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DC protection in modern HVDC networks: VSC-HVDC and MTDC systems

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Abstract. Considering the importance that HVDC systems are expected to have in the future of power networks, this paper aims to provide a wide overview of the protection against DC faults. In particular, it analyzes the detection and location techniques that have been proposed to date, focusing on the approaches that are set to be applied in modern HVDC networks, which comprise VSC-HVDC and MTDC systems.

Key words

DC faults, fault detection, fault location, VSC-HVDC, MTDC.

1. Introduction

During the last decades, the way in which the different energy sources are integrated into the power system has undergone significant changes, mainly because of the extensive development of new renewable generation technologies: photovoltaics, on- and off-shore wind, etc. Nowadays, due to the commitment from the European Union to reduce 80% in Greenhouse Gas emissions by 2050, significant quantities of renewable energies are increasingly being added to the generation mix. Since most of the renewable resources are located in remote locations where AC power systems are weak or nonexistent, the concept of a European High-Voltage Direct Current (HVDC) "Supergrid" has emerged as an interesting possibility for the future [1, 2]. A HVDC ''Supergrid'' is an ambitious concept, primarily aimed at wind power integration that utilizes a meshed HVDC grid to connect multiple offshore wind farms to onshore substations. The meshed topology enhances system reliability, which is indispensable for transmission networks with a large contribution from offshore wind generation [3]. The majority of these offshore wind farms are located relatively close to shore, but the long distances expected in new installations (e.g. 100-300 km in the North Sea [1]), along with the need for new technical characteristics, limit the choice of the transmission technology that has to be considered.

Besides, in the last few years several initiatives have been founded, which have the goal to integrate renewables by using DC grids. These are for instance MEDGRID and OffshoreGrid. MEDGRID focuses on the countries in southern Europe and North Africa around the Mediterranean Sea to develop an energy concept which includes the connection of these countries by a DC transmission grid. The initiative OffshoreGrid works on a solution for the integration of large-scale offshore wind farms into the power system. In this initiative the application of a multi-terminal system is the favoured solution [4]. Apart from those initiatives in Europe and Mediterranean countries, there are other international projects that have been planned or carried out in the last years, in which several important HVDC installations have been developed around the world: 'Tres Amigas Super Station' (connecting the three major U.S. transmission networks) [5]; the new electricity "superhighway" between Xiangjiaba and Shanghai (China) [6], the Rio Madeira-São Paolo HVDC link in Brazil [7]; etc.

In this context, the less mature Voltage Source Converter (VSC) technology and VSC-HVDC based multiterminal DC grids (MTDC), along with modular multi-level converters (MMC), are set to become the core of future HVDC meshed networks. VSC-based MTDC can provide significant benefit for transmission network, such as the decoupled control of active power and reactive power, the support to weak AC system, the black start capability and small footprint, etc. However, nowadays the maximum capacity of a VSC HVDC line is still limited within 2,000 MW level whereas the line commutated converter (LCC) based MTDC takes advantages of low cost and large capacity of more than 7,000 MW per bipole. The higher power rating makes LCC MTDC almost the only choice for bulk power/long distance applications [8]. Notwithstanding this, even well-known conventional DC systems (LCC) are unlikely to be able to meet the requirements of future networks [2].

Despite the multiple advantages of these systems (fewer harmonics, control over reactive power exchange, etc.), compared to the conventional LCC-HVDC systems, this technology implies an important drawback: VSC-HVDC systems are extremely vulnerable under DC faults, which makes a quick detection and location of the fault of the utmost importance in order to isolate the faulted zone. This paper is intended to give an insightful view in the problems and solutions proposed to date in this field, focusing in VSC-based and related systems.

2. DC fault protection in VSC-HVDC based systems

Conventional thyristor-based HVDC systems (LCC-HVDC) are a well-proven technology that offers a high power transmission capacity, but with limited reactive power control. Nowadays, IGBT-based VSC technology is available for medium scale power transmission applications, offering numerous advantages over its predecessor (black-start capability, no need for short-circuit ratio, smaller converter station size, independent control of active and reactive power, voltage variations stabilization, mitigation of voltage fluctuation, etc.) [1, 9].

