A VACUUM CIRCUIT-BREAKER WITH PERMANENT MAGNETIC ACTUATOR AND ELECTRONIC CONTROL

Edgar Dullni, Harald Fink, Christian Reuber
ABB Calor Emag Mittelspannung GmbH
Bahnstraße 39-47, P.O. Box 1220, D-40832 Ratingen (Germany)
Tel : +49 2102 12-1281 – Fax : +49 2102 12-1933 – E-mail: Edgar.Dullni@DEACE.mail.ABB.de

ABSTRACT

Vacuum circuit-breakers have obtained a high level of performance, reliability and safety. This is mostly owed to the advantages of current interruption in vacuum. However, the design of the mechanical drive, which has already been applied e.g. in minimum oil-breakers, has hardly been changed. With the introduction of an actuator with permanent magnetic limit positions and electromagnetically controlled motion, the next generation of vacuum circuit-breakers is launched promising an increase in reliability and endurance. The operation of the circuit-breaker is controlled by an electronic device implementing interlocking, signaling, releases and self-diagnosis. The electronic control and supply requires a somewhat different approach to applications compared with a conventional circuit-breaker. The experience with frequent operations reaching 100000 CO is promising.

INTRODUCTION

Innovations in vacuum switching technology have constantly increased the efficiency of vacuum circuit-breakers while at the same time reducing their external dimensions. The mechanical operating mechanisms initially used, familiar in the context of minimum oil breakers, were made more compact and adapted to suit the lower energy requirement of vacuum interrupters. The large number of parts required to control the function of a purely mechanical operating mechanism however remained a disadvantage. It will be remembered that the possibility of a failure increases in proportion to the number of individual parts. The failure statistics therefore predominantly comprise mechanical defects.

Even 20 years ago, attention was devoted to electromechanical operating devices for vacuum interrupters [1,2]. They were however only used with contactors which required extremely frequent switching. The disadvantages of a high power consumption and the necessary mechanical control and electrical switching components for the coil current opposed their further spread. Furthermore, mechanical latching in the limit positions was required. Irrespective of this, electromagnetic operating mechanisms ideally match the requirements of vacuum interrupters: both are characterized on the one hand by a short stroke (8 - 12 mm), and on the other hand - in the closed position - by a large force requirement (2000 to 4000 N per phase) and a large force capability respectively.

By means of a special combination of electric and permanent magnets [3,4] it was possible to avoid the high power requirement for switching and the disadvantages of a mechanical latching system for the limit positions. The vacuum interrupter is held in the open and close positions by the force of a permanent magnet without any electrical energy. As a result, the operating mechanism is considerably simpler in structure than a conventional mechanical system (*figure 1*). With the drastic reduction in the number of parts, the susceptibility to failures is significantly lower, and therefore no maintenance of the operating mechanism is necessary [5,6].

Figure 1: View of the VM1 circuit-breaker

A further advantage of the new device is the implementation of an electronic power control with universal power supply. Coil current switching, interlocking, signaling and also self-diagnosis is provided by a specially designed control unit. These facilities can only be implemented in conventional mechanisms by complex wiring of auxiliary switches if at all. The need for auxiliary switches operated by the device is obviated by the use of inductive proximity sensors, which indicate the open and close positions without physical contact and without mechanical moving parts.

PERMANENT MAGNET SWITCHING PRINCIPLE

A conventional stored energy spring mechanism has a large number of mechanical components: typically around 160, without standardized parts such as screws. The magnetic operating mechanism, in contrast, is significantly simpler (*figure 2*). Apart from the moving contact in the vacuum interrupter itself, it consists merely of the link rod with contact pressure spring, a welded lever shaft 1 and the permanent magnet actuator 3-6. The number of parts has been reduced to less than 40%.

