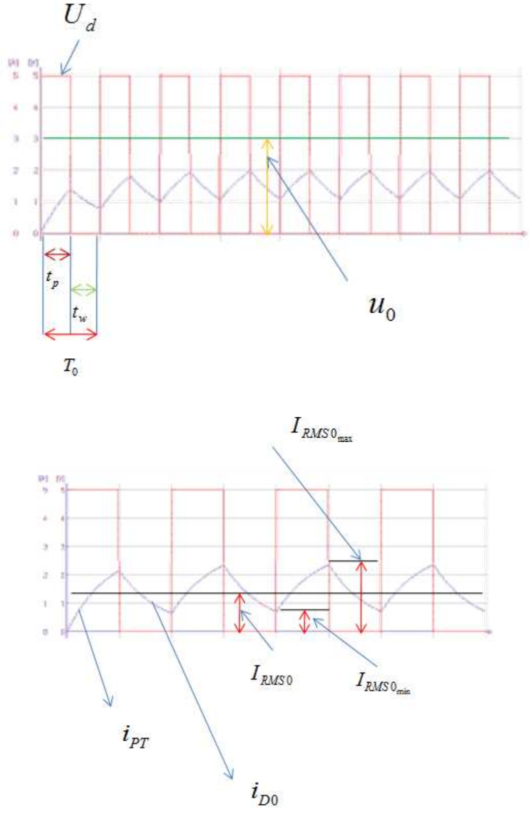


Figure 3.2.18.Waveforms of voltage and current of the choppers [3],[4],[5],[11].

In this case the medium value of current is describes by equation as:

$$I_0 = \frac{U_0 - E_0}{R_0} = \frac{\gamma \cdot U_d - E_0}{R_0} \qquad (3.2.30)$$

and the medium input (current of supplying source)- equation as:

$$I_d = \frac{1}{T_0}\int_0^{t_p} i_{PT}(t)dt = I_0 \frac{t_p}{T_0} = \gamma \cdot I_0 \qquad (3.2.31)$$

Finally it can be written as:

$$\frac{U_0}{U_d} = \frac{I_d}{I_0} = \gamma \qquad (3.2.33)$$

and power of choppers is describes by:

$$P_d = U_d \cdot I_d = U_0 \cdot I_0 = P_0 \qquad (3.2.34)$$

If compare the time of conducting current trough the thyristor i_T or freewheeling diode i_D with the time of commutation (between this two currents) its found that the time of commutation is much smaller than time of conducting. This fact impacts significant influence on estimation of elements of filter and elements of parallel or series commutation circuits of the chopper. This phenomena is presentad in the figure 3.2.19.

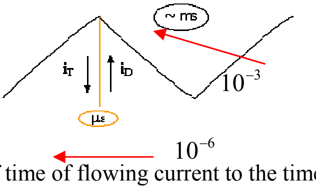


Figure 3.2.19.Relationship of time of flowing current to the time of current commutation [3],[4],[5],[11].

From the above equation one can derives the output characteristic of PWM control.

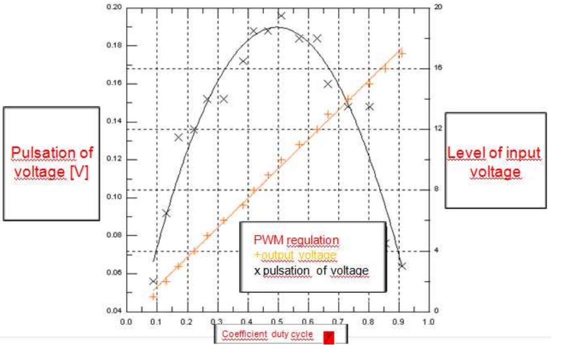


Figure 3.2.20.The characteristic of output voltage and pulsation of voltage at PWM.

It is important for estimation of parameters of input filter and the frequency of modulation. In real circuits the capacity of filter is limited themselves in the consequence the current i_{PT} indicates the pulse character and the voltage u_{CF} has the impulse shape as well. In this case the resonance frequency of input filter is equal:

$$f_F = \frac{1}{2\pi\sqrt{L_F C_F}} \qquad (3.2.35)$$

and the frequency of modulation respectively $f_0 = \frac{1}{T_0}$ .It means that $f_F \leq\leq f_0$ and $u_{CF} \approx U_d$.Therefore it can be written in form:

$$C_F \frac{du_{CF}}{dt} \approx -C_F \frac{\Delta u_{CF}}{t_p} = I_d - I_0 \qquad (3.2.36)$$

what, when include $I_d = \gamma \cdot I_0$ gives finally:

$$\Delta u_{CF} = \frac{I_0}{C_F} f_0 (t_p \cdot T_0 - t_p^2) = \frac{I_0}{C_F \cdot f_0}(\gamma - \gamma^2) \qquad (3.2.37)$$

For example when $\gamma = 0{,}5$

$$\Delta u_{CF_{\max}} = \frac{I_0}{4 C_F f_0} \text{ and } \quad C_F \geq \frac{I_0}{4 \cdot \Delta u_{CF_{\max}} \cdot f_0}.$$

Value of $\Delta u_{CF_{\max}}$ -is taken from characteristic in Figure 3.2.20.

At the end it is necessary to explain the chopper operating. The most popular is the chopper structure with parallel circuit of commutation. This circuit is presented in figure 3.2.21. The main circuit is the same as shown in figure 3.2.16 (the part of choppers is drawn in details only). In this case there are two thyristors: one main T_G and the second who operate in parallel to the main ones and is called the commutation T_K. Capacity C_k is this of the source that breaks the main thyristor. When switch on the chopper to source U_d the commutation capacity C_k is loaded in the circuit (U_d- $L_{K2} - C_K - T_K - R_0 L_0 E_0 - L_{K2}$)to the voltage value equal to U_d of polarization (+) at upper side of the capacitor.

Than after switching on the main thyristor T_G the resonance reloading of capacitor ($C_K - T_G - L_{K1} - D_K - C_K$) begins. If it is switched off the main thyristor T_G the commutation thyristor T_K has to be switch on and the circuit is loading as flowing ($C_F - L_{K2} - C_K - T_K - R_0 L_0 E_0 - C_F$).

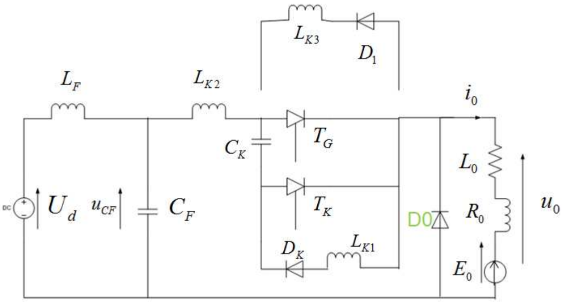


Figure 3.2.21.The circuit of chopper with parallel circuit of commutation.

In the practice there are used different types of the choppers including buc or step-down, booster or step-up, buck-boost, flyback, resonant etc. All of these types have to fulfill (in automotive engineering) tasks to control the drive in four quadrant circuits. It means that for many applications, the motor should be able to operate in two directions, however in this case the motor can develop both positive and negative torques. We can distinguish here 4 quadrants on the speed-torque diagramme. A circuit which allows to flow currents and voltages of both polarities, requires more than one power switch. In figure 3.2.22 is given explanation of main idea of control of electrical drives for 4 quadrants.

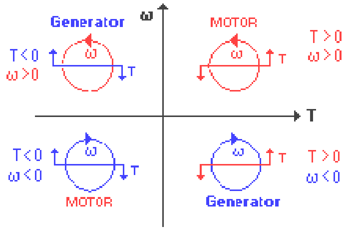


Figure 3.2.22.The principle of control of electrical drives for 4 quadrants .[1], [3],[4],[5],[11]

Depend on direction of torque and speed the drive can operate as well as the motor or as generator. Another words if the torque and speed are both positive or both negative the drive performs the motor function in another case is the generator (in the figure the motor is the red one and generator the blue one respectively).However not all of the choppers can work in this status. The detailed described circuit of the thyristor chopper can perform this operation. In general the analysis is correct for different power electronics elements if the circuits are based on the switch on-off function. In figure 3.2.23 is presented the equivalent circuit of different power electronics elements.

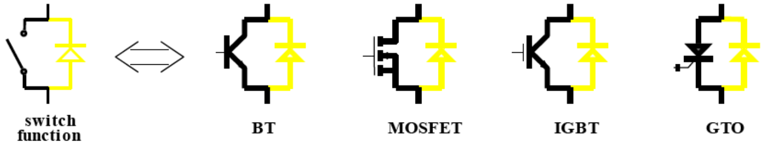


Figure 3.2.23.The equivalent circuit of different power electronics elements. [3],[4],[5],[11].

In figure 3.2.24 is shown the circuit of chopper with thyristor and MOSFET structure.

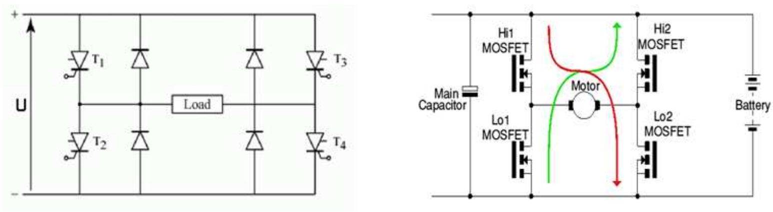


Figure 3.2.24.The four quadrant chopper with thyristors (left) and MOSFET (right) [3],[4],[5],[11].

