A Revolution in Circuit Breaker Operating Mechanism Technology

Michael A. Lane
ABB Switchgear AB
Ludvika, Sweden

Richard Thomas
ABB Switchgear AB
Ludvika, Sweden

Abstract: A brief review of current operating mechanism technology, its benefits and limitations. Introduction of a new type of operating mechanism (drive), for circuit breakers rated 72.5 kV and above, using one moving part and fully electronic control.

Keywords: operating mechanism, circuit breaker.

1 INTRODUCTION

Development of transmission circuit breakers is most often described in terms of the evolution of interrupter technologies and the insulating mediums they employ. The 1950’s to 1970’s were dominated by oil minimum and air-blast designs. During the 1970’s, SF_6 technology began to supersede oil minimum and air-blast technologies. SF_6 gas interrupters continued a trend of providing higher ratings per interrupter and thus simplifying the primary system construction of circuit breakers.

In the last twenty-five years, substantial progress has been made in increasing reliability and reducing maintenance requirements of SF_6 circuit breakers. The most successful approaches in these respects have focussed on modular designs reducing the number of components in the interrupter (see also [1]). The majority of circuit breakers rated above 72.5 kV delivered today incorporate simple, reliable SF_6 interrupters.

In contrast to the major performance leaps made in interrupter technologies, circuit breaker operating mechanism (drive) designs have seen less dramatic development in core functional performance during the past fifty years. Of course there have been major differences in type of operating principles applied (e.g. pneumatic, hydraulic and spring). While there may appear to be a wide range of operating principles for circuit breaker drives, they all share a common basis in being highly mechanical designs and essentially all performing the same core function of closing and opening the circuit breaker.

Statistically seen, most major and minor circuit breaker failures can be traced to the operating mechanism [2]. Modular designs, extended endurance testing and field experience have all contributed to raising the performance level circuit breaker drives. Nevertheless, ever-increasing demands for power system availability require that equipment availability be continually improved.

Currently, there is more focus on increasing the functionality of power system apparatus to improve electrical power quality and facilitate better system asset management. Conventional mechanical drives are inherently limited in their functional flexibility.

In order to transcend the limitations of conventional, mechanically driven operating mechanisms, it is necessary to look towards new solutions. Today, a new operating mechanism technology, Motor Drive, has emerged. The new technology, based on an electrical system design, exceeds the benefits offered with conventional operating mechanisms while at the same time overcoming previous limitations, particularly with respect to significantly enhanced functionality.

This paper briefly discusses the benefits and limitations of conventional operating mechanisms and introduces the design of operating mechanisms of tomorrow, Motor Drive.

2 CURRENT TECHNOLOGY

As outlined above, circuit breaker drives in use today are of conventional, mechanical designs using spring, hydraulic or pneumatic technology.

While a range of mechanical drive solutions exists, essentially all designs address the same basic core functions required for the operation of the circuit breaker. Five (5) major core drive functions can be identified in regard to comparing both the conventional, mechanical and new electrical design solutions:

1. Energy Transmission
2. Energy Release
3. Energy Storage / Buffering
4. Energy Charging
5. Control & Signaling.

The first four functions relate to the need to provide some form of operating energy to move the circuit breaker contacts. The variety of conventional drive designs largely arises from different methods of addressing these first four functions. As the circuit breaker forms an essential and integral part of the overall power system control, there must also be a reliable means of communication between the drive and substation control and protection system.

The total system must be highly reliable in order to support the core reliability of the circuit breaker.

2.1 Energy Transmission

This function relates to the means by which operating energy is transmitted from the drive to the circuit breaker contact system. The type of circuit breaker application (e.g. single or three pole operation, live tank or dead tank interrupter construction) can influence the method of transmission.

In general, energy transmission uses some form of mechanical linkage system, coupled to the moving contacts by way of an operating insulator. The design of such a system is influenced by many factors, not the least of which is definition of the required contact travel for the interrupter.

In respect to contact travel, mechanical design systems can be inherently limited by their fixed dimensional nature. Once implemented, a mechanical linkage system offers limited flexibility in adapting to different stroke or speed requirements of the interrupter. And, once contact travel is initiated, it must be completed with conventional drives.

