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Pole Voltage Balancing in HVDC Systems: Analysis and Technology Options

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Abstract—Maintaining balanced voltage during normal operation and rebalancing pole voltages after a pole-to-ground fault are both necessary to prevent high insulation stresses on the DC cable in a HVDC system. The state-of-the-art solution requires two separate devices to deal with normal and post-fault operation separately. This paper proposes pole rebalancing solutions using a single device applicable to both normal and post-fault operations, thus leading to reduced cost and footprint for pole rebalancing. The proposed circuits use fast switches to dynamically adapt the connected impedance in order to fulfil the requirements for rebalancing voltages during both situations. The performance of the proposed circuits are verified in a four-terminal HVDC test network using EMTP simulations.

Index Terms—HVDC grid protection, symmetrical monopole, pole rebalancing, dynamic braking system, AC side grounding.

I. INTRODUCTION

Growing energy demands and increasing concern over climate change require flexible and reliable grids to cope with an increased penetration of renewable energy and an increased exchanging of power between remote areas. Voltage source converter (VSC) based high voltage direct current (HVDC) has become one of the key enabling technologies to fulfil such requirements due to its flexible control and simplicity in forming meshed HVDC grids [1]. The demand for higher power capability and lower losses has lead to the development of modular multilevel converter (MMC) technology, replacing two-level converter technology [1].

HVDC systems typically take one of the three following configurations: asymmetrical monopolar, symmetrical monopolar or bipolar configuration. The majority of the VSC HVDC point-to-point links are built with a symmetrical monopolar configuration to reduce the DC stress on the interface transformers. The symmetrical monopolar configuration is likely to be one of options for the future HVDC grids as European TSOs are already planning to connect the existing point-to-point HVDC links to form HVDC grids [2].

One of the challenges in HVDC grids with a symmetrical monopolar configuration is to maintain balanced pole voltages, since unlike bipolar configuration, the symmetrical monopolar converters are unable to independently control the pole currents. Consequently, additional equipment is required to balance the pole voltages. Furthermore, maintaining balanced voltages during normal operation and rebalancing pole voltages after a pole-to-ground fault are both necessary to prevent high insulation stresses on the DC cable. In the

literature, equipment for maintaining balanced pole voltages during normal operation and pole rebalancing equipment after a pole-to-ground DC fault have been proposed [3]–[6]. As the two functions entail different requirements for the equipment, the state-of-the-art solution requires two devices to deal with normal and post-fault operation separately. Using one single device to handle both situations is obviously beneficial as this leads to reduced cost and footprint. However, pole rebalancing equipment suitable for both situations has not been addressed in the literature. This paper proposes pole rebalancing solutions using a single device, and analyses their controls and dimensioning applicable to both normal and post-fault operations.

This paper is structured as follows. Section II elaborates the causes of pole voltage imbalances and outlines the requirements of pole voltage balancing equipment for normal and post-fault operations. Section III proposes both DC and AC side pole voltage balancing equipment, which is applicable to normal and post-fault conditions. A four-terminal test system and its modelling are described in section IV. Section V presents case studies to demonstrate the performance of the proposed pole rebalancing equipment during normal and fault scenarios. Finally, conclusions are given in section VI.

II. CAUSES OF POLE VOLTAGE IMBALANCES AND REQUIRED EQUIPMENT

HVDC pole voltage imbalances can be caused by unbalanced pole-to-ground impedances during normal operation, or a pole-to-ground fault on one of the poles [5]. Pole voltage imbalances caused by unbalanced impedances typically have small magnitudes. In order to achieve symmetrical pole voltages, AC side groundings are currently being used [3], [7]. Fig. 1 gives two examples of such AC side groundings, a star point reactor used with Yd transformer and a neutral grounded Yyd transformer [3], [4], [8]. The neutral of the Yyd transformer is typically high impedance grounded with a surge arrester, inductor or resistor [7]. These AC side groundings has to provide a low impedance path to the ground for DC current, while a high impedance for AC current. The on-state power consumption of these AC side groundings has to be negligible as they are constantly connected to the system.

