HVDC SYSTEM PERFORMANCE WITH A NEUTRAL CONDUCTOR

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Abstract: The poles of bipolar HVDC transmission systems are often required to be capable of independent operation. In order to maintain the independence of the poles a return path for the current is needed. If a ground return cannot be used a neutral conductor must be installed, either on the same structures as the pole conductors or on separate structures. A fault on one pole of such a system may cause a fault on the neutral and a fault on the other pole; therefore, a fault must be efficiently cleared. This paper examines the effect a neutral conductor has on HVDC system reliability and the effectiveness of fault clearing devices such as arcing horns and neutral grounding breakers.

1. INTRODUCTION

Most bipolar HVDC systems in operation to date comprise of poles capable of operating autonomously. In such systems, a fault on, or an outage of, one pole must not cause an outage of the other pole. Pole independence is utilized to limit the effect of a single element outage to one pole and reduce the adverse impact of the outage on the rest of the power system.

It may not be possible to site electrodes without raising electrode interference liability concerns, and a neutral conductor along the length of the HVDC transmission line may be required for the current return path.

The neutral conductor is shared between the two poles and electromagnetically coupled with the pole conductors; therefore, a fault on one pole may cause a fault on the neutral that affects the operation of the other pole. Faults on the neutral conductor insulation will affect pole independence unless they are efficiently detected and cleared.

2. DISCUSSION

The neutral insulation is subjected to various voltage stresses. The maximum continuous dc operating voltage of the neutral insulators is equal to the voltage drop on the neutral conductor during the maximum power transfer. Switching-type overvoltages are induced on the neutral conductor during pole-to-ground faults; the neutral conductor is also subjected to very high amplitude, fast-front overvoltages resulting from lightning strikes on the line.

Two methods of clearing neutral conductor faults without power transfer interruption are available: arcing horns and diverting a portion of the neutral current through the ground using a ground breaker at the ungrounded side of the neutral conductor. If these methods are unsuccessful, a neutral-to-ground fault can be cleared by restarting the affected pole.

Table 1 and Table 2 show the annual bipolar and monopolar outage rates due to neutral-to-ground faults, and the effectiveness of the fault clearing devices.

Table 1: Annual Bipolar Outage Rate due to Pole and Neutral Insulator Faults, 15 Ω Footing Resistance

Power Transfer (MW/pole)	**Levels of Fault Clearing**			
	None	***Attempt to Restart***	***Arcing Horn***	***Ground. Breaker***
2000	1.55	0.31	0.30	0.030
1000	1.55	0.31	0.29	0.029
500	1.55	0.31	0.26	0.026

Table 2: Monopolar Outage Rate due to Neutral Insulator Faults, 15 Ω Footing Resistance

Power Transfer (MW/pole)	**Levels of Fault Clearing**			
	None	***Arcing Horn***	***Ground. Breaker***	***Attempt to Restart***
2000	3.18	3.11	0.31	0.062
1000	3.18	2.92	0.29	0.058
500	3.18	2.67	0.27	0.054

3. CONCLUSION

A neutral conductor can affect the outage performance of an HVDC system and compromise pole independence. To maintain the desired performance, neutral-to-ground faults have to be cleared efficiently and reliably. Arcing horns are effective on relatively short low-capacity HVDC lines. This work shows that arcing horns installed on relatively long or high capacity HVDC lines have little effect (except that they keep the arc away from the insulator). For such configurations the use of arcing horns may not be justified and a grounding breaker has to be considered as a main neutral-to-ground fault clearing device.

4. REFERENCES

[1] IEEE 1243-1997, “IEEE Guide for Improving the Lightning Performance of Transmission Lines”.

[2] CIGRE WG01 SC33, “Guide to Procedures for Estimating the Lightning Performance of Transmission Lines”.

[3] Canellas, J., Clarke, C.D., Portela, C.M., “DC Arc Extinction on Long Electrode Lines for HVDC Transmission,” International Conference on DC Power Transmission, pp. 127-133, Jun. 1984.

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I. INTRODUCTION

Most bipolar HVDC systems in operation to date comprise of poles capable of autonomous operation. In such systems, a fault on, or an outage of, one pole must not cause an outage of the other pole. Pole independence limits the effect of a single element outage to one pole and reduces the impact of the outage on the rest of the system.

During bipolar operation power transfer is balanced. If a fault causes an outage of one pole, a return path has to be provided for the current to allow uninterrupted operation of the other pole.