To control the motor voltage, the transistors must be chopped in pairs. Hi1 + Lo2 are simultaneously driven, while the other pair Hi2 + Lo2 are simultaneously driven in opposite phase. This means: that when the pair Hi1 + Lo2 is switched ON, the other pair is switched OFF and vice versa. For adequate chopper operation, all transistors must be equipped with a freewheel diode. MOSFETs have a power diode already integrated in the structure. For the thyristor circuits the freewheel diodes must be added as an extra components. In the figure 3.2.24 (right) is shown for example operation in quadrant 1 [3],[4],[5],[11]. During the ON-phase, the **current** flows through the transistors Hi1 + Lo2; while the diodes don't conduct. The motor current increases and the power supply delivers power to the motor. From another hand during the OFF-phase, the **current** flows through the freewheel diodes of Hi2 + Lo1. Even though these of MOSFETs Hi2 + Lo1 are switched on, the motor current continues flowing in the same direction, because of inductive character of its impedance. The current is decreasing due to loading of the power source (or the main capacitor). The latter receives power from the motor. If in the status ON the duty time is $\gamma \cdot T$ can be written that $U_0 = U_d$ [neglecting the two transistor conductive voltages]. If in the status OFF the duty time is $(1-\gamma)\cdot T$ can be written that $U_0 = -U_d$ [neglecting the two diode voltages]. Generally it can be written that U_0 what is voltage on the motor (load) is:

$$U_0 = \gamma \cdot U_d - (1-\gamma)\cdot U_d = (2\gamma - 1)U_d \qquad (3.2.38)$$

Due to the square character of the output voltage, it contains many higher order harmonics. Fortunately, those harmonics are supported well by DC motors. The motor current is much smoother, and the motor torque is proportional to this current. In the figure 3.2.25 is presented four quadrant chopper: dynamic transition from quadrant 1 to quadrant 3 via quadrant 2.

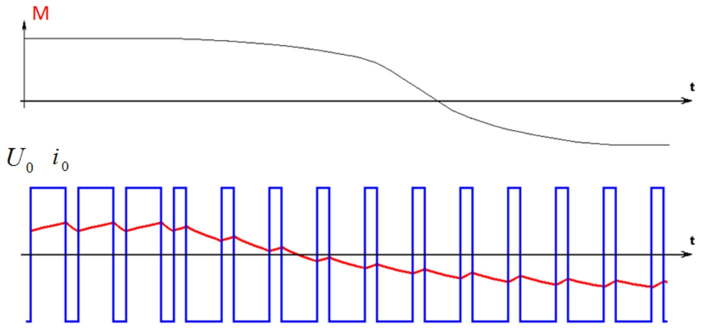


Figure 3.2.25.Transient from quadrant 1 to quadrant 3 via quadrant 2[3],[4],[5],[11].

Finally in figure 3.2.26 there are shown practical issue of choppers in automotive engineering what is servomotor control circuit using a 4 quadrant IGBT bridge . The IGBT H-bridge is controlled by a current PI controller. This current regulator has a PWM modulator as last stage. The current regulator can be controlled by a speed regulator. During torque regulation, the speed controller is disabled by a switch (Regulation switch box).

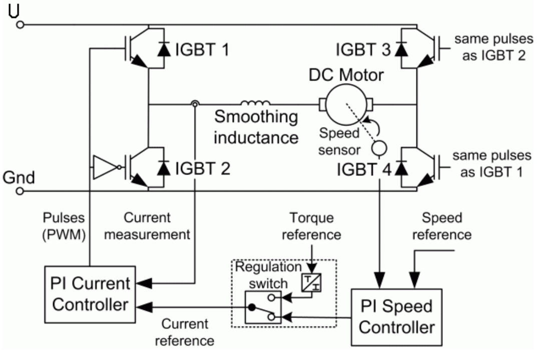


Figure 3.2.26.The servomotor control circuit [29].

In this circuit the IGBT bridge is controlling by two regulators type PI ,one speed controller and second current controller . They are operating in series circuits with speed controller like a master.

Inverters

Inverters are circuits who convert the DC energy to the AC energy. It can be done in single phase or three phase bridges structure. There are many different types of inverters depend to how inverter is collaborating with supplying network, how they are commutating in or out commutation, how they are supplying from voltage or current sources and many others. In this chapter will be describes single-phase voltage source inverter, three phase voltage source inverter, three phase current source inverter, inverter with Pulse Width Modulation (PWM). In general it can be said that inverters used in automotive engineering sometimes called full inverters or converters at all are transferring the AC energy to the DC energy and then the DC energy to the AC energy again. Of course finally it is AC to AC however with another parameters. In the figure 3.2.27 is presented very schematic this circuits.

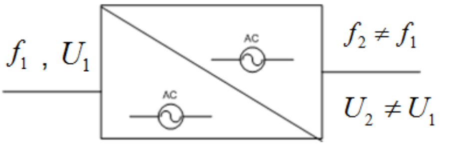


Figure 3.2.27.Schematic of the inverter.

Presently it will be described single-phase voltage source inverter often called resonance inverter. This inverter can be construct as like series or parallel (its depend of how load circuits are build up with capacitor parallel or in series).In figure 3.2.28 is shown single-phase voltage source inverter with two capacitors and two transistors or with four transistors and one capacitor.

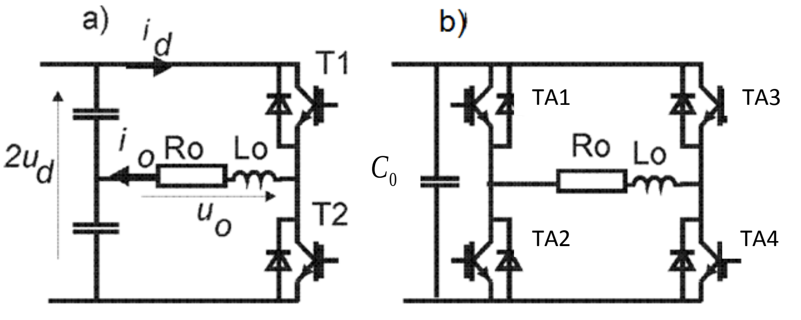


Figure 3.2.28.The single-phase voltage source inverter a)based on two transistors b)based on four transistors respectively [3],[4],[5],[11].

All of described inverters can be construct on the base of thyristors as well transistors. In single-phase voltage source inverter transistors 1 and 4 are synchronized; transistors 2 and 3 are the other synchronized pair. When 1+4 are switched on, the load voltage is positive. When 2+3 conduct of current, the load voltage is negative. Instead of conducting of current in transistor pair 1+4 or 2+3, it is also possible to switch on the transistors with odd numbers (1+3), or to switch on the transistors with even numbers (2+4). In both cases, the voltage on the load will be zero. It is thus possible to create a square wave the AC voltage on the motor. In the operating status of inverter important is pulsation of own vibrates ω_0 of the circuit inverter-load. This pulsation is estimated as the bellow equation:

$$\omega_0 = \sqrt{\frac{1}{L_0 C_0} - \frac{R_0^2}{4L_0^2}} \qquad (3.2.39)$$

and $\omega_0 = 2\pi \cdot f_0$

The second important frequency is frequency of control of inverter *f*. The current i_d flow in transistor is estimated from equation:

$$U_d = L_0 \frac{di_0}{dt} + \frac{1}{C_0}\int i_0 dt + i_0 R_0 \qquad (3.2.40)$$

with beginning conditions $(i_0)_{t-0} = 0$ and $\left(\frac{di_0}{dt}\right)_{t=0} = \frac{U_d + U_{c_0 \max}}{L_0}$

and is described as:

$$i_0 = i_d = \frac{U_d + U_{C_0 \max}}{\omega_0 L_0} \exp\left(-\frac{R_0}{2L_0}t\right) \sin \omega_0 t \qquad (3.2.41)$$

In this case the angle of duty is equal as:

$$\lambda = \omega(t_2 - t_1) = \pi \frac{\omega}{\omega_0} = \pi \frac{f}{f_0} \qquad (3.2.42)$$

where : t_1 is the time-on on transistor 1 and 4 and t_2 is the time off of them.

Another important problem for supplying of motors is the waveform of output voltage of the inverter. In every cases of operation of inverter there is the square wave what is presented in figure 3.2.29 and always contains many harmonic frequencies.

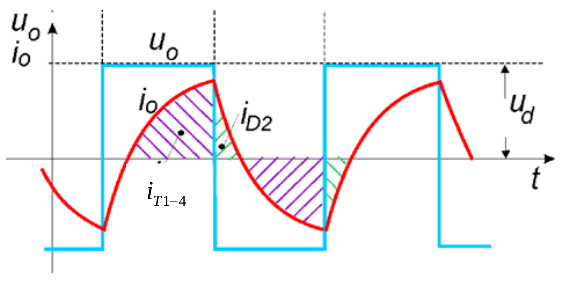


Figure 3.2.29.Waveform of output voltage of the inverter respectively [3],[4],[5],[11].

