Inductive ignition system

Ignition of the air/fuel mixture in the gasoline engine is electric; it is produced by generating a flashover between the electrodes on a spark plug. The ignition-coil energy converted in the spark ignites the compressed mixture immediately adjacent to the spark plug, creating a flame front which then spreads to ignite the mixture in the entire combustion chamber. The inductive ignition system generates in each power stroke the high voltage required for flashover and the spark duration required for ignition. The electrical energy drawn from the vehicle electrical system battery is temporarily stored in the ignition coil for this purpose.

The most significant application for the inductive ignition system is in passenger cars with gasoline engines. The most commonly used are four-stroke engines with four cylinders.

Design

Figure 1 shows the basic design of the ignition circuit of an inductive ignition system using the example of a system with distributorless (stationary) voltage distribution – as is used in all current applications – and single-spark ignition coils. The ignition circuit comprises the following components:

- Ignition driver stage (5), which is integrated in the Motronic ECU or in the ignition coil
- Ignition coils (3), designed as pencil coils or as a compact coil to generate one spark (as illustrated) or two sparks
- Spark plugs (4), and
- Connecting devices and interference suppressors

Older ignition systems with rotating high-voltage distribution require an additional high-voltage distributor. This ensures that the ignition energy generated in the ignition coil is directed to the correct spark plug.

1 Design of the ignition circuit of an inductive ignition system

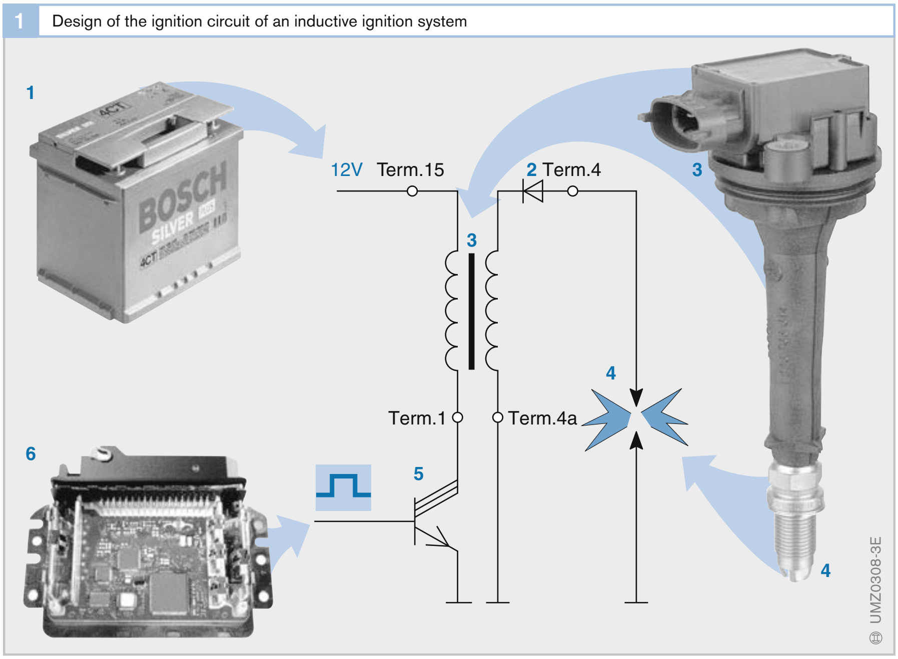

Fig. 1
Illustration of a cylinder of an inductive ignition system with distributorless voltage distribution and single-spark ignition coils

1 Battery
2 AAS diode (Activation Arc Suppression), integrated in ignition coil
3 Ignition coil
4 Spark plug
5 Ignition driver stage (integrated in engine ECU or in ignition coil)
6 Engine ECU Motronic

Term. 15, Term. 1, Term. 4, Term. 4a Terminal designation
⎍ Actuation signal for ignition driver stage

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Function and method of operation

It is the function of the ignition to ignite the compressed air/fuel mixture and thus initiate its combustion. Safe combustion of the mixture must be guaranteed in the process. To this end, sufficient energy must be stored in the ignition coil prior to the moment of ignition and the ignition spark must be generated at the correct moment of ignition.