Most HVDC schemes currently in operation use the ground as a current return path and require electrodes that inject the dc current into the ground. A certain distance between the electrode and the converter station is required; therefore, electrode lines connect the electrode to the neutral point of the converter station. The injection of the dc current into the ground can affect buried metallic infrastructure and power distribution networks in a relatively large area around the electrode and can cause corrosion, transfer of high potentials, and saturation of transformers. It may not be possible to site an electrode in areas of high population density or high infrastructure density without raising interference liability concerns. In such situations, a neutral conductor along the whole length of the HVDC transmission line can be used to provide a current return path for the current. Bipolar HVDC schemes that utilize neutral conductors may be more common in the near future, given current interest in new HVDC projects, problems with electrode site placement, and regulatory restrictions.

The neutral conductor is shared between the two poles and is electromagnetically coupled with both; a fault on one pole may cause fault on the neutral and affect the operation of the other pole. Faults on the neutral conductor insulation will affect pole independence unless they are efficiently detected and cleared. This paper examines the effect a neutral conductor has on HVDC system reliability and the effectiveness of fault clearing devices such as arcing horns and neutral grounding breakers.

II. HVDC SYSTEM WITH A NEUTRAL CONDUCTOR

A ±500 kV HVDC system configuration with a neutral conductor (see Fig. 1) is discussed in this paper. Power transfer up to 2000 MW per pole is examined. The neutral conductor in the system is solidly grounded at one converter station and connected to a surge capacitor, an arrester, and a grounding circuit breaker at the other converter station. Arcing horns on the neutral insulators are also shown in. Fig. 1. For the purposes of this study, the length of the line is assumed to be 500 km. Outlines of some typical HVDC transmission line structures with a neutral conductor are shown in Fig. 2.

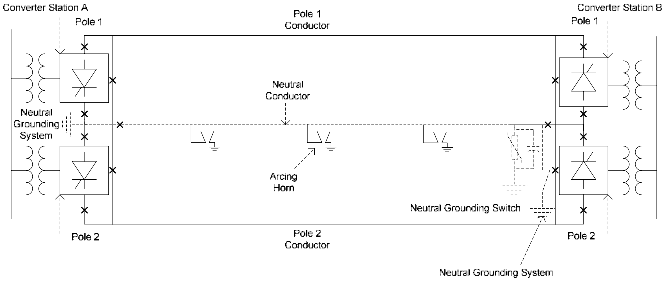

Figure 1. HVDC system configuration with a neutral conductor

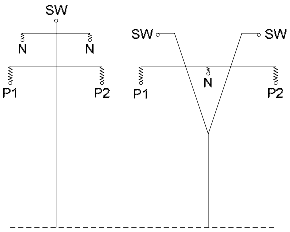

Figure 2. Outlines of HVDC structures with a neutral conductor

III. VOLTAGE STRESSES ON NEUTRAL INSULATION

The neutral insulation is subject to a number of voltage stresses. The maximum continuous dc operating voltage of the neutral insulators is equal to the voltage drop on the neutral conductor during the maximum power transfer. For a ±500 kV HVDC system, this voltage is typically in the lower tens of kilovolts range. System start-up, system shut-down, and converter commutation failure produce switching-type overvoltages on the neutral conductor of up to one hundred kilovolts. During a pole-to-ground fault, switching-type overvoltages in the range of three to four hundred kilovolts are induced on the neutral conductor. The magnitudes of these switching-type overvoltages depend on tower configuration. They are similar to the overvoltages that appear on the healthy pole during pole-to-ground faults. Lightning strikes to the transmission line subject the neutral insulation to very high amplitude, fast-front overvoltages.

The neutral insulation must be designed to withstand the continuous operating voltage on the neutral conductor, the HVDC system start-up overvoltages, the HVDC system shut-down overvoltages, and the overvoltages that occur during commutation failure. A neutral insulator string comprising of two to five units would typically satisfy these requirements. However, the neutral insulator must be much longer than that to withstand both switching-type overvoltages due to pole-to-ground faults and lightning overvoltages. Generally, utilizing neutral insulation designed to withstand these types of overvoltages is not considered to be a justifiable investment.

IV. MECHANISM OF NEUTRAL-TO-GROUND FAULTS

The neutral insulation strength is typically lower than the pole insulation strength, and consequently, the neutral insulation is more susceptible to flashovers.

If a flashover occurs only on the neutral insulation (e.g., a lightning strike) and the HVDC system was in a bipolar mode of operation before the fault, the differential dc current in the neutral conductor will be too low to support a permanent dc arc and the fault will clear spontaneously.

