Fault current limiter with solid-state circuit breakers

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Abstract. Switching of power circuit breakers is an important technical issue, especially at short circuit, since the fault current cause thermal and dynamic stresses, and the power quality worsens. Recently, the development of distributed renewable electricity induces the short circuit protection problematic because the distributed production of electric energy cause the transport networks to lose their radial character and disturbs the protective relays coordination. The modern technologies for power switching uses static fault current limiters, which offers a viable solution to remove the problems caused by large fault currents in the system. An appropriate design of the current limiting device reduces the thermal and dynamic stress and limits the fault current to a low value. The static switches are based on high power semiconductor devices that offer advantages compared to mechanical switches. Using a fault current limiter that minimizes the effect of distributed generation of electricity in a radial network on the co-ordination of protective relays is a solution to this problem in terms of switching speed and lifespan of power switches.

1. Introduction

The increasing of the generating capacity for the systems of electricity production has led to increased fault current value, which exceed the maximum short circuit current allowable at switching equipments. Therefore, all the equipments must be designed so that their switching power to be sufficient to interrupt short circuit current under conditions allowing normal operation of the equipment and does not result in damage or destruction of equipment. Normally, when a fault current appears, the circuit breaker automatically opens the circuit in 3 to 6 current semi periods. In some cases, switches cannot handle short-circuit current levels, because they are designed to withstand to a fault current of lower level and thus being unable to interrupt the circuit and can cause system crashes.

Modern technologies of power switching for short circuits currents, uses static fault current limiters, which provides a viable transport and electricity distribution system, to remove problems caused by large fault currents in the system. Static fault current limiters, improves working conditions for downstream equipment by limiting the fault current. To cut the current, static fault current limiters must quickly introduce in circuit energy absorbing devices, in order to be a successful disconnection. An appropriate design of the device current limiter reduces the thermal and dynamic stress and limits the fault current to a lower value.

Static switches are based on high power semiconductor devices that offer advantages compared to mechanical switches in terms of switching speed and lifespan. Voltage quality of power supply networks can be improved during a short circuit because the fault current is reduced in the range of

occurring of voltage distortions and at three phase short circuit, fault duration can be limited to 100 ms [1].

Integration for power quality addicted consumers in electrical systems leads to major concerns of consumers, producers and carriers of electricity.

In the medium voltage networks, the treatment of short circuits is an important issue to increase the power quality of electrical energy. This is especially true when considering the short-circuit power of networks to be built to supply new customers. One way to increase the power quality of the network and to integrate distributed renewable electricity in supply system is the use of power electronic devices.

Major disadvantages of all solutions using static devices, consist of high devices costs and power losses that occur in conduction devices. Because of these disadvantages using static devices in switching power circuit breakers has not developed extensively. Static switches in power systems can be used if costs and power losses in conduction devices are reduced.

Using power semiconductor devices can reduce short circuit currents and voltage distortion during a short circuit. Modern solutions using high power semiconductors such as thyristor with extinguishing on the gate are used to replace mechanical switches [1-3]. Previous to development of high power semiconductor devices capable of locking, such as gate turn-off thyristors (GTOs) or insulated gate bipolar transistors (IGBTs), normal thyristors were used embedded in the structure of the forced switching switches [6]. Despite the complexity of the forced switching thyristor circuit breakers, these circuit topologies are used for several decades in power conversion applications. Major drawbacks of forced commutation circuits are limited switching frequency and complexity of schemes for generating a switching command. In applications of the static switches, switching behavior is a minor issue, since it is not necessary switching at high frequency.

Comparing the existing high power semiconductor devices is noteworthy that the thyristors provides the highest blocking capacity, reduced conduction losses power and low cost manufacturing. The main disadvantage of the thyristors is that blocking is done by forced extinction or by decreasing the current through the device below the holding current [4], [5]. In the AC networks with frequency of 50 Hz, the natural commutation can take up to 10 ms, and in this time, the power supply voltage drops, leading to interruption of supply. Because of its advantages, consisting of low-power conduction losses and reduced manufacturing costs, thyristors static devices can be used in the construction of static switches used to interrupt short circuit currents [6].

