Field Experience of Encapsulated Fast Protective Device for Series Capacitors

C. HEYMAN*  S. WILLFORSS  R. GRUNBAUM  F. OLIVEIRA

ABB   ABB   ABB   ABB
Sweden  Sweden  Sweden  Brazil

SUMMARY

Series Capacitors (SCs) are a well established concept within electric power transmission, finding ever increasing use in AC transmission grids to provide enhanced power transmission capability over long lines due to improved voltage and angular stability as well as improved power sharing between parallel lines. Protection of series capacitors include capacitor over-voltage protection consisting of a non linear Metal Oxide Varistor (MOV) and may also include a forced triggered spark gap.

This paper presents both field results and lab tests of the CapThor based Fast Protective Device concept. CapThor is an encapsulated bypass device that does not have the drawbacks of traditional open air spark gaps, these being sensitivity to environmental stresses such as rain, dust, snow and animals entering the gap with a flash-over and bypass of the Series Capacitor.

The design is based on a fundamental law of physics, according to which the breakdown voltage of a plasma gap is a unique function of the product of pressure and the electrode separation for a particular gas and electrode material. By keeping the gas pressure high, this together with an efficient triggering procedure allows a plasma gap of small physical dimensions and hence, a compact FPD, saving space in the installation.

The conclusion of field experiences as well as lab tests is that it is possible to achieve a superior performance with an encapsulated design. It is shown that CapThor performs as expected during an internal fault that requires a bypass of the Series Capacitor to protect the MOV (Metal Oxide Varistor) from being damaged. It is also shown that the CapThor can bypass a Series Capacitor for line currents significant below rated current. This ability has been studied both in lab environment and field installations. The paper also elaborates on what possibilities this feature creates. The two most important are that transient torque SSR (subsynchronous resonance) and TRV (transient recovery voltage) stresses to line circuit breakers can be mitigated. Unmitigated, both these problems could cause big damage to the system where TRV stress for example could cause the line circuit breaker to re-strike with a line outage as consequence, while unmitigated SSR could lead to damage due to uncontrollable torsional vibrations in turbo-generator shafts.

KEYWORDS

Series Capacitors (SC), Flexible AC Transmission Systems (FACTS), Transient Recovery Voltage (TRV), Subsynchronous Resonance (SSR), Fast Protective Device (FPD)
1. Introduction

Series Capacitors (SCs) are a well-established concept within electric power transmission, finding ever increasing use in AC transmission grids to provide enhanced power transmission capability over long lines due to improved voltage and angular stability as well as improved power sharing between parallel lines. Protection of series capacitors include capacitor over-voltage protection consisting of a non-linear Metal Oxide Varistor (MOV) and may also include a forced triggered spark gap [1]. One major disadvantage of the spark gaps traditionally used is that they are of open air type. This makes it possible for dust, snow and rain to enter the gap with a flash-over and a bypass of the SC as a result. Such a non-triggered bypass could have major detrimental impact on the power system’s stability. Further, the flexibility of the SC is limited with the traditional open air spark gaps since the voltage required for the gaps to operate is rather high.

To achieve a higher reliability for gap protected Series Capacitors an encapsulated Fast Protective Device (FPD) that has significant advantage compared to traditional open air spark gaps has been developed by ABB. A single line diagram of a FPD protected Series Capacitor is found in Figure 1. The actual bypass device in the FPD concept is the CapThor. The advantages with CapThor are the fact that the device is totally protected from environmental disturbances due to a hermetically sealed design and also its ability to bypass the SC at very low voltages across the device. This creates new possibilities to mitigate SC related problems such as Transient Recovery Voltage stress on line circuit breakers and sub-synchronous resonance.

2. TRV & SSR

2.1. TRV

Series capacitors in a transmission line can have a significant effect on the transient voltage that appears across the contacts of a line circuit breaker when opening to clear a fault. The voltage that appears in such situations is referred to as TRV. Concerns have sometimes been raised over the potential hazards for line breakers in series compensated lines, due to TRV. By adopting the proper measures, the impact of series compensation on the TRV of line breakers can be minimized.

To mitigate the TRV the most straightforward and safest way of doing it is to simply ensure that the SC is bypassed before the line circuit breakers are operated. In such a case a costly upgrade of the line circuit breakers can be avoided. For this you must however be sure that the SC is bypassed before the line circuit breakers open for all types of currents that are strong enough to create a harmful TRV. Even though an SC bypass switch can be faster than a line circuit breaker, delays in the line protections and also in communication result in the bypass time of the bypass switch usually being too
long to ensure that the SC is bypassed before the line circuit breakers open. The conclusion is that with a CapThor installation the risk of a re-strike in the line breaker due to the Series Capacitor is removed. The positive effects of this cannot be overvalued since the consequence of a re-strike is a failed line circuit breaker with a line outage as a result.

