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Page Numbers:- 65 - 71

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Directional Protection Scheme for HVDC Transmission Lines

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Abstract:

With the rapid development of power systems, high-voltage direct current (HVDC) transmission technology is playing an increasingly significant role in recent years. This paper proposes a HVDC transmission line backup protection scheme based on the reactive energy measurement in HVDC system. Normal operating condition HVDC transmission systems mostly transmit active power, whereas the reactive power flow on the DC transmission line is nearly zero except for some small harmonic components. The quantity of the harmonic reactive power on the DC line depends on the filtering effects of the DC filters and the smoothing reactors. The directional characteristics of reactive power flow are theoretically analyzed for internal and external faults and these characteristics will be used to construct a directional protection scheme. The Hilbert transform is used to calculate the reactive power. A bipolar 12-pulse HVDC test system based on the CIGRE benchmark model is design using MATLAB/SIMULINK, and extensive simulations of various fault situations are verified to test the effectiveness of the proposed scheme.

Keywords: HVDC system, Hilbert Transform, Directional protection

I. INTRODUCTION

With advancement in power systems, HVDC transmission technology is more efficient for long distance power transmission comparing with HVAC transmission. Asynchronous power grid interconnections and renewable energy integration due to its flexible power control and large power transmission capacity [1]-[2]. Among the numerous techniques concerning HVDC, DC transmission line protection is one of the important unit in HVDC system thus it provides fast fault clearance and guarantees the operation security of the entire HVDC transmission system. In HVDC transmission line uses the voltage differential protection in which voltage differential rate to identify the faults takes place on line but this technique not efficient due to its sensitivity to faults resistance and it also not detect high impedance faults. In high-speed travelling wave based protection to transmission line, its performance is easily affected by disturbance which takes place in system. It has low sensitivity in high impedance fault situations. Distance protection is another method to identify the faults take place on line by fault distance calculation. In [4]-[5] the time difference between the initial wave and reflected wave from the fault point is used to calculate the fault distance, but it is difficult to distinguish the reflected wave from the disturbing waves in some cases. However, measurement errors cannot be avoided in this and thus, the protection zone cannot reach the entire length of the DC line. Recently a method boundary protection using single terminal data, detects internal and external faults on the frequency characteristics of one end line component. But the major drawback of these protection methods is that they are not easy to implement practically because of the requirement of very high frequency sampling rate. Transmission line backup protection is useful when primary protection scheme fails to operate. There are different backup protection techniques which are used to protect system from abnormal condition. For backup protection, DC minimum voltage protection is majorly used in practice because of the simplicity of operation, but it has no selectivity between AC system faults and DC line faults. Current differential protection [8] is also another approach for HVDC transmission line backup protection. In current differential protection, a time delay is essential to prevent mal-operation of this type of protection under external fault situations, due to fluctuating transient current at the initialization of the fault. In this paper a novel directional backup protection scheme is proposed based on reactive energy for HVDC transmission systems. In this paper reactive energy is utilized to identify different faults take place in HVDC transmission system, reactive-he energy is nothing but the integral of reactive power during a particular time. The Hilbert transform is employed to continuously calculate the reactive energy, and the reactive energy flow directions are applied to identify internal and external faults.

II. PRINCIPLE OF PROTECTION SCHEME

In HVDC systems mostly transmit active power under normal operating condition, but in fault condition the reactive power flow on the DC line due to small harmonic components in systems. The quantity of the harmonic reactive power on the DC line depends on DC filters and the smoothing reactors which used. The total quantities of the harmonic voltage and current are typically less than 5% to 10% of the rated values. When DC line fault occurs, the voltage and current at the terminals of the DC line will contain a transient component due to the inductive and capacitive components in the system, thus resulting in significant reactive power flows on the DC line. In traditional HVDC systems, shunt capacitor banks are commonly used for compensating the reactive power which the converters consume due to sudden change in firing angle. Reactive power control is designed to maintain the reactive power balance by switching the capacitor banks. The consumption of reactive power can only be changed in steps by switching in or out of the capacitor banks. This discrete kind of control needs to be blocked during the transient process to avoid frequent switch operations. Thus the reactive power is considered to be uncontrolled during the fault period, and it is primarily affected by the characteristics of the system components. The uncontrolled reactive power flows from source to the fault point during the fault transient condition. So the reactive power has different directions in internal and external fault situations.
According to the above analysis in HVDC system, the reactive power on the DC line can be utilized to find out the different faults on HVDC system such as internal and external faults.