2. Short circuit current limitation in radial network

Radial distribution systems for electricity, common in Europe and USA, normally use protective relays for coordination of protection against defects. However, the growing interest in distributed power production poses a problem for the distributed generation of electricity because the system will lose its radial nature, disrupting coordination of protective relays. Using a fault current limiter that minimizes in a radial network the effect of distributed generation on power system relay protection coordination is a solution to this problem. Fault current limiter improves the stability and limits the transient voltage recovery in distributed systems. Fault current limiters have been developed starting from the hybrid variants static and electromechanical switching.

Most distribution systems in North America are operated in radial configuration, predominantly due to simplicity of operation and reduced fault current by overcurrent protection. These two advantages are due to the fact that in radial systems, on any line, power flows only in one direction.

In these distribution systems, the protective equipment should only detect current without having to detect direction. Usually, are used inverse-time-overcurrent-relays [4], set for coordination relays. Introduction of coordination relays ensures safe and redundant protection scheme, while minimizing the consumers disturbing.

Distributed power systems are defined as a power source connected directly to the distribution network of a power system. It is estimated that by 2015, 20-30% of all installed power generators will be ranked in the category of distributed sources of electricity.

With the introduction of distributed systems in radial distribution systems, the nature of radial power flow is not determined. Depending on load conditions, it may not be possible the reconnection of protective relays. It is well known that protective devices in a multisource system must be dependent of flow direction and fault relays must be coordinated, because the current can flow in both directions. Even if the load is such that the current will flow only in one direction, distributed systems can reduce the action range of the relays and disturb their coordination. Another problem arising from the introduction of distributed systems is increasing the level of fault currents, which causes problems to inverse time overcurrent relays, which are coordinated based on presumed fault current.

Several ideas were introduced as a possible solution for the protection by overcurrent relays in distributed systems, including digital relays with fast reconnection based on microprocessor and adapted protection. Although these solutions are adequate from a technical standpoint, they involve high initial costs of equipment to replace existing relays by relays based on microprocessor, a special switches devices and the entering in the power substations the computer that coordinates the switches devices command.

Moreover, the technical intricacies of these solutions include the need to change the setting curves of the relay, when a distributed system is removed from service or put into operation. Also must ensure the security of communication lines between in station computer and protection relays. Due to these complications and their high cost of these solutions are not viable for current distributed systems.

Most proposed solutions to the problem outlined above involve the modifying of existing protection schemes in order to adapt to the requirements of distributed systems. Such solutions tend to be expensive to be implemented due to equipment costs, which reduce the benefit of distributed systems integration in the energy system. An alternative approach would be to minimize the contribution of distributed systems during a fault, without taking into account the negative effects on the network or in other words, considering that the network works without fault. A possible solution is to implement a fault current limiter that limits the current through distributed network during a fault and otherwise free flow of power from distributed grid to energy system. The advantage of this solution is that it is not necessary to replace the existing protection relays in distribution system.

Before the current technologies are taken into account to limit the fault current contribution in distributed systems must first be determined operating conditions and characteristics of such a limiter.

3. Short circuit current limitation in radial network

Typically, fault current limiters implemented in practice or analyzed in research activity are passive, which are defined as devices that are permanently connected to the supply system and must not be disconnected or externally controlled.

When a fault occurs, the nature of these devices cause switching operations, so that overcurrent is automatically reduced or limited. Passive devices include series inductance and superconducting fault current limiters.

Superconducting fault current limiters have no resistive losses during steady state operation and can effectively limit the fault current, but uncertainties about heat loss, regular maintenance and ongoing research to develop superconducting devices with low temperature cooling, reduce the viability of these devices. In addition, passive limiters will limit the fault current bidirectional, which is not the desired action to use for distributed systems.

There are two main types of power semiconductor devices limitation: limiters based on operating at the current or voltage resonance and limiters with inductors. The resonance limiters relies on the fact that energy is circulated at a constant amplitude of sinusoidal voltage and a fixed frequency, resonant LC circuit impedance is given so that the impedance device during stationary operation to be approximately zero.

During a fault, the electronic power switches, disconnect the capacity or inductance as component of fault limiter, introducing in power system an impedance of high value. The disadvantages of static circuit breakers based on resonance are:
- can cause dips during faults;

- limiting current efficiency decreases as the distance between power substations increases;
- special construction is required for capacities installation;
- adjustment devices is necessary to ensure low impedance values.