All the components of the ignition system are adapted in terms of their designs and performance data to the demands of the overall system.

Generating the ignition spark

A magnetic field is built up in the ignition coil when a current flows in the primary circuit. The ignition energy required for ignition is stored in this magnetic field.

Interrupting the coil current at the moment of ignition causes the magnetic field to collapse. This rapid magnetic-field change induces a high voltage (Fig. 2) on the secondary side of the ignition coil as a result of the large number of turns (turns ratio approx. 1:100). When the ignition voltage is reached, flashover occurs at the spark plug and the compressed air/fuel mixture is ignited.

The current in the primary winding only gradually attains its setpoint value because of the induced countervoltage. Because the energy stored in the ignition coil is dependent on the current ($E = {}^1/_2 LI^2$), a certain amount of time (dwell period time) is required in order to store the energy necessary for ignition. This dwell period is dependent on, among others, the vehicle system voltage. The ECU program calculates from the dwell period and the moment of ignition the cut-in point, and cuts the ignition coil in via the ignition driver stage and out again at the moment of ignition.

Flame-front propagation

After the flashover, the voltage at the spark plug drops to the spark voltage (Fig. 2). The spark voltage is dependent on the length of the spark plasma (electrode gap and deflection due to flow) and ranges between a few hundred volts and well over 1 kV. The ignition-coil energy is converted in the ignition spark during the ignition-spark period; this spark duration lasts between 100 µs to over 2 ms. Following the breakaway of the spark, the attenuated voltage decays.

The electrical spark between the spark-plug electrodes generates a high-temperature plasma. When the mixture at the spark plug is ignitable and sufficient energy is supplied by the ignition system, the flame core that is created develops into an automatically propagating flame front.

Moment of ignition

The instant at which the spark ignites the air/fuel mixture within the combustion chamber must be selected with extreme precision. It is usually specified as an ignition angle in °cks (crankshaft) referred to Top Dead Center (TDC). This variable has a crucial influence on engine operation and determines

2 Voltage curve at the electrodes

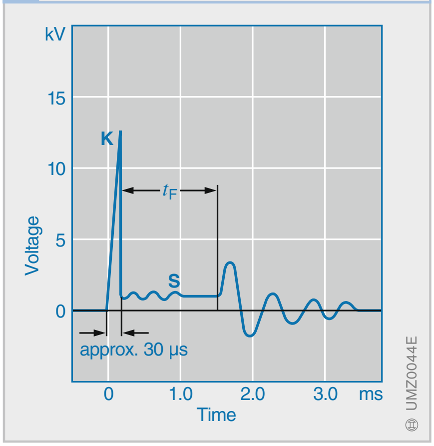


Fig. 2

K	Spark head
S	Spark tail
t_F	Spark duration

- The delivered torque
- The exhaust-gas emissions, and
- The fuel consumption

The moment of ignition is specified in such a way that all requirements are met as effectively as possible. However, continuous engine knocking must not develop during operation.

The influencing variables that determine the moment of ignition are engines speed and engine load, or torque. Additional variables, such as, for example, engine temperature, are also used to determine the optimal moment of ignition. These variables are recorded by sensors and then relayed to the engine ECU (Motronic). The moment of ignition is calculated from program maps and characteristic curves, and the actuation signal for the ignition driver stage is generated.

Knock control

Knock is a phenomenon which occurs when ignition takes place too early (Fig. 3). Here, once regular combustion has started, the rapid pressure increase in the combustion chamber leads to auto-ignition of the unburnt residual mixture which has not been reached by the flame front. The resulting abrupt combustion of the residual mixture leads to a considerable local pressure increase. The pressure wave which is generated propagates, strikes the cylinder walls, and can be heard as combustion knock.

