'Smart' low-voltage circuit-breakers

A new generation of 'smart' circuit-breakers from ABB SACE offers significantly enhanced protection for low-voltage installations that translates into a large cost saving for customers. The 'intelligence' comes from application-specific integrated circuits (ASICs), specially optimized for the product. Due to the high level of integration both the required space and the number of components are reduced, thereby increasing reliability and improving immunity to electromagnetic interference (EMI). Damage caused by short circuits can be minimized with the help of a very fast fault detection algorithm. In the event of a fault, a circuit-breaker interlocking system provides selectivity to ensure that only the affected part of the network is isolated. Communication interfaces allow remote control and monitoring via a standard field bus. The concept makes a significant contribution to reducing circuit-breaker costs and improving personnel safety.

Circuit-breakers **1** are installed in electrical distribution networks and industrial plants to protect them from damage that could be caused by short-circuit, overload or ground fault currents. Low voltage in this context refers to voltages of not more than 1 kV. However, nominal currents for low-voltage circuit-breakers can be as high as 6,300 A, and specified ultimate breaking currents can even reach values of 100 to 200 kA. If a fault occurs, it is vitally important to:

- Isolate the fault as soon as possible
- Isolate only the affected part of the installation
- Minimize downtime and damage

New concepts are needed in order to improve circuit-breaker performance with respect to these requirements. The trend today is towards fully automated, self-protected distribution systems. To this end, the circuit-breakers require local 'intelligence' as well as a communication system for exchanging information with a central control unit.

Whereas the mechanical parts are the main cost factor in the case of the larger circuit-breakers, it is the additional electronics that dominate the cost equation for the more widely used smaller breakers. Thus, to keep the cost of an installation as low as possible the electronics need to be optimized for the specific application.

Fast fault detection

The damage caused by a short circuit depends to a very large degree on its duration, ie the delay between its inception and the time the circuit-breaker opens to disconnect the short-circuited

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part of the power line. Traditional circuit-breakers monitor the current level in each phase (plus the neutral) and open if the current in at least one of them is above some preprogrammed threshold. If the frequency is 50 Hz, the signal period is 20 ms. If only the signal peak, or rms value, is monitored, fault detection will be relatively slow (10 ms). A short detection time, besides minimizing the damage to equipment, also enhances the safety of the personnel. Faster detection, however, calls for more advanced systems.

The first requirement is for high-quality current sensors. To obtain detailed information about the signal at the secondary of a current transformer, it has to be ensured that the signal accurately reproduces the actual current flowing at the primary. Moreover, the current signal, which has to be processed, must be virtually noise-free. Proper noise filtering is time-consuming, but very important. It has to be kept in mind that the purpose of the circuit-breaker is not only to open in the event of a short circuit, but also to stay closed as long as operating conditions remain normal. Plant shutdowns due to false alarms are very expensive and must be avoided.

ABB has developed an algorithm which is capable of detecting a developing short circuit in a few hundred microseconds; this time includes the analogue to digital conversion of the phase and neutral currents, noise filtering, signal processing and the sending of the opening command. Under short-circuit test conditions as per IEC 947-2, the detection time is 300 µs. Assuming the most favourable short-circuit parameters (represented mainly by the source voltage phase angle, which must be close to 90° when the short circuit becomes established), the algorithm can detect a short circuit in less than 200 µs. Extensive laboratory tests have been performed, and current waveforms dur-

ing a short circuit have been analyzed for every conceivable condition. The result is a specialized detection algorithm which is able to distinguish between short circuits and noise spikes, yet is sufficiently fast (total detection time < 1 ms).

To be able to detect an evolving short circuit at an early stage, it is not enough to just monitor the present value; what is needed is information about the 'probable future evolution' of the current. This can be obtained by looking at one or more derivatives of the phase current, d$i(t)$/dt, and tracking the connection between the actual current, $i(t)$, and its derivative for all foreseen situations. The result can be presented in so-called 'current trajectory planes' **2**.