A. Reactive Energy Measurement

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The Hilbert transform is useful signal processing method for determine instantaneous attributes of time series, especially the amplitude and frequency. It is used to calculate the reactive power [6]-[7], which is defined as the convolution of $x(t)$ with the function $h(t)$

It can be proven that from the integration of the defined instantaneous reactive power during particular time is used to calculate reactive energy. The reactive energy can calculated from sampled voltage and sample current signal, which become generated at the fault condition. In this method of calculating reactive power, not necessary to calculate the discrete Fourier transform of the voltage and current for the magnitudes and angles of all the harmonic components. Furthermore, the proposed method acquires the reactive energy continuously in real time, which accelerates the operation of the protection system. Traditional calculation method requires a complete cycle of the measured data. Therefore, the reactive energy based on the Hilbert transform is used for protection scheme. The most direct approach in solving this task is to implement Hilbert transformation on one of the variables the current or the voltage and after that to multiply the result by the other one. The average value of the product obtained gives the Reactive power. The instantaneous value of the Reactive power for Kth harmonic is calculated easily.

III. HVDC SYSTEM DIAGRAM AND IT'S EQUIVALENT CIRCUIT

A. Block Diagram of HVDC System

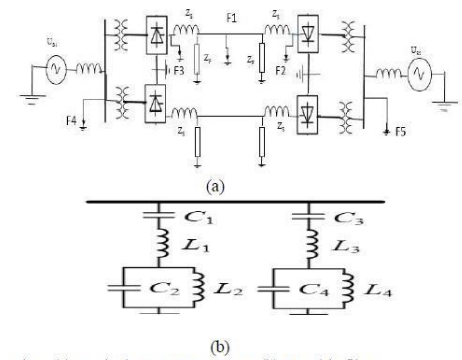

Fig.1 (a) Equivalent HVDC system (b) DC side filter

A bipolar HVDC system based on the CIGRE benchmark is built using MATLAB SIMULINK. The structure of the HVDC system [8]-[9] is shown in Fig.1 DC filters are used for the 12th, 24th and 36th harmonic filtering components. A smoothing reactor in DC side to reduce the harmonic current in DC line and possible transient over current. The sampling frequency of the DC voltage and current is 10 kHz. The HVDC transmission line is connected to AC systems via the converter and converter transformer. According to equivalent circuit, the DC converter with AC system can be modeled using a DC source and an equivalent impedance at the DC transmission system. *UdcR* and *UdcI* are the equivalent DC sources, *ZdcR* and *ZdcI* are the equivalent impedances at the rectifier side and inverter side. *ZS* and *ZF* represent the smoothening reactor and DC filter, respectively. For a bipolar HVDC system, the positive pole and negative pole operate independently. Thus, the equivalent system for the bipolar system can be considered as

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the combination of two monopolar systems.

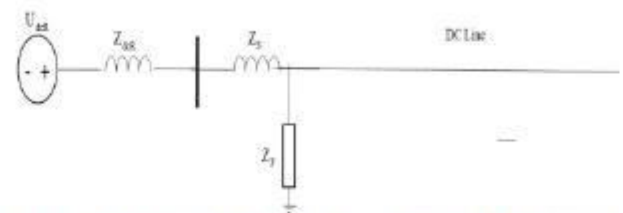


Fig. 2 Equivalent circuit of HVDC transn

IV. PROTECTION SCHEME

A. Fault Direction Identification

Directional protection is used for internal and external fault identification in this scheme. The reference direction of reactive energy is from the rectifier side to the inverter side. If the reactive energies of each side have different directions, an internal fault is identified. Otherwise, an external fault is detected. Thus, the fault direction identification criteria can be expressed as

Where are the reactive energies measured at the rectifier side and inverter side, respectively.

