

## **Protective firing in LCC HVDC: Purposes and present principles. Settings and behaviour.**

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### **SUMMARY**

Modern HVDC valves for Line Commutated Converters (LCCs) have sophisticated protections; both for a complete valve and for its individual components. Of these, the protective firing protect individual thyristors against forward voltages in excess of their capability. The capability is not a fixed value, but a function of different variables, and modern protective firing tries to approximate this function by prevent damage while causing the least unnecessary restrictions in the use.

To achieve the goal, there are principles to follow; some are applicable to protections in general and there are some that are particular to thyristor valves:

- The protection characteristics must be able to closely emulate the capability characteristics of the protected element or system.
- The necessary margins between the protection and the capability need to be used judiciously so as not to cause undue over-dimensioning.
- The protective firing protection aims at protecting individual thyristors, but:
  - Its settings may affect the complete valve dimensioning.
  - Its settings may affect the behaviour of a complete converter.

This article introduces the specific purposes of protective firing, as well as the present principles on which it is based, including its dynamic behaviour. The correlation between protective firing at thyristor level and at valve level are discussed, together with the correlation with redundancy and with uneven voltage distribution during transients.

The voltages that may appear at a valve are then presented in relation to possible chosen settings and the overall valve design aspects such as the insulation protective levels (mainly SIPL) and transients in the forward direction during operation as inverter and as rectifier. The risks that a transient occurs during either form of operation are discussed, as well as the consequences such transient may have A) on the operation and B) on the equipment, for different levels of protective firing settings.

The pitfalls into which settings can lead if the attractive aspects are not taken in appropriate balance are discussed: In one extreme, overdesign of valves, then, close to the middle, maybe un-harmful firing, and in the other extreme, un-granted commutation failures. The article then describes the process for choosing settings.

Specific examples from real HVDC projects are also presented, with information about the philosophy and reasoning behind the protective firing levels in them, as well as the resulting behaviour of the system.

### **KEYWORDS**

HVDC, Protective - firing, HVDC - valve - dimensioning, Thyristor - valve

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## 1. Introduction

It is important to remember that the voltage withstand of thyristors for reverse direction is higher than in forward direction. Besides, if a thyristor is forced into conduction by a forward voltage above its capability, the thyristor may be damaged, but if a thyristor is triggered through its gate (electrical or optical) it will force the voltage down, and it will be able to take the current stresses. This is the very basic reason for having the protective firing function in modern HVDC thyristor valves.

A voltage stress higher than the thyristor capability may come from different disturbances. One of them is a failure in the trigger signal: If the other thyristors in the valve received the trigger pulse, the voltage on the still-not-conducting thyristor would greatly exceed its capability. To avoid this, the protective firing function will trigger it.

Another possible source is a transient coming from the ac side that could stress the thyristors in a valve; the stress could be such that it is desirable to use the protective firing function to limit the stress on the individual thyristors.

Furthermore, the thyristor withstand in forward direction in the instants just after conduction is lowered by the remaining charges that have not re-combined. That is why the protective functions for the thyristors in many projects temporarily lower the level at which the thyristor would be re-triggered if a high voltage would appear at such instants. This is illustrated in Figure 1

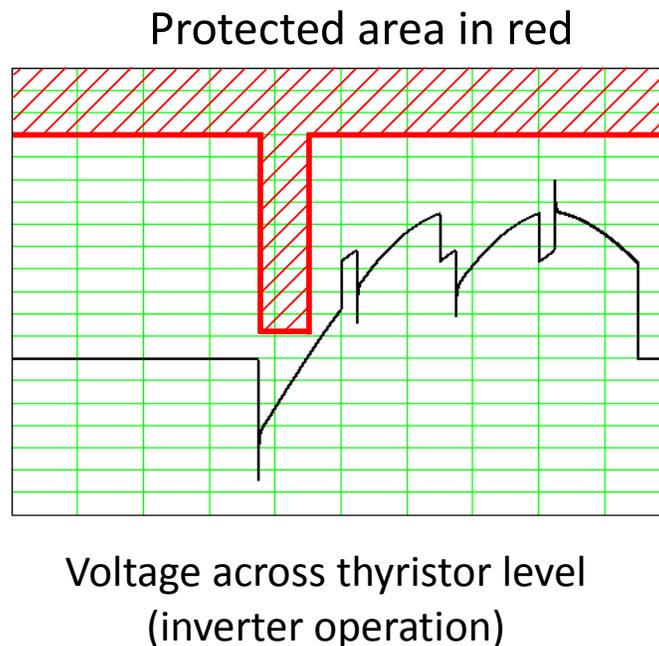


Figure 1. Protective firing, including higher sensitivity during recovery

A thyristor valve comprises many thyristors in series, and each one is provided with a protective firing function that is set to operate at a given voltage level. In this article the level for a single thyristor is denoted by **pf** in lower case. The sum of the protective pfs for the valve is also interesting, and in this article is denoted by **PF** in upper case.

