CarEcology: New Technological and Ecological Standards in Automotive Engineering

Module 3.Alternative Drive Systems

Electrical on-board power supply

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1. Introduction

With the continuous improvement of safety and comfort features, the amount of the different electrical consumers (drives, actuators, heating resistors, lamps) can already reach the number of 100 in an upper-class vehicle. Electrically actuated devices have some basic advantages in comparison with e.g. mechanical (hydraulic) actuators:

- Very low response time
- no power consumption, if not activated,
- high flexibility in speed/torque (force) characteristics)
- high efficiency

These advantages have lead to an extensive replacement of mechanical actuators by electrical ones. The expression “the belt less car” e.g. is a synonym for this trend, indicating the replacement of mechanically ICE-coupled drives by electrical ones.

The high level of “electrification” in modern vehicles leads to a considerable demand of electrical power which may reach to average values of more than 2 kW.
The different loads, which have to be supplied by the alternator/battery, can be considered as falling under three separate headings: **continuous, prolonged** and **intermittent**. Fig. 1 gives an overview of the most relevant consumers.

The high total value of the electrical loads points out the importance of the overall on-board electrical power efficiency from component level to system level.
One has to be aware of the high costs of electricity when it is produced “on-board”. Due to the poor overall system efficiency (combustion-engine+generator+battery) we must calculate with about 2 EUR per kWh compared to about 0,2 EUR per kWh for electricity from the home electricity outlet:

> What happens with 1 liter fuel which is used for producing electricity for auxiliary systems in a car, via an alternator?
>
> 1 liter fuel = 10 kWh
> Efficiency of the ICE: 20%
> Mechanical energy in the alternator = 2 kWh
> Efficiency of the alternator: 50%
> Electrical energy out the alternator = 1 kWh
> After being stored in a battery, remaining energy = 0,8 kWh
>
> 1 liter fuel costs 1,6 EUR
> 1 liter fuel produces 0,8 kWh of electric energy
> Thus 1 kWh costs 1,6/0,8 = 2 EUR.

This difference clarifies the high potential of improving the overall electrical on-board efficiency. In this chapter we will present state-of-the art technology of electrical generators, of starters and of the new combined starter-generators as well as of additional energy sources.

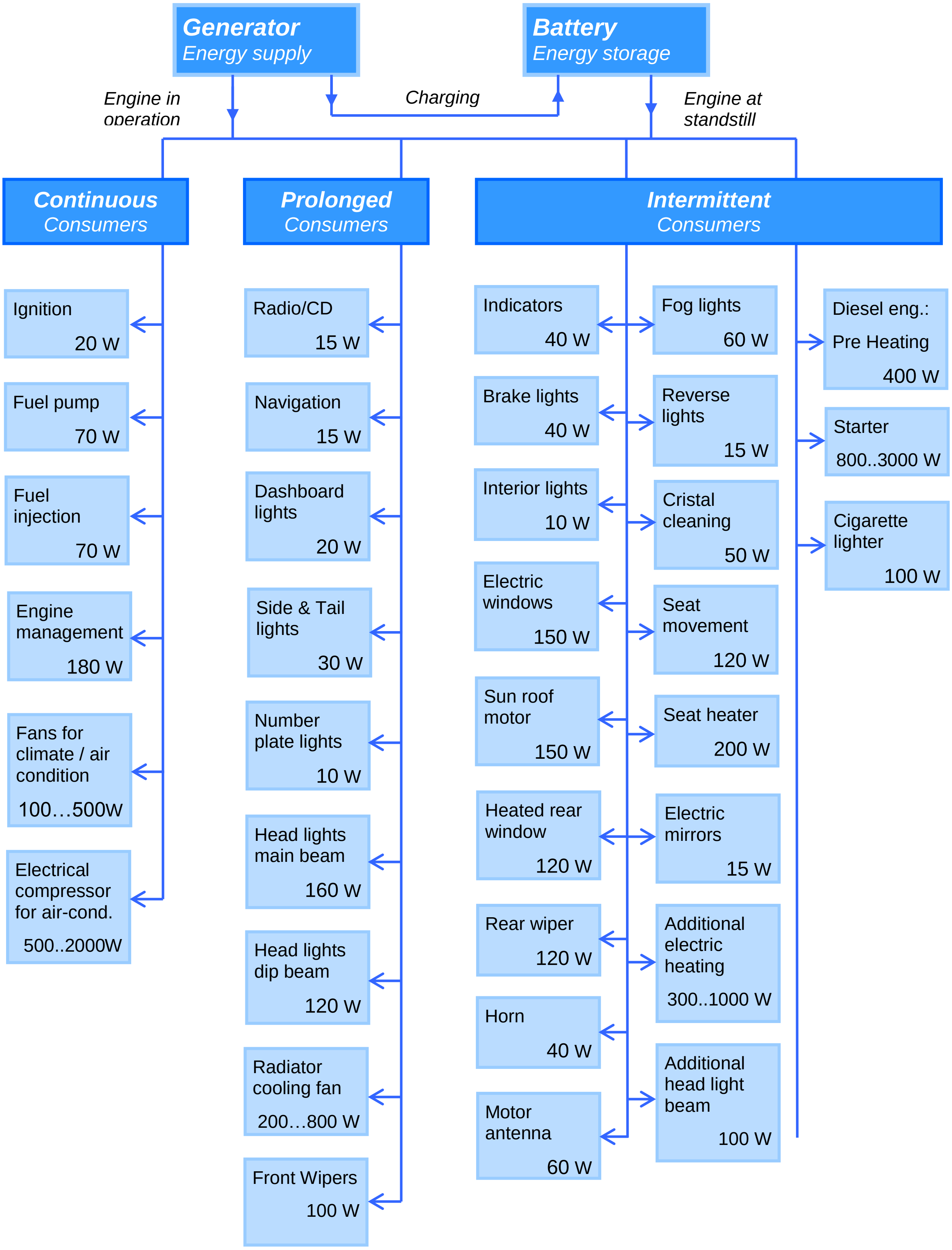


Fig. 1: Typical power requirements of electrical components (average values)

2. Generators (Alternators)

As shown in Fig. 1, the generator has to provide very high currents to cope with actual loads and to charge the battery at the same time. The charging system must meet this demand over the whole engine speed range including the idle mode.

To summarize, the following requirements have to be fulfilled by the charging system:

- Supply the current demands created by all loads
- Supply whatever charge current the battery requires
- Operate at idle speed of the combustion engine
- Supply constant voltage under all conditions
- Have an efficient power-to-weight ratio
- Be reliable, quiet, and have resistance to contamination
- Require low maintenance
- Provide an indication of correct operation

The standard solution for generating the on-board electricity is the wounded-rotor three-phase synchronous machine in combination with a three-phase diode rectifier.