Another cause of pole voltage imbalances is a pole-to-ground fault, which, without countermeasures, leads to persistent voltages of 0 pu and 2 pu on the faulted and healthy pole, respectively. Both DC and AC side equipment have

Fig. 1. Examples of AC side groundings for maintaining balanced pole voltages during normal operation. (a) Star point reactor. (b) Neutral grounded Yd transformer.

been proposed for pole rebalancing, including a dynamic braking systems (DBS), a Yd transformer with a star point reactor or zig-zag transformer, and a neutral grounded Yd transformer [6], [9], [10]. The time constraint for rebalancing the pole voltages is imposed by both the AC systems and the DC-side components. This time limit is typically in the range of 100 ms in a fully selective protection strategy using DC circuit breakers (DCCB). To rebalance the pole voltages with such speed, the impedance of the pole rebalancing equipment needs to be much smaller when compared to those AC side groundings used for normal operation. Given a fixed DC network topology, the energy needs to be dissipated by the pole rebalancing equipment is primarily influenced by the opening speed of the DCCBs. The longer the breaker opening time, the higher the required energy absorption capability. In addition, the pole rebalancing equipment should preferably only be connected after fault clearing to avoid on-state power consumption and unwanted fault current contribution. In such cases, the switching devices need to be dimensioned properly to withstand the switching transients [6].

III. POLE REBALANCING EQUIPMENT FOR NORMAL AND POST-FAULT OPERATION

The main difference between the pole balancing equipment during normal operation and post-fault condition concerns the dimensioning of the impedance. Using fast switches, however, it is possible to dynamically adapt the impedance for both situations. The proposed pole balancing circuits are shown in Fig. 2. The design principles for these circuits are the followings. (1) The total impedance of the circuit should be large enough to have negligible power consumption during normal operation. (2) The switching devices are used to adapt the connected impedance during normal or post-fault operation. The connected impedance should be designed appropriately to fulfil the trade-off between avoiding excessive current and achieving fast pole rebalancing speed. (3) The switching devices are controlled by monitoring the pole voltages or pole voltage imbalances and fault clearing. Applicable switching technologies are IGBT-based power electronic switches or fast making switches such as thyristor-based switches or high speed mechanical making switches [11]–[13].

A. Equipment Dimension

1) *Dynamic Braking System (Fig. 2 (a))*: During normal operation, both S_{D1} and S_{D2} are open. The insulation level

Fig. 2. Proposed pole rebalancing circuits for both normal and post-fault operations.

of the combined surge arresters ($\sum_{i=1,3} SA_i$) should be the same as the insulation level of the DC busbar, which is typically selected as 1.5 to 1.8 pu of the rated pole-to-ground voltage [14]. To balance the pole voltages after a pole-to-ground fault, S_{D2} of the healthy pole is closed. The insulation level of the sum of SA_1 and SA_2 should be in the range of 1.15 pu~1.2 pu [10]. To balance the pole voltages due to small deviations, both S_{D1} and S_{D2} of the pole with overvoltage are closed. The insulation level of SA_1 should be in the range of 1 pu~1.1 pu to allow for adequate but not excessive current in the DBS.

2) *AC Side Groundings (Fig. 2 (b) and (c))*: The switches S_{S1} and S_{S2} of the star point reactor (Fig. 2 (b)) are in the open position during normal operation. The dimension of the star point reactor should behave as a high impedance for AC and a low impedance for DC current [4]. This requirement should lead to negligible power consumption during normal operation. On the contrary, L_{n1} and R_{n1} are considerably smaller than the total impedance to allow for fast pole rebalancing during post-fault situation [6].

Similar principles as the star point reactor apply when dimensioning the neutral grounding resistor of the Yd transformer (Fig. 2 (c)). The total resistance of R_{g1} and R_{g2} should be in the $k\Omega$ range, whereas R_{g1} is in the order of a few hundred Ohms [6].