The basic element of the current limiter is an impedance in series with the transmission line. A pair of GTO thyristors are placed in series with this impedance and they are controlled synchronous with voltage and forms a current path with low impedance. In the event of a fault, the control signals for GTO thyristors are blocked, resulting in a high value impedance in series with the transmission line, which limits the short circuit current.

These limiters generates switching losses, since the energy is circulated in the normal operation by power electronic switches and the long-term reliability of these devices is still undermined by ongoing command.

Recently have been proposed new switches topology for short-circuit current limiters and concluded that elevated costs due to power losses are offset by other costs: lower investment value, low maintenance costs, etc.

Although the fault current limiters, offers many advantages for passive limiters, in steady state operation, power losses due to switching is a big disadvantage. Mechanical contact switches have much lower power loss, but cannot quickly open circuit and cannot achieve electrical isolation in all conditions, thanks oscillating recovery voltage.
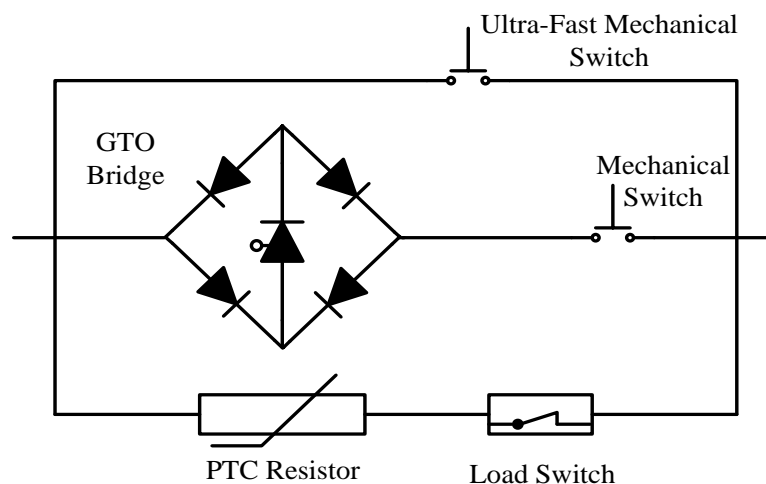

Figure 1. The hybrid fault current limiter

A direction in research developed in recent years is the use of an electronic power switch, as auxiliary switching element for mechanical breaker. With an electronic power switch it can provide the equipment, with current way of low impedance. Mechanical breaker is able to open contacts with smooth arc, arc which is generally associated with switch contacts opening at elevated voltages. In [6] is proposed such a hybrid fault current limiter based on a new fast mechanical breaker. The device is able to disconnect a circuit where the phase voltage is 12 kV and steady current is 1 kA. Figure 1 shows the hybrid fault current limiter [6].

During the steady state operation of the equipment, all three mechanical contacts are closed and the bridge GTO thyristors are blocked.

When a fault occurs, ultra-fast mechanical switch opens in some hundreds of microseconds [6]. The current is switched to the GTO thyristor bridge and after their blocking, the flow current is taken by positive-temperature coefficient PTC resistance, of which value will increase with the temperature increasing, so that lowers the current. Mechanical breaker in series with thyristor GTO disconnect shortly afterwards to prevent the emergence of a GTO thyristor surge deck.

4. The switching technique to limit the fault current

In case a fault occurs, static circuit breakers must be ordered to disconnect, in case of a short circuit, or in case the circuit breaker must be prepared for a second disconnect, after several alternations of power supply in case in which the first disconnection was unsuccessful. Therefore, the disadvantages of forced switching circuits to limit short-circuit current, become much less important in static circuit breakers applications. Therefore, they can be a solution that can be used to build static switches. Currently, thyristors are available at blocking voltages up to 12 kV. In [7], it shows a switch for a network of 10 kV, with a power of 25 MVA. Voltage thus necessary to block static switch, including the ability to block recovery must be greater than 30 kV [7] to allow blocking all types of circuits.