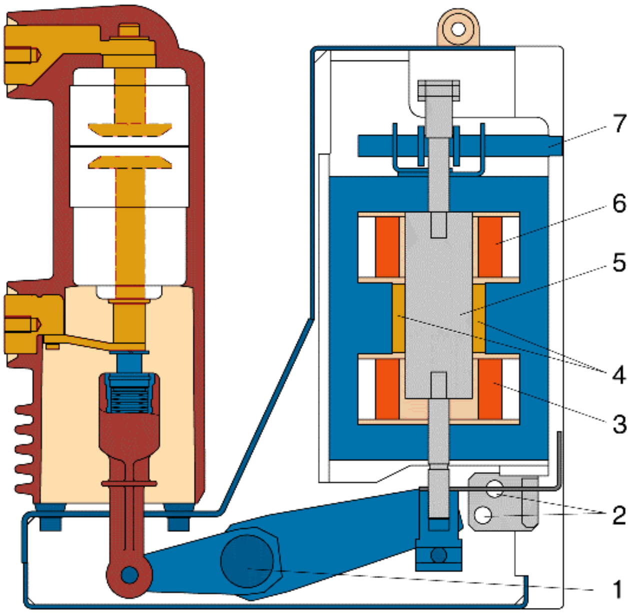

Figure 2: Section of the operating mechanism and pole part of the circuit-breaker

1 Lever shaft
2 Proximity sensors
3 Closing coil
4 Permanent magnets
5 Plunger
6 Opening coil
7 Emergency manual opening

Figure 2 shows a section of such an actuator. The figure shows the fixed laminated iron core, the permanent magnets 4, the moving plunger in steel 5 and coils for closing 3 and opening 6.

The magnetic field lines drawn in *figure 3* help to explain the function of the actuator. In the position shown, the plunger at the "top" (open position) together with the iron core forms a path of low magnetic resistance for the field of the permanent magnets. In contrast, the large gap at the bottom of the plunger represents a high magnetic resistance. The field lines therefore run almost exclusively through the end of the plunger being in contact with the core. The high concentration of field lines originating from the permanent magnets produces a large attracting force at this point. This attracting force is transmitted via the lever shaft (part 1 in *figure 2*) directly onto the contacts of the vacuum interrupter.

a)
b)
c)

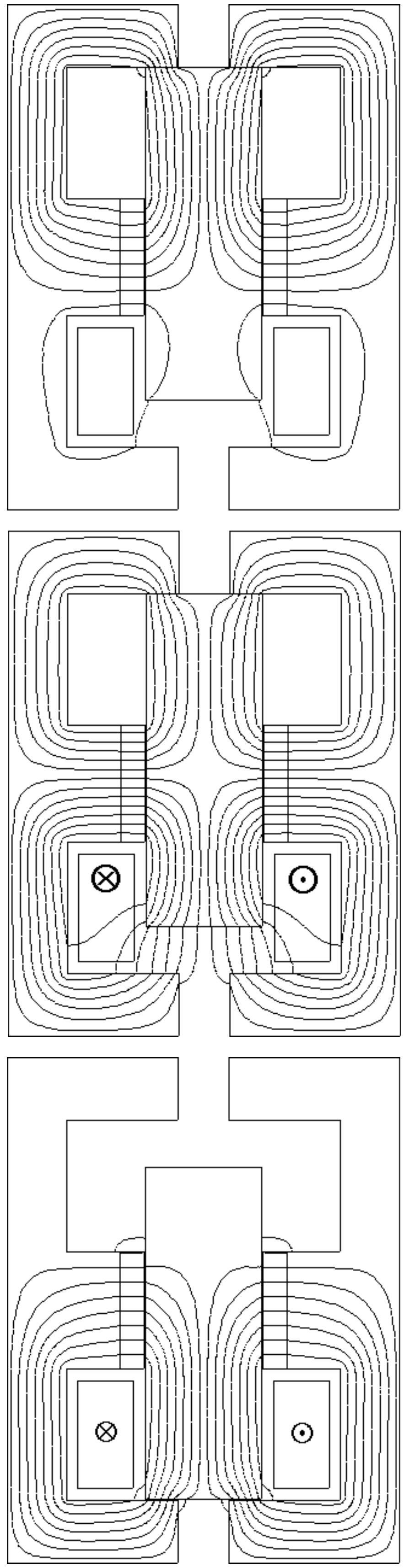

Figure 3: Distribution of the magnetic field lines
a) in the open position;
b) shortly before the start of the motion;
c) after the end of the motion and before switching off the coil-current

The coils are required for switching. *Figure 3b* illustrates the closing operation: the additional magnetic energy of the lower coil compensates for the high magnetic resistance of the gap, directing the field lines more and more towards the lower path. The retaining force at the "top" declines, while the attraction at the "bottom" increases. When a certain level of current in the coil is exceeded, the plunger moves. *Figure 3b* is an instantaneous representation of the field lines shortly before the plunger starts to move. When the final position is securely reached, as in *figure 3c*, the remaining current in the coil improves the latching process. The combination of permanent magnetic flux and electromagnetic flux leads to a very high force that damps out mechanical oscillations very effectively. Some milliseconds later, the coil current is switched off. The field line distribution is then similar to that in *figure 3a*, but this time with the plunger in the other limit position. Here, the closed position of the vacuum-interrupter contacts and the charged contact springs are latched with the static hold-force that is generated only by the permanent magnets. Current in the coils is not required as long as the circuit-breaker shall stay in this position.