The exact shape of the curve varies with the load (absolute value and power factor) and the closing angle (the source voltage phase angle at which the load is switched in). At start-up, when the current is low, the derivative can be very high (positive or negative). Under normal operating conditions, the d$i(t)$/dt versus $i(t)$ curve soon reaches the stable state, forming an oval or a circle in the plane. By plotting all the 'valid' curve shapes for a certain circuit-breaker on the same sheet and drawing an envelope curve around them, a non-short-circuit area can be defined **3**.

To decide whether a short circuit is present or not, the circuit-breaker has to sample the input currents at high speed (50–100 kHz per phase). For each input sample, d$i(t)$/dt versus $i(t)$ is compared with the non-short-circuit area stored in the memory. If the data point lies outside this area, an evolving short circuit is registered. To ensure a stable system, no action is taken until it has been checked that three consecutive samples lie outside of the non-short-circuit area. Also, when the non-short-circuit area is defined some margin must be added to the theoretical limits to avoid tripping due to distorted waveforms. After a short circuit

Low-voltage, **1**
moulded-case circuit-breaker

has been identified, the circuit-breaker checks for incoming interlock signals **4**, opening if no signal is present (ie, no lower-level breaker has detected the fault).

For this new algorithm to work, fast analog to digital conversion of the current signals is necessary. Accurate noise filtering must take place quickly and there must be no falsification of the signal characteristics. To achieve the required fast response, an auxiliary power supply is needed. It should be noted, however, that the algorithm is implemented in addition to traditional detection algorithms based on the peak

and rms value (short-circuit, long-term overload and ground fault protection). These functions operate in the 'self-supply condition', in which the circuit-breaker is only supplied with power from the mains. Thus, in the event of a power supply failure, the circuit-breaker will still work with all the usual protection functions.

Fault isolation (selectivity)

A low-voltage distribution network has a hierarchical 'tree' structure, within which the circuit-breakers are grouped in switchboards **4**. The breaker size is chosen for each position in the tree on the basis of the maximum current specified for the branch being protected.

When a short circuit occurs, only that circuit-breaker which is nearest and above the fault is allowed to open. Should a higher-level breaker open due to the current being higher than its specified maximum value for much longer than the defined delay time, more of the installation will be shut down than is required, with unnecessary extra costs for the owner. Today, this problem is solved by increasing the current thresholds and delay times (through selection of a larger-size circuit-breaker) for each level in the hierarchy. An industrial installation can have up to 10 circuit-breaker levels, and in some cases this can lead to response times of several hundred milliseconds before the circuit-breaker opens. Another weakness of the system is that there is no absolute guarantee that only the nearest breaker above the fault will open.

To avoid this, and thereby considerably reduce damage to the installation, the fast fault detection algorithm is combined with a unique interlocking system for the circuit-breakers. This system features very fast breaker-to-breaker communication. Each circuit-breaker has the same fast fault detection capability, regardless of where it is positioned in the
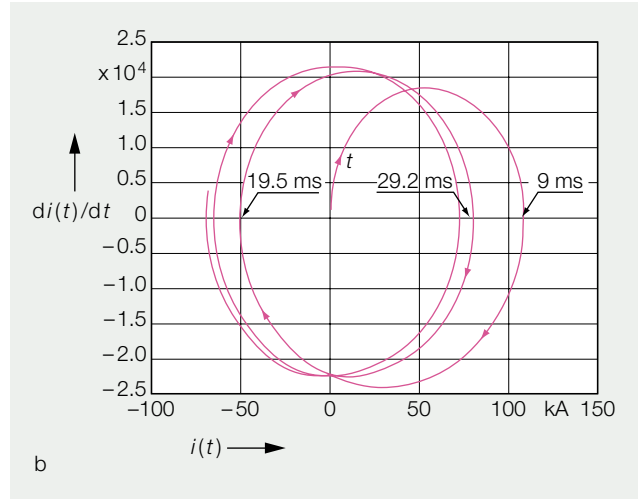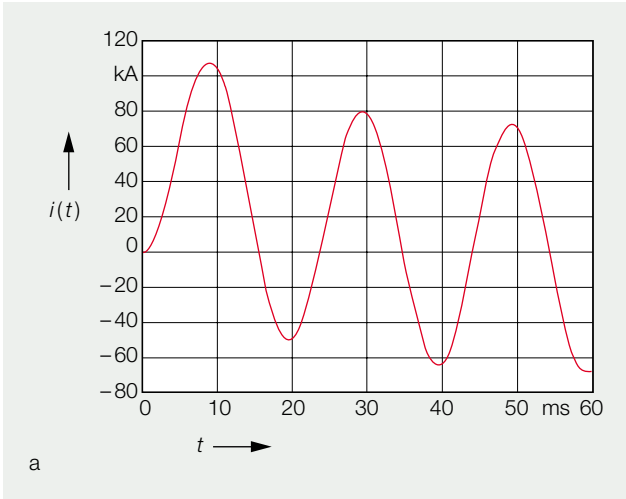
Typical start-up current and derivative (short-circuit current 50 kA, power factor 0.2, closing angle 0) **2**

