0. ABSTRACT

FACTS (Flexible AC Transmission Systems) and HVDC (High Voltage DC Transmission) are powerful devices used to enhance system performance in the evolving power markets. Increasing generation in high load density networks on one hand and on the other hand interconnections between systems increase the short-circuit power substantially. If the short-circuit current rating of the equipment in the system is exceeded, the equipment must be either upgraded or replaced, both of which are very cost- and/or time-intensive procedures. Short-circuit current limitation offers clear benefits in such cases. Current limitation using passive elements, for example reactors, is a well known practice, however it reduces the system stability, increases the risk of voltage collapse and it has impact on the load-flow. By means of innovations in FACTS technology, a new dynamic fault current limiting device, the SCCL (Short-Circuit Current Limiter), is available now. The SCCL is based on developments in series compensation, where the TPSC (Thyristor Protected Series Compensation) has been successfully applied on 3 projects in a 500 kV transmission system in the Southern Californian Grid (USA), at the Vincent substation.

**Keywords:** Market Developments - Bottlenecks in Transmission - FACTS - Series Compensation - Short-Circuit Current Limitation - Power Oscillations - Subsynchronous Resonances

1. INTRODUCTION

A global tendency towards an increase in generation capacity can be observed, for example the installed capacity is expected to grow from 3.560 GW (in the year 2000) up to 5.700 GW in 2020 worldwide [4].

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* Siemens AG, Power Transmission and Distribution, High Voltage, P.O. Box 3220, 91050 Erlangen, Germany.
e-mail: dietmar.retzmann@siemens.com
The increasing power demand and major environmental constraints (Fig. 1) require advanced solutions for transmission systems: care must be taken to insure, that the transmission system under such dynamic market conditions is not going to produce a bottleneck, but rather be the key for a high return on investment and positive cash-flow.

2. FACTS - A PROVEN TECHNOLOGY FOR POWER SYSTEM ENHANCEMENT

Flexible AC Transmission Systems are powerful devices for system performance enhancement in the evolving power markets [1, 2]. FACTS, based on power electronics have been first developed to improve the performance of long distance AC transmission [1, 5]. Later, the technology has been extended to the devices which can also control power flow [2, 12, 15]. Excellent operating experiences are available world-wide and the FACTS technology became mature and reliable.

The main idea of FACTS can be explained by the basic equation for transmission in Fig. 2. Power transmitted between two nodes in the systems depends on voltages at both ends of the interconnection, the impedance of the line and the angle difference between both systems. Different FACTS devices can actively influence one or more of these parameters and control the power flow in the systems, see Fig. 2. In Fig. 3, a summary of the key-issues and the solutions for the evolving power markets is given.

![Fig. 2: Application of FACTS - The Basic Equation](image)

![Fig. 3: Extended System Requirements of the Evolving Power Markets](image)

Main shunt connected FACTS application is the Static Var Compensator (SVC) with line-commutated thyristor technology, which provides fast voltage control, reactive power control and power oscillation damping features [2, 16]. There are hundreds of these devices in operation world-wide. Since decades, it is a well developed technology and the demand on SVC is increasing further. For long AC lines, series compensation is used for reducing the transmission angle, thus providing stability enhancement. The simplest form of series compensation is the Fixed Series Compensation (FSC). A huge number of these applications are in operation. Thyristor Controlled Series Compensation (TCSC) is used if fast control of the line impedance is required to adjust the load flow or for damping of power oscillations.

Special FACTS devices are UPFC (Unified Power Flow Controller, [1, 2]) and GPFC (Grid Power Flow Controller [4-6]). UPFC combines a shunt connected STATCOM with a series connected STATCOM, which can exchange energy via a coupling capacitor. GPFC is a simplified DC back-to-back link, which is designed for power and fast voltage control at both terminals [6]. In this way, GPFC is a “FACTS back-to-back”, which is less complex than the UPFC at lower costs, and it is also suitable for short-circuit current limitation, ref. to Fig. 3 and [3].

