Comparison of advantages and disadvantages of electronic and mechanical Protection systems for higher Voltage DC 400V

While the speed of operation of conventional circuit breakers for equipment (CBE) is suitable for the majority of modern day equipment applications, ultra-sensitive solid-state circuitry of the nature typically found in telecom power distribution applications will often require faster switching protection under overcurrent conditions than electromechanical CBEs can achieve.

Conventional electromechanical circuit breakers as not only protect AC and DC circuitry from overload and short circuit conditions, but in parallel – importantly – additionally ensure that the required physical isolation criteria after contact separation are maintained.

CBE manufacturers it is demonstrated therefore, need to be mindful, to incorporate such benefits of traditional electromechanical designs along with the enhanced solid state electronic switching requirements when considering their design options. For this reason, electronic circuit breakers are typically hybrid designs featuring an electrical contact in series with the semiconductor circuitry which remains open in the semiconductor “OFF” state thereby ensuring the required isolation voltages can be withstood.

Faced with this background this paper presents the case for solid-state electronic circuit breakers for smart datacom power distribution systems based on the concept of electronic interrupting devices. The functionality of electronic interrupting devices and their integrated serial communication bus link (enabling individual programming of the desired tripping thresholds for input under/over-voltage protection and output overload) is explained by examining integrated current limitation and protection characteristics for short circuit and overload sensing and in-built current flow interruption.

The paper further illustrates the suitability of electronic interrupting devices for low switched (minus) DC 400V next generation datacom power applications whereby particular emphasis is placed on an integrated arc fault detection capability. This aspect leads into an outlook to describe how the additional benefits of an AFDM can address in terms of highlighting switching scenarios, e.g. switch off in total or switch to redundant power matrix systems etc..

Power management aspects are also highlighted on the basis of a priority load shedding capability thereby ensuring battery buffer capacity is not wasted and saved to the utmost important service. This all leads into a matured and sophisticated power and facility management in the latest state of the art datacom applications.
MAGNETIC-HYDRAULIC

The magnetic-hydraulic trip mechanism is mainly influenced by the movement of the core within the magnetic coil (Without taking the frictional effects and leakage flux into consideration).
The delayed area typically lays between 1,3 and 6 to 8 times rated. Some applications even don’t provide this amount of energy. E.g. power supplies which are not at all batterie backed up cannot fulfill the required energy pike for a safe operation.

With higher currents the magnetic system trips the latching mechanism of the circuit breaker even before the core has travelled, theory is no longer valid. Fig. 4 shows the comparison of measurement and calculation.

Under short circuit conditions the contact system must have the capability to extinguish the arc occurring between the opening contacts within a few milliseconds. The time has to be short enough to prevent destructive thermal damage.

I.e. with DC voltage the arc voltage has to be higher than the driving voltage. Without additional measures this can only be achieved by accordingly big contact gaps in open condition. Double contact systems offer the advantage of doubling the arc voltage, but at the same time have the drawback of a higher voltage drop when operated at rated load.

The right size of the contact system and the subsequent measures for arc extinction are a vital pre-condition of mechanical switching devices for appropriate handling of the fault currents that may occur in operation.

POWER DISTRIBUTION SYSTEMS

It is vital that all telecommunication systems can be brought into service easily and quickly in spite of their growing complexity. Reconfiguration with the system operational must be possible, and ease of connection in locations difficult to access is important to keep service and maintenance costs low.
The solution is an extremely versatile plug and play design facilitates installation of a power distribution unite for 19", 21" or ETSI racks. The unite is supplied pre-wired for ease of installation and maintenance, which is especially advantageous for control cabinets difficult to access.
The magnetic-hydraulic technology maximum current per channel is 125A, and even higher ratings are possible through parallel connection. The total power which could be distributed in the unite is 600A. Hot swap capability allowing the exchange of circuit breakers with power on, to reduce downtime.
ELECTRONIC CIRCUIT BREAKERS

INTRODUCTION

Metal contacts have been used in conventional mechanical circuit breakers, relays, contactors and power switches for more than 100 years. The improvement of contact material and design meanwhile provides an optimum of circuit protection for nearly every application.

The development of suitable solid state switching devices draws attention to the fact that it might be possible to replace metal contacts for specific applications in the near future. Solid state devices perform switching without moving parts, no arcing, no contact abrasion and millions of operating cycles.

There are existing hybrid devices like ESS combining the advantages of mechanical circuit breakers for lower contact resistance, proven overload protection characteristics, low power loss with remote control function, the intelligent evaluation of the current signal and additional features like open circuit monitoring in the load circuit. In combination with an controller board one even could monitor the actual voltage, current and power consumption.

The time/current curve for the trip characteristics of SSRPC depends mainly on how fast the charge carrier concentration in the conductive semiconductor junction may be brought down to zero.