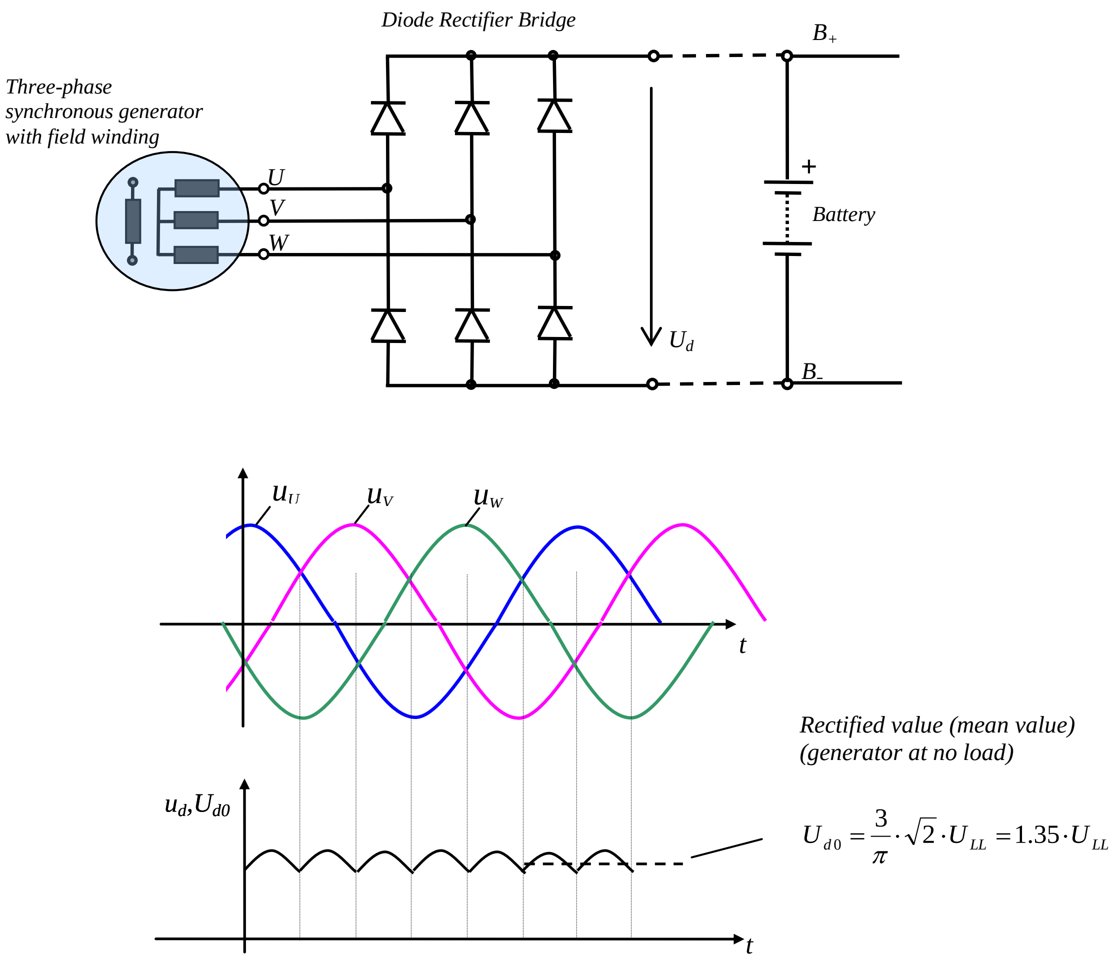
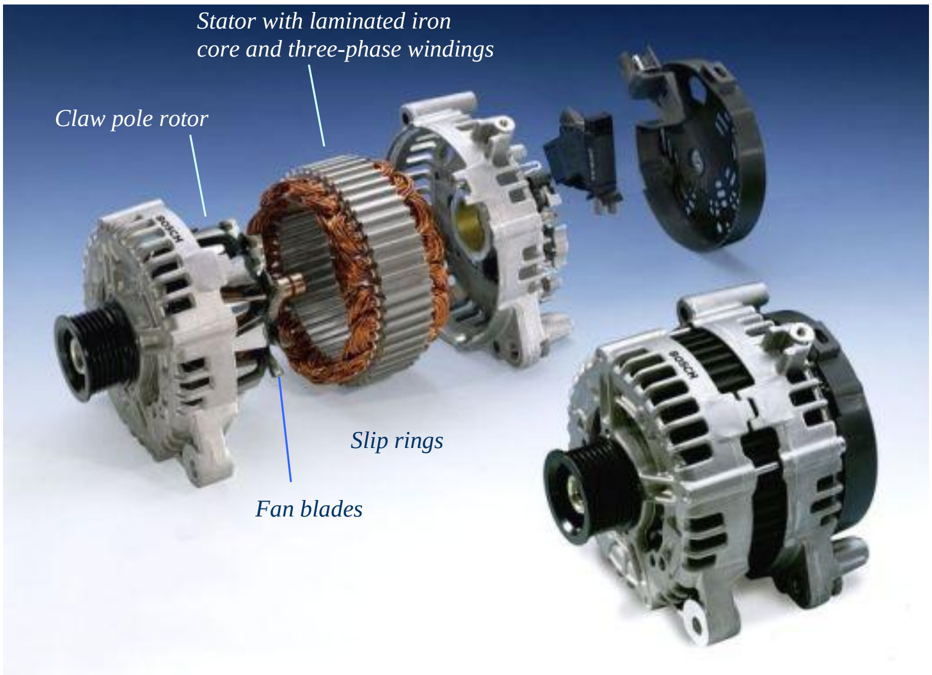
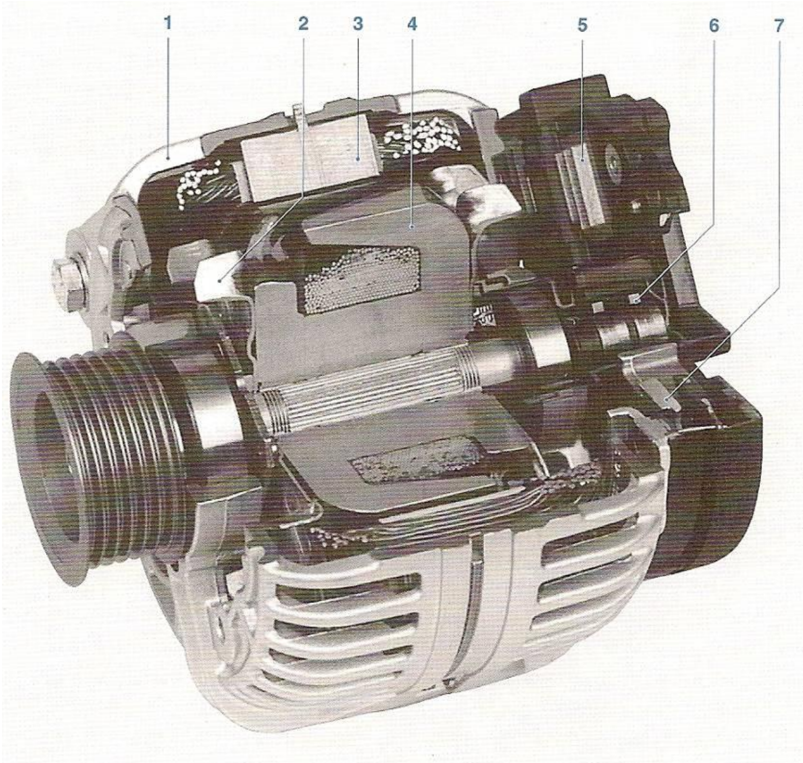