FACTS devices consist of power electronic components and conventional equipment which can be combined in different configurations. It is therefore relatively easy to develop new devices to meet extended system requirements of the evolving power markets (Fig. 3). Such recent developments are the TPSC (Thyristor Protected Series Compensation, [13, 14]) and the Short-Circuit Current Limiter (SCCL, [7]), both innovative solutions using high power thyristor technology, which are presented in details in section 4.

3. FAULT CURRENT LIMITATION - STATUS TODAY

Increasing generation in high load density networks on one hand and on the other hand interconnections between systems increase the short-circuit power substantially. However, faults in
electrical power systems are unavoidable. Apart from the damages in the vicinity of the fault - e.g. due to the effects of an electric arc - the fault currents flowing from the sources to the location of the fault lead to high dynamical and thermal stresses on all the equipment being involved. Hence, if the short-circuit current rating of the equipment in the system is exceeded, the equipment must be either upgraded or replaced, both of which are very cost- and/or time-intensive procedures.

Therefore there is a considerable interest in devices which are capable of limiting fault currents. A Fault Current Limiter (FCL) shall limit a fault current passing through it within the first half cycle [7]. In case of newly planned networks fault current limiters allow the use of equipment with lower ratings which renders possible considerable cost savings. Due to the importance of these issues, a CIGRE Working Group (WG 13.10) was established in 1996 with the task to prepare a specification for fault current limiters. This report [7] was provided in 8-2003 and is available as technical brochure from CIGRE Central Office.

Basically, there are two types of fault current limiters, ref. to Fig. 4 a):
- Fault current limitation (e.g. reactor, superconducting FCL, or the new “SCCL”)
- Fault current interruption (e.g. Iₘ-Limiter, electronic devices)

Fig. 4: Possible Locations of Fault Current Limitation in the System:
  a) Operating Principle of different Devices
  b) Application of FCL in the System

A major constraint on devices with current interruption, e.g. electronic switches, is that the protection schemes of the neighboring equipment (switchgear, lines, transformers and generators) needs to be modified, depending on the location of FCL. This is due to the fact that an FCL will eliminate a fault current much faster before any protective relay can detect and locate the fault in order to generate a trip signal for the associated breakers. High-Temperature Superconducting Fault Current Limiters (HTS FCL) can be designed as resistive [10, 11] or inductive [9] limiters. An overview on the superconducting devices (mainly high temperature design) and the system requirements is given in [8]. HTS FCL developments are focusing on medium voltage applications, because high voltage applications require tremendous cooling equipment and sophisticated electrical insulation technologies.

Fig. 4 b) shows the basic possibilities for an FCL application on different voltage levels in the power system. An FCL can be connected to the generation infeed at the generator voltage level, at different
locations in the high-voltage system (400 kV or higher), or in subtransmission and distribution networks, e.g. on 115 kV or lower.

In practice, up to now, for fault current limitation mainly conventional reactors have been applied. The drawback of this solution is that it obviously also influences the system during normal operation, i.e. it results in considerable voltage drops at high load currents [7]. This has impact on voltage quality and load-flow, furthermore, if large induction machines are connected, e.g. in industrial applications or at generator home-loads, there is a strong risk of voltage collapse. Additional measures, such as mechanically or thyristor switched capacitors will be needed for reactive power compensation (voltage drop or voltage collapse) [2, 4, 5].

4. INNOVATIONS IN FACTS TECHNOLOGY

In this section, innovative developments in the area of FACTS technology for series compensation are described and their benefits for short-circuit current limitation are shown.

4.1. FACTS for Series Compensation – from FSC to TPSC

In series compensation, a capacitor is used to compensate for the lines inductance, thus the line is "virtually" shortened and the transmission angle decreased for system stability improvement, ref. to Fig. 2. However, during transient conditions, the short-circuit currents cause high voltages across the capacitor, which must be limited to specified values. In the past, this limitation was accomplished by a spark gap, by arresters (MOV) or in a combination of both, see Fig. 5.