The current i_{T1-4} conducting in transistor 1 and 4 is presented in the figure 3.2.29. For the waveform of output voltage reason in the inverters are usually installed freeweel diodes. They are conducting the current when the bridge of inverter are in off status of operation. In the upper figure this current is presented by i_{D2} .In automotive application the loads need a nearly perfect sine wave voltage supply in order to work properly. However there are many loads who can work well with a square wave voltage.

In figure 3.2.30 is presented an example of square wave voltage with fundamental, 3th and 5th harmonics.

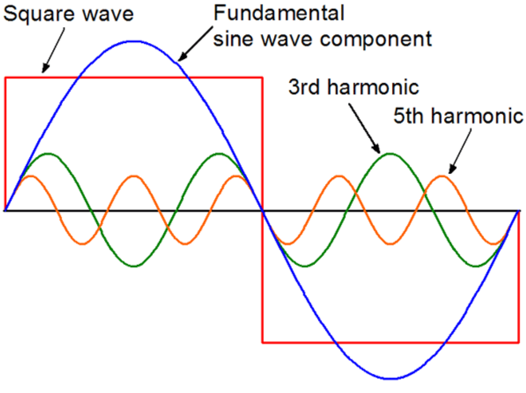


Figure 3.2.30.Square wave voltage with fundamental, 3th and 5th harmonics respectively[3],[4],[5],[11].

The quality of the inverter output voltage waveform can be expressed by using the Fourier analysis what is data to calculate the total harmonic distortion (THD). The total harmonic distortion is the square root of the sum of the squares of the harmonic voltages divided by the fundamental voltage. In figure 3.2.31 is presented an example of spectrum of harmonics waveforms from Fourier analysis [13].

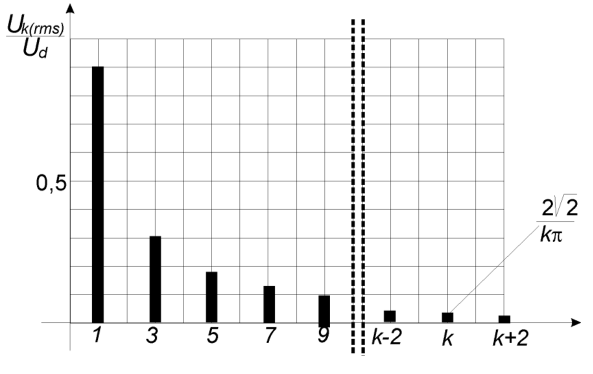


Figure 3.2.31.Spectrum of harmonics derived from Fourier analysis [3],[4],[5],[11]..

The spectrum of harmonics of squares voltage waveforms contains all of odd the upper harmonics and they are described by equation [13],[14],[15]:

$$u_0(t) = \frac{4}{\pi}\sum \frac{1}{k}\sin(k\omega t + \varphi_k) \qquad (3.2.43)$$

where: $k = 1,3,5...(2n+1)$

If the load have induction character (less resistance) the current is described by:

$$i_0(t) = \frac{4}{\pi \cdot \omega} \sum \frac{1}{k^2} \sin(k\omega t + \varphi_{ki}) \tag{3.2.44}$$

and phase between current and voltage of k series harmonics is $\varphi_{ki} = \varphi_k + \frac{\pi}{2}$

Its occurs that waveform of the voltage is more disturbed than the current for upper harmonics. The upper presented circuit have not many application, but is very easy to describe one phase in three phase inverter and understand how its operate. In figure 3.2.32 are shown the waveform of output voltage and current and signals of transistors as well.

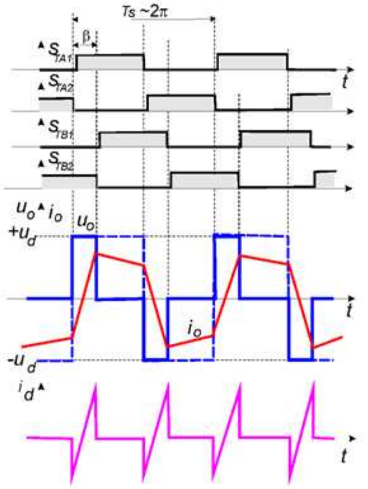


Figure 3.2.32. Waveforms of output voltage and current for the single-phase voltage source inverter [3],[4],[5],[11].

The output voltage and fundamental voltage in this case is described by respectively [3],[4],[5],[11]:

$$U_{o(RMS)} = \sqrt{\frac{\beta}{\pi}} U_d \tag{3.2.45}$$

$$U_{o1(RMS)} \frac{2\sqrt{2}}{\pi} \sin \frac{\beta}{2} \tag{3.2.46}$$

It was mentioned that the square waveform of voltage can have negative influence on the condition of operation of electrical receivers in the automotive engineering and upper harmonics must be eliminated. Harmonic elimination techniques are generally applied to the lowest harmonics, because filtering is more effective at high frequencies than at low frequencies. Some waveforms eliminate or "cancel" additional harmonics. By inserting a zero-voltage step between the positive and negative sections of the square wave, all of the harmonics divisible by three can be eliminated. Another way to improved of quality of the output voltage most popular is to construct bride inverter on the base of single phase inverters. In figure 3.2.33 is presented three phase inverter what is implementation of single phase inverter to three phase.

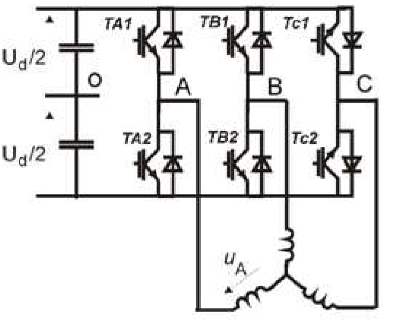


Figure 3.2.33.The circuit of the three phase inverter [3],[4],[5],[11].

Three phase inverter can be described as a combination of three independent single phase inverters. The waveform of voltage in three phases have square form each with amplitude value equal $\frac{1}{2}U_d$ and angle of duty $\lambda = 180^0$. They are transferring each other 120^0.The square waveform of voltage can be described by equation 3.2.47 and is shown in figure 3.2.34.

$$u_A = \frac{4\frac{1}{2}U_d}{\pi}(\sin\omega t + \frac{1}{3}\sin 3\omega t + \frac{1}{5}\sin 5\omega t + ...) \qquad (3.2.47)$$

If the neutral point of load (zero in U_A, U_B, U_C) will be connected with middle point 0 in the bridge (Fig. 3.2.33) the three and multiplication harmonics k=3n will not be eliminated.

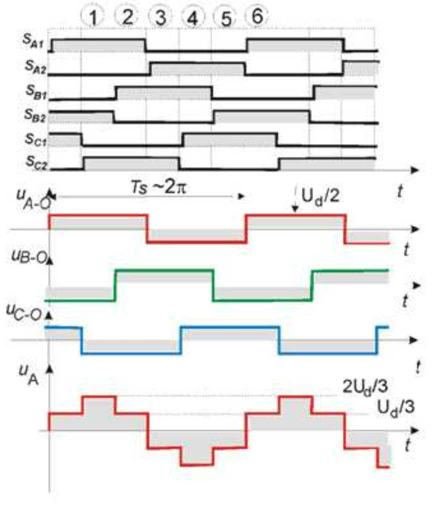


Figure 3.2.33. Square waveform of voltage of the three phase inverter [3],[4],[5],[11].

In figure 3.2.34 is presented the spectrum of output voltage for the connection of neutral point of load with with middle point 0 in the bridge.

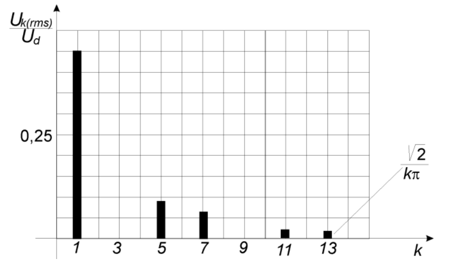


Figure 3.2.33. Spectrum of output voltage for of three phase inverter with connected neutral point [3],[4],[5],[11].

The output voltage for this circuit is estimated by:

$$U_A = \frac{4U_d}{3\pi}\sum(1+\cos\frac{\pi}{3})\frac{1}{k}\sin k\omega t \qquad (3.2.48)$$

where: *k* is number of upper harmonic.

The another method to change the output voltage waveform in a voltage-source inverter named PWM (Pulse Width Modulation). There is a fixed DC power source. The conducting phase of a transistor pair is interrupted by extra cycles of zero voltage. Zero voltage intervals can be achieved by switching off only one transistor of each switching pair, the other transistor is kept in conducting ststus. Another words PWM control is the method to control of amplitude of fundamental harmonic and as well spectrum of waveform by elimination harmonics of lower number. Idea of operating of this inverter is to approximate sinus form of output voltage by summary of very high frequency of switch on-off transistors in the period $T_s = \frac{1}{f_s}$. This method is shown in figure 3.2.34.

