

EVC 250 Main Contactor

A high-voltage contactor for hybrid- and battery-electric vehicles (HEV, PHEV, BEV)

White Paper from TE Connectivity

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Just like the fuel tank in a conventional car, the energy storage system for hybrid and electric vehicles must also be protected against thermal overload.

Therefore, for galvanic separation after turning off the vehicle or in the event of a failure, fuse and relay combinations are used at the interface between the traction battery and the electrical board net. In this article, the EVC 250 main contactor (EVC 250) is presented. The EVC 250 was particularly developed towards the requirements of this application.



1. Introduction

Battery-operated vehicles include electrical energy storage systems that have high energy content and high power density. Battery-powered vehicles must be equipped with protection devices, such as fuses, circuit breakers or main contactors, in case the rechargeable energy storage systems become overheated by overcurrent. This is in accordance with the provisions of the Economic Commission for Europe Regulation "ECE R-100, Battery-Powered Electric Vehicles". A similar requirement is contained in the standard LV123[I]; issued by the German automobile manufacturers .

LV123-393	In the case of overcurrent, the energy storage and/or HV battery must be capable of being separated from the DC HV circuit via suitable contactors, independent of the direction of the current flow.
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The requirements for such a main isolation device are derived from these standards. If the vehicle is turned off, the energy storage must be separated from the vehicle electrical system. These requirements include:

- (1) Both poles of the battery should be disconnected from the vehicle electrical system [II].
- (2) The main contactors must not open without request.
- (3) The main contactors must open when the activation signal is turned off [III].
- (4) Fuse and main contactor must securely separate the battery system from the motor in case of over currents, e.g. in the event of a crash [IV].
- (5) The main contactors must keep full functionality, i.e. carry or separate the overcurrent, as long as the fuse has not tripped.
- (6) The open contactors must ensure a sufficient insulation resistance between the energy storage system and the vehicle after a switch-off under fault conditions.

The architecture associated with these requirements is represented in the following diagram.