The way in which energy is transmitted in conventional drives also tends towards mechanical impacts. That applies to both the moving parts of the operating mechanism itself and to impacts on the foundation. High impacts on moving components of the operating mechanism cause wear over time, high operating noise and also are directly linked to the need for dampers on opening and/or closing operations.

2.2 Energy Release

This function is typically achieved in conventional drives by means of latches or valves driven by electrical coils. Reliable energy release is essential to correct circuit breaker function. The essential nature of the circuit breaker tripping function has given rise to a common convention of using two redundant trip coils. Trip circuit supervision is another indication of the importance placed on reliability of this function.

2.3 Energy Storage / Buffering

This function has been a prime source of difference between the variety of conventional, mechanical drives. The mechanical nature of conventional drives has also been in part driven by the historical desire to have a non-electrical means of providing the energy to operate a high voltage circuit breaker. This desire can arise from a perceived concern of the problem of attempting to restore the high voltage system during a total power outage.

The mechanical solution was also driven by the high operating energies and short operating times required for transmission circuit breakers, both of which necessitated use of mechanical operating systems in line with available technologies.

Today all major manufacturers can provide circuit breaker with spring operating mechanisms in large part due to the higher reliability and performance demonstrated by spring storage systems.

An important consideration in energy storage design is meeting the requirement for a high voltage circuit breaker to operate a rapid auto-reclosing sequence. IEC [3] specifies a minimum O-0.3s-CO-3min-CO sequence, while ANSI [4] tends towards CO-15s-CO. The dimensioning of the energy storage is also governed by the energy deemed necessary per operation.

2.4 Energy Charging

The method of recharging the stored operating energy is directly dependent on the type of energy storage.

Conventional drives use electric motors to drive the energy charging system, either to directly tension springs or to drive pumps for pneumatic or hydraulic systems. While the operating times of these motors are relatively short, typically 10-20 seconds during each charging cycle, they tend to have relatively high starting and running currents, ranging from 10 to as high as 90 amps per circuit breaker. These high transient loads place considerable stress on substation auxiliary supply systems (AC or DC) and are a major factor in dimensioning of auxiliary supply circuitry within the substation.

2.5 Control & Signaling

The control and signaling interface to transmission circuit breakers has generally developed more consistently and independently from the specific mechanical types of conventional drives. This is in part due to the desire for utilities to have consistency within the substation control and protection system, irrespective of the type of circuit breaker used in the substation. Also, a limited number of standard control interface functions are used; trip and close coils, energy charging, breaker status indication, dielectric monitoring.

The independent development of substation automation from primary high voltage equipment has also seen substation automation much more rapidly adopt new digital technologies in order to provide higher functionality. The state of the art in substation automation utilizes a high degree of microprocessor based system integration, whereas control logic inside transmission circuit breakers still predominantly uses discrete hard wired components based on fifty year old control logic design principles.

2.6 On-line Condition Monitoring

On-line condition monitoring has attracted much attention as a means to further enhance circuit breaker availability and asset management. Condition monitoring does not necessarily increase reliability, but may increase availability by giving an early warning that failure is imminent and allowing maintenance to be based on actual circuit breaker service.

It is, however, generally recognized that the effectiveness of monitoring the complex mechanical system of a transmission circuit breaker is limited by several factors.

For example, the failure modes in many mechanical systems are sudden, with little or no preceding indicators. Furthermore, the inherent complexity of the mechanical system is such that, even if a deviation in a performance parameter is detected, it can be difficult to determine the root cause without conducting a detailed intrusive inspection of the circuit breaker.

Another example is that most of the relevant monitoring data can only be obtained during the dynamic operation of the circuit breaker, which for many breakers is infrequent and thus further limits the ability to provide “early warning” of a problem.

2.7 Benefits of Conventional Operating Mechanisms

While operating principles used in conventional mechanical drives have not evolved substantially in the past fifty years, today’s operating mechanisms have been refined to the point where they offer an acceptable level of performance.

Following the CIGRÉ second international enquiry on reliability of high voltage circuit breakers [2], spring mechanisms have gained increasing acceptance as the most reliable form of operating mechanism. Failure rates on spring operated circuit breakers are extremely low.