a   *Short-circuit current*
b   *Short-circuit path*

i   *Current*
t   *Time*

hierarchy. When a breaker detects a fault, it checks whether the fault has been detected by a downstream (lower-level) breaker. If the answer is yes, the upstream breaker relies on the appropriate downstream breaker taking the necessary action. However, if the upstream breaker still 'sees' a short circuit after a specified period of time, it as-

sumes that, for some reason, the opening operation downstream has failed, and opens itself.

The interlocking system processes both short-circuit and ground-fault information. Long-term overload protection is not taken into account. For this function, selectivity is achieved by setting different values for the current and

opening time at each level in the hierarchy. This has to ensure that the lowest-level breaker responds first, and that the upstream breakers will have time to detect the disappearance of the overload condition well before they open.
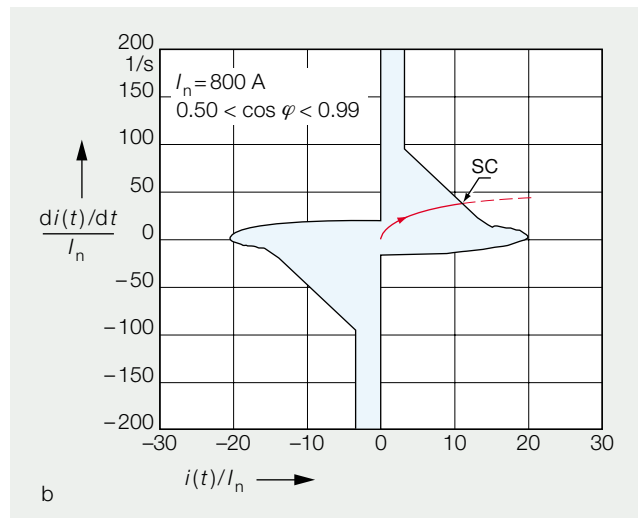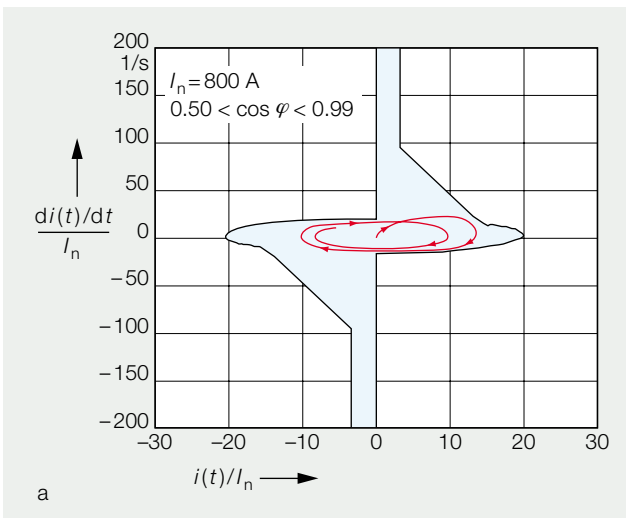
There are basically two different types of connection between circuit-breakers

Example of a non-short-circuit area and possible current trajectories **3**

i   *Current*
I_n *RMS value of nominal current*
t   *Time*

Blue *Non-short-circuit area*
SC   *Short circuit detected*

in the hierarchy. Within a switchboard, several lower-level breakers (or 'children') communicate with one higher-level breaker (or 'father') ◢. Multiple access to the line is therefore required. This is provided by the 'father' sending a short sequence of synchronization signals downwards at specified time intervals, and the 'children' answering with a status message. The messages are structured in such a way that if different messages (indicating different breaker statuses) are sent by the 'children' at the same time, the 'father' will recognize the different faults reported and act accordingly. Since the lines within a switchboard are short (no more than a few meters long), there will be no time skew or delay problems between the breakers. Twisted pairs, without electrical isolation, can be used for the physical connections.

