Research Report

Recent developments and emerging technologies in requirements for High-Voltage Direct-Current Transmission Protection and Control Equipment

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Abstract

Power System protection has been an important part of power system studies since the beginning of the first power transmission project. Proper protection system in place can save several weeks of maintenance time and budget for the utility company and provide a smoother service to the customers. In the face of legacy technologies that were well refined for AC systems, the rapid introduction of HVDC into the world has led to research and development of many protection methodologies in search for a method to provide the most reliable and fast protection scheme in the lowest cost. Some recent developments have used ingenious techniques which in coalition can be used to shut down only a part of the system that is under fault while the rest of the system remains unaffected by it. This allows for greater penetration of DG (Distributed Generation) into the smart HVDC transmission system of the future.

Introduction & Problem Statements

HVDC (High-Voltage Direct Current) is a transmission technology that is economically beneficial over HVAC (High-Voltage Alternating Current) according to the age old Kelvin's curve. The break-even distance for using HVDC over HVAC falls around 600 km, at which point the transmission lines are already long range, prone to corona effects when HVAC transmission is used.

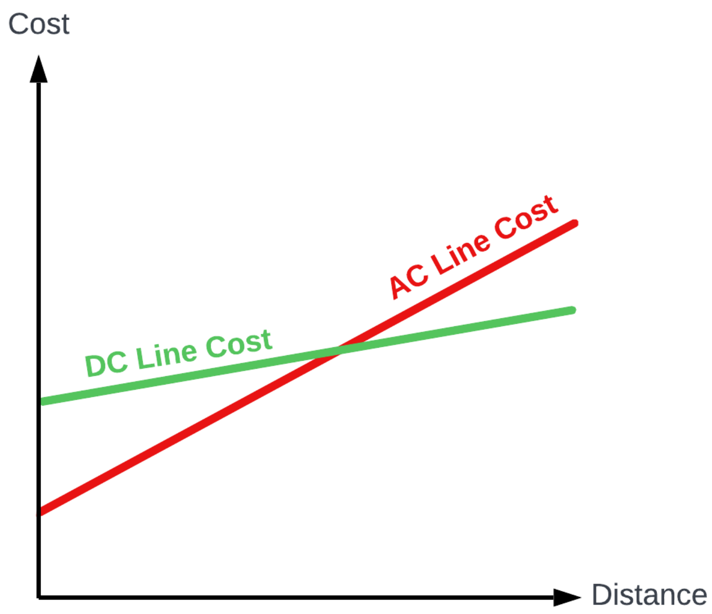

Figure 1: Kevlin's breakeven approximation made using Lucidchart

HVAC has higher charging currents for line capacitances and undergo skin and ferranti effects which creates system losses and unbalances respectively. The system also needs a lot of reactive compensation and it also isn't capable of standalone asynchronous operation i.e. devices cannot directly be connected to an AC grid and operated smoothly. Any devices that are connected will be subject to either large amounts of losses or permanent damage. AC systems also have difficulty in power flow routing and aren't as compatible with DG (Distributed Generation) prospects of the future. These overall factors greatly justify the usage of HVDC and even though, Kelvin's approximation still holds, it's obvious that cost of HVDC transmission is far less today as compared to a few decades ago due to the rapid development in solid-state electronics and materials science which has been producing ever more efficient switching devices.

But on the flipside, unlike HVAC, HVDC protection presents a completely new set of challenges. Currently used HVDC generation technology are called VSC (Voltage Source Converters) which are fast and robust & can maintain constant DC voltage for a wide variety of system states. Since VSCs are basically controlled rectifiers at the output, they allow for excellent control. This is possible through power electronic devices. These devices cannot withstand the large fault currents induced in the system as a trade-off for the excellent control they provide. These devices need to be protected with adaptive protection philosophies as mentioned in [2] along with the specific technology that suits the need of the utility company itself which. These technologies are discussed as case studies later in this document.

Effects of AC faults are fairly straightforward to analyze and account for by use of circuit breakers considering most of them are directly dependent on the fault impedance, which can be calculated through the sending end voltages and currents. But HVDC systems are hybrid by nature and therefore undergo a larger set of behaviors during faults which must be combated using a more complex protection scheme employing not only breakers but other smart devices employing multiple fault detection, mitigation and system protection approaches. For example, in a DC Line-Line fault, the system capacitance discharges quickly, bringing the DC voltage to a value close to zero [1] and then the system rectifiers start freewheeling through the system's current limiting reactor after which the diodes commutate and finally the grid current takes over and feeds itself towards the fault point. All type of HVDC faults follow a similar pattern of faults with slight variations in the oscillatory behavior of the currents and voltages. But this behavior goes up in complexity when the grid is composed of a wide range of power sources, namely PV, wind, thermal & hydro-power itself.

HVDC grids undergo high current and low voltage collapses under HVDC faults. In all HVDC faults, voltages fall sharply and currents rise sharply which overloads power electronic devices and damages them. Hence circuit breakers with multiple relaying mechanisms must be used in order to protect the system. Each relaying mechanism must be able to perform it's specific relaying operation to extract information about the system state from any of the chosen natural or derived parameters and employ appropriate fault clearing strategy. Throughout this report, protection and control equipment will be indicated by simply mentioning it as a protection system.

Case Studies

Some of the methods are reviewed by Muniappan in [2] which mention usage of many protection technologies. The protection requirements for HVDC systems are characterized by 5 major requirements and 4 major components as proposed in [3].