On the downside, VSC converters are vulnerable to DC faults. A DC voltage depression causes overcurrents in IGBTs and the system protection will trip IGBTs. Consequently, the converter becomes an uncontrollable diode bridge, discharging the ac grid into the DC fault [10, 11]. In fact, during DC fault, the converter control is lost, and the IGBTs anti-parallel diodes uncontrollably discharge AC system into the DC fault path, causing high currents through power electronics devices. Since the HVDC transmission line/cable total impedance includes only its resistance (which is much smaller than its 50Hz impedance), the current rises very sharply and reaches high levels. A DC fault can be cleared from AC switchyard using mechanical AC circuit breakers (CB) within 30-100ms, but this is too long for VSC based converters to sustain high fault currents. This way, the whole DC grid must collapse and all AC CBs trip in order to extinguish DC fault arc on overhead lines or to isolate faulted segments in case of DC cables [12].

Proven methods for AC grids cannot be applied in DC grids since they are too slow to cope with DC fault current phenomena. To clear DC faults it is important to have fast acting fault clearing, but it is at least equally important to have very fast fault detection. For time critical and economic reasons, it is also required to have a decentralized fault detection method. Due to the lack of natural zero crossings and rapid rise of DC-side fault currents, the use of existing AC protection techniques is not feasible in general. But nonetheless the development of a DC-side-protection system should be guided by the protection requirements that are well established in AC-systems. These are reliability, rapidity, economy, selectivity and accuracy [13].

Techniques developed for fault detection and location in conventional LCC-HVDC systems or AC networks are not thought to be applicable either in VSC-HVDC and MTDC systems, mainly because of the excessive time necessary to implement the techniques or due to key components being incompatible [14]. In fact, in VSC-based HVDC systems, the fault current needs to be brought to zero very quickly, reducing therefore the information available for protection purposes [15].

With the rise of VSC technology, MTDC systems have started to gain relevance and it is expected that VSC based DC transmission systems may provide the basis for future transmission networks, especially in multiterminal configurations [2]. The aforementioned European "Supergrid" will probably grow in stages from connecting one offshore wind farm to one onshore grid toward linking several far offshore wind farms to multiple onshore grids [16]. It will include many HVDC cables to integrate all offshore wind power systems. When this kind of DC grid is built, connections should be made at the DC bus, multiple undersea cables and multiple converters at the same bus, a so-called multi-terminal HVDC (MTDC) configuration. For this, VSC- HVDC is the most appropriate technology as it uses a common DC voltage and injects a variable current. The power injections in a dc grid are controlled by the converters. On a MTDC grid as "Supergrid", the power that flows into, or out of, each converter can be dynamically changed without any reconfiguration of the HVDC grid [1].

A VSC-based MTDC system consists of voltage-source converters which are connected to a DC bus network at their DC terminals. MTDCs have been proposed for off-shore wind farms, underground urban sub-transmission and distribution systems, shipboard power supplies and as the backbone for distributed and renewable generation systems [17]. MTDC VSC-HVDC technology is now commercially available and expected to be widely used [18]. Multiterminal HVDC systems, which have more than two converters connected to a common HVDC system, can have different topologies, such as point to point, general ring, and star topologies [18].

However, the MTDC case introduces an extra layer of complexity into an HVDC system. Following a short circuit fault on a multi-terminal system, large currents will flow on all parts of the system from the converter stations to the fault point, potentially reversing the pre-fault current and power flow in some lines. This sudden change of power flow may cause wider problems on the connected AC system as well as the DC system, so it is vital that the faulted zone is deenergised as quickly as possible, without loss of the healthy parts of the system. It is important that protection engineers have a number of options and combinations of protection for MTDC systems, so that they may use the various advantages and eliminate shortcomings of individual methods against each other [19]. Although the study on fault detection and location methods for conventional LCC-HVDC transmission lines has been carried out for years, the research on protecting VSC-HVDC and MTDC systems is still at the starting stage.