2.2. SSR
In very specific cases series compensation can result in adverse SSR conditions, with detrimental effects on the connected turbine generator shaft system. This condition arises if the positive mechanical damping of the shaft system is less than the negative damping of the electrical system around the torsional frequencies of the mechanical system. A lot has been written about SSR mitigation and different types of protection strategies exist. Many of these are however associated with a significant installation and maintenance cost. The most general solution here is to install a Thyristor Controlled Series Capacitor (TCSC). By doing so, the SC will always be in service without any risk of creating an SSR situation. To justify the extra cost of a TCSC the risk of SSR has to be substantial. For some types of SSR, the cheaper solution to simply bypass the SC can be used. This is of course not desirable if the estimated number of bypasses due to SSR is high but if the number is small it could be an acceptable and very cost effective method.

2.3. Mitigation measures
Both TRV and SSR problems can be solved by using CapThor that can bypass the series capacitor in times significantly below the bypass times of the bypass switch. Even if the fastest available bypass switches on the market is used this is in many cases not enough. In the presence of a current in the MOV branch of the SC the FPD will bypass the capacitor in below 1 msec after the fault has been detected. If no MOV current is detected the FPD can however still operate down to very low voltage as will be shown later in this paper.

3. CapThor design
The encapsulated design is made possible by a combination of a mechanical switch called Fast Contact (FC) and a forced triggered spark gap called Arc Plasma Injector (API). Both an external and internal view of CapThor are shown in Figure 2.

![Figure 2: To the left an external view of CapThor and to the right an internal view of the same.](image_url)

The API is made up of two high power electrodes arranged in such a way that an electric arc or plasma can be injected in the gap formed between the two electrodes. This will effectively create an electrical short circuit between the two electrodes. The electrodes are connected across the Series Capacitor and the short circuit between them will be a short circuit of the series capacitor [2]. The controlled
environment in the encapsulated design also makes it possible to bypass the SC with the API at very low line currents, current levels that are significantly lower compared with the traditional open air spark gap. The bypass times are also way below the times possible if the SC is bypassed by means of only the bypass breaker. As stated, this makes the FPD concept a very effective counter measure to common Series Capacitor related problems like SSR and TRV. This functionality is further studied and described later in the paper.

The design of the arc plasma injector is based on a fundamental law of physics, according to which the breakdown voltage of a plasma gap is a unique function of the product of pressure and the electrode separation for a particular gas and electrode material (Paschen’s Law [3]). By keeping the gas pressure high, this together with an efficient triggering procedure allows a plasma gap of small physical dimensions and hence, a compact FPD.

Additionally, with high pressure in the plasma gap, the relative content of combustion products after a discharge can be kept low, and does not to any significant degree derate the voltage withstand capability of the gap.

The Fast Contact is based on a Thomson coil actuator [2]. This makes it possible to create a switch that can operate in times below 5 msec. To ensure that the contact is not stuck in a mid position a robust solution with linkage arms with springs is used. This allows for reliable and fast operation.

In case an operation is ordered a triggering pulse will be sent to the API that will bypass the Series Capacitor bank. At the same time an operation pulse will be sent to the Fast Contact that will start to close. Within 5 msec the Fast Contact has closed and the current will commute over to the switch branch.

A picture of CapThor from a field installation is shown in Figure 3.

![Figure 3: CapThor, field installation.](image)
4. Performance

The first CapThor based FPD was employed in a pilot installation that was evaluated between 2003 and 2005 (Figure 4). The first commercial project was then put into service by ABB in late 2007. Today CapThor protected Series Capacitors are in service all across the world in all possible environmental conditions [4, 5, 6]. In this section, parts of the huge experience database that has been collected from the 20+ installations that have been commissioned with CapThor are presented.

4.1. Verification of CapThor as protection for internal faults

The main function of CapThor is to bypass the SC in case of a severe internal fault on the transmission line that is of such a magnitude that it could damage the MOV. An internal fault is defined as a fault in the same line section where the SC is situated.

During an internal fault, fast and reliable triggering of the protective spark gap is essential. If the protective spark gap fails to trigger the result will be a damaged MOV.

The encapsulated design of CapThor creates the possibility for a very reliable triggering function. Below in Figure 5 and Figure 6 measurements from a real internal fault are presented.
Figure 5: The top graph shows the line current, the second graph from the top shows the MOV current, the third graph from the top shows the CapThor current and the lower graph shows the orders sent to the CapThor.

Figure 6: A zoom in of the sequence of events presented in Figure 5, the red curve is the CapThor current, the blue is the line current and the green curve is the MOV current.