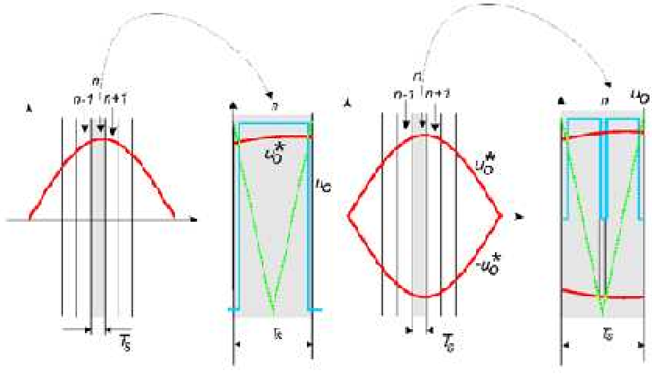


Figure 3.2.34.Idea of approximation of the sinus form of output voltage by using of a very high frequency of switch on-off (left for two transistor and right for four transistor bridge) respectively [3],[4],[5],[11].

Status of "conducting" of switches (transistors) in the bridge are defined on the idea of compare (mostly) triangle or sawtooth wave u_p with sinus wave u_M. In the bridge to switch on-off are T1 and T2 valve used in alternately. The modulated output voltage of inverter are always bipolar impulse with value $\frac{U_d}{2}$, constant frequency f_s and modulated width of pulse. In figure 3.2.35 is presented idea of control of PWM inverter.

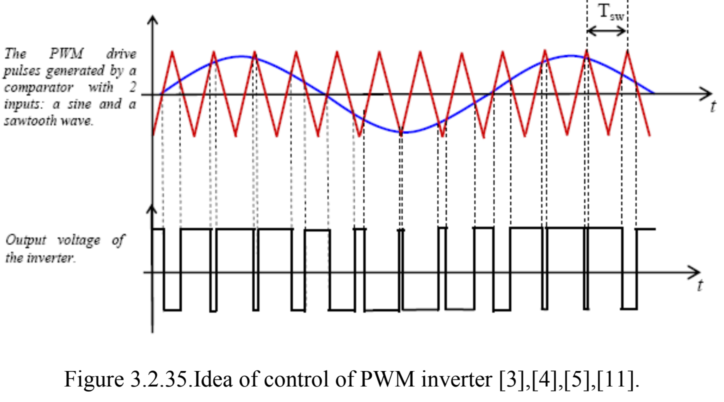


Figure 3.2.35.Idea of control of PWM inverter [3],[4],[5],[11].

The PWM type of control-modulation of inverter is described very often by two parameters – deepness of modulation of amplitude m_A and deepness of modulation of frequency m_f. This two parameters are calculated by:

$$m_A = \frac{u_M}{u_P} \qquad (3.2.49)$$

$$m_f = \frac{f_s}{f_1} \qquad (3.2.50)$$

where: u_M -max value of modulated signal
u_P -max value of triangle carry signal
f_s -frequency of triangle carry signal
f_1 - frequency of modulated signal

The PWM method of control determine the waveform of output voltage and current. Both the voltage and the current are non sinusoidal signals what in the consequence generated upper harmonics. In figure 3.2.36 are shown waveform of voltage u_M, u_P, and output voltage u_0 and current i_0.There are presented the spectrum of this signals as well.

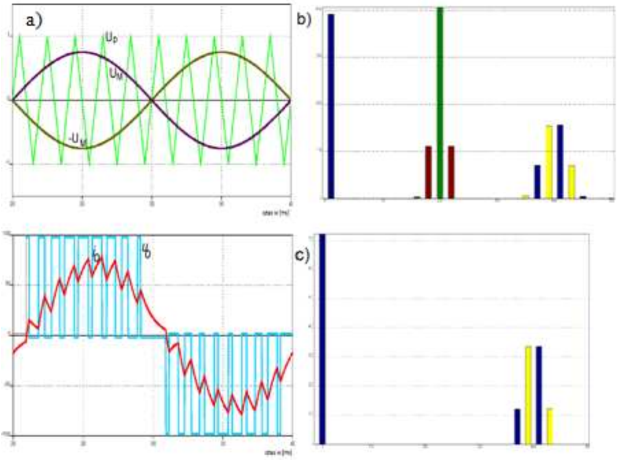


Figure 3.2.36.The waveform of output voltage and output current of the inverter a) and spectrum voltage for two switches b) and four switches [3],[4],[5],[11].

It seems that with this type of modulation it can be controlled the spectrum of signals and the upper harmonics very high frequency depend to frequency of modulation. If there will be used three phase bridge as in figure 3.2.33 than the output current will be more soft, because the spectrum of upper harmonics is transferred to more high frequency. The idea of creating of output impulse in this case is the same like for one pulse, but signals are transferred in 120^0 in each phase. The bellow figures show an example of the output voltage and the output current waveforms. In this case because the load is inductive (a motor), the current will lag behind the fundamental waveform of the motor voltage. The four ant parallel diodes are necessary to ensure a continuously conducting of the current.

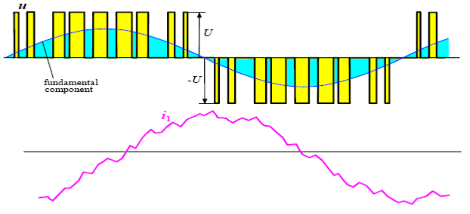


Figure 3.2.37.Example of the waveform of the output voltage and the output current of an inverter with PWM modulation [3],[4],[5],[11].

Finally in figure 3.2.38 is presented schematic idea of varying of amplitude and frequency.

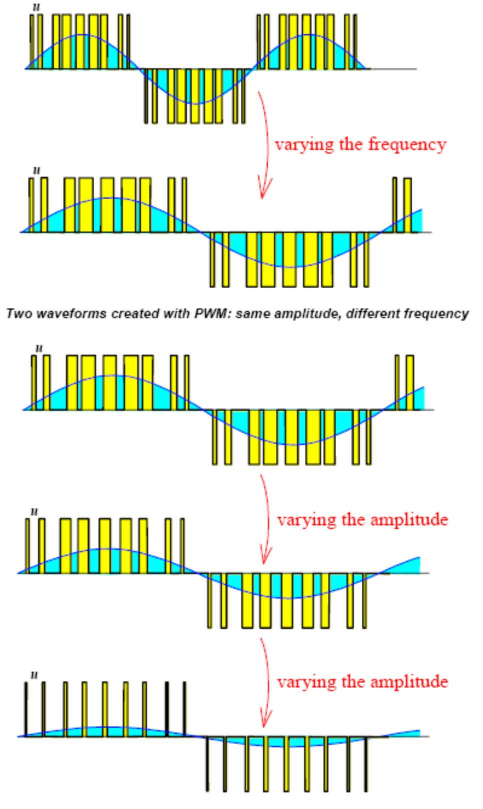


Figure 3.2.37.The idea of amplitude and frequency variation [3],[4],[5],[11].

In the last years very popular are control of inverters and drives by the method of space vector modulation. This method of control is presented in figure 3.2.38. There is the bridge circuit (schematic with valves A,B,C) and diagram of space vector V_{ref} . There is enclosed the table of status of valves $A^{+}, B^{+}, C^{+}, A^{-}, B^{-}, C^{-}$ and the value of operated vector V_S .

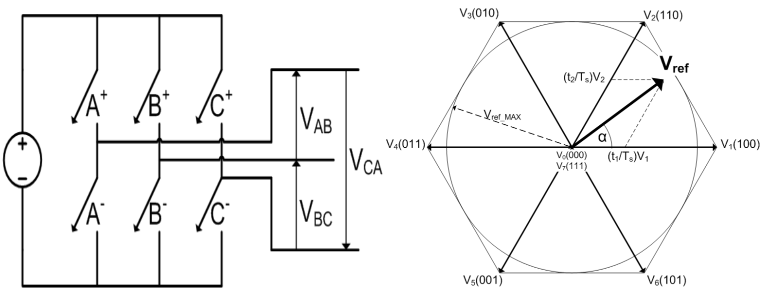


Figure 3.2.38.The method of space vector modulation [3],[4],[5],[11].

Table 3.1.The status of valves $A^{+}, B^{+}, C^{+}, A^{-}, B^{-}, C^{-}$ and the value of operated vector V_S .

Vector	A^+	B^+	C^+	A^-	B^-	C^-	V_{AB}	V_{BC}	V_{CA}	
V_0 = {000}	OFF	OFF	OFF	ON	ON	ON	0	0	0	zero vector
V_1 = {100}	ON	OFF	OFF	OFF	ON	ON	$+V_{dc}$	0	$-V_{dc}$	active vector
V_2 = {110}	ON	ON	OFF	OFF	OFF	ON	0	$+V_{dc}$	$-V_{dc}$	active vector
V_3 = {010}	OFF	ON	OFF	ON	OFF	ON	$-V_{dc}$	$+V_{dc}$	0	active vector
V_4 = {011}	OFF	ON	ON	ON	OFF	OFF	$-V_{dc}$	0	$+V_{dc}$	active vector
V_5 = {001}	OFF	OFF	ON	ON	ON	OFF	0	$-V_{dc}$	$+V_{dc}$	active vector
V_6 = {101}	ON	OFF	ON	OFF	ON	OFF	$+V_{dc}$	$-V_{dc}$	0	active vector
V_7 = {111}	ON	ON	ON	OFF	OFF	OFF	0	0	0	zero vector

In figure 3.2.39 is presented as an example the practical issue of the current source inverter in a drive train of an Electrical Vehicle.