Implementation of modern meshed HVDC grids is solely feasible with voltage source converters (VSC) that are subdivided in two-level (2L-VSC), three-level (3L-VSC), and Modular Multilevel Converters (MMC). MMC technology is a new technology of voltage source converter, which has low total harmonic distortion and loss as compared with VSC-HVDC. The MMC can be classified into half-bridge MMC (HBMMC), full-bridge MMC (FBMMC), and clamped double sub-module based MMC (CDSM-MMC). The modular feature of MMC makes it easier to increase the capacity of MMC-HVDC and, since a MMC has many advantages over the other technologies, it is very likely that future HVDC grids are based on this technology [13, 20, 21]. Nevertheless, it has to be noted that 2L-VSC, 3L-VSC, and HBMMC have the same nature during DC side faults, and they require DC CB for clearing the DC fault current [21]. In this regard, the study of MMC-MTDC is mainly in the stage of theoretical analysis and digital simulation. Currently, few studies have been done on the MMC-MTDC system protection strategies under DC faults, while the theoretical research has focused on system modeling simulation and steady-state control strategy [22].

As a result, the protection of these VSC-based HVDC systems, including the detection and location of DC faults, is of utmost concern.

3. DC fault detection and location

Many methods have been proposed in literature but, basically, all DC detection and location methods can be classified in: direct measurement based methods and signal processing based methods. On the one hand, there are several examples in the direct-measurement based methods such as overcurrent protection method, differential current method and distance protection. On the other hand, in the signal processing methods there are several examples such as travelling wave methods and neural network methods [23].

Following, the most relevant methodologies for DC fault detection and location in these systems are briefly presented.

A. High frequency and signal processing. Travelling waves and Wavelet analysis.

At present, most of the currently used fault detection and location techniques in HVDC systems are, in some way, based upon travelling waves and related methods. In case of a fault on the line, the wave of the fault will be travelling from the fault point to the system, along with subsequent reflections from the system to the fault point. These traveling-wave algorithms estimate the fault location based on the time taken by the fault-generated traveling wave to propagate along the line. The accuracy of the traveling-wave-based fault location depends on the accurate detection of the surge arrival time. These traveling-wave-based methods have generally fast response and high accuracy. The results are not easily affected by some factors, such as bus configuration, fault types, fault resistance, ground resistance, loading conditions, and system parameters. However, they also face some insurmountable technical problems (e.g. the detection of the wave-head is very difficult, it is depending on high sampling frequency, it is vulnerable to interference signals, etc.) [24-26]. In fact, the main challenge in traveling wave-based fault location for combined overhead line and underground cable is faulty section identification. This challenge is due to the reflections of the fault signal from the joint-point and the fault point as well as the unequal traveling wave velocities in line and cable [25]. For travelling wave theory based protection strategies, a very high sampling rate is also needed to reduce the error, which not easy to realize [27].

Existing approaches are based on the detection of wave fronts generated by DC fault using wavelet transformation [13]. In this regard, the wavelet analysis is a powerful method of signal analysis well suited to fault generated signals. This method is very helpful to detect abrupt, local changes in a signal (e.g. short time phenomenon such as transient processes, etc.). The necessary and sufficient condition for wavelets is that it must be oscillatory, must decay quickly to zero and must have an average value of zero. An important point is that wavelet analysis does not use a time frequency region, but rather uses a time-scale region. Wavelet analysis is based on decomposition of signals into ‘Scales’ using wavelet prototype function called ‘mother wavelet’. The generated waveforms are analyzed with wavelet analysis to extract sub-band information from the simulated disturbances. The wavelet transform decomposes signals over dilated and translated wavelets [28]. For wavelet transform techniques, a high speed processing unit is needed due to the considerable necessary calculations [27].

This way, several approaches have been proposed since 2008 that try to address the problems related to VSC-HVDC and MTDC systems, offering different solutions that include travelling waves and/or related high-frequency techniques, such as: cross correlation [29], Wavelet Analysis [30-33] (Figure 1), Fast Fourier Transform and Prony algorithm [26], energy thresholds and a decision tree [28], graph theory and mathematical lemmas [34] , etc.