Today’s conventional spring operating mechanisms are generally characterized by:

1. 10,000 close-open operation life;

2. Over 30 year field life;
3. Operation in all environments;
4. Very low maintenance;
5. Modular core designs.

Spring operating mechanisms have additional advantages due to the nature of their design. Because springs are unaffected by ambient conditions such as changing temperature, they deliver consistent operating energy. Since the energy delivered by a spring drive is quite consistent, the operating speeds are also very consistent, making spring drives ideal for applications with controlled switching. It is advantages such as these that have seen all major manufacturers use spring operating mechanisms on their SF_6 circuit breakers.

2.8 Limitations of Conventional Operating Mechanisms

While conventional drive designs have worked well, they still have a number of inherent limitations due to their mechanical nature. These can be summarized as follows:

1. Relatively high complexity;
2. Tendency towards impact operation;
3. High operating noise levels;
4. High, transient auxiliary power requirements;
5. Limited condition-monitoring scope.

To overcome the above limitations it is necessary to look towards a new technology that can not only provide the essential circuit breaker drive functions but also provide a platform for more advanced circuit breaker application.

3 TOMMORROW’S TECHNOLOGY

A solution to achieve a better circuit breaker drive can be found in utilizing the benefits of today’s digital technology coupled with the proven reliable simplicity of an electric motor. Motor Drive has been designed to meet all of the core requirements of a transmission circuit breaker drive and offer many new advantages in terms of performance and functionality.

3.1 Design of the Motor Drive

The basic design of the Motor Drive is one in which a motor, controlled via electronics, is used to directly drive the operating shaft of a circuit breaker.

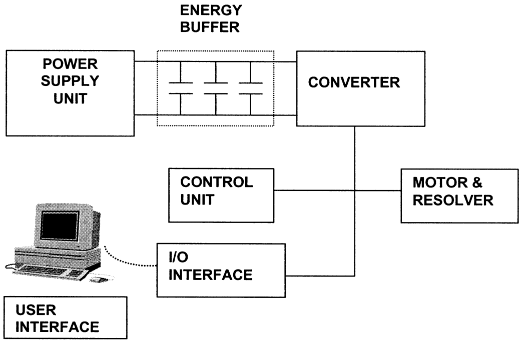

Figure 1: Design of the Motor Drive

Motor Drive consists of a number of units to perform such a function. Individual units, and the function of each, are as follows and their connection is depicted in Figure 1:

1. Motor and Resolver Unit, Energy Transmission;
2. Energy Buffer Unit, Energy Buffering;
3. Converter Unit, Energy Release;
4. Control Unit, Energy Release;
5. Charging Unit, Energy Charging;
6. Input/Output (I/O) Unit, Control and Signaling.

The motor is fed from an energy buffer unit through the converter unit. The energy buffer unit is charged by the charging unit, which also supplies power to the control and input/output units. A microprocessor based control unit facilitates control of the operation speed and condition monitoring. Access to the Motor Drive for all external user connections is via the input/output unit.

3.2 Motor and Resolver

The motor replaces the conventional energy transmission (e.g. chains, hydraulic fluid, compressed air, valves and pipes) and is the only moving part in the Motor Drive. Having only one moving part means there are no internal impacts or wearing components.

The motor (see Figure 2) is a three-phase, brushless, synchronous motor with permanent magnet rotor. Since the motor must reach full torque in a very short amount of time in order to provide the proper travel curve for a high-voltage circuit breaker, it has been specially adapted for such service conditions.

The angle of rotation of the motor is adapted to the type of circuit breaker to be operated and, today, is 180°. Using a 180° angle of rotation offers several advantages including:

1. Optimal travel curve;
2. Eliminates the need for open/close dampers;
3. Easily adjusted to fit specific circuit breaker applications.

Figure 2: Motor

On the axis of the motor is mounted a resolver, a device that sends precise information about the rotor angle to the control unit. With such information, the control unit can determine the exact position of the circuit breaker contacts at any given point during an operation (i.e. actual travel curve is known by the control unit). The resolution of the resolver is 0.2 degrees and the reslover actively sends information to the control unit at all times, even when the rotor is stationary.

3.2 Energy Buffer Unit

The energy buffer unit replaces conventional energy storage units such as springs or compressors (see Figure 3).