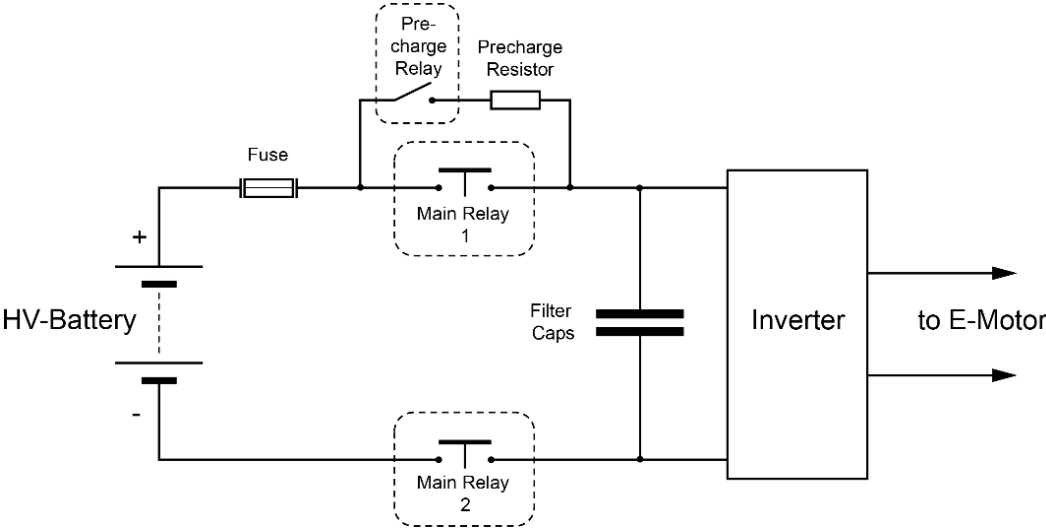


Fig. 1 Schematic of the connection between the battery and the electrical system

In accordance with the requirement (1), there are two main contactors, one interrupting the negative pole and the other interrupting the positive pole of the battery. In the positive path, a serial fuse is inserted. At the inverter input, filter capacitors exist, that generate a severe inrush current when the circuit is closed. This inrush current is only limited by the cable resistance and the source impedance of the battery. The effective resistance lies in the range of around 100 mΩ. In order to reduce the load to the components when switching into this capacitive short circuit, the capacitance is pre-charged before closing the main contactor via a pre-charge circuit. With a pre-charge level of 95%, a 450 V battery system will generate an inrush current limited to approximately 230 A. This current must be switched on by the main contactor at each vehicle start. The EVC 250 main contactor was developed precisely for this application. Unlike other hermetically sealed and gas filled switching solutions, the EVC 250, with its optimized design of the switching chamber, provides full current switch off capability, even under reduced air pressure conditions of up to 5,000 m above sea level. The EVC 250 contactor fulfils the requirements of the ISO 6469 [V] and of the DIN EN 60664 (IEC 60664) [VI] (isolation coordination) for control devices with rated voltages < 500 VDC. In conclusion, a simplified mechanical design, optimized for fully automatic assembly, has successfully been realized, that ensures full current switch off capability over the entire service live, independent of the proper condition of a pressure-tight encasing.

2. Requirements

2.1. Current switch off capability and overload behaviour

From the requirements (5 and 6), it follows that the necessary switch off capability and the overload tolerance of the main contactor have to be co-ordinated with the characteristic of the fuse.

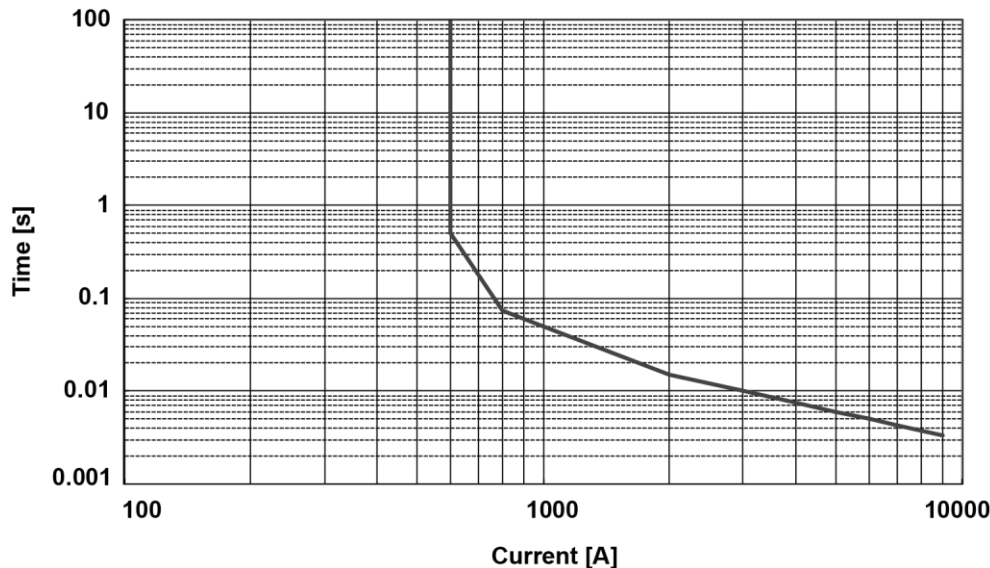


Fig. 2 Typical tripping characteristic of a 600 A fuse

According to IEC 60947-2 [VII] the switch off capability limit (ICU) and the nominal current load limit (ICW) of the main contactor must match with the fuse characteristic. If an overcurrent is detected, the contactor opens after a pre-set time delay. In the event of a hard short-circuit, this delay is meant to prevent the contactor from switching a load that exceeds its nominal limit. This means that, after the time delay, the contactor must be capable to switch off a current level that was just not high enough for the fuse to trip within the time delay.

Since the source impedances of vehicle batteries are within the range of 100 m Ω , short-circuit currents can reach a level of 6 kA or more. Based on the typical fuse characteristic as shown above and assuming a system response time of 200 ms, the contactor must be able to carry a current of up to 6,000 A for 5 ms or 2,000 A for 20 ms without damage and to switch off a current of 2,000 A.

