Implementing the protection and control of future DC Grids

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1. The challenge of the DC Grid protection
   (1) High speed requirement. The DC system circuit breaker (CB) should clear the fault current within 5ms, due to the low impedance of the DC system (reactance and resistance is so small for DC system that it could be neglected). The total tripping time for the DC protection must be less than 1 millisecond (including the time delay in hardware in the loop).
   (2) Identifying the faulted section (selectivity should be satisfied); Unlike the point to point HVDC, the DC grid is made up by several DC lines forming a DC network, where the protection for the DC line is required to only clear the faulted line. The conventional HVDC line protection which is based on the traveling wave, du/dt or over current will not work on the DC grid, because there is no direction identification in such protection schemes.
   (3) The long length of a typical HVDC transmission line results in a relatively long communication time delay, which makes the current differential protection much slower than the speed that a DC grid requires.

2. The protection philosophy for DC Grid
Although the HVDC grid protection is still in development phase (a commercial DC breaker has not been used in the field to date), one can see that the protection philosophy and the protection principle for the AC system still can be used in the DC networks. The DC breaker, which can provide fast clearance of the DC fault within 5 ms (total fault clearance time), will play a principal role for isolation of the faulty line and devices in the DC system. Therefore, the philosophy, principle and scheme of the protection for the HVDC grid will still follow those for AC system.

However, new philosophies which are being evolved are based on, breakers at every end tripping simultaneously for a fault in the DC grid, and then making selective re-closure. This will be covered in another article.

2.1 The principle of DC Grid (or multi-terminal DC (MTDC)) protection
The principles (or general requirements) for DC network protection will still be same as those of AC systems, which are listed below:
   ➢ **Selectivity:** the protection is required to accurately identify the faulty section of the system or faulty device. For faults which are in the protected zone (internal faults), the protection must reliably trip however, for the faults which are outside the protective zone (external faults), the protection must not trip.
   ➢ **Speed:** the protection should be capable of clearing fault as fast as the system requires.
   ➢ **Sensitivity:** the protection can be sensitive to weak faults (for example, a fault with high resistance).
   ➢ **Security:** the protection must not mal-operate for an external fault, which means the fault is not in the defined protective zone.

The four principles for protection are in contradiction with each other, for example, if the protection has higher sensitivity, then it must somehow be less secure; if the protection has higher selectivity, then it must lose some speed. The protection researchers and developers have long worked on the balancing of these 4 properties to provide a secure and reliable protection for AC power system.

2.2 Unit versus non-unit protection
The protection which is only based on the information and measured voltage and/or current at local end (where the protection is installed) is called non-unit protection. Nevertheless, the protection which is based on the information and measurements at both ends (for multi-terminals, all the ends) is called a unit protection.

In an AC system, the over-current protection and distance protection belong to the category of non-unit protection. The current differential, phase comparison belongs to the category of unit protection.
The advantage of the non-unit protection is that the communication links and devices are not required, not only minimising costs but the speed of the protection is not limited by the communication time delays, meanwhile the reliability and security are not limited by the communication errors or failure. The disadvantage of non-unit protection is that it cannot provide absolute selectivity. For example, the trip signal of non-unit protection will be delayed when the fault occurs out of the protective zone I, see Fig. 1.  
For example, consider the basic distance protection (no aided-schemes) which is installed at substation M, see Fig. 1, the protected line is MN, that is the protective zone should be line MN. According to the principles of protection, the protection should have selectivity, which means when fault occurs at F1, where is in-zone of the boundary N, the protection should trip, whereas, it should not trip when fault occurs at F2 where is outside the protective zone. However, there is no significant difference in the measured impedances when faults occur between F1 and F2. In order to avoid mal-operation of the protection, the protective zone I is decreased to 80% of the line length. In order to compensate the gap between zone I and rest part of line MN, another distance protection which protective zone is over 120% of the protected line (zone II) with 0.5s delay is designed. The reason why the time delay is set for protection of zone II is that the mal-operation can be avoided when the fault occurs in the overlap zone II with Zone I of next line (for example, if the fault occurs at F2, although it is in Zone II, it will reset when the protection of next line trips because of the time delay).

Therefore, the tripping time for non-unit protection can be expressed as following:

\[
T_{\text{trip}} = \begin{cases} 
T_{\text{algorithm}} & \text{if fault is in zone I} \\
T_{\text{algorithm}} + T_{\text{delay}} & \text{if fault is in the rest of zone I}
\end{cases}
\]

Where \(T_{\text{algorithm}}\) is the time spent by protection algorithm, \(T_{\text{delay}}\) is the setting time delay for zone II. There is no such disadvantage for unit protection, of course, whose tripping speed is limited by the communication time delay.

For example, using current differential protection, the differential relay in station M only can give out the decision after the current data from the remote end is received via communication links and devices. Therefore the tripping time for unit protection is shown below:

\[
T_{\text{trip}} = T_{\text{algorithm}} + T_{\text{comm}}
\]

In terms of a DC grid, the DC transmission lines are normally longer than the lines in an AC system, that is to say, the \(T_{\text{comm}}\) (communication time delay) would be longer, due to the distance involved. If the line length is longer than the limitation of direct communication, then inter-connection relaying to forward the information is required, which can cause an extra time delays (this could reach 100ms for lines over 500km).

Therefore, for the future HVDC grids, the non-unit protection will play the dominant role of protection and unit-protection as the role of backup protection.
The $T_{algorithm}$ in the tripping time of the protection is determined by which protection algorithm is implemented. In AC system protection, there are 2 categories, transient based and steady-state based protection.

