International Journal of Emerging Technology in Computer Science & Electronics (IJETCSE)
ISSN: 0976-1353 Volume 20 Issue 3 – MARCH 2016.

FAULT TOLERANCE SYSTEM FOR HVDC AGAINST COMMUTATION FAILURE

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Abstract— **This project compares how a dc fault affects a multi terminal dc (MTdc) network depending on the HVDC transmission system topology. To this end, a six-step methodology is proposed for the selection of the necessary dc fault protection measures. The network consists of four voltage-source converters radially connected. The converters natural fault response to a dc fault for the different topologies is studied using dynamic simulation models. For clearing of the dc faults, four different dc breaker technologies are compared based on their fault interruption time, together with a current direction fault detection method. If necessary, the converters are reinforced with limiting reactors to decrease the peak value and rate of rise of the fault currents providing sufficient time for the breakers to isolate the fault without interrupting the MTdc network operation. The study shows that the symmetric mono polar topology is least affected by dc contingencies. Considering bipolar topologies, the bipolar with metallic return exhibits better fault response compared to the one with ground return. Topologies with ground or metallic return require full semiconductor or hybrid breakers with reactors to successfully isolate a dc fault.**

***Index Terms*— multi terminal dc (MTdc), voltage-source converters, fault interruption time.**

INTRODUCTION

A high-voltage, direct current (HVDC) electric power transmission system (also called a power super highway or an electrical super highway) uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current (AC) systems. For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses. For underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance each cycle. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may still be justified, due to other benefits of direct current links. HVDC allows power transmission between unsynchronized AC transmission systems. Since the power flow through an HVDC link can be controlled independently of the phase angle between source and load, it can stabilize a network against disturbances due to rapid changes in power. HVDC also allows transfer of power between grid systems running at different frequencies, such as 50 Hz and 60 Hz. This improves the stability and economy of each grid, by allowing exchange of power between incompatible networks.

The modern form of HVDC transmission uses technology developed extensively in the 1930s in Sweden (ASEA) and in Germany. Early commercial installations included one in the Soviet Union in 1951 between Moscow and Kashira, and a 100 kV, 20 MW system between Gotland and mainland Sweden in 1954. The longest HVDC link in the world is the Rio Madeira link in Brazil, which consists of two bipoles of ±600 kV, 3150 MW each, connecting Porto Velho in the state of Rondônia to the São Paulo area. The length of the DC line is 2,375 km (1,476 mi)

I. HV TRANSMISSION

High voltage is used for electric power transmission to reduce the energy lost in the resistance of the wires. For a given quantity of power transmitted, doubling the voltage will deliver the same power at only half the current. Since the power lost as heat in the wires is proportional to the square of the current for a given conductor size, but does not depend on the voltage, doubling the voltage reduces the line losses per unit of electrical power delivered by a factor of 4. While power lost in transmission can also be reduced by increasing the conductor size, larger conductors are heavier and more expensive. High voltage cannot readily be used for lighting or motors, so transmission-level voltages must be reduced for end-use equipment. Transformers are used to change the voltage levels in alternating current (AC) transmission circuits. Because transformers made voltage changes practical, and AC generators were more efficient than those using DC, AC became dominant after the introduction of practical systems of distribution in Europe in 1891 and the conclusion in 1892 of the War of Currents, a competition being fought on many fronts in the US between the DC system of Thomas Edison and the AC system of George Westinghouse. Practical conversion of power between AC and DC became possible with the development of power electronics devices such as mercury-arc valves and, starting in the 1970s, semiconductor devices as thyristors, integrated gate-commutated thyristors (IGCTs), MOS-controlled thyristors (MCTs) and insulated-gate bipolar transistors (IGBT)

II. PRINCIPAL COMPONENT ANALYSIS

A common problem in data processing is that large amounts of data are expensive to *transmit*, *store* or *process*. For transmitting we need high bandwidth, for storing large storage space and for processing we need complex computer systems to reduce the long processing time. To reduce the amount of data, would mean a reduction in expenses. But simply throwing away part of the data would result in a loss of information, which could be important. In so called *random data*, like for example data from classs, sounds or other samples, there is however a difference in how important each part of data is to the information which is stored in the data. By leaving out the part of data which is the least valuable to the information, we reach a reduction of the amount of data. *Principal Components Analysis* (PCA) is used to compress data in such a way that the least information is lost. It does so by truncating data and thereby leaving out the data which is of the least importance to the information stored in the data. This PCA process is called *dimensionality reduction*, because a vector $\bar{x}$ which contains the original data and is N-dimensional is reduced to a compressed vector $\bar{c}$ which is M-dimensional, where M<N. The question that is answered by PCA is: how can we map vector $\bar{x}$ into a vector $\bar{c}$ with a smaller dimension, but where the information contained in $\bar{x}$ is more or less equal to the information stored in $\bar{c}$?