If knock continues over a longer period of time, the engine can incur mechanical damage caused by the pressure waves and the excessive thermal loading. To prevent knock on today's high-compression engines, no matter whether of the manifold-injection or direct-injection type, knock control is now a standard feature of the engine-management system. With knock control, knock sensors (structure-borne-noise sensors) detect the start of knock and the ignition timing is retarded at the cylinder concerned (Fig. 4). The pressure increase after the mixture has ignited therefore occurs later, which reduces the tendency to knock. When the knocking stops, the ignition-timing adjustment is reversed in stages. To obtain the best-possible engine efficiency, therefore, the basic adaptation of the ignition angle (ignition map) can be located directly at the knock limit.

3 Pressure curve in the combustion chamber

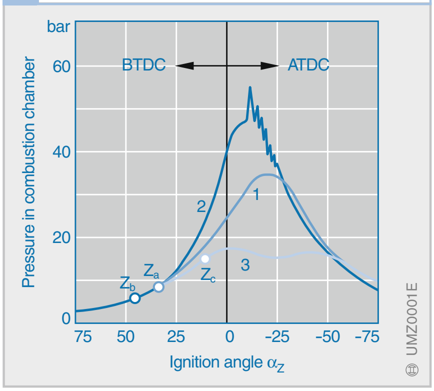


Fig. 3
Pressure curves at different moments of ignition
1 Ignition Z_a at correct moment
2 Ignition Z_b too advanced (combustion knock)
3 Ignition Z_c too retarded

4 Control algorithm of knock control

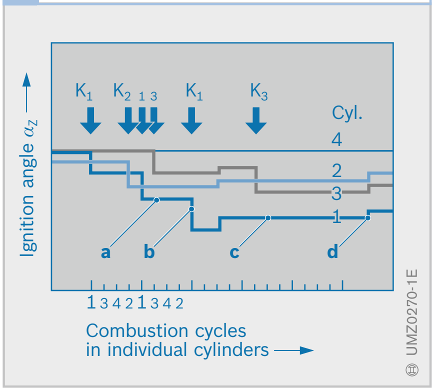


Fig. 4
K1…3 Occurrence of knock at cylinders 1…3, no knock at cylinder 4
a Dwell time before timing retardation
b Drop depth
c Dwell time before reverse adjustment
d Timing advance

Ignition parameters

Moment of ignition

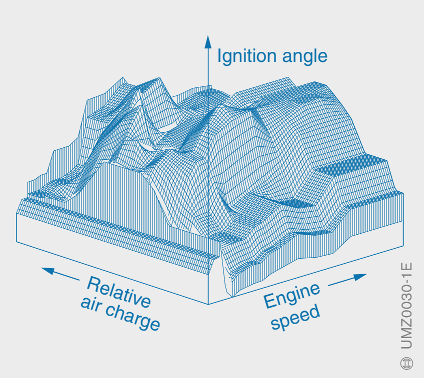
Engine-speed and load dependence

Once ignition has been initiated by the ignition spark, it takes a few milliseconds for the air/fuel mixture to burn completely. This period of time remains roughly constant as long as the mixture composition remains unchanged. The moment of ignition point must be selected so that main combustion, and the accompanying pressure peak in the cylinder, takes place shortly after TDC. As engine speed increases, the ignition angle must therefore be advanced.

The cylinder charge also has an effect on the combustion curve. The flame front propagates at a slower rate when the cylinder charge is low. For this reason, with a low cylinder charge, the ignition angle must also be advanced.

In the case of gasoline direct injection, the range for variation of the moment of ignition in stratified-charge mode is limited by the end of injection and the time needed for mixture preparation during the compression stroke.

5 Ignition map



Basic adaptation of ignition angle

In electronically controlled ignition systems, the ignition map (Fig. 5) takes into account the influence of engine speed and cylinder charge on the ignition angle. This map is stored in the engine-management system's data memory, and forms the basic adaptation of the ignition angle.