The protective firing function at each thyristor level was introduced to protect the healthy thyristors from failing in case there was a failure affecting a significant number of thyristors. It also protects a thyristor against other phenomena, as described above. As for any other protection, its principles, settings and actions were analysed, as well as the possible consequences of malfunctions. As the protective firing level at each thyristor level (**pf**) is a function of the thyristor used, it is more or less

fixed for a given thyristor-snubber combination. The relationship between **pf** and the thyristor characteristics is beyond the scope of this article. The equivalent protective firing level for the complete valve (**PF**) is what this article mainly deals with. Even though **PF** grows with the number of thyristors, it is not a linear function of that number.

## 2. Philosophies for choosing PF

There have been different philosophies regarding the use and purposes of the thyristor protective firing function. The question is closely related to the resulting protective firing level for the complete valve in comparison with the voltage limitation afforded by the arrester in parallel with the valve. The main differences in the philosophies depend on the weight given to the following aspects: on one hand, it is desirable to have as low a **PF** as possible so that the valve cost will be optimised(1); on the other hand, it is desirable to have as high a **PF** setting as possible, as this will ensure that no miss-operations will occur(2). These aspects are discussed below.

(1)

As the **pf** per thyristor is fixed for a given thyristor, a low **PF** setting allows the use of fewer thyristors; however, if the **PF** level is chosen too low, the risk of firing the valve for cases in which there are no partial failures in the valve increases; namely, for external faults.

(2)

A high **PF** setting requires a valve that can at least withstand the setting without firing. This is similar to wanting to have a high setting in overcurrent relays: It is possible only if the protected equipment can withstand the current defined by the protection setting. In a thyristor valve, a high **PF** level will result in a valve design with higher withstand, which in turn will mean more thyristors, and a more expensive design: The additional costs will affect the valves, and may also affect the valve hall.

The perceived optimum between these trends has been debated several times before, and this is reflected in the variety of **PF** settings discussed below:

## 3. Valve voltage stresses, withstand and insulation coordination

During operation, in addition to the normal steady state voltage stresses on a valve there will come some stresses caused by external disturbances. The voltage level reached by such disturbances will be affected by the arrester in parallel with the valve. As the voltage is controlled by the arrester it is normally called residual voltage. This voltage level is not just one exact number, since arresters reach different residual voltages for different currents resulting from different scenarios. The highest residual voltage from all the credible conditions and disturbances with a switching impulse front time is defined as Switching Impulse Protective Level (SIPL). The concept is well defined in the standards, and does not depend on if it occurs during rectifier or inverter operation. Further, SIPL is one number, rather than a set of values. It is important to keep in mind the difference between residual voltages and SIPL because many transient voltage stresses on the valve not reaching SIPL may also be interesting, as is discussed further down. Please see Figure 2.

The valve insulation levels are defined from the protective levels. SIPL is obtained as described above, and in similar way the fast front and lightning protective levels are defined. On top of the protective levels margins are applied to cover for uncertainties, and insulation levels (or voltages) are obtained. As HVDC valves are not interchangeable nor mass produced, there is no incentive to follow standard insulation levels or voltages such as those defined for e.g. ac equipment, in which the savings in engineering and production easily surpass the costs of over-dimensioning. This process is illustrated in Figure 3, where a valve Switching Impulse Withstand Level (SIWL) can be chosen at level ① to achieve the desired margin, and there's no point in choosing level ② just because it is a standard level.