The control signal causing the charge carrier concentration to becoming zero can be a voltage (SCR 2), TRIAC 3), GTO 4)-thyristors, MOSFET 5), IGBT 6)) or a current bipolar-transistor. Fig. 6 shows a typical TRIAC-curve. A TRIAC is high-resistance in both polarities until the respective igniting voltage is reached and will suddenly become low-resistance until the polarity changes again. Height of the igniting voltage may be influenced by the gate drive via a series resistor. Unlike with the described magnetic and magnetic-hydraulic trip systems the current sensor of an SSRPC is not an actuator at the same time. For creating a control signal an external current sensor is needed and an electronic control unit. As soon as this signal is applied to the corresponding control input, the conductive semiconductor junction will change its state within few m-seconds. Besides the rise time of the control signal the electronic trip time only depends on the re-combination conditions (decomposition of stored charge carriers, circuit-commutated recovery time) in the semi-conductor.

This means that the electronic trip time is basically determined by the time needed by the electronic control unit to create the control signal. This is no problem in the lower overload area of the semiconductor characteristic curve. The trip times may be in the range of seconds and are determined by a corresponding circuit or programming of the electronic control unit. A current limitation may be implemented within semiconductor switches which limits the current even in the event of a short circuit to values below the thermal and physical load limits of the semiconductor junction, i.e. if the power supply is very low-resistance, the main current path will become more high-resistance within few m-seconds and the prospective short circuit current will not flow. A typical value for initiation of the
current limitation of electronic circuit breakers up to 60V DC is e.g. 1.8 times rated current. Fig. 7 shows the time/current characteristic of such a device. The trip time is typically 5 seconds in the range between 1.1 and 1.8 times rated current IR. Electronic current limitation starts up at 1.8 x IR, which means under all overload conditions, independent of the power supply and the resistance of the load circuit, the max. overload until disconnection will not exceed 2 x IR. The trip time is between 100ms under short circuit conditions and about 5 seconds at overload conditions with high line attenuation.

CHALLENGES OF SOLID STATE SWITCHING TECHNOLOGY

There are a few issues on the solid state switching that need to be addressed. It is known that Solid State Power Switches have higher voltage drop compared to mechanical contacts, and therefore need a heat sink because of the power dissipation, which normally needs more space than the semiconductor itself. They have a leakage current at OFF-state and they need EMI 1)-protection, which means additional components like filters, zener- or transorb-diodes. At the OFF-state the semiconductor does not provide an absolute OFF-state. It has a leakage current still flowing through the semiconductor. Normal industry standards allow a typical maximum of 10 mA. The leakage current flowing at OFF-state also depends on the temperature. At the present technology, Solid State switching cannot provide the physical isolation equivalent to an air gap available at open mechanical contacts. The Solid State OFF-state is not a clean cut off from power, it does not provide physical isolation from source like mechanical contacts do. The voltage drop on electrical contacts is much lower than on Solid State switches available today. The generated heat dissipates by radiation and convection and through the terminals. For semiconductors the power dissipation is higher because of higher voltage drop or ON-State saturation voltage between the junctions. The generated heat must be taken from the semiconductor substrate. A lot of Solid State Power Switching components provide heat sink surfaces to dissipate the heat through open air. Extra heat-sink panels add weight, which e.g. is an important factor, enlarge the physical dimensions and this rises the expense. Existing high performance heat sink panel e.g. weight 4.5 pounds to provide 0.50 oC/W in natural convection. (0.50 oC rises from ambient at 1 watt.). The basic operation principle of Solid State switching is using high efficient semiconductor devices like SCR, MOSFET and IGBT. Those devices are using high impedance input to turn the semiconductor ON. The sensitive input characteristics also subject to electromagnetic field induction and ESD 1) damages. Electromagnetic shield and supply line filtering is required for reliable operation of the device.

An example for a functional diagram of an Electronic Circuit Breaker for DC applications is show in fig.8. For switching ON and OFF the load a power MOSFET is used. The current is continuously sensed with the shunt Rsen. After detection of an overload or short circuit the control circuit switches the power MOSFET from ON to OFF state and the integral circuit breaker is tripped thus providing physical isolation. Fig. 9 shows a functional diagram of an Electronic Circuit Breaker for 230V AC, 50/60Hz applications using a TRIAC for switching the load ON and OFF. The control circuit is optically isolated from the load circuit to achieve
higher current surge capability. AC3 loads in the range of 5A can be handled. Depending on the application the gate control circuit can be zero crossing or instant ON switching alternatively. For physical isolation a mechanical contact - to be opened after the TRIAC has been set to OFF state - may be added in series to the load. To ensure physical isolation for both types there is a series mechanical contact.