The map's x and y axes represent the engine speed and the relative air charge. A specific number of values, typically 16, forms the data points of the map. One ignition angle is stored for each pair of values. The map therefore contains 256 adjustable ignition-angle values. By applying linear interpolation between two data points, the number of ignition-angle values is increased to 4096.

Using the ignition-map principle for electronic control of the ignition angle means that, for every engine operating point, it is possible to select the best-possible ignition angle. These maps are ascertained on the engine test stand, or dynamic power analyzer, where demands pertaining to, for example, noise, comfort and component protection are also taken into account.

Additive ignition-angle corrections

Different impacting factors on the moment of ignition are taken into account through additive corrections of the basic ignition angle, such as, for instance, knock control or warming-up after the starting phase. The engine temperature has a further influence on the selection of the ignition angle (e.g., shifting of the knock limit when the engine is hot).

Temperature-dependent ignition-angle corrections are therefore also necessary. Such corrections are stored in the data memory in the form of fixed values or characteristic curves (e.g., temperature-dependent correction). They shift the basic ignition angle by the specified amount. The ignition-angle correction can be either an advance or a retardation.

Ignition angles for specific operating conditions

Specific operating states, e.g., starting or stratified-charge mode with gasoline direct injection, require ignition angles that deviate from the ignition map. In such cases, access is obtained to special ignition angles stored in the data memory.

Dwell period

The energy stored in the ignition coil is dependent on the level of the primary current at the moment of ignition (cut-out current) and the inductance of the primary winding. The level of the cut-out current is essentially dependent on the cut-in period (dwell period) and the vehicle system voltage. The dwell periods for obtaining the desired cut-out current are stored in voltage-dependent curves or program maps. Changing the dwell period by way of the temperature can also be compensated for.

In order not to thermally overload the ignition coil, it is essential to adhere rigidly to the time required to generate the required ignition energy in the coil.

Ignition voltage

The ignition voltage at the point where flashover between the spark-plug electrodes occurs is the ignition-voltage demand.
It is dependent, among other things, on

- The density of the air/fuel mixture in the combustion chamber, and thus on the moment of ignition
- The composition of the air/fuel mixture (excess-air factor, lambda value)
- The flow velocity and turbulence
- The electrode geometry
- The electrode material, and
- The electrode gap

It is vital that the ignition voltage supplied by the ignition system always exceed the ignition-voltage demand under all conditions.

Ignition energy

The cut-out current and the ignition-coil parameters determine the amount of energy that the coil stores for application as ignition energy in the spark. The level of ignition energy has a decisive influence on flame-front propagation. Good flame-front propagation is essential to delivering high-performance engine operation coupled with low levels of toxic emissions. This places considerable demands on the ignition system.

Energy balance of an ignition

The energy stored in the ignition coil is released as soon as the ignition spark is initiated. This energy is divided into two separate components.

Spark head

In order that an ignition spark can be generated at the spark plug, first the secondary-side capacitance C of the ignition circuit must be charged, and this is released again on flashover. The energy required for this increases quadratically with the ignition voltage U ($E = {}^1/_2\, CU^2$). Figure 6 shows the component of this energy contained in the spark head.

Spark tail

The energy still remaining in the ignition coil after flashover (inductive component) is then released in the course of the spark duration. This energy represents the difference between the total energy stored in the ignition coil and the energy released during capacitive discharge. In other words: The higher the ignition-voltage demand, the greater the component of total energy contained in the spark head, and the less energy is converted in the spark duration, i.e., the shorter the spark duration. When the ignition-voltage demand is high, due for instance to badly worn spark plugs, the energy stored in the spark tail may no longer be enough to completely burn an already ignited mixture or to re-ignite a spark that has broken away.

Further increases in the ignition-voltage demand lead to the ignition-miss limit being reached. Here, the available energy is no longer enough to generate a flashover, and instead it decays in a damped oscillation (ignition miss).

Energy losses

Figure 6 shows a simplified representation of the existing conditions. Ohmic resistance in the ignition coil and the ignition cables combined with the suppression resistors cause losses, which are then unavailable as ignition energy.