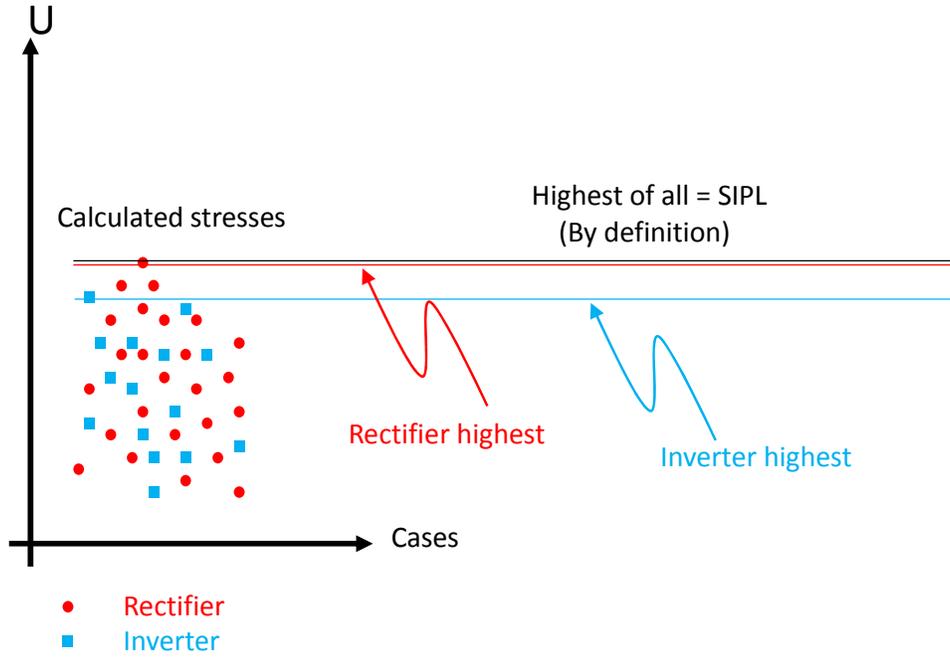


Figure 2. Stresses from many cases have a rectifier highest, an inverter highest and a highest of all

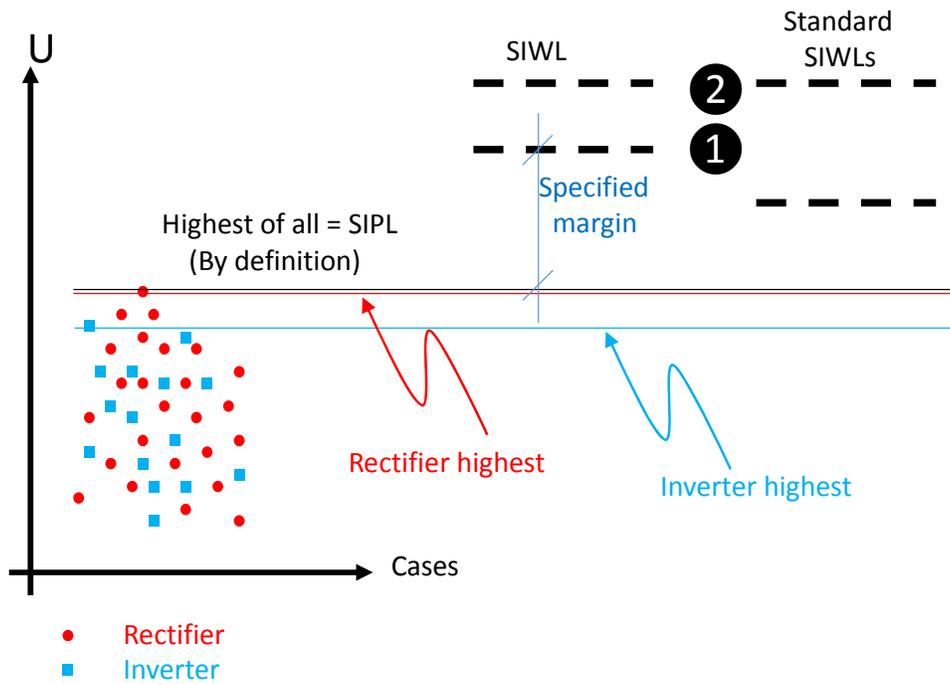


Figure 3. Choice of SIWL

Another part in the process is to compare the residual voltages for different contingencies in different operating conditions; i.e. as rectifier and as inverter. It is important to take this step because in most, if not all, HVDC projects, the highest voltage stresses on the valve occur for rectifier operation cases, and these will define the SIPL as explained above, but those that occur in inverter operation will be interesting for defining the **PF** of the valve. Please refer to Figure 4, where the stresses are shown together with the possible choices of PF.