Fig. 2: Synchronous machine with three-phase rectifier

Fig. 3 shows the most common design, which is known as “claw pole rotor”. Due to the optimized efficiency they are commonly realised with 12 or 14 poles.





1 Housing with double-flow ventilation
2 Internal fan
3 Stator with laminated iron core
4 Claw pole rotor
5 Electronic controller
6 External slip rings
7 External rectifier

Fig. 3: “Compact-generator LIC-B” from Bosch
a) Exploded view and
b) Cutaway view

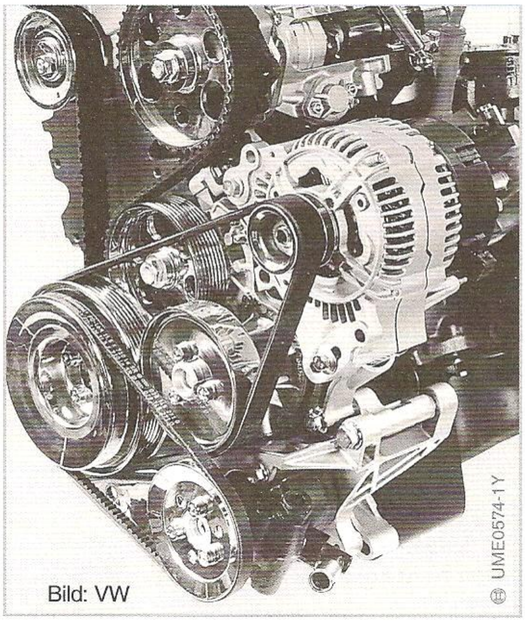


Fig. 4: Mounted "Compact generator"

Fig. 5 illustrates the claw pole rotor. It consists of a ring coil with the field windings and the two disks building up the magnetic poles. The field winding is supplied via slip rings.

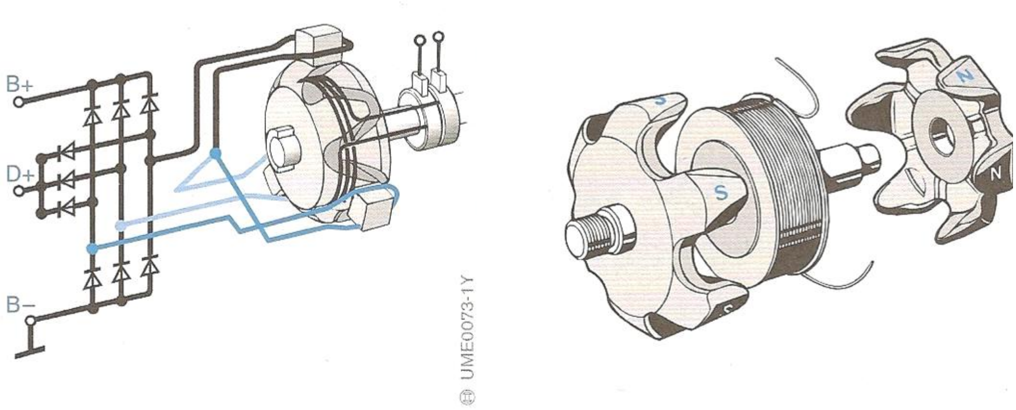
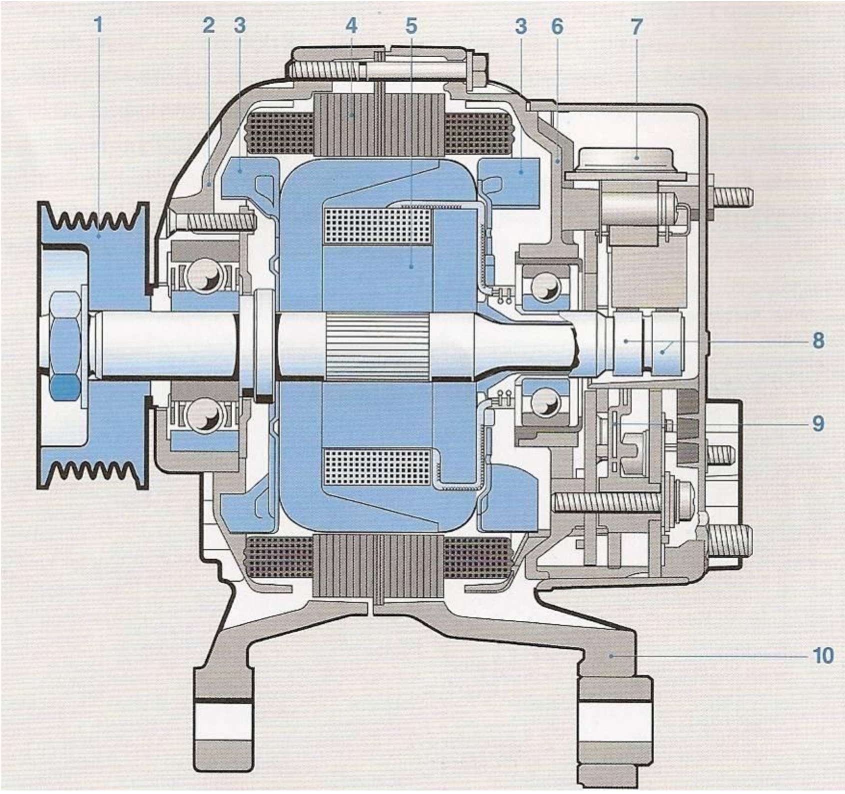


Fig. 5: Claw pole rotor with 12 poles



1 belt pulley for a ribbed V-belt
2 Bearing shield at drive side
3 Internal fan
4 Stator with laminated iron core
5 Claw pole rotor
6 Slip ring bearing shield
7 Electronic field current controller with brush fixture
8 Slip rings
9 Diode Rectifier
10 Swivel arm

Fig. 6: Drawing of a compact generator in cross-sectional view

2.1 Field excitation and output-voltage control

Fig. 6 shows the full alternator circuit using a Zener-Diode main rectifier and a standard bipolar diode field rectifier.