Additional losses are produced by shunt resistors. While these losses can result from contamination on the high-voltage connections, the primary cause is soot and deposits on the spark plugs within the combustion chamber.

The level of shunt losses is also dependent on the ignition-voltage demand. The higher the voltage applied at the spark plug, the greater the currents discharging through the shunt resistors.

Mixture ignition

Under ideal (e.g., laboratory) conditions, the energy required to ignite an air/fuel mixture with an electrical spark for each individual injection is approximately 0.2 mJ, provided the mixture in question is static, homogeneous and stoichiometric. Under such conditions, rich and lean mixtures require in excess of 3 mJ.

The energy that is actually required to ignite the mixture is only a fraction of the total energy in the ignition spark, the ignition energy. With conventional ignition systems, energy levels in excess of 15 mJ are needed to generate a high-voltage flashover at the moment of ignition at high breakdown voltages. This additional energy is required to charge the capacitance on the secondary side. Further energy is required to maintain a specific spark duration and to compensate for losses, due for instance to contamination shunts at the spark plugs. These requirements amount to ignition energies of at least 30...50 mJ, a figure which corresponds to an energy level of 60...120 mJ stored in the ignition coil.

6 Ignition energy balance without shunt, resistance and Zener losses

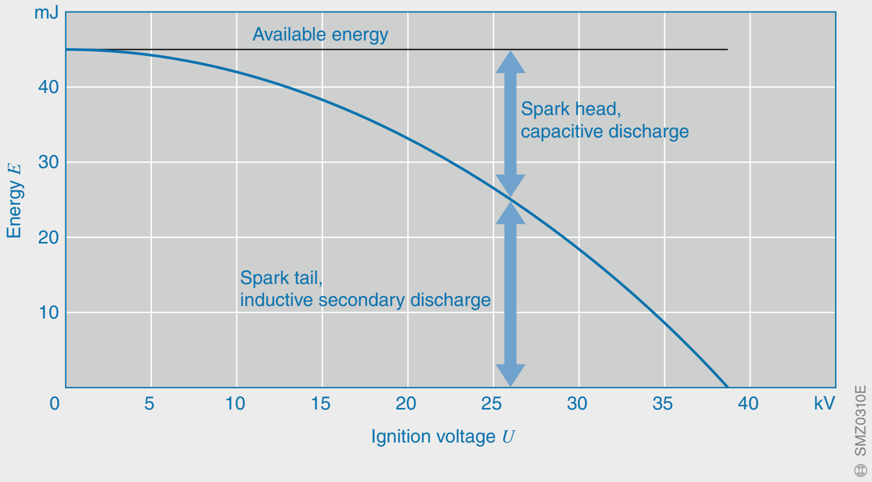


Fig. 6
The energy figures are for a sample ignition system with a coil capacitance of 35 pF, an external load of 25 pF (total capacitance C = 60 pF) and secondary inductance of 15 H.

Turbulence within the mixture of the kind encountered when engines with gasoline direct injection are operated in stratified-charge mode can deflect the ignition spark to such an extent that it breaks away (Fig. 7). A number of follow-up sparks is then needed to ignite the mixture, and this energy must also be provided by the ignition coil.

The ignition tendency decreases in the case of lean mixtures. A particularly high level of energy is therefore required to be able to cover the increased ignition-voltage demand and at the same time to ensure an effectively long spark duration.

If inadequate ignition energy is available, the mixture will fail to ignite. No flame front is established, and combustion miss occurs. This is why the system must furnish adequate reserves of ignition energy: To ensure reliable detonation of the air/fuel mixture, even under unfavorable external conditions. It may be enough to ignite just a small portion of the mixture directly with the spark plug. The mixture igniting at the spark plug then ignites the remaining mixture in the cylinder and thereby initiates the combustion process.