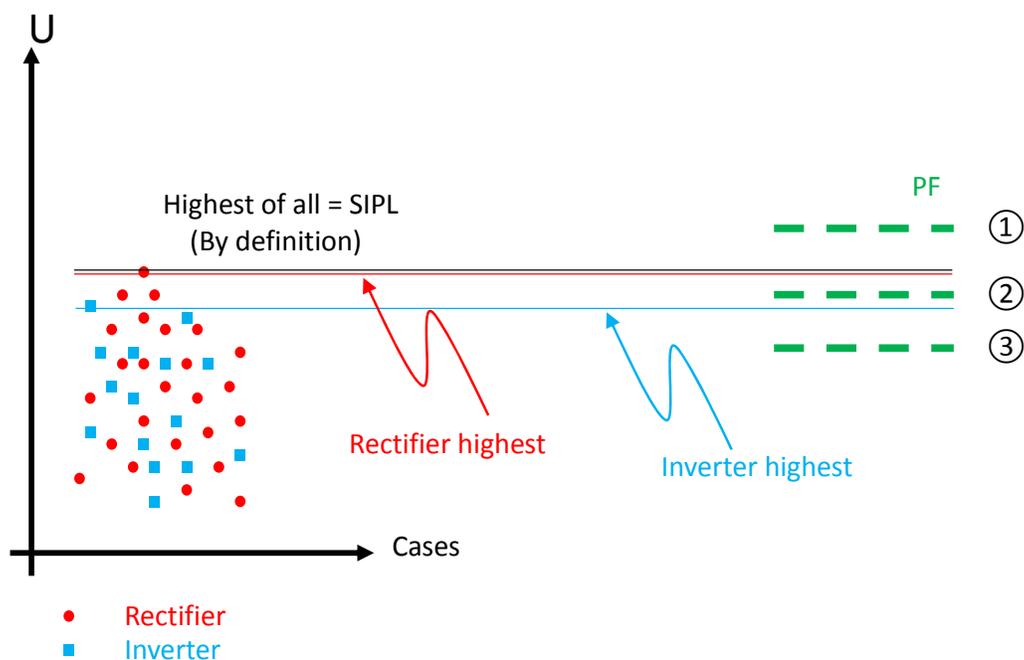


Figure 4. Choice of PF as function of highest stresses in either rectifier or inverter operation

#### 4. Considerations for choosing the valve PF

The protective firing level at valve level, **PF**, is provided by the combination of the **pf** on individual thyristor levels, whereas the SIPL and other stresses at valve level are defined by the arrester on the complete valve basis. A sound philosophy follows the principle that protective firing operation should be avoided for ac network faults for which it is preferred that the arrester performs the primary protection. Experience has shown that such discrimination can be achieved if the protective firing level **PF** is chosen somewhat lower than, or at most equal to, the SIPL.

If the **PF** is higher than SIPL, as shown by level ① in Figure 4, the valve withstand will always be above the arrester for all types of faults and the protective firing will probably never act in the life time of the valves.

If the **PF** is lower than SIPL, as shown by levels ② and ③ in Figure 4, the possible adverse effects, if any, of protective firing operation on the transmission and on equipment need to be considered. They are discussed below.

In rectifier operation, the valves have blocking voltage in the forward direction during a short portion of the fundamental frequency cycle period. Thus, the probability of an overvoltage occurring in forward direction when the valve is not conducting is considerably smaller than in inverter operation. This can be seen in the left part of Figure 5. Even more important: if a protective firing occurs due to transients in the a.c. network, no serious stress on the valves or the system will occur. Firing the valve once at a lower  $\alpha$  will not stress the valve. For the system, firing one valve at a lower  $\alpha$  than what the control would order will give a slight increase in the dc voltage of the bridge, since this would occur only once.

In inverter operation, for external faults when the pole remains in operation, the situation during the fault, and at the instants following its clearing, is different: Fault clearing in the a.c. system may cause switching surge overvoltages that can be transmitted through the converter transformers, as determined by the turns ratio. The valves in inverter operation have blocking voltage in the forward direction during a relatively long portion of the fundamental frequency cycle, as shown in the right part of Figure 5. The probability that an overvoltage in the forward direction occurs when the valve is not conducting could be relatively high. Furthermore, if a valve is fired earlier due to protective firing acting, the result could be a commutation failure and the recovery time for the transmission after a fault clearing would be increased.