B. Control and Operation

The proposed DBS controller (Fig. 3 (a)) uses the fault detection signal to distinguish between a normal and post-fault operation. The DBS operation is initiated by monitoring the pole voltage imbalance during normal operation. Once the pole voltage imbalance exceeds the allowed voltage limit, S_{D1} and S_{D2} are closed to discharge the pole under higher voltage. Similarly, if a pole-to-ground fault is detected and the pole voltage exceeds the allowed limits, S_{D2} is closed to discharge the healthy pole. To avoid adverse interactions between the DBS and the DCCBs, the DBS operation is delayed based on the DBS controller proposed in [6].

When experiencing unbalanced pole voltages during normal operation, zero-sequence current will flow in the AC side groundings without any control or switching action. During

Fig. 3. Proposed pole rebalancing controllers for (a) DBS (b) AC side groundings.

a pole-to-ground fault, however, the switches S_{S1} , S_{S2} or S_Y are controlled similar to those of the DBS (Fig. 3 (b)).

IV. TEST SYSTEM DESCRIPTION AND MODELLING

A four-terminal test system is developed to demonstrate the performance of the proposed pole balancing circuits, based on the test system used in [6].

Fig. 4. A four-terminal symmetrical monopolar test system.

A. Converter Model

The converters are modelled with an averaged equivalent model, where individual submodule switching states and capacitor voltages are aggregated as one voltage source per arm [15]. During normal operation, MMC2 and MMC4 are operating in active power control mode, exporting 1200 MW and 600 MW, respectively. MMC1 and MMC3 are operating in voltage power droop control mode, importing 600 MW and 1200 MW, respectively. The main parameters of the converter station are listed in Table I.

B. Pole Rebalancing Equipment and Controller Parameters

The pole rebalancing circuits are implemented at the two onshore stations: MMC1 and MMC3. For each study, only one of the options, DBS, star point reactor or Yyd transformer is activated. The parameters of the pole rebalancing circuits and controllers are listed in Table II. Typical values are used for the switching impulse protection levels (SIPL) of the surge arresters, which should be studied in insulation coordination study based on main circuit and converter control & protection parameters in practical applications. The start point reactor and neutral grounding resistor of the Yyd transformer are dimensioned to have negligible power consumption level during normal operation [6].

TABLE I
CONVERTER AND GRID PARAMETERS

Parameters	Value	Unit
Rated apparent/active power S/P_{DC}	1265/1200	[MVA/MW]
Rated DC voltage U_{DCp}, U_{DCn}	± 320	[kV]
Rated transformer voltages	400/333	[kV]
Transformer leakage impedance	0.18	pu
Arm capacitance C_{arm}	22	[μF]
Arm inductance L_{arm}	42	[mH]
Arm resistance R_{arm}	0.6244	[Ω]
Converter DC smoothing reactor L_{DC}	10	[mH]
Line inductor L_{line}	50	[mH]

TABLE II
MAIN PARAMETERS OF THE CONTROLLERS AND POLE REBALANCING EQUIPMENT

Parameters	Symbol	Value	Unit
Hysteresis	HI_1/LO_1	0.02/0.0	[pu]
	HI_2/LO_2	1.1/1.05	[pu]
Surge arrester SIPL	SA_1	1.0	[pu]
	SA_2	0.2	[pu]
	SA_3	0.6	[pu]
Star point reactor impedances	L_{n1}/L_{n2}	50/1046	[H]
	R_{n1}/R_{n2}	400/1240	[Ω]
Yyd transformer neutral grounding resistance	R_{g1}	220	[Ω]
	R_{g2}	4780	[Ω]

C. DC Grid Protection

A fast non-unit DC line protection algorithm based on [16] is used in this paper for fault detection and identification. The algorithm uses undervoltage, voltage derivative and current direction to identify the faulted cable. Detailed description of the non-unit algorithms can be found in [16]. The breaker opening time and the series inductor are 20 ms and 50 mH, taken from [6].