A. Concept of PCA

Principal Component Analysis (PCA) has been proven to be an efficient method in pattern recognition and class analysis, PCA in six steps, Given a random vector $\bar{x}$ of dimension N and its correlation matrix $\bar{\bar{R}}$ we can reduce its dimension to M (with M<N) by Principal Components Analysis :

1. Find the eigenvectors $\bar{\bar{Q}}$ and eigenvalues λ_i of correlation matrix $\bar{\bar{R}}$:

$$\bar{\bar{R}}\,\bar{q}_i = \lambda_i \bar{q}_i$$

2. Arrange the eigenvalues in decreasing order:

$$\lambda_1 > \lambda_2 > .. > \lambda_M > .. > \lambda_N$$

3. Pick up the eigenvectors which belong to the first M largest eigenvalues.
4. Calculate compressed vector $\bar{c}$ by $c_i = \bar{x}^T \bar{q}_i$ for i = 1, .., M
5. Use vector $\bar{c}$ for storage, transmission, process, etc.
6. Decode the resulting vector $\bar{c}'$ into N-dimensional vector $\tilde{\bar{x}}'$ using the eigenvector matrix $\bar{\bar{Q}}$.

$$\tilde{\bar{x}}' = \sum_{i=1}^{M} c_i \bar{q}_i$$

B. Generating a Correlation Matrix

To use Principal Components Analysis we need to have a correlation matrix, which defines the similarity between different input vectors. To obtain a correlation matrix $\bar{\bar{R}}$, we construct one by means of observations of different input vectors. We examine for example K different classs for constructing matrix $\bar{\bar{R}}$ for a PCA of classs. We note $\bar{x}^{(k)}$ as being the k-th observed class.

We use the following empirical approximation of $\bar{\bar{R}}$:

$$\tilde{R}_{ij} = \frac{1}{K}\sum_{k=1}^{K} x_i^{(k)} x_j^{(k)}$$

The more observations are made, the better the approximation $\tilde{\bar{\bar{R}}}$ of $\bar{\bar{R}}$ gets. Instead of matrix $\bar{\bar{R}}$ we use matrix $\tilde{\bar{\bar{R}}}$ in the PCA calculations.

C. Kernel Method

To determine the eigenvectors of correlation matrix $\bar{\bar{R}}$, we have to construct the matrix $\bar{\bar{R}}$ by calculating the outer product of vector $\bar{x}$. In most applications of PCA, this vector $\bar{x}$ is very large, as it represents the data which is to be compressed. The complexity of the calculations are high, namely $O(N^3)$. There is a way in which we can reduce this complexity to $O(K^3)$, where K is much smaller than N, when we use the limited number of observations of vectors $\bar{x}$ to construct the needed eigenvectors for PCA.

III. Inference Analysis

A. The Conversion Process

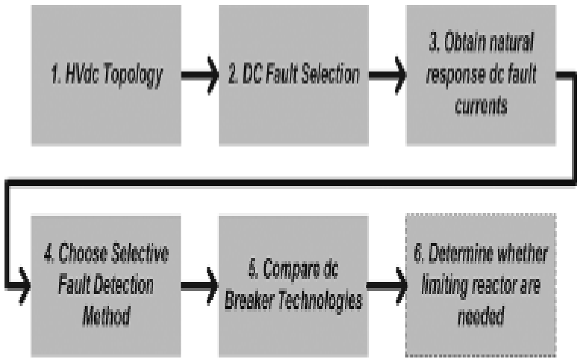
At the heart of an HVDC converter station, the equipment which performs the conversion between AC and DC is referred to as the converter. Almost all HVDC converters are inherently capable of converting from AC to DC (rectification) and from DC to AC (inversion), although in many HVDC systems, the system as a whole is optimised for power flow in only one direction. Irrespective of how the converter itself is designed, the station which is operating (at a given time) with power flow from AC to DC is referred to as the rectifier and the station which is operating with power flow from DC to AC is referred to as the inverter. Early HVDC systems used electromechanical conversion (the Thury system) but all HVDC systems built since the 1940s have used electronic (static) converters. Electronic converters for HVDC are divided into two main categories:

i. Line-commutated converters

Most of the HVDC systems in operation today are based on line-commutated converters. The basic LCC configuration uses a three-phase bridge rectifier or six-pulse bridge, containing six electronic switches, each connecting one of the three phases to one of the two DC rails. A complete switching element is usually referred to as a valve, irrespective of its construction. However, with a phase change only every 60°, considerable harmonic distortion is produced at both the DC and AC terminals when this arrangement is used. An enhancement of this arrangement uses 12 valves in a twelve-pulse bridge. The AC is split into two separate three phase supplies before transformation. One of the sets of supplies is then configured to have a star (wye) secondary, the other a delta secondary, establishing a 30° phase difference between the two sets of three phases. With twelve valves connecting each of the two sets of three phases to the two DC rails, there is a phase change every 30°, and harmonics are considerably reduced. For this reason the twelve-pulse system has become standard on most line-commutated converter HVDC systems built since the 1970s. With line commutated converters, the converter has only one degree of freedom – the firing angle, which represents the time delay between the voltage across a valve becoming positive (at which point the valve would start to conduct if it were made from diodes) and the thyristors being turned on. The DC output voltage of the converter steadily becomes less positive as the firing angle is increased: firing angles of up to 90° correspond to rectification and result in positive DC voltages, while firing angles above 90° correspond to inversion and result in negative DC voltages. The practical upper limit for the firing angle is about 150–160° because above this, the valve would have insufficient turn-off time. Early LCC systems used mercury-arc valves, which were rugged but required high maintenance. Because of this, many mercury-arc HVDC systems were built with bypass switchgear across each six-pulse bridge so that the HVDC scheme could be operated in six-pulse mode for short periods of maintenance. The last mercury arc system was shut down in 2012. In a line-commutated converter, the DC current (usually) cannot change direction; it flows through a large inductance and can be considered almost constant. On the AC side, the converter behaves approximately as a current source, injecting both grid-frequency and harmonic currents into the AC network. For this reason, a line commutated converter for HVDC is also considered as a current-source inverter.

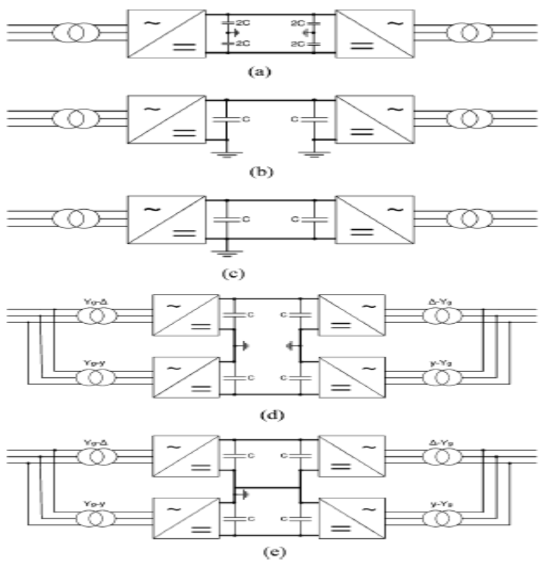
ii. Voltage-sourced converters

Because thyristors can only be turned on (not off) by control action, the control system has only one degree of freedom – when to turn on the thyristor. This is an important limitation in some circumstances. With some other types of semiconductor device such as the insulated-gate bipolar transistor (IGBT), both turn-on and turn-off can be controlled, giving a second degree of freedom. As a result, they can be used to make self-commutated converters. In such converters, the polarity of DC voltage is usually fixed and the DC voltage, being smoothed by a large capacitance, can be considered constant. For this reason, an HVDC converter using IGBTs is usually referred to as a voltage sourced converter. The additional controllability gives many advantages, notably the ability to switch the IGBTs on and off many times per cycle in order to improve the harmonic performance. Being self-commutated, the converter no longer relies on synchronous machines in the AC system for its operation. A voltage sourced converter can therefore feed power to an AC network consisting only of passive loads, something which is impossible with LCC HVDC.HVDC systems based on voltage sourced converters normally use the six-pulse connection because the converter produces much less harmonic distortion than a comparable LCC and the twelve-pulse connection is unnecessary. Most of the VSC HVDC systems built until 2012 were based on the two level converter, which can be thought of as a six pulse bridge in which the thyristors have been replaced by IGBTs with inverse-parallel diodes, and the DC smoothing reactors have been replaced by DC smoothing capacitors. Such converters derive their name from the discrete, two voltage levels at the AC output of each phase that correspond to the electrical potentials of the positive and negative DC terminals. Pulse-width modulation (PWM) is usually used to improve the harmonic distortion of the converter. Some HVDC systems have been built with three level converters, but today most new VSC HVDC systems are being built with some form of multi-level converter, most commonly the Modular Multi-Level Converter (MMC), in which each valve consists of a number of independent converter submodules, each containing its own storage capacitor. The IGBTs in each submodule either bypass the capacitor or connect it into the circuit, allowing the valve to synthesize a stepped voltage with very low levels of harmonic distortion Although at HVDC converter stations connected directly to power stations some of the reactive power may be provided by the generators themselves, in most cases the reactive power consumed by the converter must be provided by banks of shunt capacitors connected at the AC terminals of the converter. The shunt capacitors are usually connected directly to the grid voltage but in some cases may be connected to a lower voltage via a tertiary winding on the converter transformer.