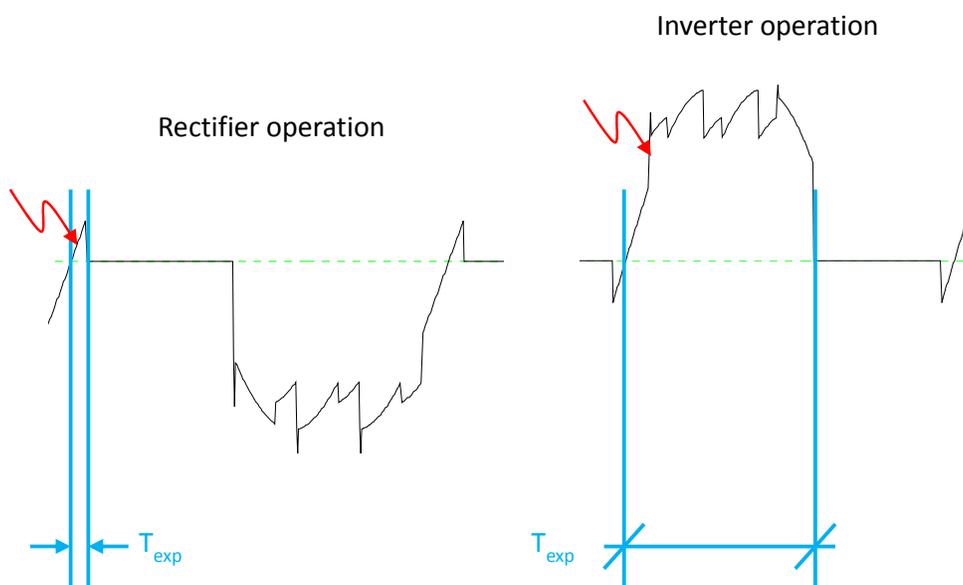


Figure 5. Exposure times when a transient may cause protective firing operation

A sound philosophy for the selection of the minimum protective firing level is that an ac fault and its clearing during inverter operation, should not lead to protective firing action of the valves. Thus, the residual voltage across a valve, as defined by the corresponding arrester current following the worst fault case for inverter operation is used as a base for the selection of the minimum protective firing **PF** level.

## 5. Influence on valve dimensioning

The valve **PF** is a function of the individual thyristors **pf**, but the function is not linear: the unevenness in the voltage distribution between thyristors has to be considered. The unevenness arises from differences in stray capacitances and in snubber circuit capacitances. The redundant thyristors have also to be considered as well: No redundancy for calculating the minimum **PF**.

As per IEC 60700-1 requirement, during dielectric test, the valve is allowed to protectively fire in the forward direction, and it is tested up to the **PF** level in the forward direction. The test becomes thus a dimensioning factor for the complete valve.

## 6. Recommendation

The **PF** level for the valves should be the result of studies, considering cases for which protective firing action is and is not acceptable; e.g. for avoiding repeated commutation failures, and considering cases for which protective firing action may be acceptable; e.g. for transients during rectifier operation. If the **PF** is lower than the highest stresses as inverter (level ③ in Figure 4), recovery after

faults will be compromised for some inverter operation disturbances. If the **PF** is chosen equal to or slightly above the highest stresses as inverter (level ② in the same figure), recovery will not be compromised, and an optimum will be achieved.

Referring again to Figure 4, if the **PF** for the valve is higher than SIPL (level ①), the valve will never see a voltage corresponding to the **PF** in real operation, since the arrester will always act first and keep the residual voltage at or below SIPL. It follows thus, that by putting the **PF** level higher than SIPL nothing is gained other than making the valves, the valve halls, and the losses costlier by having extra thyristor levels. It is therefore not recommended to define just an over-dimensioning factor above SIPL, as this does not improve the installation nor the operation, and only adds to the cost

In some very special stages of special projects it may happen that the highest stresses as inverter are higher than those as rectifier. Then, both SIPL and **PF** will be defined by inverter operation cases.

## 7. Experience from some HVDC projects

Relative positions of **PF** as demanded by the Owner in relation to SIPL and as provided by the HVDC supplier in various similar projects, including the experience to date are shown below:

Project	Required PF	Supplied PF	Comments
<b>Three Gorges-Changzhou</b> (China)	15% above SIPL	15% above SIPL	The Insulation Levels study suggested <b>PF</b> = SIPL
<b>Three Gorges Shanghai</b> (China)	15% above SIPL	15% above SIPL	The Insulation Levels study suggested <b>PF</b> = SIPL
<b>Chapad</b> (India)	10% above SIPL	10% above SIPL	
<b>VIZAG</b> (India)	5% above SIPL	5% above SIPL	
<b>Rihand-Dadri</b> (India)	NIL	5% under SIPL	No adverse PF operation in service
<b>Québec-New England</b> (Canada-USA)	NIL	7% under SIPL	No adverse PF operation in service

It can be seen from the data above that there is operating experience with both approaches: with **PF** higher or lower than SIPL. The experience has shown that there is no difference in thyristor failure levels between these cases.

Further, the occurrence of spurious firing of the valves has not been a problem in the projects with **PF** below SIPL. The reason is that the different external cases that can introduce stresses to the valve were analysed during the detailed design stage, and the **PF** was set accordingly.

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