In a monopolar HVDC system, single pole reactive energy is used for direction identification, whereas in a bipolar system, the sum of the reactive energies at the two poles is used.

B. Startup Component

A protection startup component is introduced to ensure the reliability of the protection scheme in case of disturbances. Once the startup requirement is satisfied, the protection scheme is triggered to start the calculation process. In this

study, the DC voltage differential du/dt or current differential di/dt is used as the startup component.

C. Time Delay

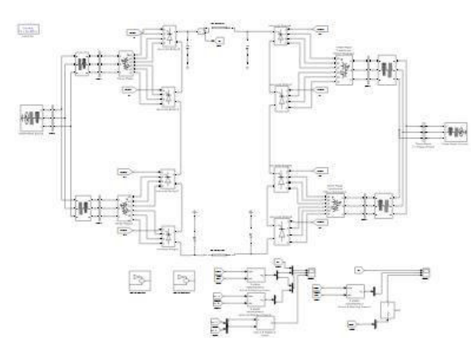
Frequent energy exchange due the inductive and capacitive components at the beginning of the fault so the reactive energy varies between positive and negative values, which results in fluctuate directions during this period. So time delay is required to prevent this fluctuating nature of reactive energy direction.

D. Threshold Setting

A threshold for the reactive energy is necessary to prevent mal-operation during disturbances. When the calculated reactive energy is larger than the threshold, the fault direction identification module is activated.

E. Fault Pole identification

In a bipolar HVDC transmission system, fault pole selection is required for the protection scheme in single pole to ground faults to isolate the faulty pole and maintain continuous operation of system through healthy pole. Due to the mutual coupling effect of the two poles, the healthy pole may also generate reactive energy during a single-pole to ground fault. However, this reactive energy is considerably smaller than that in the faulty pole. By which three types of faults can be classified. When $k \leq 1/kset$, the fault pole is determined as the negative pole, whereas a positive pole fault results when $k \geq kset$ where $kset$ is the setting threshold of the pole selection coefficient. The fault is considered a bipolar fault when $1/kset < k < kset$. Where k is the ratio of reactive energy at positive pole and reactive energy at negative pole.



F. Flow Diagram

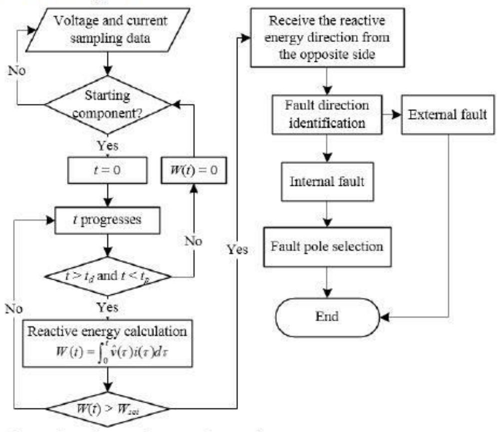


Fig.5 Flowchart of protection scheme

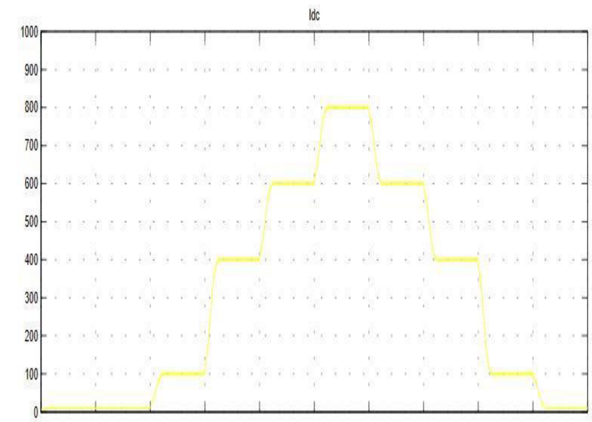
The integrated flow diagram of the protection scheme is shown in Fig. 5. When the startup condition is satisfied. As time progresses *t* is incremented. When the time delay is satisfied, the protection scheme begins to calculate the reactive energy. When *t* exceeds the protection time *tp*, the reactive energy index is reset to 0, and the protection algorithm waits for the next startup. If the calculated reactive energy is larger than the setting threshold value of reactive energy, an internal or external fault can be identified according to the reactive energy direction information from the other side. Finally, the faulty pole is selected in the internal fault situation by measuring the reactive energy on both pole.