The situation is different, however, for the communication between the switchboards. The distance between the circuit-breakers can be up to 1000 m, cor-responding to a long line. For this reason, there is always only one 'child' connected to the 'father', enabling one-way communication to be used to shorten the transmission time and avoid possible collisions. In contrast to the internal switchboard communication, the 'child' sends the short synchronization sequence and its status message to the 'father' at certain time intervals. The 'father' monitors the incoming signal continuously. Differential connection with electrical (galvanic) isolation is used between the switchboards.

The speed of the interlocking system is limited by the length of the lines between the switchboards. The pertinent standards recommend that not more than 100 kbit/s be used for lines 1 km long. This means that messages sent over such a system must be short to ensure that neither the fault handling is delayed nor the fast fault detection concept impaired. It is always sufficient to send a message one level upwards, because if the circuit-breaker above has not detected the fault and sent a message itself there will be no violation at that point, ie the overall condition of the network is good.

The physical location of each installed circuit-breaker defines the type of communication scheme that has to be used upwards and downwards, making extra programming for this unnecessary. The interlocking system, like the fast fault detection, makes use of an auxiliary power supply.
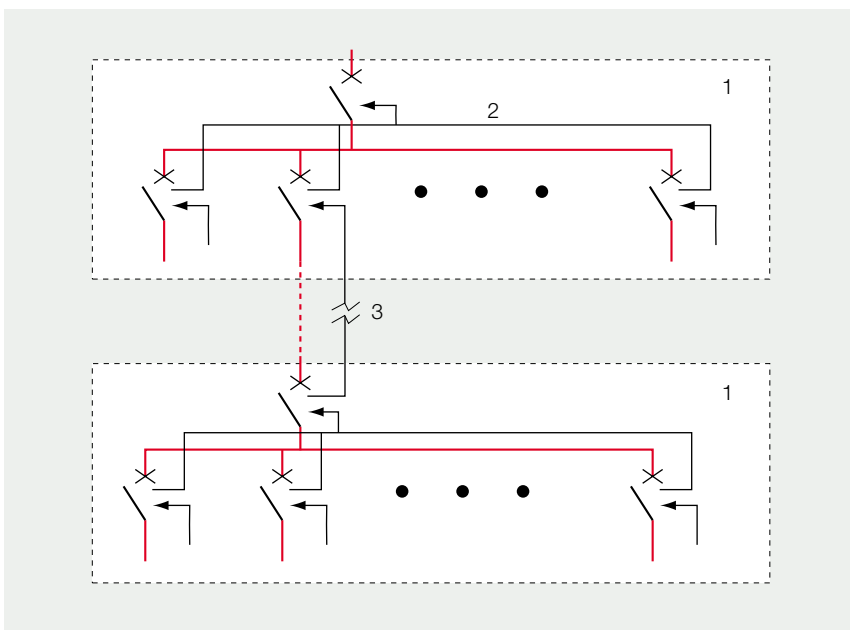
The fact that the size of each circuit-breaker is now determined solely by its required current handling capability and is not influenced by the hierarchical position, has several advantages. For example, a smaller average circuit-breaker can be chosen, making smaller, less cost-intensive switchboards possible.

The new concept allows fast fault detection to be implemented at all levels in the hierarchy, ensuring that the opening command is given in less than 1 ms irrespective of where the breakers are located in the plant. With present-day technology, this time varies between 2 and 50 ms. A special 'selective short-circuit' protection function is no longer needed, and the damage caused to the installation in the event of a fault is drastically reduced.