Factors affecting ignition performance

Efficient preparation of the mixture with unobstructed access to the spark plug improves ignition performance, as do extended spark durations and large spark lengths or large electrode gaps. Mixture turbulence can also be an advantage, provided enough energy is available for follow-up ignition sparks should these be needed. Turbulence supports rapid flame-front distribution in the combustion chamber, and with it the complete combustion of the mixture in the entire combustion chamber.

Spark-plug contamination is also a significant factor. If the spark plugs are very dirty, energy is discharged from the ignition coil through the spark-plug shunt (deposits) during the period in which the high voltage is being built up. This reduces the high voltage whilst simultaneously shortening spark duration. This affects exhaust emissions, and can even lead to ignition misses under extreme conditions, as when the spark plugs are severely contaminated or wet.

Ignition misses lead to combustion misses, which increase both fuel consumption and pollutant emissions, and can also damage the catalytic converter.

7 Ignition spark in an engine with direct injection

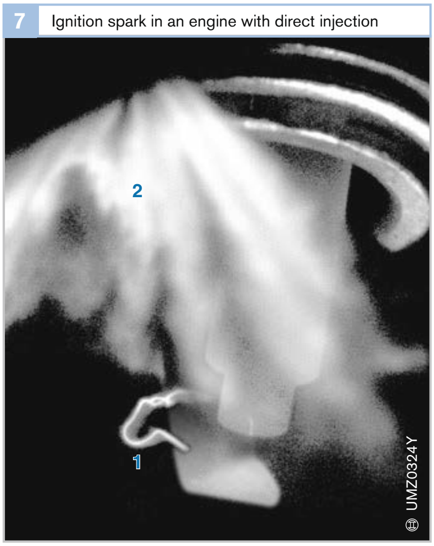


Fig. 7
Photograph of an ignition spark: taken in a transparent engine using a high-speed camera

1 Ignition spark
2 Fuel spray

▶ Danger of accident

All electrical ignition systems are high-voltage systems. To avoid potential dangers, always switch off the ignition or disconnect the power source before working on any ignition system. These precautions apply to, e.g.,

- Replacing components, such as ignition coils, spark plugs, ignition cables, etc.
- Connecting engine testers, such as timing stroboscope, dwell-angle/speed tester, ignition oscilloscope, etc.

When checking the ignition system, remember that dangerously high levels of voltage are present within the system whenever the ignition is on. All tests and inspections should therefore only be carried out by qualified professional personnel.

Voltage distribution

Rotating high-voltage distribution

The high voltage generated in the ignition coil (Fig. 8a, Pos. 2) must be applied at the correct spark plug at the moment of ignition. In the case of rotating high-voltage distribution, the high voltage generated by this single ignition coil is mechanically distributed to the individual spark plugs (5) by an ignition distributor (3).
The rotation speed and the position of the distributor rotor, which establishes the electrical connection between the ignition coil and the spark plug, are coupled to the camshaft.

This form of distribution is no longer of any significance to new, modern-day engine-management systems.

Distributorless (stationary) voltage distribution

The mechanical components have been dispensed with in the distributorless, or stationary, voltage-distribution system (Fig. 8b). Voltage is distributed on the primary side of the ignition coils, which are connected directly to the spark plugs. This permits wear-free and loss-free voltage distribution. There are two versions of this type of voltage distribution.

System with single-spark ignition coils

Each cylinder is allocated an ignition driver stage and an ignition coil. The engine ECU actuates the ignition driver stages in specified firing order.

Since there are no distributor losses, these ignition coils can be very small in design. They are preferably mounted directly over the spark plug.

Distributorless voltage distribution with single-spark ignition coils can be used with any number of cylinders. There are no limitations on the ignition-timing adjustment range. In this case, the spark plug of the cylinder which is at firing TDC is the one that fires. However, the system does also have to be synchronized by means of a camshaft sensor with the camshaft.