The literature shows that there are solutions using normal thyristor switching devices [1] or gate lock thyristors [7]. Thyristors solution using lock gate is composed of four switching modules, mounted in series per phase, which are able to block each voltage of 9 kV. In addition, each module consists of two thyristors with extinction gate connected in series with blocking voltage of 4.5 kV. The overall circuit is composed of 24 extinguishing gate thyristors and of 48 diodes. Based on this topology, it will determine the losses for switching gate thyristor contactor compared with the solution of the static switch equipped with normal thyristors. Solution based on normal thyristors, is composed of four normal thyristors mounted in series on each phase and four rectifier diodes antiparallel mounted to allow bidirectional current flow. During normal operation, the current circulates through 24 thyristors. Costs due to power losses have a major impact on the whole system and total cost of ownership [7]. Therefore, by reducing conduction losses and by increasing service life, operation costs by using static switches can be reduced significantly. In addition, it can be used forced air cooling instead of water cooling forced cooling. From an economic perspective, a thyristor static switch can be more competitive compared to static switches equipped with the quenching thyristor gate. Given the importance of cost in industrial applications thyristor-based systems tend to be integrated into existing electricity grids.

Although it requires a complex auxiliary circuit that allows forced extinguishing, the normal thyristors also provides an economic advantage compared to the solution with extinguishing gate thyristor. In the case of extinguishing gate thyristor, drivers are expensive, and in case of normal thyristor, the pulse transformer drivers, can be avoided by using optical thyristor normal controlled. The range lock to a normal thyristor switch is longer compared to a switch with extinction gate thyristors, which leads to increased short circuit current values. However, given the relatively large time constants at industrial frequencies of 50 Hz or 60 Hz power specific systems, it is found that low switching speed of approx. 1 ms to normal thyristors, compared with approx. 400µs at the gate thyristors with gate extinguishing is acceptable. In general, this leads to the conclusion that forced commutation circuits can provide a practical alternative for power applications breakers in medium voltage systems.

Distribution systems, especially some local distribution systems that were extended were designed and built with passive switching equipment, unidirectional, which circulates transported electricity grids or electricity from transformer stations. The value of short-circuit current is limited to longitudinal impedance of the power distribution and transmission system components by which the fault current is circulating. This value and also the network conductor cross section are involved in reducing short-circuit current in case of failure, which depends also on the power system interconnection. Normally, the limiting of fault currents, due to the increasing of network extensions require costly replacement of equipment in substations or require changes in system configuration, which can decrease the system flexibility and reliability.

It is therefore necessary to use current limiting devices that can prevent or limit the fault current value. A current limiter suitable-FCL into operation very quickly, preventing transitory fault currents to become larger, thus protecting the system equipment.

A static switch can provide the following advantages:
• Limited fault current;
• Growth current limited even if capacitive loads;

- • Connection-disconnection repeated with great reliability and wear;
- • Reduced switching shocks;
- • Improve power quality.

The aim of fault current limiters introducing is to reduce the amplitude of the transient short circuit currents, which occur either as a result of the occurrence of a fault or the voltage peaks due to switching surges.

The need to reduce the fault current is determined by the following considerations:

- • to reduce thermal and mechanical stresses;
- • improving the life of the switching equipment;
- • to improve power quality by reducing voltage peaks or dips resulting from short circuit occurrence.

The defects can be classified into two broad categories namely [8]: active and passive faults.

Active faults occur when current is closed from one phase to another phase or a phase close to the ground. This type of defect can be classified into two groups, namely permanent defect and early defect. Early defect usually occurs as a result of deterioration of insulation resistance.

Passive defects are not real defects in the true sense of the word, but rather defects that are creating conditions that make the system work more than design capacity, so they created conditions of developing active faults. Typical examples are:

- • overload, leading to overheating of insulation and have as a consequence insulation deterioration;
- • surge, leading to the insulation stress over the limit;
- • low frequencies, causing incorrect behavior of the system;
- • power oscillations when generators operate asynchronously.

Figure 2 shows the waveforms of a short-circuit when the current is not limited [9] and the influence on short circuit current, in situation where fault current limiter devices with and without fault current interruption capability occurring in the system. U_n- rated voltage; I- peak value of rated current; i_{min}- the minimum value of initial short circuit current; i_{max}-maximum value of limited current; i_p-the maximum value of prospective current; i_{fol}-peak value of the follow current; ta-action time from $t = 0$ to i_{max}; t_d-fault duration time.