An AC-fault current flowing through a MOV always leads to a high energy dissipation of the MOV. The MOV heats up heavily. Due to an upper temperature limit the MOV must cool down before the next current stress can be absorbed. Cool-down requires a substantial amount of time, time constants of several hours are typical. During this time, the series compensation must be taken out of service (bypass-breaker closed) and consequently the power transfer on the related line needs to be reduced, dependent on the degree of compensation.

Both the (mechanical) gap function and the MOV can now be replaced by an innovative solution with special high power light-triggered thyristors. These thyristors are designed and tested for a 110 kA peak current capability and they have a very fast cool-down time [13, 14].

Fig. 6 shows the fast cool-down time, which is an outstanding feature of this new development for the TPSC (Thyristor Protected Series Compensation). It can be seen, that the TPSC will be ready for additional contingencies, such as multiple fault conditions, before the end of the auto-reclosure dead-time.

For the TPSC, innovative developments in thyristor-technology have been applied: Light-Triggered Thyristors (LTT, now State of the Art for FACTS and HVDC applications) and a special heat-sink to enable a self-cooling of the valves [13].
Using this new technology, significant cost savings after system faults can be achieved. Fig. 7 shows the principle of the TPSC and the cost savings for each system fault on one of the three lines at the 500 kV TPSC installation at Vincent Substation, USA. In case of faults nearby the substations, all three lines are involved in the fault strategy. Then the savings sum up to 270,000 US$ per single event.

Fig. 6: Benefits of TPSC – Full Availability after Fault Clearing Time

The TPSC has been successfully put into service in three projects in a 500 kV transmission system at the Vincent substation in the Southern Californian Grid (USA, 1999 and 2000).

Fig. 8 shows a photo of a Vincent TPSC and Fig. 9 highlights the benefits of the used LTT technology. Due to its excellent benefit-cost ratio and its fully proven, high availability (robust layout), two new orders have been placed for the TPSC in the same transmission system.

In Fig. 10, recordings of a real fault event at the 500 kV system are shown. In the small figure (upper part), the non-affected line current is shown (phase A). In the enlarged part, for one of the affected phases (C) the measured valve current and the (calculated) valve temperature rise is depicted. It can be seen, that the initiation of the thyristor firing is depending on the fault current level: in the first half cycle of the current rise (peak value approx. 5 kA), the preset fault detection level is not yet reached, whereas in the second half-cycle, the thyristor is fired due to the increased current level. The level settings are design parameters with regard to load-flow conditions and TPSC rating. In Fig. 10, the
valve temperature raise is only about ten degrees (K), which shows the efficiency of the thyristor self-cooling: there is still a very large margin for more temperature rise up to 260 degrees in case of higher currents stresses, ref. to Fig. 6.

Based on these successful project experiences, the use of TPSC for short-circuit current limitation has been initiated, because this highly reliable technology can fulfill the challenging requirements for an utmost reliability and availability, which is a must for all electronic FCL solutions [7].

4.2 SCCL - Application of TPSC as Short-Circuit Current Limiter

By combining the TPSC with an external reactor, whose design is determined by the allowed short-circuit current level, this device can also be used very effectively as short-circuit current limiter (SCCL). This new device operates with zero impedance in steady-state conditions, and in case of a short-circuit it is switched within a few ms to the limiting-reactor impedance. Fig. 11 shows the basic
function, the operating principle and a 3-D view of the SCCL. In comparison with the TPSC site view in Fig. 8, it can be seen, that the TPSC is just complemented by an additional reactor for the current limitation. A detailed schematic of the SCCL equipment is given in the single-line diagram Fig. 12.

Fig. 12: Components of the SCCL

The main bypass breaker and the current limiting reactor LO (Fig. 12) are mounted nearby the platform, ref. to Fig. 11. All other equipment is mounted on the platform itself. As an option, an additional bypass bus coupler can be provided (not shown in the 3-D view). The reactors L1 and L3 are designed for discharging the capacitor either by thyristor or breaker. Fault detection is done by the SCCL current CT, the other functions which marked in Fig. 12 are needed for the SCCL internal protection. The bybass-breaker is operated only in cases of very high fault currents.