Communication

If the present trend continues to the year 2000 and beyond, the low-voltage electrical distribution system will have become fully automated and integrated in the production process, making it completely transparent to the user. The development of advanced, cost-effective microelectronics allows 'low-end' devices, such as circuit-breakers, to have a high level of local intelligence. For full automation of the distribution system, the key issue is communication. Besides the 'internal' interlocking communication between the circuit-break-

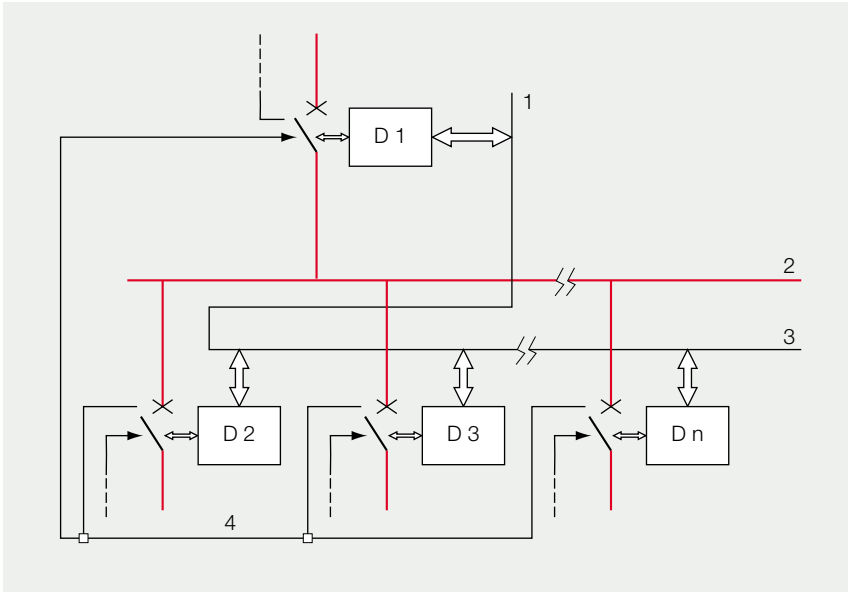***Circuit-breaker hierarchy in switchboards: interlocking concept*** ◢

1   *Switchboard*
2   *Interlocking connection: short line (several meters)*
3   *Interlocking connection: long line (max 1 km)*

Internal interlocking system and field bus communication **5**

1   *To central control system*
2   *Busbar*

3   *Field bus*
4   *Interlocking connection*

D1–D n   *Circuit-breakers*

ers, each breaker must be able to communicate with the central control system **5**.

Until recently, communication interfaces were available only for the large circuit-breakers. Today, they are also available for smaller industrial breaker series, which are installed in much larger numbers. When the communication interface is fitted, the user has access to all the vital data from each circuit-breaker. Currents, voltages, power, breaker status (open/closed), number of operations, etc, can all be monitored. If a fault should occur, it can be located immediately and repairs carried out quickly to ensure minimum downtime for the installation.

A major advantage of communication is that it makes the control system flexible. Operation of the complete installation can be 'dynamic', ie with real-time changes to protection functions, load conditions and plant topologies (adaptive protection). All the parameters characterizing the circuit-breaker and its

protection functions (eg, current thresholds, short-circuit definitions and timing parameters) can be down-loaded from the central control system. This means that each protection function can easily be modified during operation.

The communication is implemented with a standard field bus for industrial control, a whole range of different physical media being possible (twisted pairs, optical fiber, power line communication, etc).
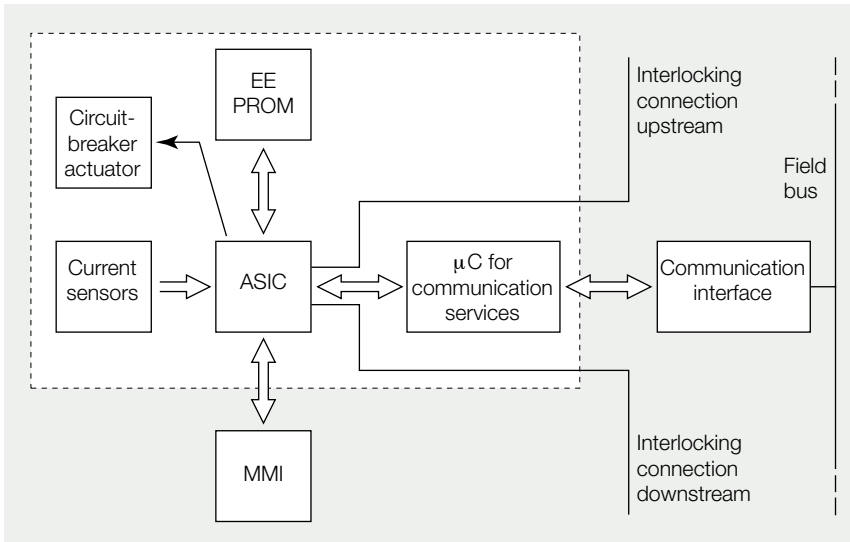
Implementation