1 We have 2 types of distance protection scheme. They are a) Basic scheme b) Distance + aided scheme (aided scheme means the local end distance relay operation is accelerated by the received information (via communication) from the remote end distance relay by having various distance scheme options).

### 2.3 The transient based protection vs. the steady based protection

The protection algorithm is generally formulated by the characteristic difference between internal and external fault. Those protection algorithms which are based on the characteristic difference of transient voltage or current signals are called transient based protection; those based on the character of steady state voltage and current signals are called steady based protection.

For AC system, the steady state signal is the power system frequency (50 or 60 Hz nominally) component in the measured signal. Most of the protections installed in AC power grids are steady-state based protection, therefore the Fourier transform for extracting the power system frequency tracked phasors is widely used in these algorithms. The time-window length for Fourier is just a cycle of the power system frequency. Additionally, the high frequency transient period is no longer than 10 ms, therefore the operation time for an algorithm of steady based protection in AC system is typically $>20$ ms. If we want to improve the tripping speed, the transient based protection should be used.

For DC grid, the steady state signal is DC, therefore the Fourier based protection does not work in the DC system. On the other hand, the transient period in a DC system is much longer than the period of transients in an AC system. Therefore, the only way of formulating the algorithm for DC grid protection is employing the transient based protection.

### 2.4 Sampling rate, time window and tripping time

The time window for transient based protection is very important, which will directly impact on the speed of the protection algorithm.

The time window subsequently determines the sampling rate, so that in the time window there should be sufficient samples for detection of the faults and for determination of internal or external faults.

As per IEC 61869-9, the sampling rate for DC grid protection is 96 kHz, that is, 96 samples per millisecond. If the requirement of the total fault clearance time is less than 5 ms, then the window length should be less than 0.5 ms as well.

Using the above sampling rate, the decision of internal or external fault can be made by an algorithm less than 0.5 ms, which can meet the requirement of DC fault clearance.

### 3. New algorithms for DC grid protection

#### 3.1 Protection schemes for DC Grid protection

Based on the analysis above, the only difference of DC grid protection schemes from the AC system is that the non-unit protection may be the primary protection function for a DC grid and the unit protection as backup protection.

Similar to the protection schemes of AC grid, there can be several protection schemes for HVDC grids, which are listed below:

- Primary protection: transient based direction over current relay or transient based distance relay + transient based high speed remote trip detection (*without relying on communications between the ends*).
- Backup protection: transient current differential or transient based directional comparison unit protection or transient based distance unit protection + aided scheme (*schemes relying upon communication between the ends*).
See Fig 2, what is shown in the figure is a typical DC grid, which connected three AC networks. There are DC breakers equipped on both end of the DC lines. Protection R1 and R2 are responsible for protecting the line MN, R3 and R4 for line MR, and R5 and R6 for line NR.

Taking R1 and R2 as an example:
- If the fault is in the overlap zone 1 of both R1 and R2, then the directional distance protection will be trip immediately;
- If fault occurs in zone 1 of R1 and outside of R2, then, directional distance R1 will trip first, R2 will trip after detecting the breaker tripping by transient remote trip detection.
- Similarly, if fault occurs in zone 1 of R2 and outside of R1, then, directional distance R2 will trip first, R1 will trip after detecting the breaker tripping by transient remote trip detection.

In the light of the DC Grid, all the above mentioned protection philosophies have to be re-developed.

3.2 Protection Algorithm for transient based directional over current relay
- The steady state voltage and current should be removed by DC filters; the transient voltage and current should be the fault component which only contains the fault information rather than the load or other information.
- For a forward directional fault, the voltage of the fault component will be in opposite direction as the current of the fault component; they are in same directions when a reverse directional fault occurs.
- A transient polarity comparison algorithm should be employed to extract such fault information.

3.3 Protection Algorithm for transient based distance relay
- The steady state voltage and current should be removed by DC filters; the transient voltage and current should be the fault component which only contains the fault information rather than the load or other information.
Similar to the distance protection algorithm for AC system, the transient operating voltage is defined as the operating voltage of protection for DC system assuming that there is no fault in the protected zone.

An accurate distributed parameter line model should be employed for extra-long DC lines.

Based on comparison of polarities between operating and polarising voltages can help in formulation of transient distance protection.

### 3.4 Protection Algorithm for transient based current differential relay

- Utilise a sample based differential algorithm, to perform a sample by sample comparison of the currents measured at each line end.
- The main technical issue is that the accurate distributed parameter line model should be employed for extra-long DC lines when the compensation of capacitive current is calculated before the differential current is made.

### 4. Conclusions

- DC breaker will be widely used in the DC grid for isolating the faulty sections or faulty devices.
- The biggest challenge for DC grid protection is achieving the tripping time of less than 5ms without losing any security and sensitivity.
- Non-unit protection will be the primary protection and the unit protection will be the backup protection due to the communication time delay for long distance DC transmission lines.
- The transient based non-unit protection algorithm can meet the requirement of total fault clearance time less than 5ms, in which the window-length should be only 0.5ms. High sampling rate are required; the IEC 61869-9 for the DC sampling rate is 96 kHz.
- The principle, philosophy and scheme of the protection for DC systems can be inherited from that of AC systems.

The algorithm of all the relays for DC grid should be redeveloped, being reconstructed from the algorithm based on the fundamental frequency component to that based on transient components.