IV. OPERATIONAL ANALYSIS

The following different architecture of HVDC system has been considered in our work



A. *Monopole*

In a common configuration, called monopole, one of the terminals of the rectifier is connected to earth ground. The other terminal, at a potential high above or below ground, is connected to a transmission line. The earthed terminal may be connected to the corresponding connection at the inverting station by means of a second conductor

.

B. Monopole and Earth return

If no metallic conductor is installed, current flows in the earth and/or sea between two specially designed earth electrodes. This arrangement is a type of single wire earth return system. The electrodes are usually located some tens of kilometres from the stations and are connected to the stations via a medium-voltage electrode line. The design of the electrodes themselves depends on whether they are located on land, on the shore or at sea. For the monopolar configuration with earth return, the earth current flow is unidirectional, which means that the design of one of the electrodes (the cathode) can be relatively simple, although the design of anode electrode is quite complex. For long-distance transmission, earth return can be considerably cheaper than alternatives using a dedicated neutral conductor, but it can lead to problems such as: Electrochemical corrosion of long buried metal objects such as pipelines. Underwater earth-return electrodes in seawater may produce chlorine or otherwise affect water chemistry. An unbalanced current path may result in a net magnetic field, which can affect magnetic navigational compasses for ships passing over an underwater cable.

C. Monopole and Metallic return

These effects can be eliminated with installation of a metallic return conductor between the two ends of the monopolar transmission line. Since one terminal of the converters is connected to earth, the return conductor need not be insulated for the full transmission voltage which makes it less costly than the high-voltage conductor. The decision of whether or not to use a metallic return conductor is based upon economic, technical and environmental factors. Modern monopolar systems for pure overhead lines carry typically 1.5 GW. If underground or underwater cables are used, the typical value is 600 MW. Most monopolar systems are designed for future bipolar expansion. Transmission line towers may be designed to carry two conductors, even if only one is used initially for the monopole transmission system. The second conductor is either unused, used as electrode line or connected in parallel with the other (as in case of Baltic Cable).

D. Symmetric Monopole

An alternative is to use two high-voltage conductors, operating at ± half of the DC voltage, with only a single converter at each end. In this arrangement, known as the symmetrical monopole, the converters are earthed only via a high impedance and there is no earth current. The symmetrical monopole arrangement is uncommon with line-commutated converters (the NorNed interconnection being a rare example) but is very common with Voltage Sourced Converters when cables are used.