The Zener-Diodes act as over voltage protection breaking through at reverse bias voltages of e.g. 24V in case of a 14V system. They are able to cut-off voltage spikes and thus protect the generator, the voltage controller and other sensitive loads.

The warning light in the alternator circuit, in addition to its function of warning in case of charging faults, also acts to supply the initial excitation of the field windings. This pre-excitation circuit is necessary, as self-excitation from residual magnetism in the rotor coil might not be sufficient to induce enough voltage to overcome the 0.7 V needed to forward bias the rectifier diodes. Afterwards the power supply for the field winding is supplied separately via three diodes in order to make the field excitation circuit independent from the battery's state of charge

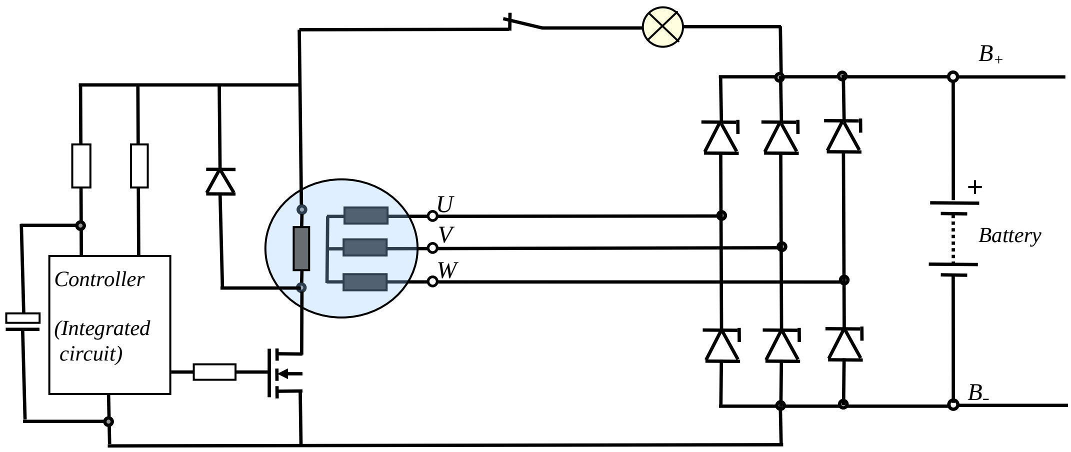


Fig. 7: Schematics of the field excitation circuits

To prevent the vehicle battery from being overcharged the regulated system voltage should be kept below the gassing voltage of the lead-acid battery. A figure of 14.2 +/-0.2 V is used for all 12V charging systems.

The output of an alternator without field regulation would rise linearly in proportion with engine speed. Generators with permanent magnets cannot be field weakened, that's why brushless machines (BLDC) are not used.

The output voltage of the alternator is proportional to the magnetic field strength and this, in turn, is proportional to the field current. Thus the task of the regulator is to control this field current in response to the output voltage.

This is accomplished by switching on and off the MOSFET with the corresponding duty cycle (step-down-converter principle: The current flows either over the transistor or - when the transistor is switched off- over the freewheeling diode).

The controller drives the MOSFET with a pulse-width-modulated signal (with e.g. 20kHz switching frequency) in order to supply the field excitation winding with an average voltage, that causes the appropriate field current. Due to high inductance of the field windings the current response is not very dynamic. This makes the design of the overall control loop a challenging task (e.g. rapid acceleration of engine speed could create overvoltages, when field weakening is not carried out dynamically enough).

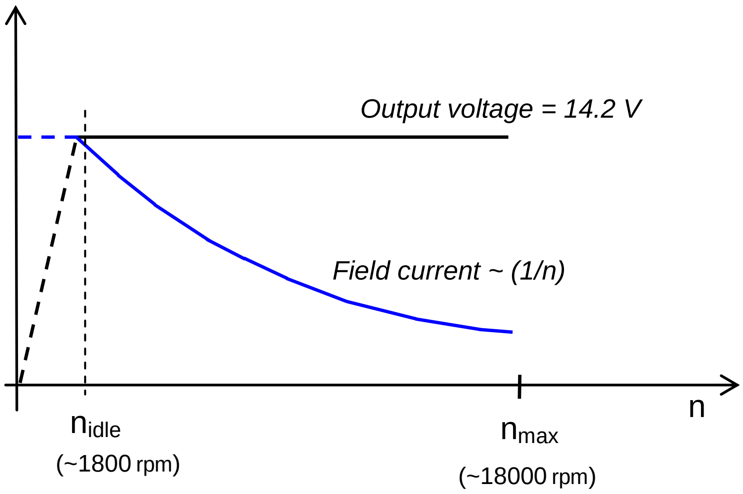
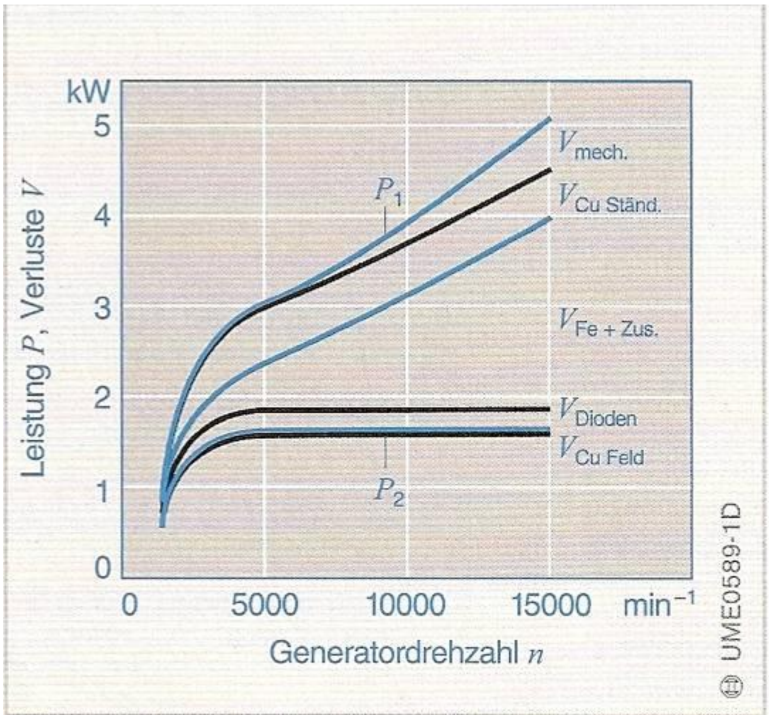


Fig. 8: Characteristics of field current vs. speed
(Compact-generator with a belt drive transmission ratio of ~ 3)

2.1 *Losses and Efficiency*

As volume and weight are critical parameters for every component in a vehicle, generators are designed in a very compact way providing high energy density. This however results in rather high losses and relatively poor efficiencies.