1. Requirements
   - Accuracy: Protection systems should protect only its designated protection zone
   - Speed: It must be fast in isolating and clearing faults
   - Sensitivity: Faults must be detected by the system
   - Selectivity: Should be able to differentiate between internal and external faults
   - Recoverability: System should be able to clear out the faults in order of 10ms [4]
2. Components
   - Measurement Devices
   - Protection Algorithms
   - Circuit Breakers
   - Fault-Clearing Strategies

The paper also defines some fault clearing strategies

1. Non-selective: Whole system is shut down after fault by AC-CB(Circuit Breakers). Faulty part is isolated by DC switches located at terminals of each zone. After this the whole system re-energized. This method of fault clearing is effective and has a high reliability because others parts of the system are immediately shut down which means fault induced blackouts are completely prevented. But this strategy is not suitable for faults that need to be cleared fast.
2. Fully-selective: HVDC-CBs at terminals of every protection zone. Such a fault clearing strategy is rapid and very responsive towards faults and can clear faults in less than 10ms. Such systems are rarely used in practice as installation of such large number of protection devices is not a well-engineered decision and is economically counterproductive.

3. Partially Selective: This is a hybrid of both of the above strategies. Areas with specialized machinery or synchronous devices employ fully-selective strategy while areas with regular requirements employ non-selective strategy. The basic idea behind this is to vary the no. of CBs per protection unit with respect to the fault clearing time(t_c).

$$\text{CBs per unit} = f(t_c)$$

Protections systems and algorithms are discussed in [2]. Various approaches have been taken to develop protection systems as explored in this literature review. The most conventional techniques include distance, overcurrent and differential relaying that breaks the circuit based on current thresholds.

Newer approaches include a method of traveling waves where a transient signal of upto 25 kHz is used to perform CWT (Constant Wavelet Transform) on the received signal. If the length of the line is 'L' and the current surge due to the fault occurs at the terminals after a time 't' which is determined by using GPS to synchronize the clocks at both terminals & if 'v' is the velocity of EM wave propagation in the medium given by 1/sqrt(LC) of the line. Then the distance to fault is given by

$$\text{fault distance} = L - tv$$

Another protection approach tackles the problem by monitoring the transient energy of the voltage waveform. Transient energy is very high during faults which make it a reliable method of detecting abnormality in the system. Another approach making use of transients performed WT (Wavelet Transform) on the signals to keep track of regular transients in order to set a discriminating threshold to separate regular transients from abnormal system transients.

Another novel approach used measurements of the sheath voltage. Sheath of transmission cables are grounded at each HVDC substation. Normally, the sheath voltage is 0V but not in case of system abnormality. This proves to be a very subtle but important observation as this can be due to one of two things, either capacitor unbalance or a fault. Transient energy analysis of this sheath voltage thus clarifies this by showing large transient energy in case of faults.

Other approaches used detection of fault locations using a distributed voltage divider models and usage of rate of change of current at either ends of the current limiting reactor.

Future Technology Recommendations

Due to the shift towards a data driven world, data driven techniques utilizing things such a combination of decision trees and neural networks can allow for detection of faults with a higher accuracy and may even allow to predict faults moments before it happens to prepare the fault clearing strategy in advance to clear faults on the order of 1 ms. The way data driven methods can do this is by analysis of historical current and voltage curves and data on old faults. Most faults are not coincidental but circumstantial. Maybe it was a day with bad weather or maybe the transmission line passes through a thick forest with many tall tree branches that can sway a lot during windy conditions. Data driven methods can see these hidden patterns in the location of the faults and what magnitude of faults they induce on a seasonal basis. This can make a well-trained model a reliable protection technique. Machines like synchronous generators exhibit a certain pattern in their other parameters before a fault occurs. Data methods can identify these non-linear patterns and draw a correlation to the probability of fault occurrence.

Conclusion

As with all methods. A mix of multiple protection methods and philosophies address various parts of the grid well. For example, a drier and barren part of the grid can employ the resistive divider fault detection method to locate the fault and isolate it using locally fully-selective relaying mechanisms. In grids located in difficult terrain, traveling wave and transient energy methods can be used to detect faults and locate them, then conduct a system wide shutdown in order to ensure that other parts of the circuit in the terrain are completely safe before the DC breakers at the terminals of the fault isolate it. Fault tolerant systems are hard to achieve with a single method at hand especially in DC systems where the generation unit itself is susceptible to it's own internal faults. Compared to traditional AC systems where faults might destroy the magnetization of the synchronous motors, which was of course a temporal and economic hassle to replace, DC systems are a complex network of switching devices themselves so internal fault location itself presents a challenge in building fault tolerant systems. Hence the reason for usage of a coalition of methods, each fulfilling the task of recognizing a certain effect at defined parts of the system due to the fault and controlling those in an effective way.

References

1. A. Shobole, M. Baysal, M. . Wadi, and M. R. . Tur, "An Adaptive Protection Technique for Smart Distribution Network", ELEKTRON ELEKTROTECH, vol. 26, no. 4, pp. 46-56, Aug. 2020.

2. M. Muniappan, "A comprehensive review of DC fault protection methods in HVDC transmission systems - protection and control of Modern Power Systems," *SpringerOpen*, 11-Jan-2021. [Online]. Available: https://doi.org/10.1186/s41601-020-00173-9. [Accessed: 11-Nov-2022].

3. M. J. Pérez-Molina, D. M. Larruskain, P. Eguía López, and G. Buigues, "Challenges for protection of future HVDC grids," *Frontiers*, 01-Jan-1AD. [Online]. Available: https://doi.org/10.3389/fenrg.2020.00033. [Accessed: 11-Nov-2022].

4. Descloux, J., Rault, P., Nguefeu, S., Curis, J., Guillaud, X., Colas, F., and Raison, B. (2012). "HVDC meshed grid: control and protection of a multi-terminal HVDC system,", *CIGRÉ Session Paris*