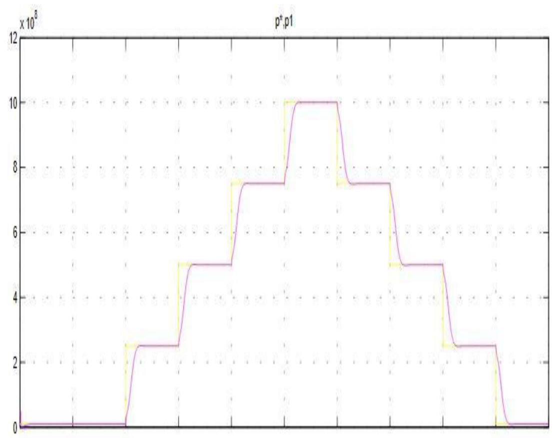
V. SIMULATION RESULTS

Different fault and disturbance situations in HVDC transmission system are simulated to test the effectiveness of the proposed protection scheme according to fig 1 (a). The protection setting parameters are set as follows. The reliability coefficient *kr* is set to 1.5, and the proportion coefficient of the harmonic components *khar* is 0.05. The delay time *td* is set which equals specific AC frequency cycles and the reactive energy threshold is calculated as depends on the line parameter.

A. DC Internal Faults

DC transmission line fault is located at F1 in Fig. 1(a), and a positive pole fault is simulated. The fault occur at middle of DC transmission line.





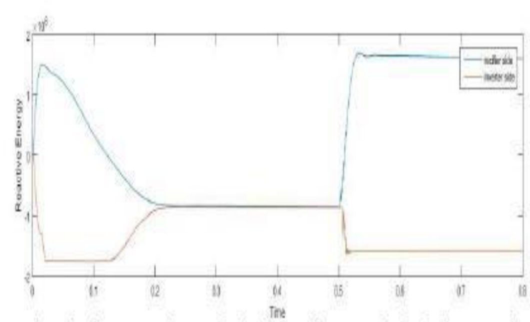


Fig. 6 Simulation results of dc line (internal faults) reactive energy

The reactive energies at both sides during the line fault are shown in Fig. 6. The fault occurs at 0.5s, and the calculated reactive

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energies of both sides exceed immediately. The directions of the reactive energies from two sides are opposite, as previously analyzed. A negative pole fault and bipolar fault of HVDC system can also be simulated. The results show that the proposed protection is adaptive for internal fault types.

B. DC External Faults

When fault takes place at F2 and F3 as shown Fig. 1(a) at one end of DC transmission line means external faults. This are simulated and simulation results of both sides are displayed in Fig. 7 and 8. The reactive energies in network are both positive when the faults occurs at the inverter end, whereas they are both negative when the rectifier side fault take place. Thus, the directions of the reactive energies flow having same when faults takes place at any end of line means rectifier end of line as well as inverter end of line in HVDC system.

VI. CONCLUSION

In this paper a novel protection scheme is proposed based on reactive energy flow in HVDC transmission line. The reactive energy is measured using a Hilbert transform. The equivalent circuit of the HVDC system are used to analyze theoretically to construct the direction protection. The analysis of reactive energy is carried out and applied to develop a protection scheme. The simulated results shows that this protection scheme is fast, accurate and effective. The proposed protection scheme is verified using rectifier, inverter end faults and internal fault. The proposed scheme correctly identifies external and internal faults.

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