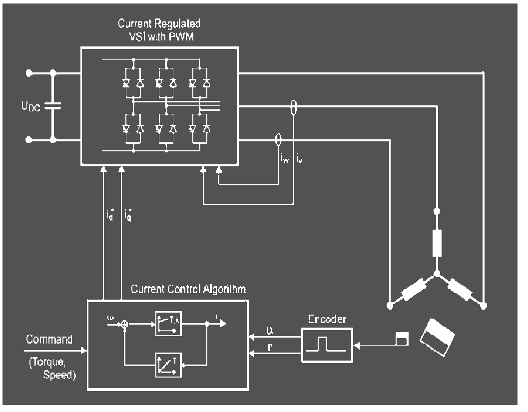


Figure 3.2.39.The current source inverter in a drive train of an Electrical Vehicle [30].

4. THE ELECTRICAL MACHINES

The motor is the main component of an electric vehicle (EV). It is very important to select the proper type of motor with a suitable rating. It is also confusing to compare electric motors to internal combustion (IC) engines, since electric motors are given a continuous rating under load, and IC engines are rated at their peak horsepower under unloaded conditions. In the figure 4.1 is presented the diagram of various types of electrical machine used in hybrid and electrical vehicles.

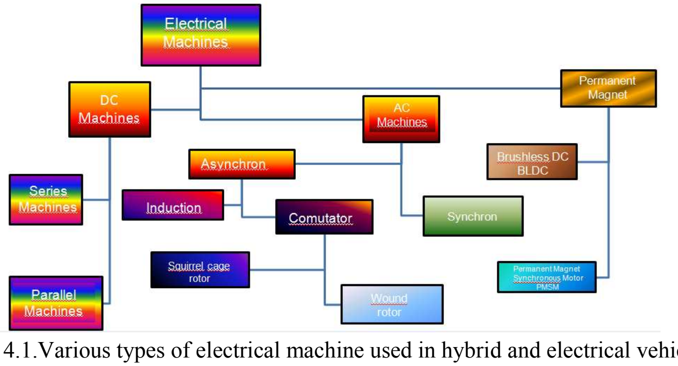


Figure 4.1.Various types of electrical machine used in hybrid and electrical vehicles.

Only few of all of families of electrical machines will be describes in this chapter. The first of all conventional machines the DC and then the AC.

4.1. DC motors

DC motors consist of rotor-mounted windings (armature) and stationary windings (field poles). In all the DC motors, except permanent magnet motors, the current must be conducted to the armature windings by passing current through carbon brushes that slide over a set of copper surfaces called a commutator, which is mounted on the rotor. The commutator bars are soldered to armature coils. The brush/commutator combination makes a sliding switch that energizes particular portions of the armature, based on the position of the rotor. This process creates north and south magnetic poles on the rotor that are attracted to/ or repelled by north and south poles on the stator, which are formed by passing direct current through the field windings. It is this magnetic attraction and repulsion that causes the rotor to rotate. In figure 4.1.1 are presented the model of conventional the DC motor with two and four sectors.

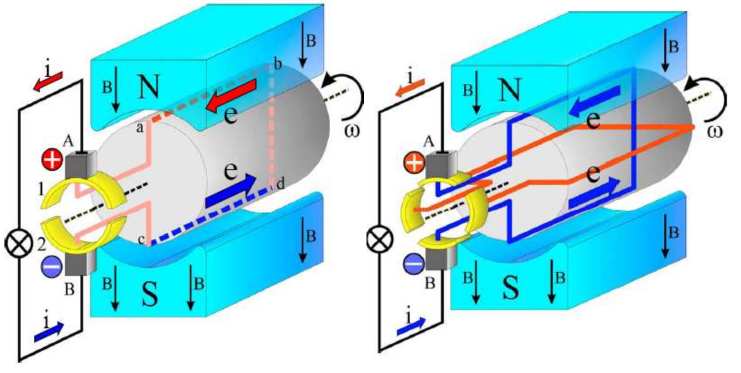


Figure 4.1.1. The model of conventional DC parallel motor with two and four sectors [12].

During the work of the DC parallel shunt machines it is inducted electromotoric force (EMF) **e** with waveform what is presented on figure 4.1.2.

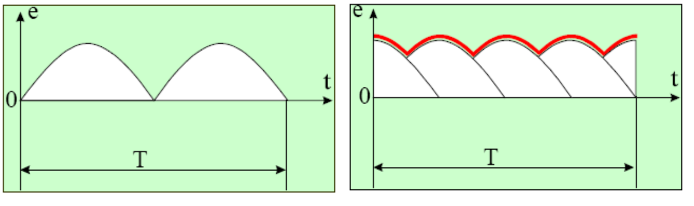


Figure 4.1.2.The waveform of electromotoric force **e** for the model in figure 4.1.1[12].

In figure 4.1.3 is presented in detail the phenomena what occurs in the space magnet N-S with equivalent circuit of parallel shunt DC motor.

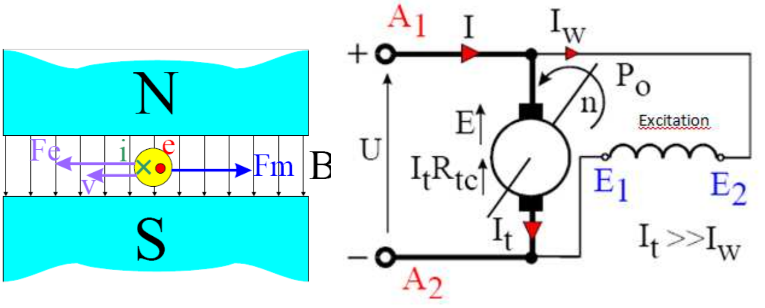


Figure 4.1.3.The phenomena in the space of magnet N-S with equivalent circuit of parallel shunt DC motor (right) [12].

For the circuit can be written with presumption that:

$$E = c_E \cdot \phi \cdot n \tag{4.1.1}$$

$$M_e = c_M \cdot \phi \cdot n \tag{4.1.2}$$

where: E -electromotoric force
ϕ -exctitation-field
n–speed of rotor (revolutions per minute)
c_E, c_M construction parameters

For the equivalent circuit of the DC motor presented in Figure 4.1.3 supplying voltage U can be calculated as:

$$U = E + I_t \cdot R_{tc} = c_E \cdot \phi \cdot n + I_t R_{tc} \tag{4.1.3}$$

and

$$n = \frac{U - I_t \cdot R_{tc}}{c_E \cdot \phi} = \frac{U - \frac{Me}{c_M \cdot \phi} R_{te}}{c_E \cdot \phi} = \frac{U}{c_E \cdot \phi} - \frac{R_{te}}{c_M \cdot c_E \cdot \phi^2} M_e \tag{4.1.4}$$

In figure 4.1.4 is presented the mechanical characteristic of the DC parallel shunt motor.

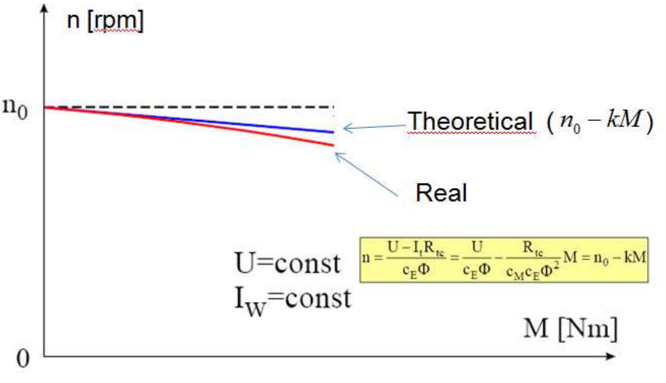


Figure 4.1.4. Mechanical characteristics of the DC parallel shunt motor [12].

When motor is in start up operating status what means $n = 0$ and the current of the motor I_t is described as:

$$I_t = \frac{U - E}{R_{tc}} = \frac{U - c_E \cdot \phi \cdot n}{R_{tc}} \qquad (4.1.5)$$

From equation 4.1.1 to 4.1.4. occurs that speed can be controlled by resistance including in circuit of rotor what is ease ,but not economically and is used rather rarely. Sometimes for control is used circuit of excitation, but in this case is dangerous of non control speed if this circuit is broken. Usually control of the speed is done by controlling of the supplying voltage. It can be done by rectifiers. In the figure 4.1.5 are presented control characteristic of the DC motors.

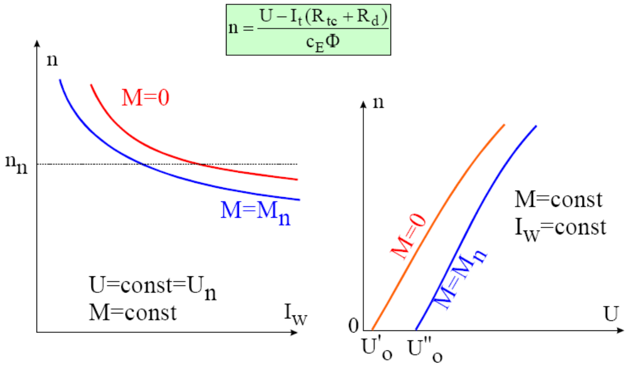


Figure 4.1.5.Control characteristics of the DC motors [12].