Fig. 9 gives an overview on the particular origins of losses.



P_1	*mechanical power (input)*
P_2	*electrical power (output)*
V_{mech}	*mechanical losses* *- friction in bearings and slip rings* *- air friction of rotor and fan*
$V_{Cu,Ständ}$	*stator winding losses*
V_{Fe+Zus}	*iron + additional losses*
V_{Dioden}	*rectifier losses*
$V_{Cu\ Feld}$	*field winding losses*

Fig. 9: Particular losses vs. speed

It is particularly noticeable, that iron losses are the absolutely dominating part of all loss components at higher speed. Maximum efficiency of an air-cooled generator only reaches values of about 65%. This efficiency however is decreasing rapidly towards lower values at higher engine revolutions. In practical driving operation the generator runs at partial load resulting in typical average efficiencies between 50% and 60%. Taking into account the combustion engine's efficiency we get overall values in the range of only 10 to 20% for the on-board generation of electricity in a vehicle.

Fig. 10 shows the relation between maximum current (which is proportional to the electrical output power) and the therefore necessary mechanical input power P_1 versus speed.

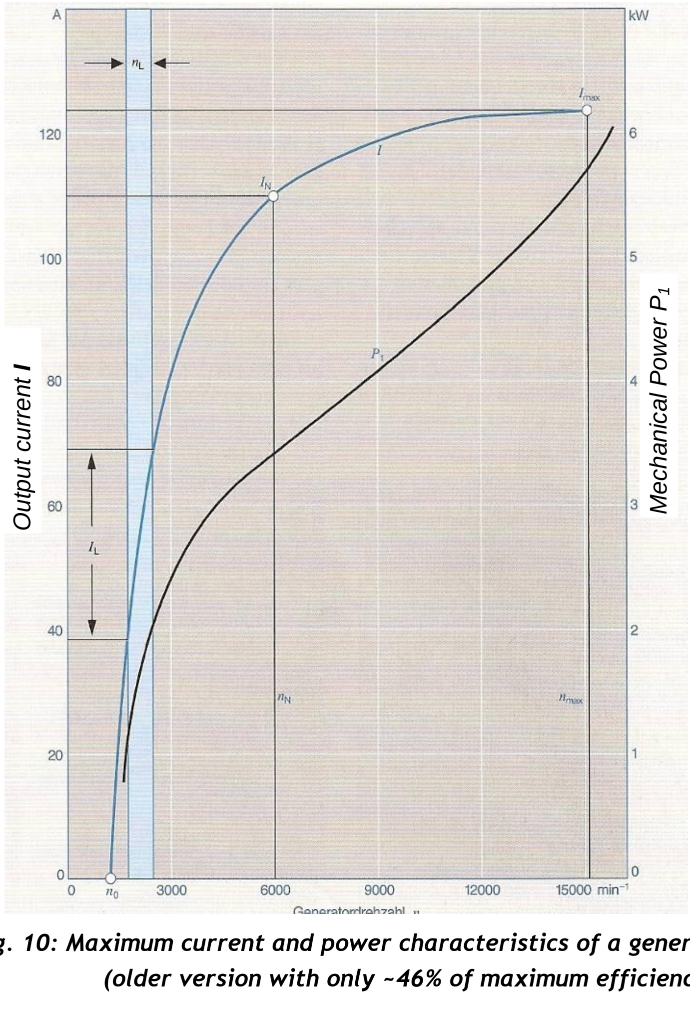
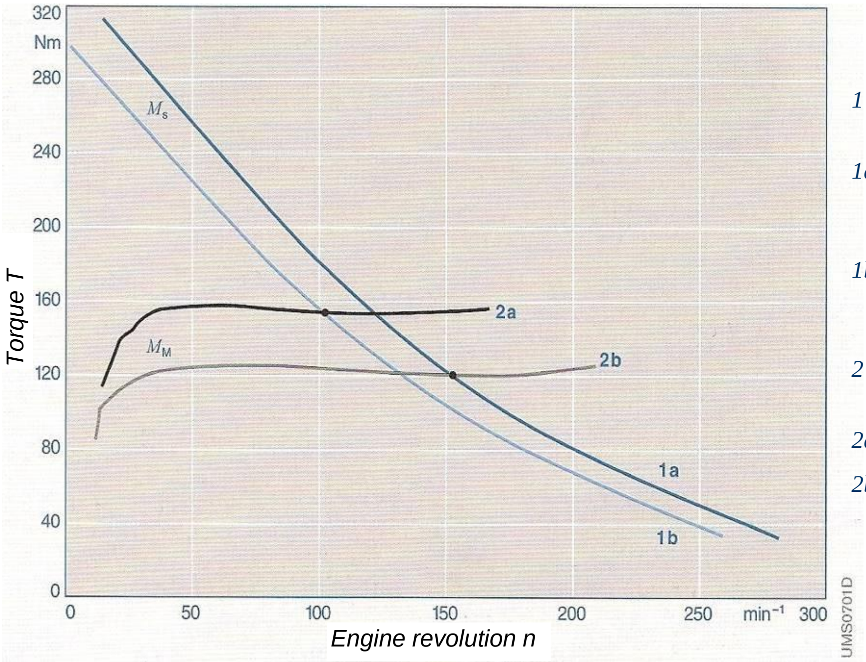


Fig. 10: Maximum current and power characteristics of a generator (older version with only ~46% of maximum efficiency)

3. Starting Systems

Combustion engines need external aid in order to start and to continue running. The applied torque must overcome the piston compression and high friction resistances, which depend on the viscosity of lubricants. Consequently, the cranking torque increases substantially as temperature decreases.

As starter motors are generally supplied by lead-acid batteries (showing a high internal resistance at low temperatures) typical starting limit temperatures lie in the range of -18°C to -25°C.