Applications of SCCL in typical systems configurations, which are expanded by new generation infeeds, are depicted in Fig. 13. Optional, also B2B/GPFC can be used for fault current limitation.
In Fig. 13, for an application of SCCL as bus-coupler, simulation results for a reduction of the fault current from 80 kA to 50 kA are shown. This fault current reduction would lead to significant cost-savings for the substation upgrade, because a rating of the existing equipment with 63 kA would be sufficient in the case of system expansion, e.g. by connection of new power plants, hence an expensive uprating on 80 kA could be avoided if SCCL is used.

It must to be stated, that the SCCL application is not limited to high-voltage systems only, it can also be applied with same benefits to medium voltage levels, e.g. for the connection of generator home-loads.
5. TPSC AND SCCL - DYNAMIC CONTROL ADD-ON FUNCTIONS

5.1 Power Oscillation Damping

In case that power systems are expanded or interconnected, in addition to the task of current limitation, there is often a need for damping of power oscillations. This would not be possible with conventional reactors and other FCL devices or with fixed series compensation elements. However, with the TPSC, this feature is available. Using the thyristor for control, an additional value for the user can easily be created by means of software add-on functions. In the same way, this feature can also be applied for the SCCL. Fig. 15 gives an example of this innovative solution, applied in a typical, interconnected AC power system.

![With POD Control: Fast & effective Damping](image)

![No POD Control: System close to Instability](image)

Fig. 15: First Add-On Control Function – Power Oscillation Damping

In the upper traces of Fig. 15, the TPSC (or SCCL, respectively) is operated in a bang-bang control mode, thus the oscillations are damped very efficiently, whereas in the case without active damping (lower traces), there is a large risk for instability of the coupled parts of the system.

5.2 SSR Mitigation

For systems interconnections, in many cases Fixed Series Compensation is used. However a significant disadvantage of FSC is the possibility of exciting subsynchronous resonances (SSR) in neighboring network generators under certain conditions: SSR is a specific and disastrous phenomenon with large (thermal) generation units, which often are constructed with long shaft configurations. These shafts can oscillate at low order frequencies, and such phenomena can lead to shaft destruction [17]. This circumstance is excited when there is a “matching” electrical frequency value, which may occur in a neighboring series compensated line. A typical example: a turbine generator shaft is resonant at 25 Hz, the system frequency is 60 Hz, then, a resonance of the series capacitor and the line plus source impedance at 35 Hz has to be avoided. However, as system conditions change, this often cannot be prevented. As a consequence, the degree of series compensation needs to be modified (reduced) immediately, when SSR is detected. However, in practice, SSR detection is a rather sophisticated task, and a reduction of the compensation leads to a decrease in transmission stability, so the power transfer must be reduced (less return on investments).

Now, for TPSC and SCCL, a control add-on function can be provided, with automatic SSR detection and mitigation to avoid such severe transmission constraints.

Fig. 16 shows the simulation results of a power system interconnection with a series compensated line. In the simulation, a TPSC has been used, which can either be blocked or be operated in a controlled mode (like TCSC). In Fig. 16 a), the TPSC is fully blocked (= conventional FSC), and the
subsynchronous oscillation quickly rises above the critical torque level of the generator under investigation, see the first trace in the figure.

![Diagram showing subsynchronous oscillation](image)

Fig. 16: Second Control Add-On Function of TPSC/SCCL – SSR Mitigation
a) TPSC blocked
b) TPSC active

In Fig. 16 b), the TPSC control add-on function is enabled, hence the SSR oscillation remains below the critical and dangerous torque level. This leaves time for remedial actions, ref. to the figure.

6. CONCLUSIONS

New developments for Thyristor Protected Series Compensation have been successfully applied in a 500 kV transmission system in the United States. Using the TPSC, in combination with an additional
reactor, a new FACTS element for system expansion, the SCCL, is available now. It offers significant benefits for short-circuit current limitation, in high-voltage and also in medium-voltage systems. By means of control add-on functions, both TPSC and SCCL offer additional advantages for power system enhancement.

Further investigations have shown that with both TPSC and SCCL, an active damping of SSR phenomena is feasible up to resonance frequencies of about 30 Hz (electrically).

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8. REFERENCES