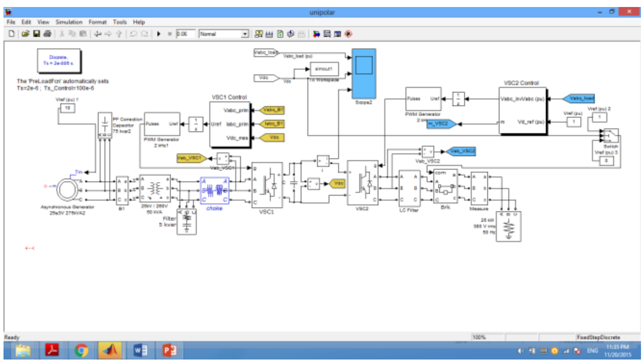
E. Bipolar

In bipolar transmission a pair of conductors is used, each at a high potential with respect to ground, in opposite polarity. Since these conductors must be insulated for the full voltage, transmission line cost is higher than a monopole with a return conductor. However, there are a number of advantages to bipolar transmission which can make it an attractive option. Under normal load, negligible earth-current flows, as in the case of monopolar transmission with a metallic earth-return. This reduces earth return loss and environmental effects.When a fault develops in a line, with earth return electrodes installed at each end of the line, approximately half the rated power can continue to flow using the earth as a return path, operating in monopolar mode. Since for a given total power rating each conductor of a bipolar line carries only half the current of monopolar lines, the cost of the second conductor is reduced compared to a monopolar line of the same rating.In very adverse terrain, the second conductor may be carried on an independent set of transmission towers, so that some power may continue to be transmitted even if one line is damaged.A bipolar system may also be installed with a metallic earth return conductor. Bipolar systems may carry as much as 4 GW at voltages of ±660 kV with a single converter per pole, as on the Ningdong–Shandong project in China. With a power rating of 2000 MW per twelve-pulse converter, the converters for that project were (as of 2010) the most powerful HVDC converters ever built. Even higher powers can be achieved by connecting two or more twelve-pulse converters in series in each pole, as is used in the ±800 kV Xiangjiaba–Shanghai project in China, which uses two twelve-pulse converter bridges in each pole, each rated at 400 kV DC and 1600 MW.

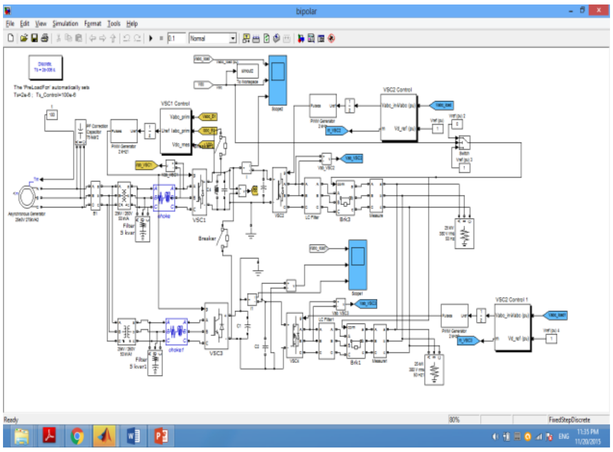
V. Simulation Results

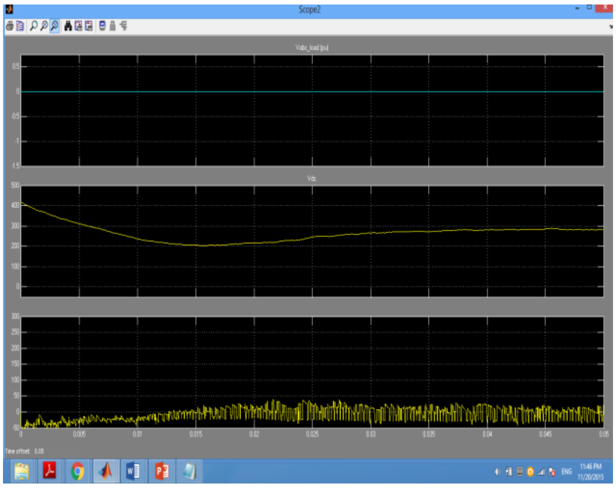
Line commutated converter based high voltage direct current (LCC-HVDC) has been wildly applied in many areas, such as asynchronous ac grid connection, long distance bulk power transmission, etc.. However, if the short circuit ratio (SCR) of ac network is low, the LCC-HVDC system would have poor voltage regulation ability and be susceptible to commutation failures (CFs). The CFs issues can be alleviated by synchronous condenser (SC), static synchronous compensators (STATCOM) or Voltage source Converter based HVDC (VSC-HVDC), all of that can supply the dynamic reactive power for LCC-HVDC. However, more extra capital costs are required for additional apparatus to CFs mitigation.