A distinction between different types of fault current limiters is made at their design, for to limit the fault current active or passive. Current limiter design for passive defect applies to sources with high impedance in normal operation or fault, since active faults lead to a decrease in source impedance under fault conditions.
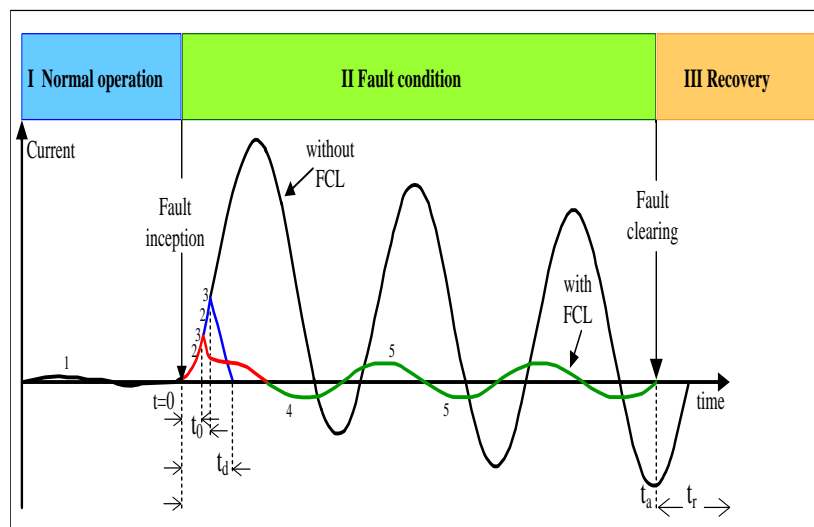

Figure 2. Waveforms of a fault current

In case you are not using short circuit current limiters, the problems connected to the growth of fault current level is solved by the following procedures:
- Increase efficiency of electrical equipment in the transformer stations;
- Changing of network topology, such as cutting or sectioning the bush bar or network;
- Raising the voltage level;
- The use of complex control strategies such as sequential disconnection.

Since a fault current limiter is a series device, it must have a low impedance when in normal operation. When the fault current occurs, its impedance must grow quickly to limit the current that closes by the circuit impedance. Conceptually, all current limiters can be regarded as normally closed switches, having impedance in parallel. Type of the switch and circuit impedance type can vary from one model to another.

Being dependent on the method used to increase the impedance series, the current limiters can be classified into four groups:
- inductive;
- electronic;
- electromagnetic;
- superconducting, resistive type.

Electronic fault limiters are classified as follows:
- fault current limiter resistance;
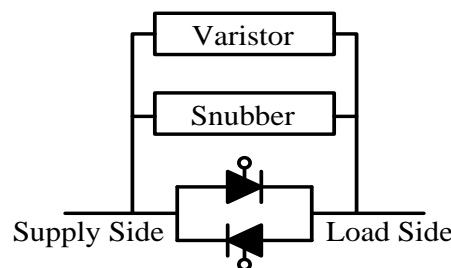- fault current limiters with resonant circuit.

Figure 3. Resistance fault current limiter

Resistance fault current limiter is composed of a fault current limiter and a switching device. In Figure 3, is presented the configuration of a single-phase fault current limiter with resistance. This is composed of a high-speed bidirectional switch, power semiconductor devices made with a varistor and a surge limiting circuit (snubber) connected in parallel with current limiter.

For operation without fault, the semiconductor devices are constant power driven, the command of the two thyristors being synchronized with the network. Alternatively, resistance fault current limiter can be by-passed using a mechanical switch, in order to reduce conduction losses. Bypass switch is open when fault current limiter should act. Considering that there is a short circuit to load, the semiconductor device will initially lead the fault current. The switch is closed when the fault current reaches a predetermined value I_{max}, which must be within the maximum power, able to be interrupted by semiconductor device used. Next, the fault current will close by the varistor.

Varistor voltage limit is chosen so as to be greater than the maximum supply voltage. Therefore, defective circuit current begins to decrease. Varistor voltage remains almost constant while it is de-energized. Further, the semiconductor device is resettled to reset circuit current to a preset value I_{min}. Fault current switching logic is identical for both semi periods, positive and negative. This mode is maintained as required for the current system can give information to coordinate protection. If the fault persists, semiconductor devices are permanently locked and the fault current is interrupted completely.