Figure 3: Capacitor Unit

Naturally, a three-phase synchronous motor operating at a high speed requires a high feeding current. Operating current required can be obtained in various ways, including a direct feed from the station AC or DC (through a converter) supplies or from an energy buffer. To limit the power drainage from substation supplies during a circuit breaker operation, an energy buffer has been chosen.

The energy buffer unit consists of a bank of series/parallel connected electrolytic capacitors (see Figure 3). The number of capacitors used in the series/parallel-connected bank varies depending on the load (e.g. three-pole versus single-pole operated circuit breaker).

When fully discharged, it takes approximately three minutes to fully charge a capacitor unit, depending, of course, on the size of the capacitor bank for a given application. Current drawn from the substation auxiliary supply during charging is approximately 2 A. Not only is the current drawn during charging considerably less than for conventional drives, but perhaps more importantly, there are no high transients.

Energy buffering capacity is designed to meet the requirements for operating sequences specified by international standards [3][4].

The energy buffer unit is fitted with alarms indicating stored energy level. Further, it is possible to monitor the energy buffer unit to ensure that each individual capacitor is working properly.

While the energy stored in the capacitors is continually replenished, the entire Motor Drive, including energy buffer unit and electronics but excluding heaters, draws a continuous load of less than 100 W.

3.3 Charging Unit

The charging unit is used to charge the energy buffer unit. It has redundant power supply inputs with the main supply being ac and additional dc supply serving as back-up.

In the event that the main ac supply is lost, the charging unit automatically switches to the back-up dc supply and sends an alarm to indicate supply failure. When the ac supply is restored, the charger unit will automatically switch back to the main supply.

In the unlikely event that both main and back-up supplies are lost, it is possible to perform a pre-programmed opening operation after which the circuit breaker is blocked from further operation. If such an option is not desired, possibilities exist to achieve the same function as the mechanical trip of conventional operating mechanisms, but in a very different way. If all supply power is lost, it is possible to charge the Motor Drive using a car or truck battery and thus allow the necessary operations to isolate the circuit breaker.

At each circuit breaker operation, power is drawn from the energy buffer unit thereby decreasing the voltage. The charger unit is then activated and the energy buffer unit is recharged. Again, the current drawn during such a charging operation is less than 2.0 A and there are no current surges on the ac or dc supply.

3.4 Converter Unit

The converter unit plays a key role in the energy release function by transmitting the energy from the energy buffer unit to the motor. It simply converts the dc voltage to a switched ac voltage.

3.5 Control Unit

The microprocessor based control unit is the heart of the Motor Drive and is a key component in the energy release function. It is fitted with an EEPROM that contains data such as the circuit breaker travel curve and memory of historic data. Information from the other Motor Drive units shown in Figure 1 is collected in the control unit.

Interface between the control unit and motor is via the resolver, which indicates the exact angular position of the rotor. If the reslover indicates to the control unit that the travel curve of the circuit breaker is deviating from the pre-programmed travel curve, the control unit will signal the converter unit to increase or decrease current to the motor causing the circuit breaker to accelerate/decelerate. With such a feedback loop, it is ensured that the circuit breaker always follows the same, pre-programmed travel curve. Additionally, such precise control of the contact travel means that dampers are not required.

Monitoring of the travel curve and motor current are inherent in the Motor Drive. To monitor the memory and processor, a watchdog function is incorporated in the control unit. The watchdog monitors the Motor Drive electronics and software and sends a signal if failure occurs.

3.6 Input/Output (I/O) Unit

Interface between the Motor Drive and the user is via the I/O unit (see Figure 4). The I/O unit sends monitoring signals (i.e. energy charge level, charger unit supply status, watchdog, etc.) from the Motor Drive to the user. Signals received from the control room (e.g. trip and close commands) are received by the I/O unit and then forwarded to the control unit.