Emergency manual opening operations are also possible using a special crank. The crank engages directly with the armature (7 in *figure 2*), and thus bypasses all intermediate transmission components.

The function of the actuator can be described as that of a bistable position switch which requires no mechanical control or latching functions. With such a system, 100,000 operating cycles can easily be reached with only minor maintenance. Therefore, the new circuit-breaker is extremely interesting for applications comprising frequent switching e.g. in paper mills and arc furnaces. Apart from the conducted endurance tests, importance was attached to long-term durability. The permanent magnets in neodymium-iron-boron (NdFeB) are not only chosen because of their high permeability, but also because of their high stability against demagnetization and their low aging [4].

ELECTRONIC CONTROL UNIT

The electronic power supply and control unit for the circuit-breaker has to fulfil all the functions familiar from conventional mechanical operation mechanisms. In addition it provides and monitors the energy for switching the actuator (*figure 4*).

A power supply 3 with an input voltage range of either 20 to 66 V DC (20 to 48 V AC) or 93 to 375 V DC (93 to 265 V AC) provides a constant operating voltage of 80 V, independently of the stability and quality of the auxiliary voltage supplied. Time-consuming adjustment of the equipment in the breaker to match the customers supply voltages is therefore no longer necessary. Undervoltage and overvoltage have no effect on switching times.

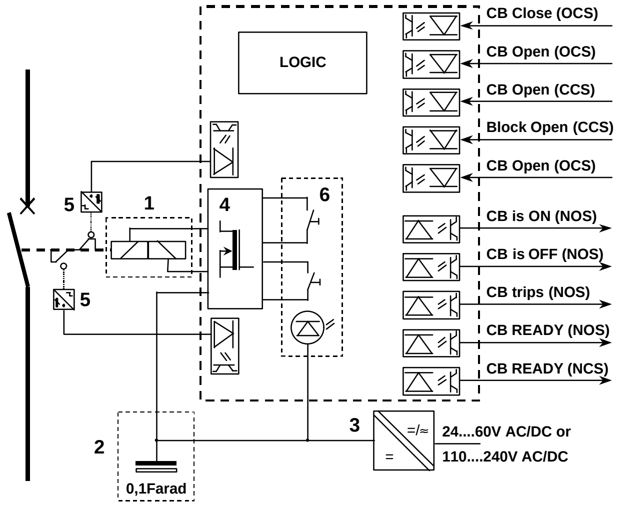

Figure 4: Block diagram of the control electronics

1 Opening and closing coils
2 Storage capacitor
3 Power pack
4 Power semiconductors
5 Proximity sensors
6 On and off button and readiness indicator

An electrolytic capacitor provides the surge power of up to 2600 W required for energizing the opening and closing coils 1 in the actuator. It stores the electrical energy of less than 200 J for a complete O-CO operating cycle. After such an operating cycle, the capacitor recharges within less than 10 s with a peak current of max. 2 A.

Power semiconductors, in this case a combination of MOSFET transistors and thyristors, control the current for switching the actuator coils. The switching voltage induced by the inductivity of the coils on interruption of the current are reduced by parallel free-wheeling diodes to such an extent that they have no further influence on the semiconductor components. Generous dimensioning of the components ensures a maximum of quality and long life, especially compared to conventional electromechanical relays. The MTBF[1] of the electronic control unit, including the power supply, results in a value of 62.5 years (assuming an ambient temperature of 40°C).

A field programmable gate array (FPGA) controls the circuit-breaker. Switching commands are only executed taking account of the switch position, which is detected by two inductive proximity sensors, and the charging condition of the storage capacitor. In the open position, for example, there must be sufficient charge available for a complete CO switching operation. The controller blocks a closing operation, if an opening command is active at the same time. It also prevents a second closing operation, if an opening operation has been performed while a closing command is active. The proximity sensors detect impermissible intermediate positions, e.g. failure to reach a limit position, and signal these.