1 Starter torque M_s (available torque)

1a at -20°C, U_0 = 10,9V, R_i=4,5mΩ, R_{wire}=1,3mΩ

1b at -24°C, U_0 = 10,6V, R_i=5,6mΩ, R_{wire}=1,3mΩ

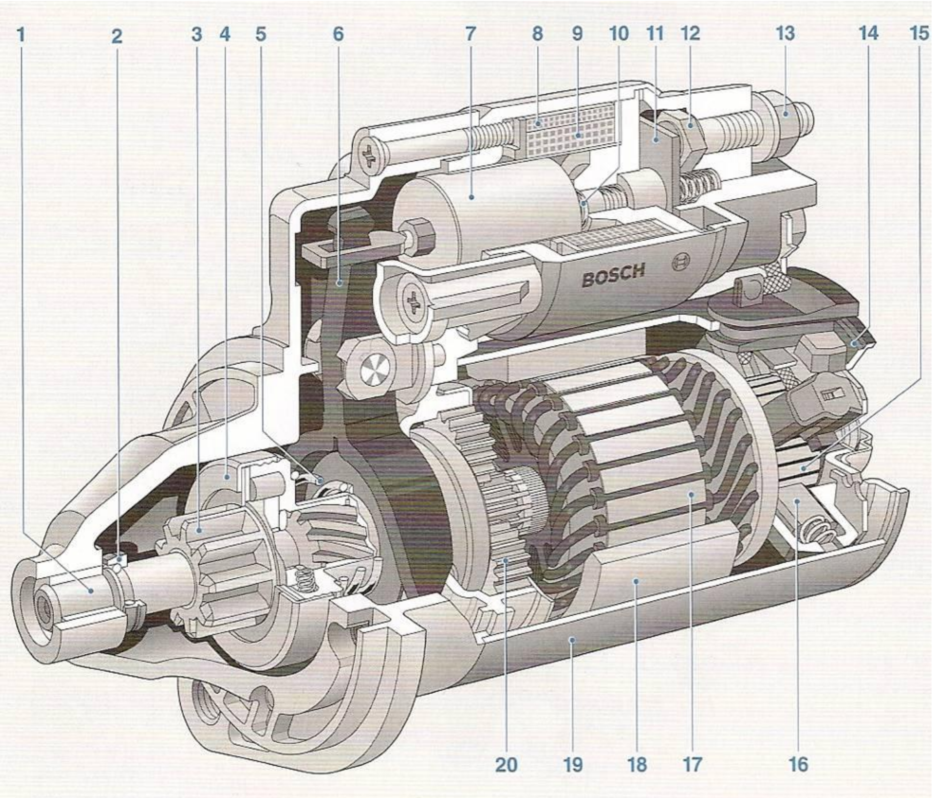
2 Engine cranking resistance (necessary torque)

2a at -24°C (lubricant SAE10W40)

2b at -20°C (lubricant SAE10W40)

Fig. 11: Temperature dependency of starter-torque and engine-torque (cranking resistance)

The principle operation of starters will be explained by means of the permanent-magnet DC-motor starters (see fig. 12), which are nowadays the standard in passenger car applications. The starter motor has brushes and a collector. The main advantages of the permanent magnet DC-motor types are less weight and smaller size.
In order to achieve very high shaft torques, the motor is combined with an intermediate transmission (epicyclical type). This planetary gear has a typical transmission ratio of ~ 5, which allows the armature to rotate at a higher and more efficient speed, whilst still providing the torque, due to the gear reduction.



1 Drive axle
2 Terminal ring
3 Pinion
4 Rollenfreilauf
5 Engaging spring
6 Engaging lever
7 Solenoid switch
8 Retain winding
9 Retract winding
10 Return spring
11 Contact bridge
12 Contact
13 Terminal
14 Commutator bearing
15 Commutator
16 Brush plate with carbon brushes
17 Armature
18 Permanent magnet
19 Field frame
20 Planetary gear (intermediate transmission)

Fig. 12: Starter with permanent magnet DC motor and intermediate transmission

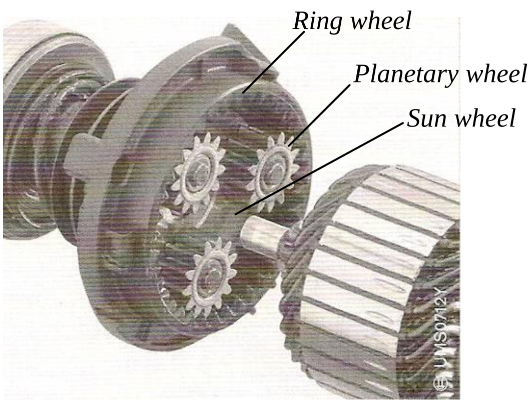


Fig. 13: Planetary intermediate transmission

The Starter engages with the flywheel ring gear by means of a small pinion. The common so called “Pre-engaged” starters provide that full power is not applied until the pinion is fully in mesh with the ring gear. This procedure is explained in detail in Appendix C.

When closing the Starter switch (Fig. 14) some current is already flowing through the DC motor (over the pull-in winding) in the first moment, which will allow the motor to rotate slowly in order to facilitate engagement. At the same time, the magnetism created in the solenoid attracts the plunger and, via an operating lever pushes the pinion into mesh with the flywheel ring gear. When the pinion is fully in mesh the plunger, at the end of its travel, causes a heavy duty set of contacts to close.

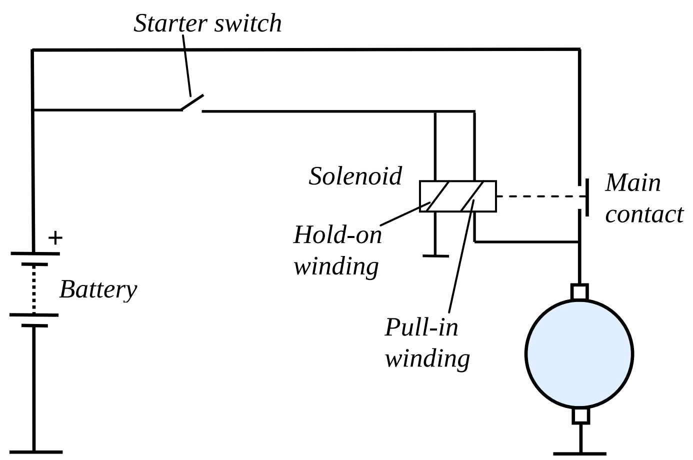


Fig. 14: Circuit diagram for a pre-engaged starter

These contacts now supply full battery power to the main circuit of the starter motor, which results in very high current values and thus a high starting torque. The current is only limited by the Resistors / voltage drops shown in the equivalent circuit of Fig. 15.

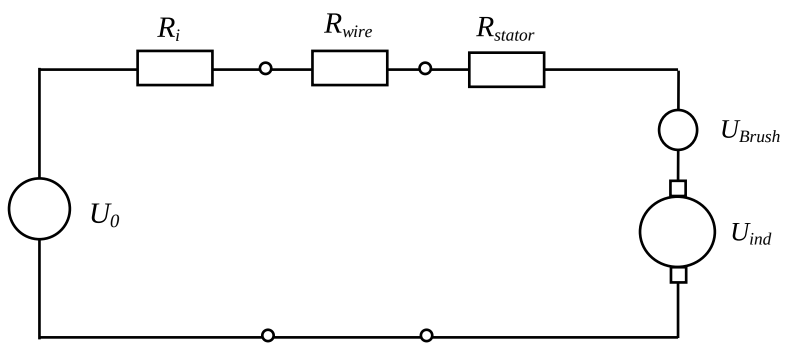


Fig. 15: Equivalent circuit diagram for the main current path

The characteristics of starter-motor current and its speed during a typical cranking process is shown in Fig. 16.