V. POLE REBALANCING EQUIPMENT PERFORMANCE

A. Pole Voltage Balancing During Normal Operation

The voltage imbalance during normal operation is simulated by connecting a high pole-to-ground impedance to the positive pole of line L_{13} [5]. Both temporary impedance imbalance on a overhead line and permanent impedance imbalance on a cable are studied to evaluate the pole balancing circuits. The high impedance is disconnected when operating the pole balancing equipment if the voltage imbalance is temporary on a overhead line. The pole rebalancing circuits are enabled at 0 s in the simulation.

Before operating the pole rebalancing equipment, the voltage imbalances of the temporary case on a overhead line and permanent case on a cable are 10.1 kV and 6.8 kV, respectively. The negative pole current i_{13n} and voltage u_{bus1n} are plotted with absolute value to easily compare the voltage imbalances in Fig. 5 – 7.

1) *DBS*: Once the DBSes (Fig. 2 (a)) are enabled, the pole voltages are rebalanced almost immediately for both a temporary and permanent voltage imbalance (Fig. 5). However, for a permanent voltage imbalance, the pole voltages slowly drift back to an imbalance after rebalancing, resulting in repeated DBS operation until the permanent imbalance source, such as cable degradation, is identified and removed (Fig. 5 (c2)).

The required energy absorption per operation due to a small voltage imbalance is dependant on the fault location. The DBS at MMC1 and MMC3 absorbs 0.4 MJ and 0.2 MJ per operation, respectively. The required energy absorption capability for a small temporary voltage imbalance in normal operation is not significant. However, for a permanent voltage imbalance, the surge arresters have to be dimensioned for long-term repeated operations.

Fig. 5. Pole voltage balancing during normal operation using DBSes.

2) *Star Point Reactor*: The star point reactors (Fig. 2 (b)) take approximately 1 s to rebalance a small voltage imbalance in both temporary and permanent voltage imbalance cases (Fig. 6). The main difference compared to the DBS is that the pole voltages are approximately balanced after the star point reactor operation even for a permanent voltage imbalance on the cable. This is because the star point reactors are always connected and therefore allow a small current to flow between the high impedance and the star point reactors. The steady-state neutral current is approximately 0 A and 0.2 A in the resistor R_{n1} at MMC1 for a temporary and permanent voltage imbalance, respectively.

The required energy absorption capability of the star point reactor for balancing a small voltage imbalance is negligible. However, the star point reactor needs to be designed for a small steady-state DC current in the case of permanent voltage imbalances.

Fig. 6. Pole voltage balancing during normal operation using star point reactors.

3) *Neutral Grounded Yyd Transformer*: The performance of the neutral grounded Yyd transformer (Fig. 2 (c)), in terms of the speed and required energy absorption capability, is equivalent to the star point reactor (Fig. 7). The steady-state averaged neutral current is similar in magnitude to that of the star point reactor, approximately 0.3 A for a permanent voltage imbalance.

Fig. 7. Pole voltage balancing during normal operation using neutral grounded Yyd transformers.

4) *Summary*: All proposed pole rebalancing circuits are capable of rebalancing small pole voltage imbalances caused by pole-to-ground impedance differences. For a temporary voltage imbalance, the DBS and AC side groundings can

achieve pole rebalancing with insignificant requirement on the energy absorption capability of the pole rebalancing circuits. However, for a permanent voltage imbalance, using DBS results in repeated operations and using AC side groundings results in a small steady-state DC current in the AC groundings. Therefore, the DBS is required to be dimensioned for long-term repeated operations; and the AC side groundings are required to allow a small steady-state DC current.

B. Pole Voltage Balancing During Pole-to-Ground Fault

A solid pole-to-ground fault is applied at the terminal of cable L_{13} at 0 s in the simulation. After fault detection, the line breakers B_{13} and B_{31} are ordered to open with a breaker opening time delay of 20 ms. Once the line breakers are opened and the pole voltage imbalances exceed the hysteresis limits, the switches of the pole rebalancing circuits are ordered to close. The pole rebalancing time after a pole-to-ground fault is defined as the time interval from fault inception to the instant when the pole voltage returns within the normal range ($[0.95 - 1.05]$ pu).