The requirements for the main contactor under normal operation conditions are summarized here:

- Connect the battery to the 95% pre-charged filter capacity
- Ensure full galvanic isolation, when the vehicle is turned off
- Carry several 100 A with low power dissipation

The requirements for failure cases are:

- The contacts must remain closed in case of overload (especially at short circuits), as long as the contactor is activated
- The contactor must still be capable of separating the circuit after an overload
- The contactor must be able to switch off overcurrents of up to 2,000 A

2.2. Service conditions / ambient requirements

Compared to the conditions in vehicles with internal combustion engine, the temperature range for these contactors is reduced to -20°C to + 85°C, as they are installed within the vicinity of the battery. The contactor's function must however not be affected by an exposure to the relatively aggressive Li-ion electrolyte. The magnetic system of the EVC 250 is designed so that the contacts remain closed, even during the voltage drop when cranking an internal combustion engine in hybrid vehicles. In accordance with the requirements of ISO 6469 and IEC 60664, the contactor ensures galvanic separation between the vehicle electrical system and the battery. During normal operation, the contactors are switched on after a 95% pre-charge of the filter capacity and they have to switch off up to 30 A at 450 V per drive cycle. At the end of the service life, the overcurrent carry capability must still be ensured, despite the expected contact wear.

2.3. Characteristic values of EVC 250 main contactor

The requirements derived in Section 2.1 and 2.2 are covered by the below mentioned performance characteristics of EVC 250.

2.3.1. Contact system

2.3.1.1. Voltage range

The clearance and creepage distances inside the EVC 250 main contactor meet the requirements of the IEC 60664. The standard version of the EVC 250 is designed for a load voltage of up to 450 V at altitudes of up to 5,000 m and an overvoltage category I. For higher voltages up to 1,000 V, a higher performance version of the single-coil EVC 250 is required.

2.3.1.2. Maximum continuous current and load conductor cross-section

The heat dissipation out of the relay is primarily provided by the load cables. A sufficient dimensioning of the conductor cross section is important, since a too small cross section will turn the cables to a heat source for the contactor, instead being a heat sink.

Current [A]	250	300	350	400	500
Cross section [mm ²]	Permissible Current for T _{um} = 25°C				
35	Green	Green	Red	Red	Red
50	Green	Green	Green	Red	Red
70	Green	Green	Green	Green	Red
85	Green	Green	Green	Green	Green
115	Green	Green	Green	Green	Green

Current [A]	250	300	350	400	500
Cross section [mm ²]	Permissible Current for T _{um} = 65°C				
35	Green	Red	Red	Red	Red
50	Green	Green	Red	Red	Red
70	Green	Green	Green	Red	Red
85	Green	Green	Green	Green	Red
115	Green	Green	Green	Green	Green

Current [A]	250	300	350	400	500
Cross section [mm ²]	Permissible Current for T _{um} = 85°C				
35	Red	Red	Red	Red	Red
50	Green	Red	Red	Red	Red
70	Green	Green	Red	Red	Red
85	Green	Green	Green	Red	Red
115	Green	Green	Green	Green	Red

Current [A]	250	300	350	400	500
Cross section [mm ²]	Permissible Current for T _{um} = 105°C				
35	Red	Red	Red	Red	Red
50	Red	Red	Red	Red	Red
70	Green	Red	Red	Red	Red
85	Green	Red	Red	Red	Red
115	Green	Green	Red	Red	Red

Table 1: Permitted continuous current for different load cable cross-sections in green

2.3.1.3. Permitted over-currents (load current limits in terms of service life)

Since the duration of an overcurrent pulse is short, the conductance of the heat, generated at the contacts, can be neglected. The heat is absorbed by the contacts, the contact bridge and the connected leads. Whereas the ability to carry currents up to 1,000 A only depends on the heat transfer efficiency and possibly on the current duration, the static design of the contact force becomes increasingly important for high current pulses. The effect of the current-induced force that works against the static contact force is represented in Fig 3 below. If a current flows through a flexible conductor loop, the force, generated by the magnetic field of the current, drives the loop to the outside.