System with dual-spark ignition coils

One ignition driver stage and one ignition coil are allocated to every two cylinders. The ends of the secondary winding are each connected to a spark plug in different cylinders. The cylinders have been chosen so that when one cylinder is in the compression stroke, the other is in the exhaust stroke (applies only to engines with an even number of cylinders). Flashover occurs at both spark plugs at the moment of ignition. Because it is important to prevent residual exhaust gas or fresh induction gas from being ignited by the spark during the exhaust stroke additional spark, the latitude for varying ignition timing is limited with this system. However, it does not need to be synchronized with the camshaft. Because of these limitations, dual-spark ignition coils cannot be recommended.

8 Voltage-distribution concept

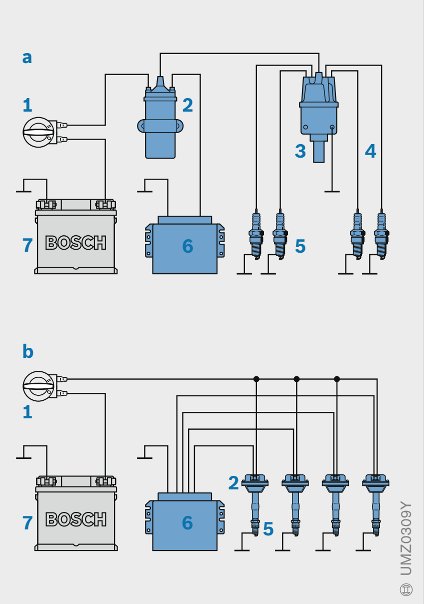


Fig. 8
a Rotating distribution
b Distributorless (stationary) distribution with single-spark ignition coils

1 Ignition lock
2 Ignition coil
3 Ignition distributor
4 Ignition cable
5 Spark plug
6 ECU
7 Battery

Ignition driver stage

Function and method of operation

The function of the ignition driver stage is to control the flow of primary current in the ignition coil. It is usually designed as a three-stage power transistor with BIP technology (Bosch Integrated Power, bipolar technology). The functions of primary-voltage limitation and primary-current limitation are integrated as monolithic components on the ignition driver stage, and protect the ignition components against overload.

During operation, the ignition driver stage and the ignition coil both heat up. In order not to exceed the permissible operating temperatures, it is necessary that appropriate measures be taken to ensure that the heat losses are reliably dissipated to the surroundings even when outside temperatures are high. In order to avoid high power loss in the ignition driver stage, the function of primary-current limitation is only to limit the current in the event of a fault (e.g., short circuit).

9 Block diagrams of ignition driver stages

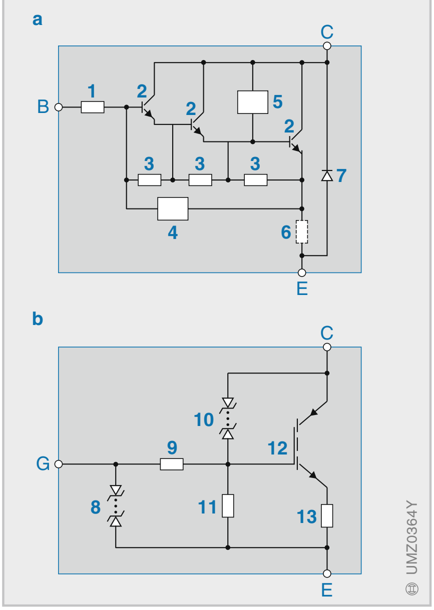


Fig. 9
a BIP ignition driver stage (monolithic integrated)
a IGBT ignition driver stage (monolithic integrated)

1 Base resistor
2 Triple Darlington transistor
3 Basic emitter resistors
4 Emitter current regulator
5 Collector-voltage limitation
6 Current-recording resistor
7 Inverse diode
8 Polysilicon protective-diode chain
9 Gate resistor
10 Polysilicon clamp-diode chain for collector-voltage limitation
11 Gate emitter resistor
12 IGBT transistor
13 Resistor (omitted from standard IGBT)