ADVANTAGES OF SOLID STATE SWITCHING TECHNOLOGY

The development of semiconductors for power management systems has proceeded very fast. The improvement of ON resistance on MOSFET and reduction of Vsat (ON Saturation voltage) makes the Solid State power switches very attractive compared with metal contact switching. Solid State Switches turn a semi-conductive material form a conductive state in a non-conductive state. Thus it has no mechanical moving parts and of course no arcing is generated during power switching. Solid State power switches can reach millions of cycles. The operational life is only limited by environmental conditions.

Some IGBT transistors are designed for operating voltages up to 1200V. Solid state switches have indisputable advantages compared to mechanically switching contacts at such high DC voltages. No additional complex means are necessary for arc extinction such as permanent magnets, big contact gaps, vacuum- or gas-filled switching chambers. Solid State controlled power management and circuit protection is not limited to thermal or magnetic trip time characteristics like described above. It opens a wide range of programmable capabilities like rated current, overload trip time curve, undervoltage threshold, overcurrent threshold, grouping and ganging of ESS.

HYBRID DESIGN OF MECHANICAL CONTACTS AND SOLID STATE SWITCHES

To overcome the lack of physical isolation electronic circuit breakers often use mechanical contacts in series to the power semiconductor, which will stay open in the OFF-state. This hybrid design provides both all advantages of semiconductors as well as physical isolation to the power source. The sequence of operation is to turn the Solid State OFF and then to open the mechanical contacts. The turn ON sequence of operation is to close the metal contacts and then to turn the Solid State ON. The hybrid design also works very well at high DC voltage applications. There is only minimal abrasion on the metal contacts because of low switching currents.

There are solutions using an additional mechanical switching contact to minimise voltage drop and thus power loss in ON condition. Power loss often represents a problem particularly at AC applications, as often a TRIAC, GTO-thyristor or IGBT has to be used because of the higher electrical switching power. A MOSFET, which is very low-resistance in the ON condition and therefore create less power loss, cannot be used as it only features cut-off voltages of approx. 50..100V. In the blocked state the full rated voltage, e.g. 240VRMS, is applied to the semi-conductor valves (TRIAC, GTO, IGBT), therefore the current limitation method cannot be used. Preferably algorithms are used which are able to provide a prognosis regarding the expected current within only a few sampled values thus enabling the solid state switch to be triggered very quickly into cut-off state even before the full current height is reached [7].
The application of mechanical contacts parallel to the semiconductor will minimise the on-state power loss of semiconductors. Combinations like a TRIAC in parallel to a contactor are especially known for switching AC circuits. The on-resistance is determined by the low contact resistance of the mechanical part. During switching operation an arc will occur during the first few microseconds (typical 50 to 200 s) till the current commutates to the semiconductor. To assure the required electrical isolation after circuit interruption an additional mechanical contact in series is an appropriate method. Above described combinations have been successfully tested in so-called hybrid contactors to extend the life of the mechanical contact pieces significantly [11].

Another challenge for semiconductor devices is inductive load switching. There are two types of inductive loads to be discussed. The Internal Emitter Inductance (LE) between the bonding pad on the die and the electrical connection at the lead slows down the turn-on of the solid state device by an amount that is proportional to the di/dt of the collector/drain current flow.

Turning off an external inductive load the voltage swings from a few volts to the over-voltage spikes with opposite polarity. The inductive energy could damage the Solid State switching device. For this reason some applications suggest the use of gate drive resistor to slow down the turn-off di/dt to reduce the inductive energy and over-voltage spikes. An additional Parallel electric contact as shown on fig. 10 will protect the solid state circuit breaker from over-voltage spikes. The parallel electric contact shunts the semiconductor device and bypasses all over-voltage spikes that appeared across the circuit breaker. The turn-off sequence of operation is to open the parallel electric contact, to turn the solid state off and then to open the series electric contact. The turn-on sequence of operation is to close the series electrical contact, to turn on the solid state and then to close the parallel electrical contact.

PROTECTION OF POWER DISTRIBUTION SYSTEM

For switched mode power supplies generally used in industrial installation and control systems the protection with conventional circuit breakers may lead to complete system breakdown, because of short circuits. Conventional circuit breakers cannot react quick enough to protect the switched mode power supplies from voltage dips leading to an unstable state of the whole system. Also the stored energy in the smoothing capacitor may cause to non discriminating nuisance tripping. Often mechanical circuit breakers do not react quickly enough, because of the low value of the short current. The reason for these values in the range of two times rated current is the line attenuation by the relatively long cables usually installed for such applications. Magnetic circuit breakers are addicted to nuisance tripping and normally will trip when only switching ON and OFF. Electronic circuit breakers can be programmed to trip at small overloads and they also do not react to inrush currents. In case of a short circuit they only interrupt the faulted branch and provide discriminating protection. The power semiconductor itself requires protection from voltage spikes by output inductors and free-wheeling diodes. These components have to be added externally if not built in. Fig. 11 shows oscillograms of a fault in a switched mode power supply feeded circuit. The electronic circuit breaker with a series mechanical contact provides physical isolation and avoids nuisance reclosing of the semiconductor thus ensuring an optimized protection.
Two types of circuit protection are compared. First a conventional thermal magnetic circuit breaker is applied. It protects the wire from further damage, but leads to an immediate voltage breakdown (oscillogram a), because the power supply itself limits the current.