A. Unipolar

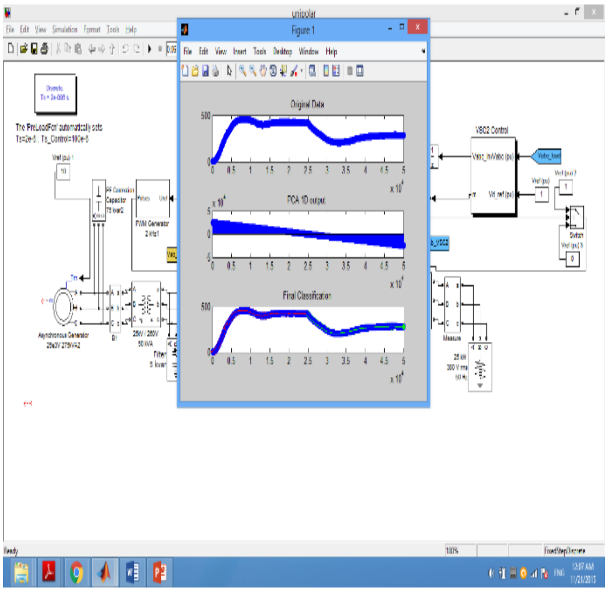


B. Bipolar

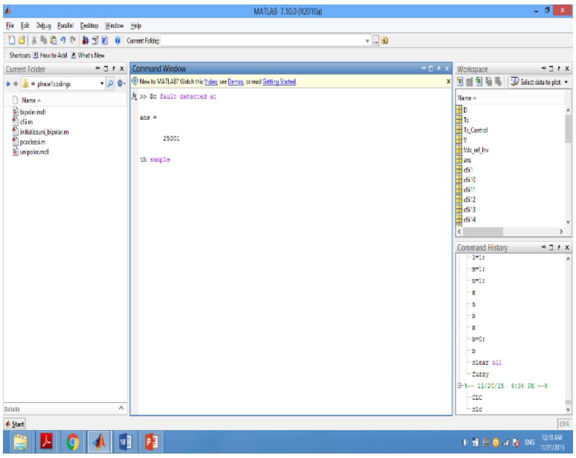




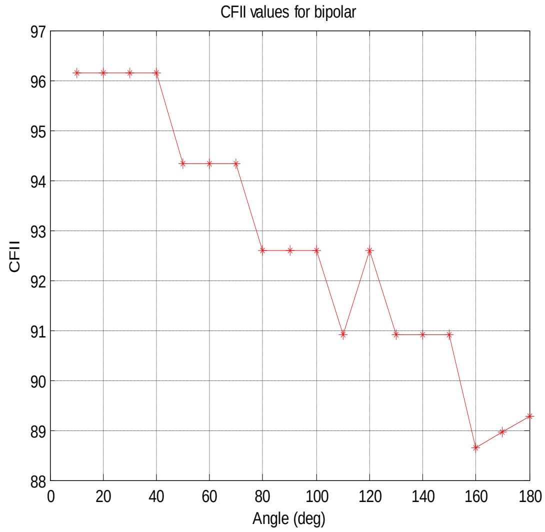
C. *PCA Outputs*



Command window detecting the fault and timing



D. *CFII Values*



The CFII index is adopted here to evaluate the susceptibility of LCC converter to CFs and it is defined as in equation The CFII is determined by conducting a sequence of EMT simulations, each with an inductive fault applied to the converter bus. The *Critical Fault MVA* is the strength of the most severe fault that the tested system can survive without experiencing any CFs. *Pd* is the dc power of the converter. The larger CFII value represents stronger immunity of LCC inverter to CFs

$$CFII = \frac{Critical\ Fault\ MVA}{P_d} \cdot 100\ (\%)$$

VI. CONCLUSION & FUTURE WORK

A methodology has been proposed to compare different VSCHVDC topologies with regard to faults on MTDC networks. The proposed methodology consists of six steps which are carried out based on results from a dynamic simulation model of the complete system. Among all analyzed topologies, the symmetric monopolar has the best fault response, especially in combination with at least 50-mH reactors. If the power to be transmitted in the dc network requires the use of bipolar topologies, the bipolar topology with metallic return, although it has higher capital installation costs, has superior performance with regard to dc faults than the one with ground return. In conclusion, a successful fault isolation in topologies with ground or metallic return requires solid-state breakers or Hybrid I breakers with reactors higher than 50 mH or 100 mH, respectively. Since the breakers' interruption time is somewhat uncertain, sensitivity analysis can be performed using the proposed methodology. The other two breaker technologies—the Hybrid II and the resonant breakers—are not yet fast enough to handle dc contingencies for these grid topologies. The value of CFII found in our proposed method is very compromising. This system is more advantageous where, the DC source is kept at a distance. Online tracking is possible, and hence source damage is avoided. Presently the fault have been detected only at the commutator side and the DC capacitor faults. There could be a still more implementation to solve both DC and AC tolerant systems. The control algorithms can be programmed via an ASIC (application specific integrated circuit) to implement a hardware part of the same. Breakers connected to ethernet would be highly useful for online tracking and instantaneous decision making based on the faults occurred.

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