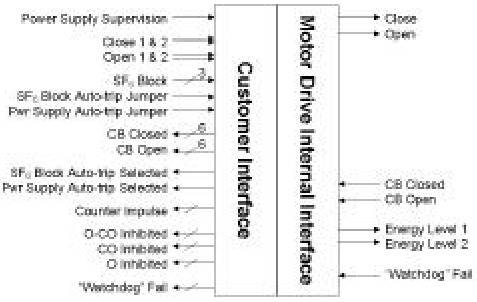

Figure 4: Input/Output Unit

Other functions interfaced via the I/O unit include:

- SF_6 monitoring for purposes of blocking operation on low SF_6 density;
- Operating panel with local/remote and open/close switches, indication lamps, operation counter, etc.;
- Auxiliary relays (Auxiliary contacts have been replaced by bistable auxiliary relays activated once the rotor has reached a specified angle, depending on whether they are “a” or “b” contacts.);
- Dual trip command inputs;
- Dual close command inputs;
- Continuous trip signal block.

4 CONDITION MONITORING

As discussed above, due to the nature of the Motor Drive design, condition monitoring is inherent. Motor Drive has an extensive array of data that can be retrieved either locally from the control unit or remotely via a modem. Monitored parameters include:

- Contact travel;
- Opening and closing times (measured from command impulse to a defined rotor angle);
- Energy consumption during operation;
- Energy buffer discharging characteristics;
- Motor current and torque;
- Temperature of the control unit;
- Watchdog status.

All data is stored at the time of the most recent operation and is then available for download.

Additional to the monitoring functions described above, it is possible to operate the circuit breaker a few milli-meters every day to check the status of the entire chain (i.e. charger, control, motor, reslover and energy buffer units). Thus, it is possible to know in advance if the circuit breaker and drive are ready for operation or not, regardless of the frequency of operation of the circuit breaker. With conventional drives, such monitoring possibilities do not exist.

5 TESTS

Motor Drive has been exposed to numerous tests to verify its performance. The following tests have been performed:

- Extensive EMC tests in accordance with IEC 60694 [5] and IEC 60255 [6]. Beyond the EMC tests required by the standards a capacitor bank inrush current switching and shunt reactor switching tests were performed. The latter two test were used to simulate actual field conditions.
- Extended mechanical endurance test on a live tank circuit breaker with Motor Drive comprising 20,000 close-open operations;
- High and low temperature tests on a live tank circuit breaker with Motor Drive from -50° C up to +70° C;
- Making and breaking tests comprising test duties T100s and T100a.

6 CONCLUSIONS

Motor Drive offers a completely new and versatile way to operate high voltage circuit breakers. Motor Drive will be progressively implemented on all ABB transmission circuit breakers in the coming years and has the following advantages:

- One moving part, simple and reliable;
- Optimal, pre-programmed travel curve;
- Contact travel characteristics independent of aging and change in ambient temperature;
- Condition monitoring is inherent without the need for additional sensors;
- Software related auxiliary contact, easily adaptable;
- No mechanical auxiliary contacts needed;
- Low power demand, no high short term loads;
- Low mechanical stress and noise level;
- Modular design for easy maintenance;
- Redundant power supply inputs;
- All connection to substation control via one programmable circuit board;
- Serial communication port for external connection;

7 BIBLIOGRAPHY / REFERENCES

[1] BOSMA, A. and SCHREURS, E., Cost optimization versus function and reliability of HVAC circuit-breakers, CIGRÉ Session 200, 13-102

[2] CIGRÉ WG 13.06, Studies on the Reliability of Single Pressure SF_6-Gas High-Voltage Circuit-Breakers, CIGRÈ, Paris, 1996

[3] IEC 60056, 1987: High-voltage alternating-current circuit-breakers

[4] ANSI C37.04-1979: IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis

[5] IEC 60694, 1996: Common specifications for high-voltage switchgear and controlgear standards

[6] IEC 60255: Electrical relays (in applicable parts)

8 BIOGRAPHIES

Michael A. Lane received his Bachelor of Science degree in Electrical Engineering from the Pennsylvania State University, State College, USA in 1991. Employed by ABB since 1991, he has worked with testing, marketing and technical support of disconnectors, circuit breakers (live tank and dead tank) and circuit switchers.

Richard Thomas received his Bachelor of Engineering degree from the University of New South Whales, Australia in 1988. Employed by Sydney Electricity from 1984, he joined ABB in 1991 and has worked with commissioning, control design, technical support and marketing for live tank circuit breakers, generator circuit breakers and GIS.