B Base
E Emitter
C Collector
G Gate

In the future, the three-stage circuit-breakers will be superseded by the new IGBTs (Insulated Gate Bipolar Transistors, hybrid form on field-effect and bipolar transistors), also for ignition applications. The IGBT has some advantages over BIP:

- Virtually power-free actuation (voltage instead of current)
- Low saturation voltage
- Higher load current
- Lower switching times
- Higher clamp voltage
- Higher holding temperature
- Protected against polarity reversal in the 12 V vehicle electrical system

Design variations

Ignition driver stages are categorized into internal and external driver stages. The former are integrated on the engine ECU's printed-circuit board, and the latter are located in their own housing outside the engine ECU. Due to the costs involved, external driver stages are no longer used on new developments.

Furthermore, it is becoming increasingly common for driver stages to be incorporated in the ignition coil. This solution avoids cables in the wiring harness which carry high currents and are subjected to high voltages. In addition, the power loss incurred in the Motronic ECU is accordingly lower. Stricter demands with regard to actuation, diagnostic capability and temperature load are made of the driver stages integrated in the ignition coil. These demands are derived from the installation circumstances directly on the engine with higher ambient temperatures, ground offsets between ECU and ignition coil, and the additional expenditure involved in transmitting diagnostic information from the ignition coil to the ECU either via an additional cable or through the intelligent use of the control line to include the return transmission of diagnostic information.

Connecting devices and interference suppressors

Ignition cables

The high voltage generated in the ignition coil must be delivered to the spark plug. For this purpose, plastic-insulated, high-voltage-proof cables with special connectors at their ends for contacting the high-voltage components are used with ignition coils which are not mounted directly on the spark plug (e.g., dual-spark ignition coils).

Since, for the ignition system, each high-voltage cable represents a capacitive load which reduces the available secondary voltage, the ignition cables must be kept as short as possible.

Interference-suppression resistors, screening

Each flashover is a source of interference due to its pulse-shaped discharge. Interference-suppression resistors in the high-voltage circuit limit the peak current during discharge. In order to minimize the interference radiation from the high-voltage circuit, the suppression resistors should be installed as close as possible to the source of interference.

Normally, the suppression resistors are integrated in the spark-plug connectors and cable connectors. Spark plugs are also available which feature an integral suppression resistor. However, increasing resistance on the secondary side leads to additional energy losses in the ignition circuit, with lower ignition energy at the spark plug as the ultimate result.

Interference radiation can be even further reduced by partially or completely screening the ignition system. This screening includes the ignition cables. This effort is justified only in special cases (official government and military vehicles, radio equipment with high transmitting power).

10 Ignition cables

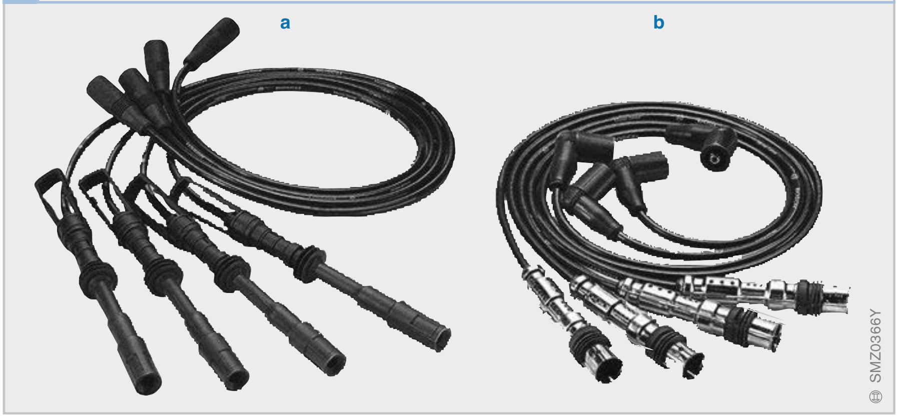


Fig. 10

- a Cable set with straight connectors and unscreened spark-plug connectors
- b Cable set with elbow connectors and partially screened spark-plug connectors