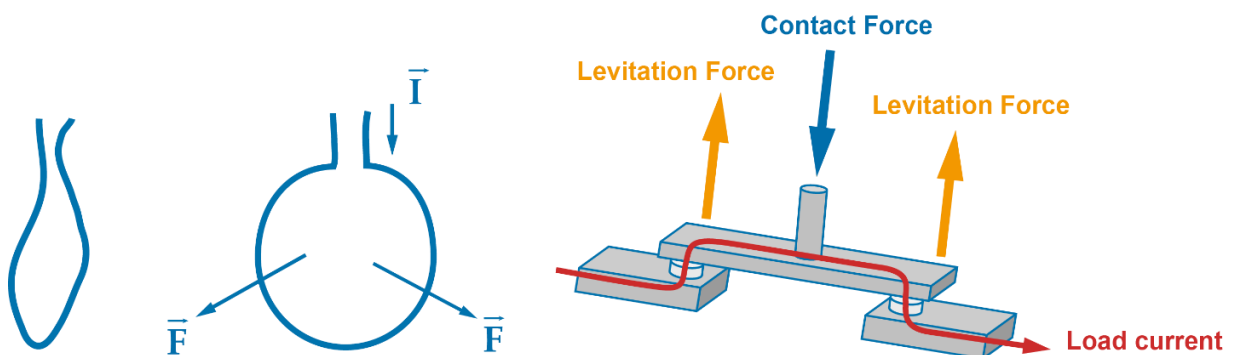


Fig. 3 Schematic representation of the repulsive electrical force effect

The repulsive force increases with the square of the current. At 1,000 A, the repulsive force on the contact bridge shown in the right image is already about 1 N. When the current is high

enough, the contact force is overcome. If the current exceeds this so called levitation limit, the contacts will separate, and immediately an arc is formed. The contacts are then either welded together or the switching device is thermally destroyed after a contact opening with a burning arc. The permitted maximum overcurrent duration for the EVC 250 is:

Pulsed current	Pulse duration [ms]
6,000 A	20
5,000 A	100
4,000 A	500
3,000 A	1,000

Table 2: Permitted duration for pulse currents

Overcurrents below this levitation threshold, will cause the contact temperature to increase, until the melting temperature is reached. The contact piece will then mechanically collapse, and the contact pressure suddenly becomes lower, so that levitation occurs at this lower current. Once the arc burns, the arc resistance limits the further increase of the current. The contacts will therefore re-close again and immediately weld together. In pressurized, gas filled devices, if the overcurrent is substantially greater than the current limit, the free-burning arc generates such a strong pressure in the contact chamber that the enclosure can burst explosion-like, quickly releasing the pressurized gas. Under such conditions, the non-pressurized design of EVC 250 has the advantage that excess pressure can escape without damaging the enclosure, significantly reducing likelihood of an explosive-like destruction of the component.

2.3.1.4. Switching Operation

The ability to separate high voltage is achieved by a large contact gap, a special design of the contact chamber and by the magnetic field of permanent magnets, working within the arc range. Due to the placement of the permanent magnets, the EVC 250 has an asymmetric switching capability, depending on the direction of the load current.

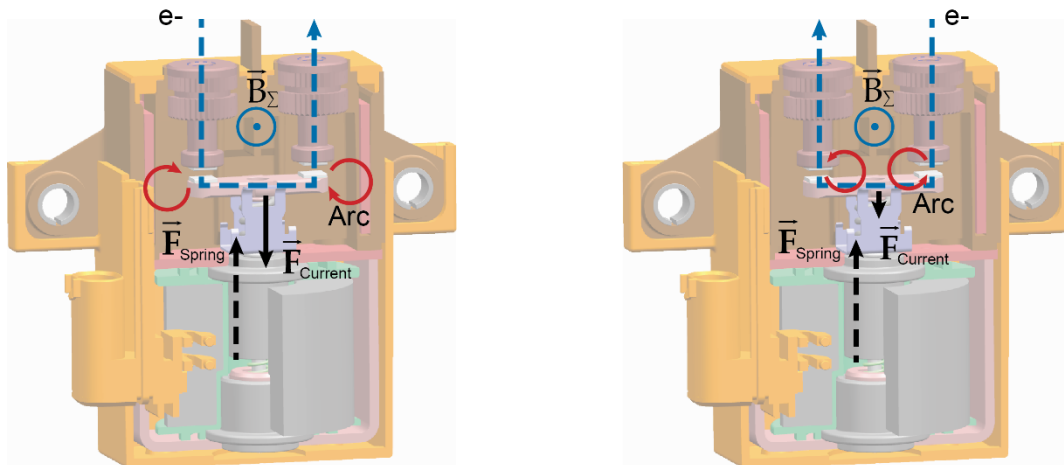


Fig. 4: Repulsion and attraction force of the current in the external magnetic field discharge charge

In figure 4, the effect of the current on the contact arrangement for the two current directions *battery charge* and *battery discharge* is outlined. The arc is deflected either to the side or to the centre. In the right picture (*battery charge*), the two arcs could merge in the centre in case of large currents. An interruption of the current is then no longer possible. This results in the below limits of the switching capability of EVC 250 main contactor.