[1] **M**ean **T**ime **B**etween **F**ailures

Five inputs and five outputs, which are electrically isolated for 2.5 kV, form the interface to a panel or station automation system. The open circuit inputs accept pulses from 48 to 250 V AC/DC. Therefore, there is no need of an adaptation to the different requirements of customers minimizing co-ordination problems. The inputs are:

1. Close the CB (Open Circuit System; OCS)
2. Open the CB (OCS)
3. Open the CB (Closed Circuit System; CCS)
4. Block the closing of the CB (CCS)
5. 2^{nd} Open CB (OCS)

An OCS means here that voltage has to be applied for an action, while for CCS an action takes place when voltage is removed.

Input 4 can be used with a circuit-breaker on a withdrawable unit. Closing should only be possible in the terminal positions of this unit. In any intermediate position, the auxiliary switches in the withdrawable unit interrupt the feeding of this input, so that closing is impossible.

Input 5 can be used for a redundant tripping circuit.

For the monitoring of the device, five output-channels are available:

1. CB is ON (Normally Open Contact; NOC)
2. CB is OFF (NOC)
3. CB is tripping ("wipe-contact"; NOC)
4. CB is READY (NOC)
5. CB is READY (Normally Closed Contact; NCC)

E.g. for output 1, NOC means that this contact is only closed when the signal "CB is ON" is true. The contact of output 3 is closed for about 40ms during tripping.

Output 4 is closed when the following parameters are assured:

- Internal supply voltage is available
- The internal control of the FPGA ("watchdog") is positive
- The position of the CB has been detected and is plausible
- The voltage level of the capacitor is high enough:
  - for closing and opening if the CB is open or
  - for opening if it is closed

Output 5 is the inverse of output 4. This logical combination gives the customer a clear indication of the functional ability of the breaker. Additionally, the READY-signal is monitored via a LED at the front panel of the circuit-breaker.

The NOC ON and OFF signals are designed from electronic relays capable of carrying and switching a current of up to 0.5A at a voltage of up to 400 V DC or 280 V AC. This is sufficient for energizing e.g. a multiplication relay. The most important functions known from conventional circuit-breakers are available. Wiring diagrams can be taken over with only minor modifications concerning the number of ON and OFF signaling outputs.

The EMC compliance of the electronic control unit has been demonstrated in accordance with IEC 1000-4-x by various switching capacity tests and extreme voltage tests. Furthermore, extensive endurance tests of the electronic control unit inside the circuit-breaker have been performed. Here, no electrical problems occurred. However, some parts with high masses and small leads showed mechanical problems. They occasionally broke off the board. All these parts were identified. After they had been glued onto the board, several endurance-tests with 100,000CO each have been performed without any problems.

APPLICATIONS OF ELECTRONIC CONTROL UNIT

The energizing of the coils of the actuator for closing and opening operations requires a continuous connection to some auxiliary voltage supply. In principle, this is also true for the conventional mechanical drive. It needs electrical energy for the tripping and closing coils. However, this energy amounts to only 1/10th of that necessary for the actuator. Because of this reason the actuator coils cannot be directly connected with the control voltage, but only via a storage device. Batteries or capacitors are very common for this purpose. Capacitors have the advantage of longer lifetime and do not need maintenance in contrast to batteries. Even at a relatively high environmental temperature of 55°C, the lifetime of modern electrolytic capacitors is over 30 years.
The power supply of the electronic control unit shall be connected directly to the control voltage supply. The circuit-breaker has then the same availability and priority as all other protection devices. In steady-state the whole unit consumes a power of 2 W. Only during recharging of the capacitor after switching (2 - 10s) and during the first energizing of an empty capacitor (8 - 50s), the current may increase to a maximum of 2 A limited by the electronics. There is no need for another supply as it is necessary for the conventional drive to charge the storage spring. Therefore the availability of the new breaker has increased.
On failure of the auxiliary voltage, the storage capacitor ensures that a breaking operation is possible for further 2 minutes. Thus, short voltage breakdowns are bridged without problems. Conventional breakers would deny tripping in such a case, unless a second independent protection unit is available. In this connection, it can be understood that manual closing has no sense, because without auxiliary supply voltage any protection function is missing.