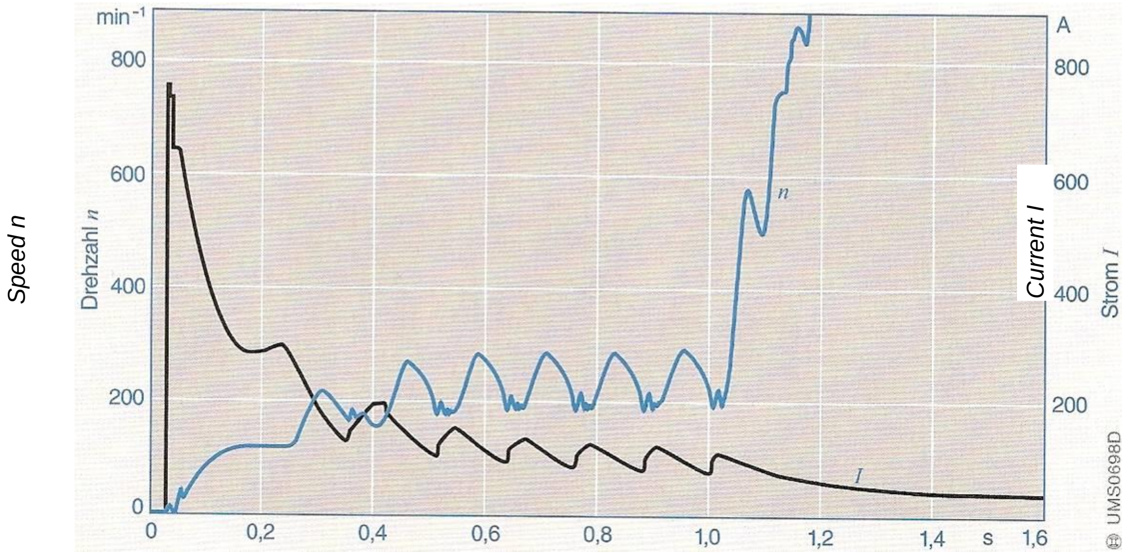


Fig. 16: ***Characteristics of Motor current and speed vs. time***

4. Starter-Generators

There have been already solutions for the combination of generator and starter functionalities in one device in the early 1930s. Because of poor efficiency, however, these products have not been successful at that time.

Hence, nowadays available power electronic devices and optimized motor constructions offer new promising approaches.

Starter-Generators are built in a power range of typically 2 to 12kW enabling the so-called “Start-Stop” function, which switches off the combustion engine whenever the car stops or gets into a cruising mode. In combination with intelligent control of the generator functionality (=loading the battery only during favourable engine operation) these systems can save typically up to 15% of fuel.

Various solutions are already available on the market, ranging from **belt-driven starter generators** for smaller combustion engines to **crank-shaft integrated** ones based on 42V supplied permanent magnet machines for medium and large combustion engines. In the following we are going to have a closer look at these two representative types.

Belt driven starter generators:

Optimized belt and pulley technologies allow very economic starter-generator solutions for small combustion engines. The difficulty of transmitting the high torque during cranking is solved by adaptive tensioning fixtures providing high tension in motor operation and lower tension (with reduced losses) in generator operation. The belt-driven starter generator has the advantage, that no adaptations in the combustion engine are required. In case of a sufficiently generous dimensioned electrical machine (from the thermal point of view) the start-stop functionality for the combustion engine can be provided even for urban driving cycles with repeated cranking.

Fig. 17: ***Multiple V-ribbed belt for Starter-Generator applications***

To cope with both requirements of starter and generator functionalities, the electrical machine will need larger active volume in order to deliver the high starting torque. Anyhow the dimensioning of a starter generator is a very demanding challenge in case of the 14V on board supply. In case of this low supply voltage the problem can only be solved for relatively small combustion engines by utilising rotor-wound synchronous machines.
As recuperation of breaking energy is only possible to a very limited extend, this generator solution can be seen as the smallest version of a micro hybrid.

Fig. 18: ***Rotor-wound claw pole synchronous machine as a belt driven Starter-Generator for small combustion engines***

In a Starter-Generator a three-phase MOSFET inverter is connected in parallel with the rectifier diode bridge.

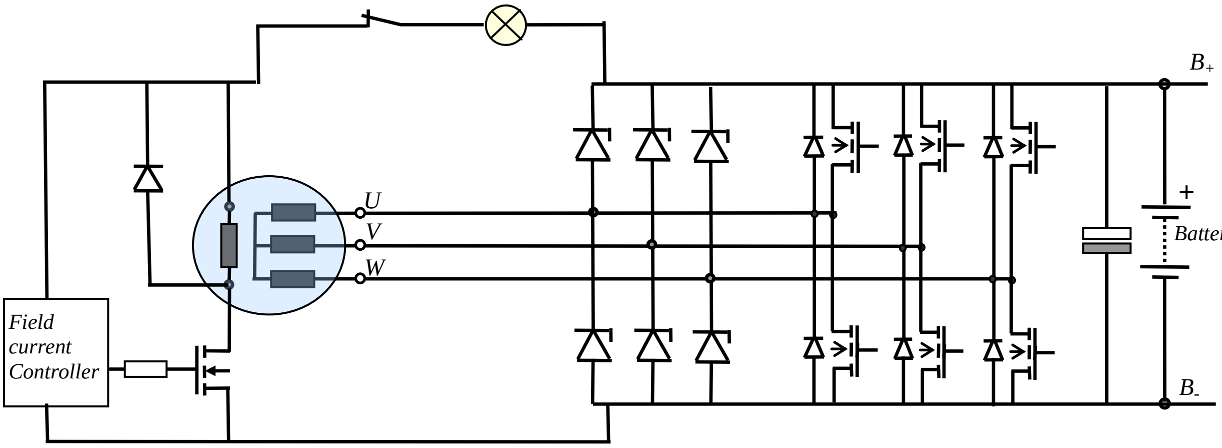


Fig. 19: Schematics of a Starter-Generator with wounded-rotor synchronous machine and three-phase MOSFET inverter (for belt-driven solutions)