	Current [A] on/off	Voltage [V] on/off	Switching cycles	R _{iso}
Charge/Discharge	200/27	22.5/450	100,000	>1 GΩ
Charge/Discharge	30/30	450	100,000	>1 GΩ
Charge	0/100	450	50	>1 GΩ
Charge	0/200	450	50	>100 MΩ
Discharge	0/500	450	50	>100 MΩ
Discharge	0/1,000	450	1	>100 MΩ
Discharge	0/2,000	450	1	>100 MΩ
Discharge	0/3,000	400	1	>100 kΩ

Table 3: EVC 250 switching capability

Since the contact chamber of EVC 250 contactor is not hermetically sealed and the contacts are exposed to an oxygen containing atmosphere, a silver-tin-oxide material is used as contact

material. With this contact material, a good resistance against welding is achieved. Naturally, some material is worn from the contacts under load with every switch cycle. However, the contact volume was designed so that the contactor achieves the current carrying capability in table (2) with the mentioned standard loads.

2.3.3. Relay drive

A large contact spacing is needed in order to ensure a sufficient isolation resistance at reduced air pressure. A relatively large current is required for the driving coil so that the electromagnetic drive system of the relay is able to overcome this large distance. This pull-in current must be reduced to a holding current after the relay contacts are closed. Otherwise, the coil would be thermally damaged by a permanent current supply.

There are two possibilities to adapt the coil power of the EVC 250 contactor.

2.3.3.3. The EVC 250 as a single-coil variant and external current reduction

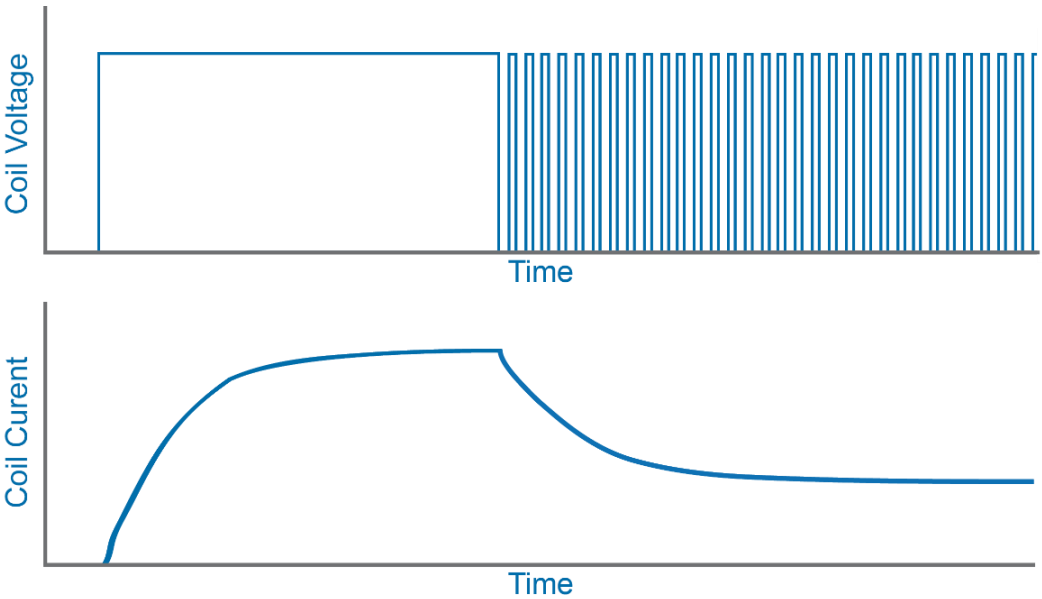
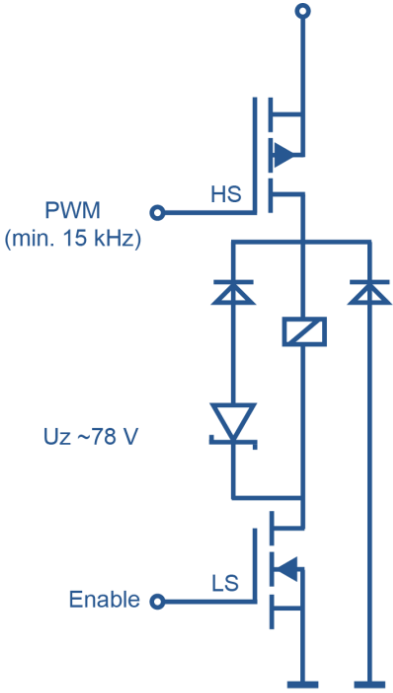