Undervoltage Release

The electronic control unit also allows for the function of an undervoltage release using input 3. If it is not used, it shall be connected to the internal supply voltage of 80V. Then it may also serve as part of an external interlock circuit. An undervoltage release is realized, when the CCS tripping input 3 is connected to a commercial undervoltage relay. Then, switching levels with respect to the primary voltage can be precisely defined (e.g. 70% according to IEC standards).

For the protection of motors, it is not only necessary to control the motor voltage by the undervoltage relay but also to supply the magnetic actuator with the same motor voltage. Otherwise the circuit-breaker would not have the same availability as the undervoltage release. This is achieved by a small voltage transformer having a power of approx. 200 VA using the remarkably low power consumption of the circuit-breaker.

Overcurrent Release

The electronic control unit is suited well for the application of an overcurrent or short-circuit current release, if an auxiliary voltage supply for the protection unit is available. With no external supply voltage present, a voltage transformer can be used for energizing the circuit-breaker as described above.

GENERAL ASPECTS

The new circuit-breaker of type VM1 is fully compatible with its predecessor, the VD4 circuit-breaker. This facilitates direct replacement in panels, taking account of course of the specific electrical connection conditions which result from the removal of the conventional auxiliary switches.

Figure 2 contains a schematic diagram of the structure of the breaker and a section through the embedded pole part. With the embedding in cast resin, which in first place upgrades the external dielectric withstand capability of the vacuum interrupter and reduces environmental influences such as contamination of the surface and condensation, the number of detachable components have been kept as low as possible. This too, significantly reduces the failure potential in relation to assembled pole parts. The mechanical strength of the pole parts has been demonstrated in extensive climate and temperature cycle tests (-30 to + 105°C). Complex electrical and mechanical tests have been performed to demonstrate resistance to aging in operation.

The circuit-breaker meanwhile is available with three different actuators and two pole part variants for the following performance data, which have been demonstrated to IEC 694 and 56:

rated voltage	rated current	breaking current
12 kV	630 / 1250 A	20 - 25 - 31.5 kA
17.5 kV	630 / 1250 A	16 - 20 - 25 kA
24 kV	630 / 1250 A	16 - 20 - 25 kA

The different short-circuit ratings are achieved with different sizes of actuators coping with the respective peak making currents and contact forces. Circuit-breakers with higher rated currents of up to 2500 A have been launched recently.

PROSPECTS

The circuit-breaker of type VM1 represents a remarkable leap forward in quality. With the permanent magnet actuator and without sensitive latching and control components, the operator now has a maintenance-free switching device. Further breakers with higher rated data will extend the range in the near future, making an entire family of magnet-operated breakers available. With the use of pole parts embedded in cast resin, the way forward has been prepared for even more compact circuit-breakers for use in switchgear installations of minimum dimensions.

These maintenance-free components in conjunction with the integrated intelligence for control and diagnosis, and in future also for measurement and protection, ensure reliable, continuous operation. Favorable experience with the new VM1 circuit-breaker in service has already been gained. The technical solution presented here shows that even with a highly developed switching device like the vacuum circuit-breaker, the symbiosis of the familiar vacuum switching technology with a new magnetic operating system represents a further optimization of customer benefit.

REFERENCES

[1] M. Minovic, *Schaltgeräte - Theorie und Praxis*, Hütlig und Pflaum Verlag München, Heidelberg, 1977

[2] H. Brungsberg, "Über die Verwendung von polarisierten Magnetsystemen für größere Schaltgeräte", *ETZ* vol. 86, 1965, pp.371-375

[3] B. Mckean; D. Kenworthy, "Bistable magnetic actuator". World patent WO 95/07542, 1994

[4] B.A.R. Mckean, C. Reuber, "Magnets & Vacuum - the perfect match" in *Proceedings 1998 IEE Trends in Distribution Switchgear* , London, pp.73-79

[5] E. Dullni; H. Fink; G. Hörner; G. Leonhardt; Chr. Reuber, "Totally maintenance-free: new vacuum circuit-breaker with permanent magnet actuator", *Elektriziätswirtschaft*, 1997, no 11, pp. 1205-1212

[6] E. Dullni: "A vacuum circuit-breaker with permanent magnetic actuator for frequent operations", in *Proceedings 1998 ISDEIV XVIII*, Eindhoven, pp.