To ensure all the described functionality and still be able to offer a competitive product, tailor-made solutions are necessary for the electronics. Standard, off-the-shelf components cannot meet these requirements. Also, the space available for the electronics is very limited **6**. The fast fault detection concept requires high-speed data processing to be performed on four current signals, while the broad functionality

of the communication interface also makes it energy-consuming. A separate power supply is used for all of these functions; however, if it should fail the circuit-breaker must still be able to perform its basic protection functions (short-circuit, ground-fault and long-term overload) with power supplied from the mains only. With low nominal currents, the current available for this is very limited (5 mA from a 5-V supply). The electronics therefore need to be very power efficient in the self-supply mode. If too much current is needed for the calculations, there may not be enough energy left to trip the relay, and thereby open the breaker, in the event of a fault.

To meet these needs, application-specific integrated circuits (ASICs) were developed. They are designed to operate in different modes, depending on whether the auxiliary power supply is present or not. When it is present, all protection functions are active and the ASIC operates at full speed. In this case, the power consumption is not critical. As soon as the power supply disappears, the fast fault detection algorithm, the interlocking system and the communication interface are switched off and the basic function is run at a moderate speed with very low power consumption. The advantage of using an ASIC is that almost all of the func-

Electronic relay   **6**
for moulded-case
circuit-breakers;
size 9 × 5 × 3 cm

Implementation architecture for the electronics **7**

age and downtime for the process. What is more, circuit-breaker sizes no longer have to be harmonized, ie selective circuit-breakers are no longer required. This allows smaller breakers to be used for a given nominal current, making the switchboards smaller and less cost-intensive. Besides the total cost of the installation being significantly reduced, its functionality is enhanced. This new approach to implementation, with a higher level of integration, ensures increased reliability as well as better immunity to EMI in harsh environments.

tionality resides in one component and the power-consuming I/O circuitry can be kept to a minimum. Also, the circuitry for the different operating modes can be specified all the way down to transistor level.

The ASIC approach has several other advantages. First, all possible functions are integrated in one component, significantly reducing the cost of the electronics. Physical space is saved and the number of printed circuit-boards needed in the breaker reduced. Since reliability and electromagnetic compatibility (EMC) depend strongly on the number of components and interconnections in the electronics, circuit-breaker performance is considerably improved.

In addition, a dedicated non-short-circuit area can be defined for each circuit-breaker, resulting in an optimized 'profile' for the installation **3**. To add flexibility to the product, the architecture of the electronics has been designed using an EEPROM (Electrical Erasable Programmable Read Only Memory) **7** in which all the protection parameters, including the non-short-circuit area, are stored. This allows the parameters to be easily modified both by the operator and via the central control system.

Other applications

The flexibility of the electronics allows the device to also be used for other applications besides low-voltage circuit-breakers. Medium-voltage applications are currently under evaluation. The non-short-circuit area can be changed according to the needs and characteristics of the installation. Since the short-circuit detection time depends to a large degree on the definition of the non-short-circuit area, performance can be substantially increased by reducing the detection time to less than 100 µs (theoretically $10+20$ µs). Other applications in which fast detection of a parameter and its derivative is needed are, of course, also conceivable.

Benefits of the new LV circuit-breakers

The new circuit-breakers make a very large contribution to solving the problem of selectivity in industrial plants. They are completely compatible with conventional circuit-breakers and can easily be employed in existing installations. Fast detection of short circuits translates into increased safety for the personnel and a very significant reduction in both dam-

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