1) *DBS (Fig. 8)*: The switches S_{D1} of the two DBSes are kept open, while S_{D2} at MMC1 and MMC3 are controlled by monitoring buses 1 and 3 voltages, respectively. The DBS current is about a few kA due to the high overvoltage level on the healthy pole. Prior to closing the switch S_{D2} at MMC1, the maximum voltage across the switch is -184 kV, which means that these switches should be dimensioned to withstand such continuous DC voltage. The DBS is able to rebalance the pole voltages in 80 ms. The required total energy absorption capability of the two DBS is approximately 32 MJ.

2) *Star Point Reactor (Fig. 9)*: Both switches S_{S1} and S_{S2} are closed at MMC1 and MMC3 once the line breakers are opened. The maximum transient current in the grounding resistor R_{n1} is 0.2 kA, indicating that, the star point reactor should be designed to withstand one third of such transient current without causing saturation. The voltage insulation requirement of the neutral resistor switch S_{S2} is relatively low, about tens of kV. On the contrary, the switch S_{S1} is required to withstand the pole-to-ground DC voltage superimposed on the converter AC side voltage. The pole rebalancing speed using star point reactors is approximately 150 ms; however, the total required energy absorption capability of the neutral resistors is 2.4 MJ, which is much lower than that of the DBS.

3) *Neutral Grounded Yyd Transformer (Fig. 10)*: The maximum total transient current in the neutral of the Yyd transformer is 1.2 kA partly due to the contribution from the neutral grounding surge arrester SA_g . The voltage insulation requirement of the neutral resistor switch S_Y is determined by the surge arrester SA_g protection level. In this study, the maximum voltage across the switch S_Y is 192 kV. The pole rebalancing speed and the total required energy absorption capability of the neutral grounded Yyd transformer are similar to those of the star point reactor, approximately 140 ms and 8 MJ, respectively.

4) *Summary*: The DBS gives the shortest pole rebalancing time after a pole-to-ground fault compared with the AC side

Fig. 8. Pole voltage balancing during a pole-to-ground fault using DBS.

groundings. However, the required energy absorption capability is one order of magnitude higher compared with the AC side groundings. The two AC side groundings give similar performance in terms of pole rebalancing speed and required energy absorption capability.

VI. CONCLUSIONS

This paper proposed pole rebalancing circuits capable of rebalancing pole voltages under both normal and post-fault operations. The proposed DBS circuit has the best performance in terms of pole rebalancing speed for both small and large voltage imbalances, but it requires higher energy absorption capability compared to the AC side grounding options. The two AC side grounding options have approximately equivalent performance for both small and large voltage imbalances.

The analysis on the performance of the proposed pole rebalancing equipment for both normal and post-fault situations shows that there are a number of key requirements the pole rebalancing equipment has to fulfil. The key requirements for the DBS circuit are that (1) the surge arresters are required to be dimensioned for long-term repeated operation until the source of the imbalance is removed for small permanent voltage imbalances, (2) the energy absorption capability of the DBS should be adequate to discharge the energy in the healthy pole in the case of a pole-to-ground fault, and (3) the operation speed of the DBS switches should be selected to

Fig. 9. Pole voltage balancing during a pole-to-ground fault using star point reactors.

Fig. 10. Pole voltage balancing during a pole-to-ground fault using neutral grounded Yyd transformers.

achieve acceptable pole rebalancing speed following a pole-to-ground fault. The key requirements for the AC side grounding circuits are that (1) the AC side groundings are required to allow a small steady-state DC current in the case of small permanent voltage imbalances, (2) the star point reactor should

be designed to withstand sufficient transient current without causing saturation, and (3) the three phase switches of the star point reactor should withstand the pole-to-ground DC voltage superimposed on the converter AC side voltage.

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