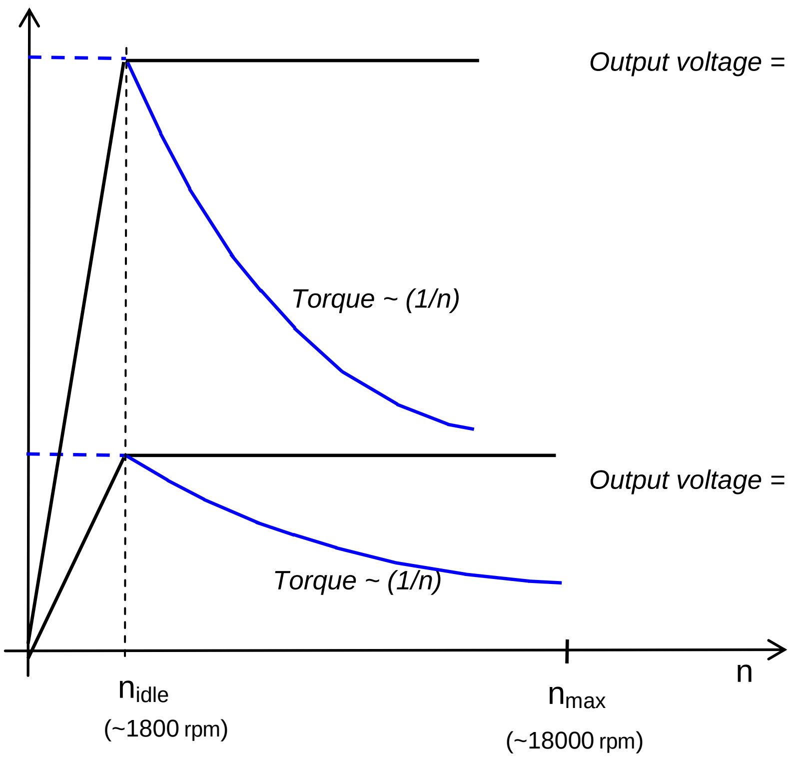


Fig. 20: Comparison of torque/speed characteristics (blue) for a starter/generator at different supply voltage levels.

Crank-shaft integrated starter-generators:

The crank-shaft integrated starter generator represents a more sophisticated solution for medium and powerful combustion engines offering already multiple features as

- Repetitive starting with high cranking torque
- Power Generation with improved efficiency
- Supporting the engine for improved acceleration (Boost mode).
- Active Damping of crank-shaft's ripple torque caused by the pistons of the engine

The toroidal machine is of the Permanent magnet type offering high efficiency at small active volume. These devices use preferably a 42V supply in order to reduce machine size and to make the adaptation of torque/speed characteristics easier. The design of an electrical machine is much easier if more voltage is available.

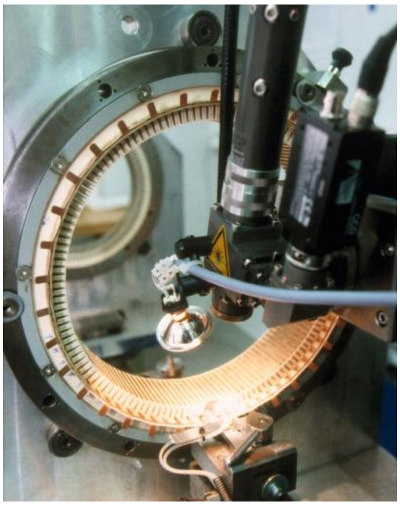


Fig. 21: Stator ring of crank-shaft integrated Starter-Generator (Permanent Magnet Synchronous machine)

For connecting the 42 V supply level with the 14V board supply an additional MOSFET half bridge is needed which will act as a synchronous step-down converter when the PSM runs in generator mode and as a synchronous step-up converter respectively when the PSM runs in motor (starter) operation.

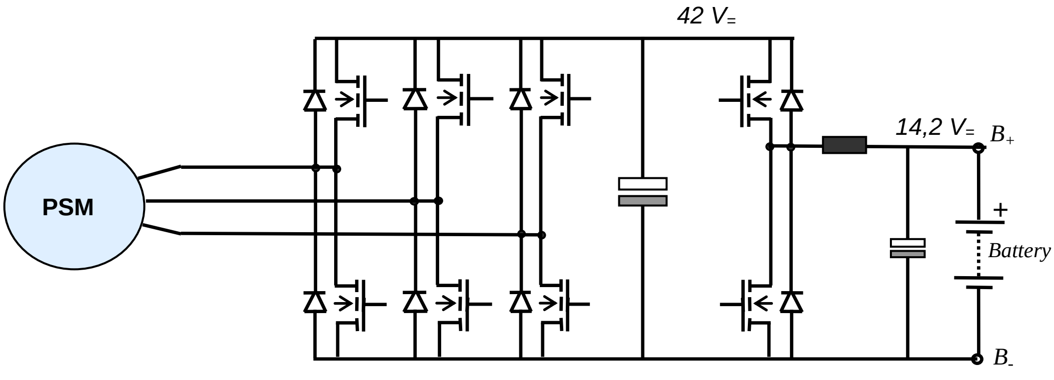


Fig. 22: Schematics of a Starter-Generator with Permanent magnet synchronous machine and three-phase MOSFET inverter at 42V

The control of such a drive is based on field-oriented vector control methods, which offers very high dynamic torque response thus enabling additional features like active damping of the crank-shaft.

A heavy drawback of these micro-hybrid/ mild-hybrid solutions is, that in energy recuperation mode the combustion engine can not be decoupled and hence has still to be towed. Methods like opening the valves will reduce the tow torque but friction of the pistons is still producing losses and thus limiting the fuel reduction potential.

Questionnaire and Exercises:

1. What are the advantages of electrically driven auxiliary components (pumps and blowers) compared to mechanically driven ones (coupled with the engine via belts)

2. Estimate the price for electricity generated on board of a vehicle.

3. Draw the schematics of a standard generator system (wounded rotor synchronous machine with three-phase rectifier and battery.

4. What is a claw pole rotor?

5. What type of diodes are used in the rectifiers of generator systems (explain why)

6. Estimate Diode-losses in a three-phase rectifier with a 14V output voltage at a load of 60A DC How much are these losses expressed as percentage of the transmitted power.
   Search for adequate MOSFETS which could replace the diodes and calculate the losses for these components, when the would be operated as the diodes (so called “natural commutation”)

7. Calculate the frequency of the output-voltage of a claw pole generator with 14 poles at an engine speed of 5000 rpm.

8. Consider how the efficiency of a standard claw-pole generator could be improved.

9. Which motor type is used for standard starter motors, how is the necessary high cranking torque achieved and why does the starter have to be decoupled from the engine after starting.

10. Calculate the frequency of the mechanical ripple torque at the crank-shaft generated by the cylinders of a 4-stroke 4 cylinder combustion engine. Consider up to which speed a permanent magnet synchronous machine could be able to actively damp this ripple.

Appendix: book