Furthermore in generator networks with several sources and in large distribution networks with fluctuating power transmission a slow monitoring of current and voltage changes is not sufficient for arc fault detection.

On Power-D-Box level an electromechanical high Voltage DC circuit breaker could be used for branch protection in datacom environment. At that point, physical isolation is definitely needed. Further downstream on the supplementary protection level, an electronic device is more preferable.

The AFD module is built into a distribution box for A and B feed to detect serial arcing. The possible switching scenario could be:

1. Failure occurs in the cable to a server at PDB A, ESX goes into current limitation mode.
2. In the event of a short current interruption (e.g. unplug situation) a circuit breaker with a current limitation will not trip.
3. If the limitation status lasts for a longer period of time, PDB A can be switched off and PDB B takes over.

Figure 9 Schematic of a DC 400V power network

It is vital that all telecommunication systems can be brought into service easily and quickly in spite of their growing complexity. Reconfiguration with the system operational must be possible, and ease of connection in locations difficult to access is important to keep service and maintenance costs low.

The solution is an extremely versatile; plug and play design facilitates installation of a power distribution unit for 19", 21" or ETSI racks. The unit is supplied pre-wired for ease of installation and maintenance, which is especially advantageous for control cabinets difficult to access.
The electronic version of the High Power-D-Box is incorporating all advantages of electronic circuit breakers as described and in addition it provides monitoring capabilities.

Instead a fast broad-band monitoring system is needed to detect the noise effects caused by arcs in current and/or voltage (see figure 7).

![Figure 7 Spectrum of current signal without and with arc fault in the DC-cabling of an AC-gridconnected photovoltaic system](image)

The typically used high frequency filters in converters mostly prevent the propagation of the noise effects caused by arcs, so for each part of the network which has to be monitored a separate arc fault sensor is needed.

In most applications inductively coupled sensors are better than to capacitive ones due to the mostly used relatively large capacitors for voltage stabilization and the voltage control circuits in the converters.

After A/D-conversion the measured data stream can be analyzed by means of pattern recognition in local microcontrollers or in centralized processors to distinguish between serious arc faults and other effects like short-time arcs during switching operations or electromagnetic impact. The analyzed frequency band and the algorithm have to be adapted to the topology of the converters used, to their switching frequencies and harmonics and to their control methods.
In some applications it is important to distinguish between serial and parallel arcs to provoke the right switching decision, especially in generator networks. Furthermore cross-talk-effects caused by arcs in neighboring lines have to be ignored, if each line is equipped with a separate arc fault detector.

Figure 8 E-T-A’s arc fault sensor for datacom, photovoltaic and other DC applications

**Summary and Conclusions**

Electronic circuit breakers offer compared to mechanical ones more features like nearly unlimited short circuit capacity by current limitation, programmable rated current, programmable trip time curve, wire break indication, remotcontrollability and monitoring functions for current and voltage. In addition millions of operations without any abrasion, (it should be mentioned, that the life of an electronic circuit breaker and the one of a mechanical circuit breaker are differently defined and therefore not comparable) but they do not provide physical isolation due to the leakage current at OFF-state and they show susceptibility to especially line induced voltage spikes, which have to be suppressed by additional components like suppressor diodes. Protection against field induced electromagnetic pulses needs additional shielding. Therefore electronic circuit breakers often use an electrical contact in series to the power semiconductor, which will stay open in the OFF-state thus withstanding the required isolation voltages.

For high DC voltage applications conventional circuit breakers need big air gaps, sophisticated arc extinguishing means or they use expensive technologies like vacuum or gas filled switching chambers. Solid state based circuit breakers can meet the requirements in size and performance, but they need an additional electrical contact for isolation. This is the reason, why electronic circuit breakers do also need electrical contacts!

Assignment of DC 400V in datacom environment requires more than a standard protection device which cannot detect serial arcing at all. Arc Fault Detection as well as electronic circuit breakers could benefit a lot in the sense of supporting the high availability of data center equipment. Furthermore monitoring and diagnostics options can underline the necessity of high sophisticated protecting devices.
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