4.2. Induction motors

Induction motors are the alternating-current motors in which a primary winding on one member (usually the stator) is connected to the power source, and a secondary winding on the other member (usually the rotor) carries only current induced by the magnetic field of the primary. Most popular IM are asynchronous motors, i.e., the speed of the rotor is almost equal, but lower, than the speed of the electromagnetic field created by stator windings. The induction motor has two main parts; a stationary part called the stator and a rotating part called the rotor, to which the mechanical load is connected. The stator has windings slotted into a segmented iron frame to reduce the eddy current and magnetic losses. The windings establish a rotating magnetic field necessary to circulate the current, by induction, into rotor windings. The stator winding absorbs the electric power needed to balance the mechanical torque. The rotating part carries the rotor windings. Two various rotor types can be found:

- Wound rotor

In this type the rotor windings are again slotted into a segmented iron frame and connected together at one end externally.

- Squirrel cage rotor

This type is simply a shorted aluminium bar. The bars are housed in a slotted iron frame. This is the most common type due to its rigidity and simple construction, and is known as the squirrel cage induction machine.

The stator is a classic three phase stator with the winding displaced by 120°.The most common type of induction motor has a squirrel cage rotor in which aluminum conductors or bars are shorted together at both ends of the rotor by cast aluminum end rings. The equation described status of operation of AC machines are using a new parameter called slip s , what is defined as:

$$s = \frac{n_1 - n}{n_1} \qquad (4.1.6)$$

where: n_1-speed of field of stator

n -speed of rotor

The electromagnetic torque M can be described as:

$$M = F \cdot r \qquad (4.1.7)$$

where: M- electromagnetics torque

F- electromagnetic force on the radius of rotor

r- radius of rotor

Than the electromagnetic power P is described as:

$$P = \frac{W}{t} = \frac{F \cdot l}{t} = F \cdot v = F \cdot \omega \cdot r = F\frac{\pi \cdot n}{30} r = \frac{M}{r}\frac{\pi \cdot n}{30} r = M\frac{\pi \cdot n}{30} \qquad (4.1.8)$$

and

$$M = \frac{30P}{\pi \cdot n} = 9{,}55\frac{P}{n} \tag{4.1.9}$$

where:

P- electromagnetics power

M- electromagnetics torque

In figure 4.1.6 is presented characteristic of work of induction motors as the torque *M* of machine in the function of speed *n* or slip *s*.

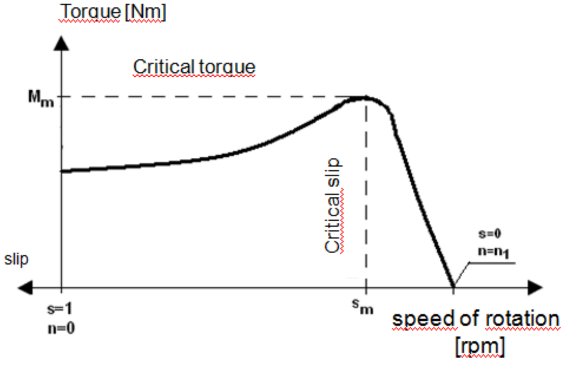


Figure 4.1.6. Torque versus speed [8].

For controlling the voltage *U* supplying the IM motor its occurs the family of characteristics. There is an example of it presented in figure 4.1.7.

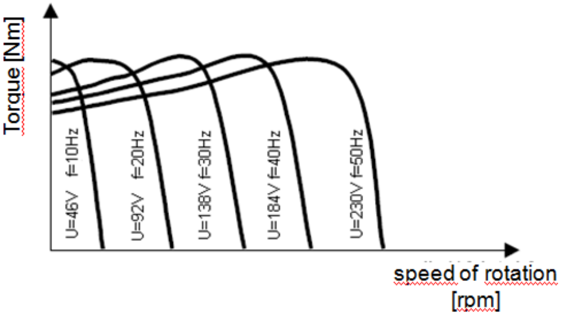


Figure 4.1.7. Family of torque characteristics versus speed [8].

Usually it is used equation describing of torque in the function of slip known as a Kloss equation:

$$\frac{M}{M_m} = \frac{2}{\frac{s}{s_m} + \frac{s_m}{s}} \qquad (4.1.10)$$

For the presented in figure 4.1.7 characteristics is important to fulfill condition as:

$$\frac{U}{f} = const \qquad (4.1.11)$$

$$n = n_1(1-s) = \frac{60 \cdot f}{p}(1-s) \qquad (4.1.12)$$

where: p is number of double pools

In figure 4.1.8 is presented as an example the practical issue of the drive with induction machine.

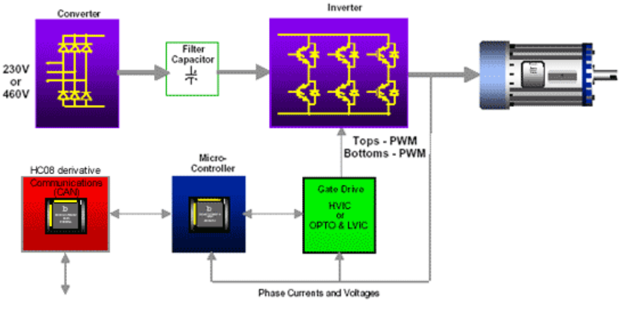


Figure 4.1.8. Three-phase AC induction motor driven by a power converter [31].

4.3. Brushless DC motors (BLDC) and permanent magnet synchronous motors (PMSM)

Permanent magnet (PM) motors are one of the motor types rapidly gaining popularity. The PM motors are used in industries such as appliances, automotive, aerospace, consumer, medical, industrial automation equipment and instrumentation. The PM motors have many advantages over the brushed DC motors and induction motors. A few of these are:

1. Better speed versus torque characteristics.
2. High dynamic response.
3. High efficiency.
4. Long operating life.
5. Noiseless operation.
6. Higher speed ranges.

In addition, the ratio of torque delivered to the size of the motor is higher than in brushed motors and making it useful in applications, where space and weight are critical factors. The BLDC motors are a type of synchronous motor.

This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotate at the same frequency. The BLDC motors do not have the "slip" that is normally seen in induction motors. The BLDC motors can be done in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. So most of the BLDC motors have three stator windings connected in star fashion. Each of these windings are constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings are distributed over the stator periphery to form an even numbers of poles. There are two types of stator windings variants: trapezoidal and sinusoidal motors. In figure 4.1.9 are presented trapezoidal and sinusoidal signal of phase voltage describes earlier.

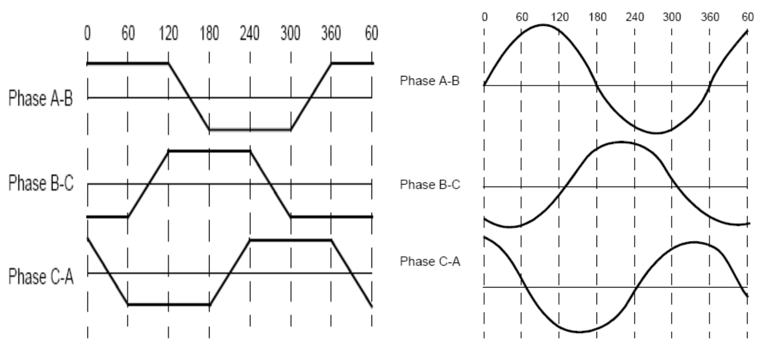


Figure 4.1.9.The electromotive force for the BLCD trapezoidal (left) and sinusoidal (right) [7],[8],[33],[35].

The idea of construct of brushless electrical motors is to replace of electromechanical commutator by electronic circuits. This circuit should be equipped with Hall sensors to control of operational status what means the waveform of signals in the electrical machines. Very often this machines are called conventional with electronic commutator. There are many different solutions of brushless motors, where in figure 4.1.19 are presented two more typical.

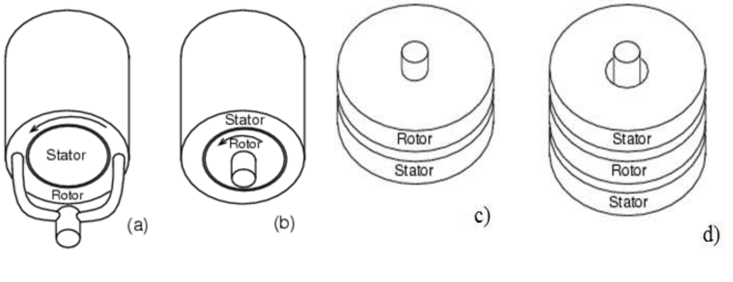


Figure 4.1.10. The cylindrical construction: (a) outside rotor, (b) inside rotor and Pancake motor construction: (a) single stator, (b) double stator [33],[35],[48].

For understanding of Hall sensors in figure 4.1.11 is presented schematic circuits of brushless motors with connection of them. To rotate the BLDC motor, the stator windings should be energized in a right sequence. It is important to know the rotor position in order to which winding will be supplied. Rotor position is sensed using Hall effect sensors embedded into the stator.

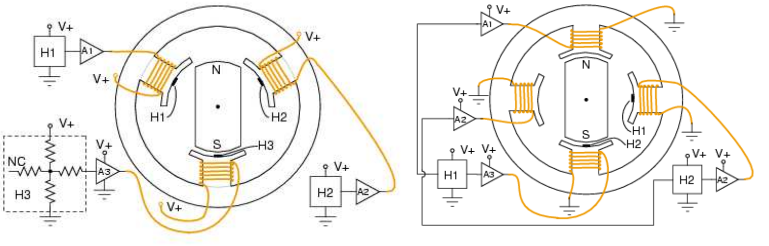


Figure 4.1.11.The Hall effect sensors commutation of 3-φ brushless motor (left) and 2-φ push-pull drive (right) [7],[8],[33],[35] .