Resonance fault limiters limit the fault current by inserting a resonant LC circuit. The LC resonant circuit has a resonance frequency of 50Hz and is composed by an impedance and a capacitor connected in series or in parallel. When the circuit is connected to the system, its impedance is

growing rapidly and reduces the fault current. In steady state, where losses are neglected, the circuit impedance is very high. To be effective, the resonant circuit must be connected by power electronic switches [10] in the system immediately after detection of a fault. Usually are used two variants of this type of limiter:

- fault current limiter with series resonant circuit;
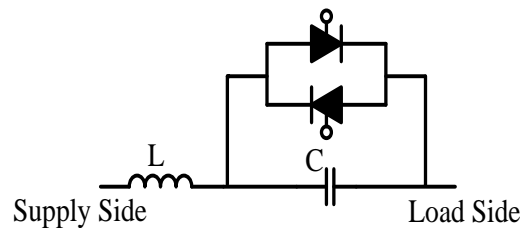- fault current limiter with parallel resonant circuit.

Figure 4. Fault current limiter with series resonant circuit and controlled thyristors

Resonance frequency of the LC circuit series is chosen so as to be fundamental frequency. Fault current limiter with controlled thyristor series resonant circuit limits the fault current by inserting a coil in series with the power circuit. During normal operation, when the frequency is close to the fundamental frequency, the resonant circuit has a very low impedance and under fault conditions, a high value impedance. This type of circuit is shown in Figure 4 [11].

Line voltages are filtered with respect to high frequency oscillations. However, there are low voltage gaps, which can be reduced using a high value inductance *L* and a low value capacitor *C*. Another effect that is achieved by introducing a high value inductance *L* is the decreasing values of fault currents. When thyristor contactors are switched, the voltage on the fault current limiter capacitor is approximately zero, in the case of fault current limiter with series resonant circuit.

For fault current limiters with series-parallel resonant circuit, the principle diagram is shown in Figure 4. During normal system operation, the thyristors are not connected.

The voltage drop on the fault current limiter will be neglected as the series connection of the coil and condenser, are adapted to resonate at a frequency of 50Hz.

Series-parallel fault current limiter is due to series circuit performances very different in operation from series resonant circuit fault current limiter [11].

Since the fault current limiter is tuned to supply voltage frequency, in normal operation impedance will be infinite. β - transition frequency is higher than the supply voltage frequency ω and is given by [11]

$$\beta = \frac{1}{\sqrt{L \cdot C}} \cdot \sqrt{\frac{L + L_S}{L_S}} = \omega \cdot \sqrt{\frac{L + L_S}{L_S}} \tag{1}$$

5. Conclusions

Connecting and disconnecting electrical networks is a topical issue especially when fault current must be disconnected. Mechanical power switches have the disadvantage that the occurrence of short circuit current, between contacts, arcing occurs and not always the disconnection is galvanic, which can lead to damage and even destroy the system equipments. Also, the lower switching speed of mechanical power breakers allows increasing of short-circuit current value, sometimes exceeding the breaking capacity. Current problems in electrical networks are not only switching problems but also problems of short-circuit protection. Development of renewable electricity sources, poses problems of short circuit protection by disturbing the coordination of protective relays.

Static switch power systems can be used in power switching technology if the costs and the power losses in conduction devices are reduced. Comparing the existing high power semiconductor devices is noteworthy that thyristors provides the highest blocking capacity, reduced conduction power losses and low cost manufacturing. The main disadvantage of the thyristor is that blocking is done by forced switching or by the decreasing of current through the device below the holding current.

The advantages static switching, both in AC, DC and more especially in DC where you disconnect the maximum short circuit current, is the reducing of the time of disconnection and by default the maximum value of short-circuit current, no arcing thanks to the static switching and reduced maintenance costs, mainly due to lack of moving contacts.

The development of static power devices with reduced conduction losses, high current gradient and higher blocking capability, also the developing of hard and soft switching techniques will allow widespread use in the future, of the static circuit breakers in the power system.

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