Due to the resolution in the measurement system there is an error margin in Figure 5 and Figure 6. The total bypass time from fault to bypass of the SC is between 0.50 – 0.83 msec. This is measured as the time from when the fault current is actually measured to when the Capacitor and MOV are bypassed.

In Figure 7 another real example where the CapThor has successfully protected the Series Capacitor from an internal fault is presented. A detailed study shows that the bypass time in this case is between 0.6 – 0.7 msec.
The two examples show that the CapThor based FPD concept protects the SC fast and accurately. Since the first commissioning in 2007 no reports of missed protective actions have been received.

### 4.2. Verification of CapThor for TRV and SSR mitigation

#### 4.2.1. Lab Tests

The FPD bypasses the SC by triggering the API. The API’s ability to trigger has been studied in a lab test. The test was set up by applying a variable AC voltage across the test object. To limit the discharge current through the test object a resistor was mounted in series with it. A simplified schematic diagram of the setup is shown in Figure 8.

![Figure 8: Setup used in the tests to determine the triggering ability of the API.](image)

A 50 Hz sine wave was applied to the test object and at a given phase position it was ordered to trigger (two different phase positions on the 50 Hz sine wave were tested for). The triggering time, defined as the time difference between the triggering order and the voltage breakdown across the test object, was recorded. The result is presented in Figure 9.
Figure 9: Results of triggering test for API at low capacitor voltage. The vertical axis shows the triggering times [µsec] and the horizontal axis is showing applied voltage [kV\textit{rms}].

The test was carried out for 5 kV\textit{rms}, 10 kV\textit{rms} and 15 kV\textit{rms} across the test object. For each voltage 2 different phase positions were tested, 6.8 msec and 16.8 msec after zero crossing. Each phase position and voltage level is presented in the diagram with a separate data series.

The result as presented in Figure 9 shows that there is a small spread in the triggering time but the triggering function is very reliable even at voltage levels very low for a Series Capacitor. The average triggering time in the 22 tests that were carried out was around 0.6 msec. Note that this time is higher than one would see during a normal protective bypass of the SC bank due to the lower voltage across the API.

4.3. Field Performance

The result presented in the previous section shows a reliable and satisfactory functionality in a lab environment. This function is today common practice for ABB and is used in a number of projects around the whole world.

The feature of fast and accurate by-passing by means of CapThor is demonstrated in a set-up in western USA where two series capacitors (Figure 10) were installed to enhance the power transmission capability of a 500 kV power interconnector. The degree of compensation in each case amounts to 50%. For certain grid fault scenarios which were more or less unlikely but could not be ruled out altogether, the line, series compensated at both ends, would find itself in a radial mode together with a large thermal power station (>700 MW) at one of the line ends. System studies performed prior to installation had shown that in cases like that, under some system conditions the generator could be subjected to high transient torques due to SSR. To avoid running into states of SSR, FPDs were supplied as integral parts of the series capacitors, enabling fast, controlled capacitor by-pass upon any possible SSR indication.
To verify the lab results against real field performance the data in Figure 9 is compared with measurements done at site. The measurement was done at the SC bank seen in Figure 10, the result is presented in Figure 11.

![Figure 10: Series Capacitor platform.](image1)

In Figure 11 the sampling frequency is 6 kHz which implies that the bypass time is found in the interval 0.3 – 0.7 msec. It is in other words in line with the results shown in the lab results above. At the time of the test the line current was only approximately 0.6 kA_{rms} which in this installation corresponded to 0.3 p.u.

5. Conclusions

This paper has presented results from field experience of CapThor and lab tests with the same. The conclusion is that it is possible to achieve a superior performance with an encapsulated design. The encapsulated design allows for a device that is totally protected from all possible environmental stresses that could cause an open air spark gap to flash-over. It has been shown that CapThor performs
as expected during an internal fault that requires a bypass of the Series Capacitor to protect the MOV from being damaged. It has also been shown that the CapThor can bypass a Series Capacitor for line currents significant below rated current. This ability has been studied both in lab environment and field installations. The paper has also discussed around what possibilities this creates. The two most important features are the fact that transient torque SSR can be mitigated, as well as TRV stresses to line circuit breakers. Unless properly remedied, both these problems could cause considerable damage to the system where TRV stress for example could cause the line circuit breaker to re-strike with a line outage as consequence, while unmitigated SSR could lead to damage due to uncontrollable torsional vibrations in turbo-generator shafts.

BIBLIOGRAPHY

[4] “Series Capacitor for increased power transmission capacity in the Finnish 400 kV grid”, ABB Application Note A02-0222 E, 2010
[5] “Series Capacitors for increased power transmission capacity of regional 230 kV grid in Brazil”, ABB Application Note A02-0212 E, 2010