Fig. 5: Coil current adaptation via PWM

With the Single-coil variant of the EVC 250, current reduction is provided by an external circuit outside of the relay in the controller electronics. For example, a pulse width modulation (PWM) technique can be applied to reduce the effective coil current to a holding value after the first 100 ms of uninterrupted supply. The single-coil variant of the EVC 250 has a coil resistance of 4 ohms. A current of approximately 1.8 A needs to be ensured for at least 20 ms for full pull-in. The current must then be lowered to less than 800 mA after at most 0.5 seconds to reduce the 64 W of power that could otherwise thermally overload the coil.

The circuit represented in Fig. 6 is a realization proposal for the driver circuit, which furthermore ensures the particular demagnetization required when deactivating the relay. At the moment when the coil voltage is switched off, the energy stored in the coil generates a very high voltage peak. A protective circuit is required in parallel to the coil to protect other electronic components from this voltage peak. The PWM is generated with the upper transistor, whereas the lower transistor (*Enable*) ensures a quick shutdown. The induction voltage generated during the off-state of the PWM is limited by the diode on the right side of the coil to a value below 1 V. The time constant and, therefore, the ripple of the coil current is relatively small because of the low forward resistance of the diode and the relatively large inductance of the coil. This is favourable for the PWM operation as long as the contactor is switched on, however during shutdown, the coil current reduces only slowly and the relay armature would start moving away from the closed position with delay and only very slowly. When a high load current is disconnected, this slowed opening would lead to an elongated arc burning time and, in worst case, to the destruction of the contactor



6. Switching recommendation for the single-coil variant

However, if the lower transistor is used for switch off, demagnetization occurs via the Zener diode on the left side and a slowdown of the armature movement is no longer observed. With a clamping voltage higher than 60 V a slowdown of the armature movement is no longer observed. The contacts open at maximum speed.

2.3.3.4. Dual-coil variant with internal coil current reduction

In addition to the single-coil variant, the EVC 250 main contactor is also available as a dual-coil variant with internal coil current reduction. The necessary measures for coil control functions are outlined in the block diagram below.

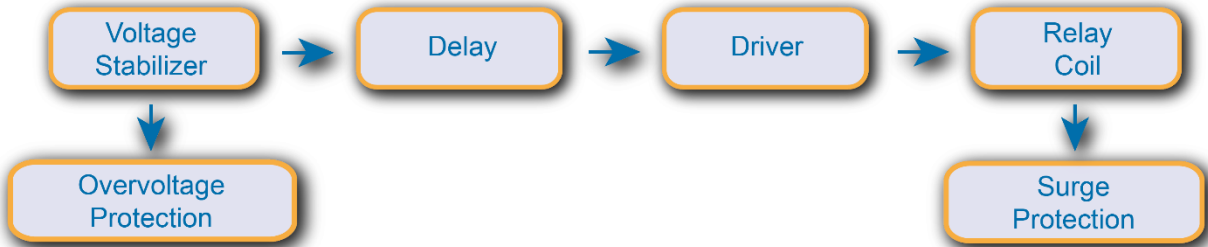


Fig. 7: Function blocks for coil current adaptation

With these elements, the coil current is adapted in the manner outlined below after a constant voltage is applied.