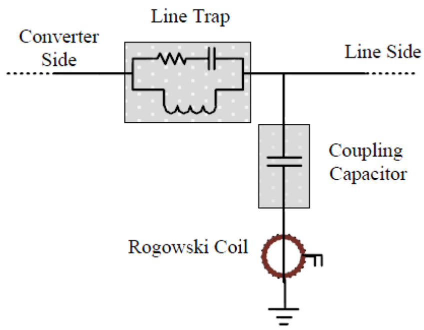

Fig. 1. Travelling wave detection [30]

Furthermore, these methods are usually grouped into different subcategories with respect to the measurements taken in the receiving or sending end: single-ended and multi-ended (synchronized). The single ended principle makes use of the fault induced transient travelling waves and the associated reflected waves to determine the fault location at one line terminal. The double ended travelling wave principle calculates the fault distance using the time difference between the absolute arrival time of fault induced initial surges measured at both terminals of the line. The double ended principle is more reliable than the single ended one as it only makes use of the fault generated initial surges. But it requires two equipments to be installed at both ends of the supervised line, and its accuracy is affected by the errors of the given line length and the synchronization clock system, such as the global positioning system (GPS). The single ended principle is more cost effective to be realized with higher accuracy, but its reliability is not satisfactory due to the complexity of fault reflected surge [35].

B. Current differential protection and related strategies.

Despite current differential protection having been widely used in AC networks, many problems arise when using this concept in HVDC systems (such as distributed capacitance current problem, lack of valid setting principle, etc.), which may prevent the operation speed requirement from being met. Consequently, the traditional differential protection is often used as back-up protection for HVDC transmission lines [36].

In differential current protection, the main principle is to measure the currents at both line ends, so a parallel telecommunication link must be available [13]. The difference between the two measure currents is calculated and compared with a threshold, if the threshold is exceeded, the protection is tripped [23]. If measurements from both ends have to be taken, synchronous current data of both stations could be necessary, along with accurate parameters of HVDC lines, high sampling rate and communication speed [36]. This way, a protection system based on these algorithms is costly as it requires a large number of accurate and fast current and voltage sensors [37]. Besides, the reliability of the entire protection system would depend on telecommunication system's availability, so telecommunication-based DC protection systems may not be desirable due to economic and reliability reasons. Hence, a local detection principle should be preferred [13].

In this regard, whereas some authors propose to use a two-ended differential current algorithm (similar to the one used for AC grid protection) [33] (Figure 2), along with a telecommunication link set up in parallel of each power cable, other authors base their proposals on a novel pilot protection principle for VSC-HVDC cable lines [38], based on fault component current (using only terminal currents and without the need of a serious synchronization). Even in some cases, the importance of the sign in the differential current is highlighted [15], especially when it comes to detect the faulty branch in MTDC grids.

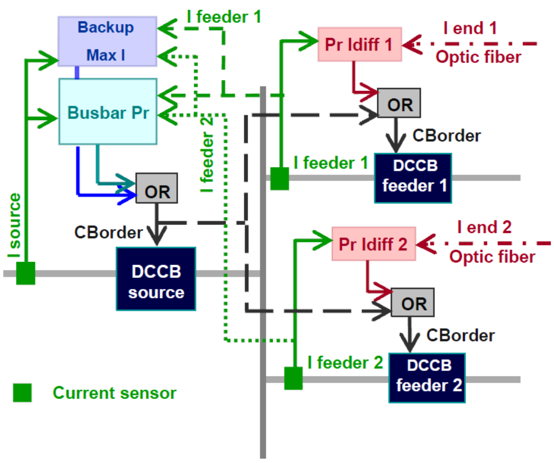

Fig. 2. Differential current protection strategy [33]

C. Artificial Intelligence

Although they have more widely developed for conventional LCC-HVDC systems, artificial intelligence techniques have not been very used when proposing new DC fault detection and location techniques for VSC-based HVDC systems.