The Hall sensors are normally mounted on a PC board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors to align with the rotor magnets, in order to achieve the best performance. It was shown in figure 4.1.12.

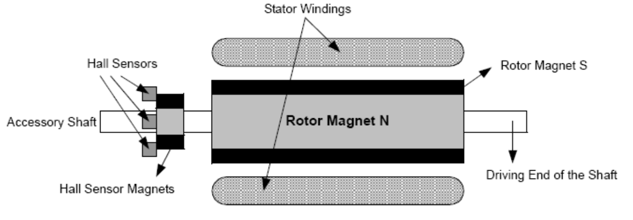


Figure 4.1.12. Schematic of the motor transverse section[33],[35],[48] .

The status of operation of brushless motors depend to present method of control of the voltage and the current. The Hall sensors make control of the current conduction in the coils depend to rotation of rotor (in the consequence of reaction of magnetic field of coils and the concrete magnet of stator). It means that the torque of rotation is fluked between maximum and zero. It can make some problems with starting of the motors. For solving of this problem is used multilevel parts coil. Coming back to control of the motors the physical position of the Hall sensors, there are two versions of output. The Hall sensors may be at 60° or 120° phase shift to each other. Based on this, the motor manufacturer defines the commutation sequence, which should be followed when controlling the motor. For this reason it is used two different methods of control what is called unipolarity and bipolarity. In figure 4.1.13 is show the main circuit of two phase of this two forms of motor. This is the equivalent version of motors presented in the figure 4.1.11.

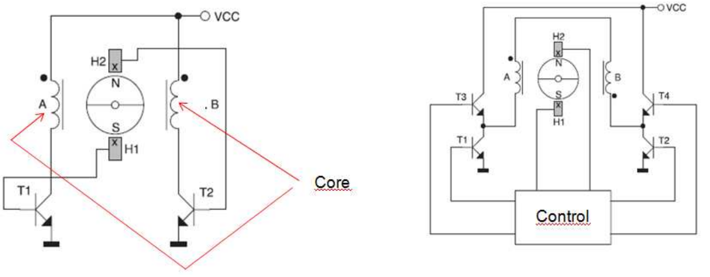


Figure 4.1.13.The main circuits of control BLCD machines: unipolar (left) and bipolar (right) [7],[8],[33],[35].

For understanding of the control of machines important is to know waveform of the current depend of time. In figure 4.1.14 are presented the current waveform of two and three phase of unipolarity (a and b) and three phase of bipolarity (c) method of control.

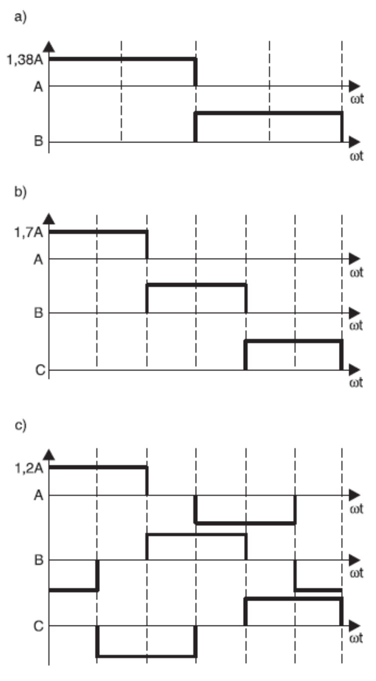


Figure 4.1.14.The current waveform a)two phase unipolar ,b)three phase unipolar, c)three phase bipolar [6],[7],[8],[33],[35].

The rotor position is usually detected by Hall Sensors. The Hall sensors directly detect the commutation moment. The presented application use the Quadrature Encoder to sense the rotor position. Therefore, the rotor position must be translated and to determine the commutation moment. The coils in the case of three phase motor are connected in stern circuit. For three phase bridge and stern circuit coil the direction of conduction of the current is given in figure 4.1.15.

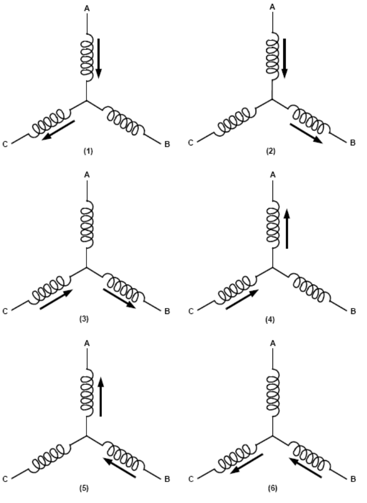


Figure 4.1.15. The winding energizing sequence with respect to the hall sensor [7],[8],[33],[35].

Control of the machines can be deviated in two groups : unipolarity and bipolarity what was mentioned. The angle of duty can be transferred in plus minus 60 and 120 degrees. Both of upper deviation is shown in figure 4.1.15.

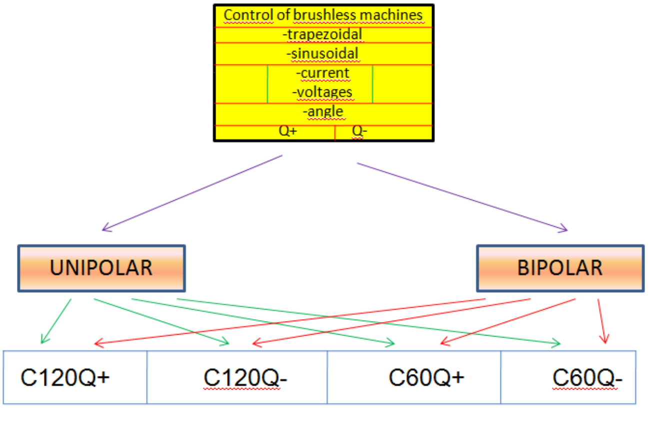


Figure 4.1.16. Methods of control of brushless machines.

If in the described method controlled value is current - it is indicated by "C" , if voltage by "V". Most popular and described in this material is C-method. From another way if the current value is controlled during 120° of electric angle it is indicated by symbol "120" if during 60° by "60" as well. Finally if function of control is provided by valves of positive group (above valves in Fig 4.1.16) it is indicated by “Q+” ,if by negative (bellow valves in Fig 4.1.16) “Q-“. If at the same time function of control is done by two groups of valves (above and below) this method of control is named bipolar and have no special symbol. The strategy of control of valves are the same for current and voltage one.

For example in figure 4.1.17 (left) is presented main circuit of six pulse bridge. The current value depend to sequence of conducting of transistor are in the same figure (right).

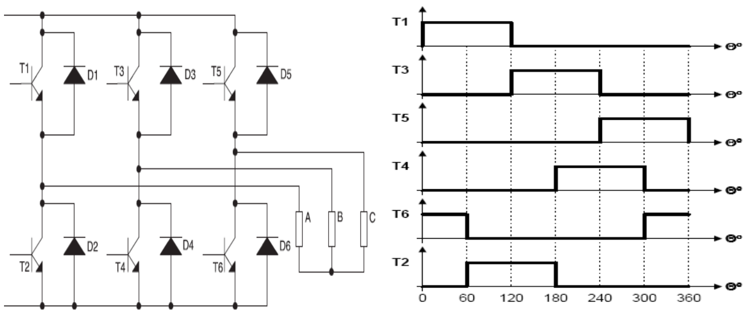


Figure 4.1.16. The six pulse full bridge (left) and general sequence of switching of transistor (right) [6],[7],[8],[33],[35].

Practical issue of the control and especially sequence of switching of transistors for strategy C120Q+ , C120Q–, C60Q+ and C60Q– are some modification of presented above method and is given in figure 4.1.17. The valve of positive group must to have the function of control in the method of sequence C120Q+ and C60Q+ as well. The negative valve group at the same time have function of commutation only ,it means are in switch on status. Than in the sequence C120Q–, C60Q– the negative valve group must to have the function of control and the positive group have the function of commutation only. This method is relatively easy ,but sometimes make many problems with troubleshooting, because of nonsymmetrical use of valve (only one group is working with high frequency in the same time).