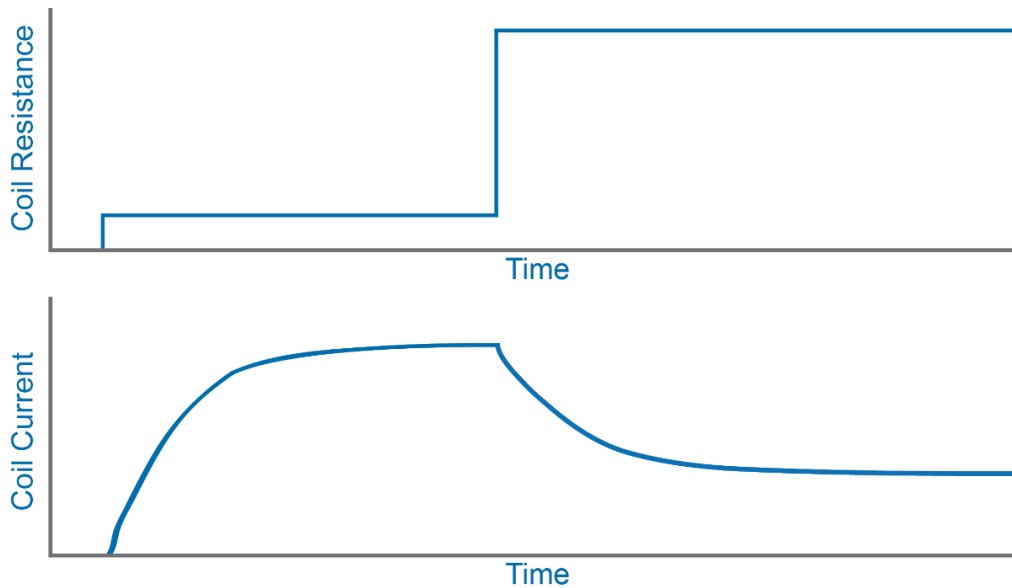


Fig. 8 Booster and holding current as a function of time

This version can directly be connected to a power source without further measures. An external control of the supply voltage is not necessary. A booster coil with low resistance is placed in parallel to the working coil on the bobbin, which provides the additional magnetic flux necessary for pull-in at 7 V. The holding coil has a resistance of 36 ohms and the booster coil has a resistance of 4 ohms. If a voltage is applied to the coil terminals, both coils are initially supplied with current. At this point, it must be ensured that the pull-in voltage is reached within 100 ms. After 200 ms, the booster coil is turned off. After de-activation of the relay, the circuit is ready for the next operation again after 200 ms. The power consumption of the holding coil is typically 4 W at 12 V. This way, the contactor can be permanently operated up to an ambient temperature of 105°C. The polarity of the coil connections has to be observed so that the booster circuit can operate.

3. Summary

The new EVC 250 high-voltage contactor for hybrid and electric vehicles was developed specifically as a safety element for the requirements at the interface between the energy storage system and the vehicle electrical system. Together with the fuse, this component has the task of protecting the battery from thermal overloading and, under normal operating conditions, ensuring the separation of the drive system after each drive cycle. Since it was designed as non-pressurized contactor without gas filling and with high contact forces, an increased overcurrent capability could be achieved. Overcurrents of up to 6 kA can be carried for 20 ms without any key properties being affected. Excess overcurrents can possibly restrict the switching function; however, they do not lead to any dangerous condition.

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 - II. SAE J1766; Recommended Practice for Electrical and Hybrid Vehicle Battery Systems Crash Integrity Testing; (Item 3.4.2) APR 2005
 - III. SAE J2344 Guidelines for Electric Vehicle Safety; 2010-03-05
 - IV. SAE J2289 Electric Drive Battery Pack System: Functional Guidelines, 2008-07-29
 - V. ISO/NP 6469-4 Electrically propelled road vehicles -- Safety specifications -- Part 4: Post crash electrical safety requirements
 - VI. DIN EN 60664-1 VDE 0110-1:2008-01, Isolationskoordination für elektrische Betriebsmittel in Niederspannungsanlagen, Teil 1: Grundsätze, Anforderungen und Prüfungen, (IEC 60664-1:2007); Deutsche Fassung EN 60664-1:2007
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