Each artificial intelligence techniques have their own advantages and disadvantages. For example, researchers proved that artificial neural networks (ANN) approaches give a satisfactory performance but require large amount of training effort to attain the required results. To eliminate this kind of problem, a simple fuzzy logic based approach is introduced in the application area of HVDC system fault analysis. The basic concept underlying fuzzy logic is that of a linguistic variable, which is a variable whose values are words rather than numbers. Fuzzy logic is a form of many-valued logic and deals with reasoning similar to human reasoning from the ambiguous data (fuzzy data). Fuzzy logic is a rule based approach where a set of rules are used to make the relevant decision. The first stage is a fuzzification, then the application of the rule base and finally the defuzzification [39].

Concerning this type of approaches, the few methodologies that address the DC fault problem in VSC-HVDC systems use ANN combined with a feature extraction system (wavelet analysis, independent component analysis (ICA), etc.) [40, 41] (Figure 3), a fuzzy inference engine [39] or even genetic algorithms [42].

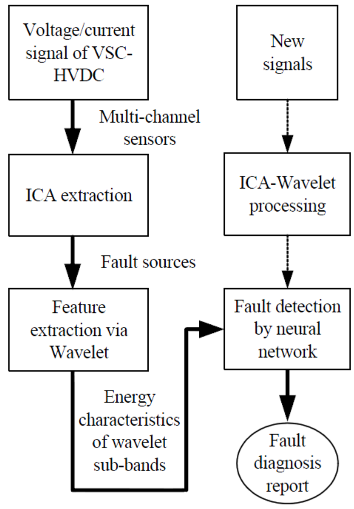

Fig. 3. Workflow diagram of ICA-ANN methodology [41]

D. Electrical measurements and parameters. Other methodologies.

Overcurrent methods use directly the magnitude of the current as indicator that a fault has occurred. Any protection trips if the measured current overcomes certain threshold. However, overcurrent schemes are generally not suitable for DC grids because they offer little selectivity. On the contrary, directional protection can provide more selectivity since its operation depends upon the direction of the fault current, although in DC grids some protections near to the fault may be tripped unnecessarily as well. Distance protection methods estimate the fault distance using the impedance between the fault point and the protection device point. The impedance is obtained using the local sampling data of the voltage and current but, in DC systems, the frequency changes abruptly during fault transients, so no fundamental frequency can be defined. This way, the influence of the frequency may give inaccurate fault distance estimations [23].

In this heterogeneous group of proposals, the so-called “handshaking method” is probably the best known approach [17], without using communication channels and based on local current and voltage measurements. Other methods include an analysis based on an electrical circuit parameter evaluation [3] (Figure 4), an active impedance estimation technique [43] or even a novel distance protection [44], taking into account the frequency-dependent nature of line parameters and the presence of harmonics during transients, in order to enhance the measurement accuracy.

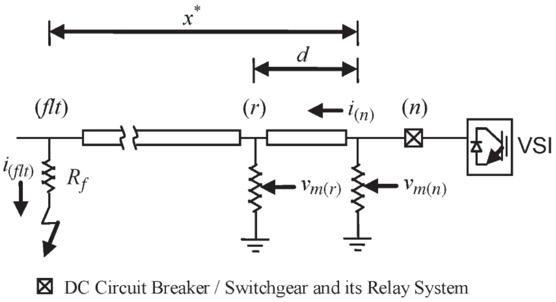

Fig. 4. Distance evaluation with two voltage divider measurements [3]

4. Conclusion

This paper is intended to provide a strong basis for further research in the field of protection of modern HVDC systems, including the development of suitable protection strategies to operate safely and securely, by giving an accurate review of the techniques for DC fault detection and location developed to date.

From this analysis, it can be concluded that the number of proposals to detect and locate DC faults in VSC-HVDC and MTDC systems is still considerably lower than the approaches proposed for the conventional LCC-HVDC systems. Besides, many of the proposals presented to date can only be considered incomplete studies, since they usually lack a rigorous analysis of many of the problems that has to be faced when detecting and locating DC faults in these systems: fast response times, different fault resistances, different fault distances, etc. Few are the cases where the proposed methodologies are thoroughly analyzed and whose results can be directly applicable in this kind of systems.

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