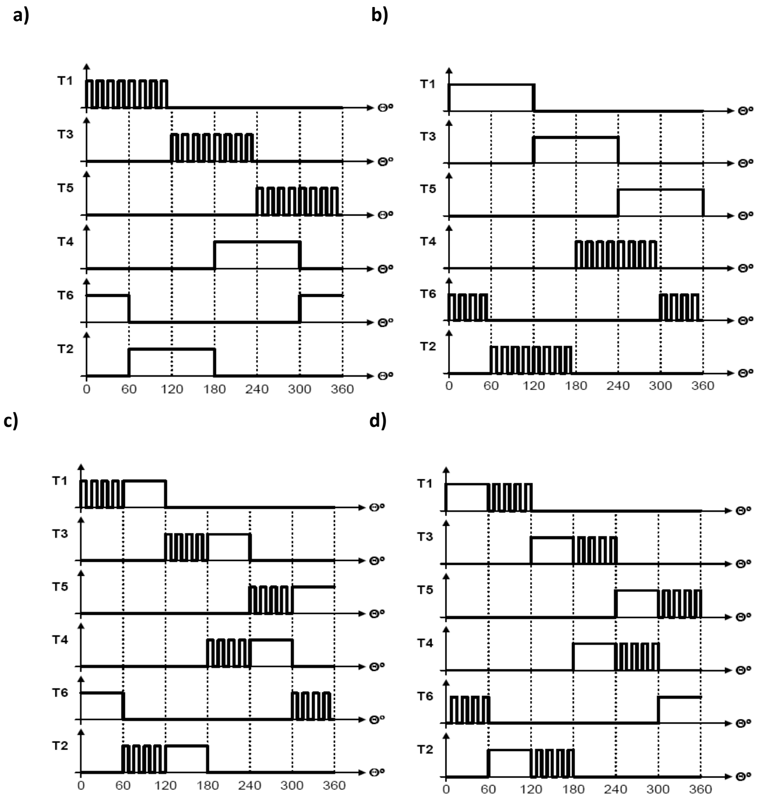


Figure 4.1.17. The sequence of control of unipolar status switching of valve a) C120Q+ sequence, b) C120Q– sequence, c) C60Q+ sequence, d) C60Q– sequence [6],[7],[8],[33],[35].

It was mentioned that in unipolar sequence of control the valves are working in nonsymmetrical mode. This is the reason that often it is used bipolar method of control. In this case all valves are operating in the same condition. Also the quality of control is better than in unipolar status. Of course in bipolar sequence method of control of motor the condition of work of machine are different than in unipolar. To have the same quality of operation of machine especially torque ripple constants, it is necessary to control with higher frequency than in unipolar (usually 50 %). In figure 4.1.18 is presented the method of sequence control of six pulse bridge in bipolar mode of control.

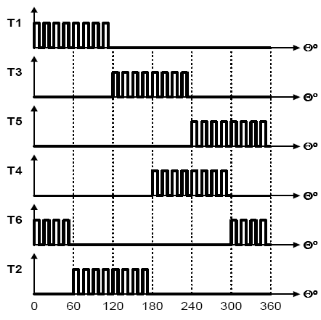


Figure 4.1.17. Sequence of control of bipolar status switching of valve .[6],[7],[8],[33],[35].

The equivalent to above presented method of control is to observe the electrical circuit of machine controlled in unipolar and bipolar mode what is presented in figure 4.1.18.

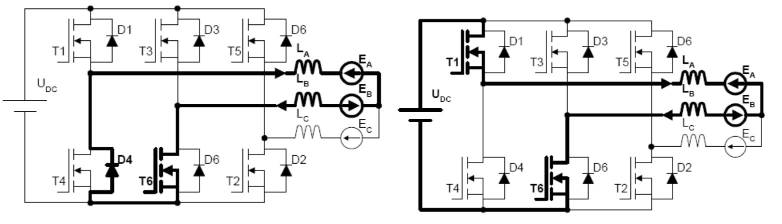


Figure 4.1.18. Electrical circuit of machine controlled in unipolar (left) and bipolar (right) mode [6],[7],[8],[33],[35].

Of course in each mode of control can be different switched on-off combination of elements between one or two groups. This means that it can be mixed transistor-diode or transistor-transistor or finally diode-diode sequences. For practical reason it is necessary to calculate time of turn on and turn off of valves. It can be estimated on the base of waveform of the current value for two mode of control and six phase bridge. In figure 4.1.19 is presented waveform of current in one phase with indicated moment of time (t_{on}) and time (t_{off}).

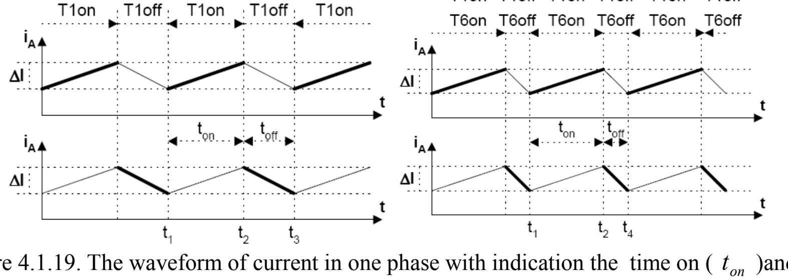


Figure 4.1.19. The waveform of current in one phase with indication the time on (t_{on})and the time off (t_{off}) for unipolar (left) and (bipolar) mode of control [6],[7],[8],[33],[35].

Than it can be written on the base of electrical circuits (Fig.4.1.18) and its waveform (Fig.4.1.19) for unipolar mode as:

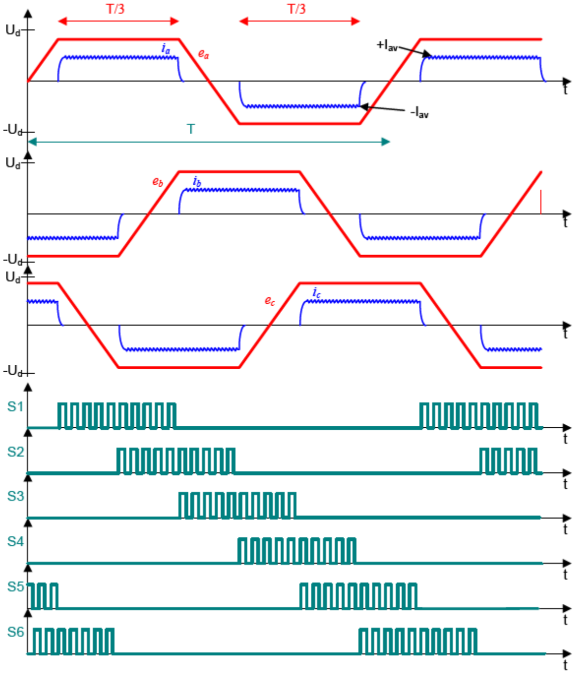
$$t_{on} = \Delta I \frac{2L}{U_{DC} - 2 \cdot E} \tag{4.1.13}$$

$$t_{off} = \Delta I \frac{L}{E} \tag{4.1.14}$$

For bipolar mode time on (t_{on}) are estimated in the same way as in unipolar , but time off (t_{off}) is described as:

$$t_{off} = \Delta I \frac{2L}{U_{DC} - 2 \cdot E} \tag{4.1.15}$$

The real application is presented in figure 4.1.20. There are waveform of phase currents and back electromotive force BEF with form of impulse of inverter for bipolar mode of control.



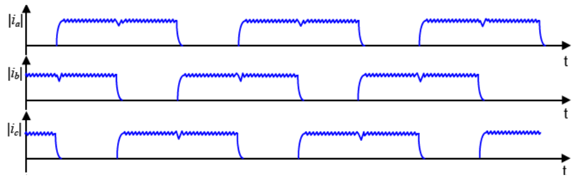


Figure 4.1.20.The real waveforms of the phase currents and back electromotive force BEF with form of impulse of bipolar mode control.

In figure 4.1.21 is presented practical application of control of brushless motors in the hybrid vehicles on the example of HONDA Civic IMA and the motor/generator used in the car. In the same figure is presented control unit with inverters supplying motor and generator in TOYOTA Prius III as well.

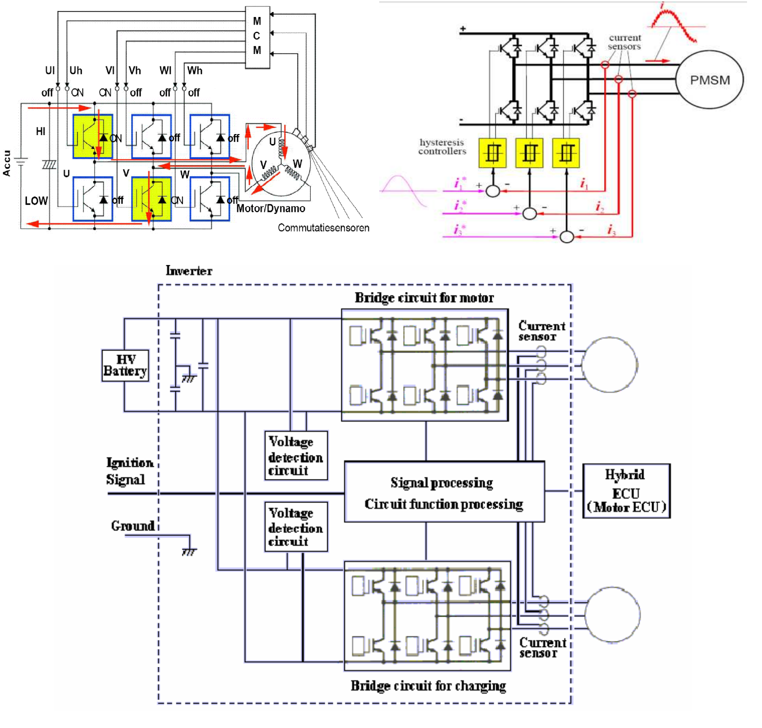


Figure 4.1.21.The inverter supplying motor/generator of Honda Civic IMA (above left) with detailed of control of brushless motor current (above right), control unit with inverters supplying motor and generator in TOYOTA Prius III (bellow) [29],[35].

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