In these situations one event will cause flashover on the pole insulation and the neutral insulation simultaneously:

- A pole-to-ground line insulation flashover (e.g., due to pollution) will produce high switching-type overvoltages on the neutral conductor that will cause a flashover on the neutral insulator.
- A lightning strike that causes pole-to-ground insulation flashover will cause a flashover on the neutral insulation (because of the shared transmission line structure and lower neutral insulation level).

In the above situations, the neutral insulation fault will be supported by the dc current and will turn into a dc arc. Such arcs are difficult to clear spontaneously because there is no zero crossing of the current.

Faults on the neutral insulation may affect the operation of the HVDC system if one pole is already out of service and the neutral conductor is being used as a current return path.

Because the neutral conductor is shared by the two poles, simultaneous faults on the pole insulation and the neutral insulation jeopardize pole independence. Faults on the neutral insulation do not cause power transfer interruption; however, they must be cleared to avoid outage of the other pole.

V. NEUTRAL INSULATOR FAULT CLEARING METHODS

Two methods of clearing neutral conductor faults without power transfer interruption are available: arcing horns and a ground breaker at the ungrounded side of the neutral conductor, which diverts a portion of the neutral current through the ground.

Arcing horns are insulator hardware devices that keep an arc away from the insulator surface (thereby preventing damage) and elongate the arc until it becomes unstable; this instability leads to its extinction. The thermal motion of the dc arc (rather than the effects of electromagnetic forces) is the greatest contributor to this elongation [3]. The arcing horns can reliably extinguish dc arcs only if the arc current and supporting voltages are within the capabilities of the arcing horns. The V-I characteristics of the arcing horns depend on their size and shape, as shown in [3].

A neutral insulation fault can be cleared by diverting a portion of the neutral current through the ground by using a grounding breaker at the ungrounded end of the neutral conductor; this reduces the arc current. The normally open neutral grounding breaker closes for a time sufficient to allow the arcing horns to clear the arc (one to two seconds). If the arc persists after the grounding breaker is opened the power transfer will have to be interrupted by force retarding the active pole to reduce the arc current to zero and clear the fault.

The application of a grounding breaker requires injection of dc current into the ground. If this poses a risk of interference with other control equipment, remote grounding grids for the neutral conductor have to be considered.

VI. FREQUENCY OF POLE-TO-GROUND AND NEUTRAL-TO-GROUND FAULTS ON AN HVDC LINE

Most faults on the pole insulation are caused by pollution and lightning strikes. The frequency of flashovers on the pole insulation due to pollution is difficult to predict, but there are methods of predicting the frequency of lightning flashovers.

Because of the large dimensions of the pole insulators and the effective shielding of the HVDC towers, flashovers due to shielding failures are practically impossible; therefore, the lightning performance of the pole insulation is equivalent to the back-flashover performance. Table 1 shows the annual back-flashover rate of a ±500 kV HVDC line, calculated with IEEE Flash software [1] assuming a ground flash density of 2 $km^{-2} \cdot year^{-1}$.

The neutral insulation is more susceptible to lightning flashovers, as can be seen from Table 1. In some tower configurations (Fig. 2), the neutral conductor can be exposed to direct lightning strikes (i.e., shielding failures), which is not the case with the pole conductors. The total number of flashovers (SFFOR+BFR) is significantly affected by the length of the arcing horn gap.

Table 1. Annual Flashover Rate of the Pole and Neutral Insulation for a ±500 kV, 500 km HVDC Transmission Line

Tower Footing Resistance (Ω)	**Pole Insulator Length (CFO)**	**Arcing Horn Gap Length (m) (CFO)**			
	30 Units (2800kV)	***0.3 m (180 kV)***	***0.5 m (300 kV)***	***1.0 m (590 kV)***	***1.5 m (880 kV)***
20	2.6	166	135	65.3	37.5
15	1.55	159	120	52.7	31.1
10	0.8	148	100	40.4	25.6
5	0.3	127	73.9	29.7	21.2

A typical ±500 kV HVDC tower geometry with the neutral conductor at the top cross arm (tower height 45 m; average span 400 m; and minimum pole-to-ground distance 12.5 m) was used to produce the results presented in Table 1.

VII. FAULT CLEARING EFFICIENCY OF THE ARCING HORNS AND GROUNDING BREAKER

An equivalent of the HVDC system shown in Fig. 1was developed to analyze the neutral insulation fault-clearing efficiency of the arcing horns and the grounding breaker.

Fig. 3 shows the system neutral fault equivalent where R_p is pole conductor resistance, R_L is load resistance, R_N is neutral conductor resistance per unit length, R_g is resistance to ground, R_{tower} is tower resistance, $R_{Footing}$ is tower footing resistance, x is neutral fault location, V_{arc} is neutral voltage at the fault location, and L is total line length.

Fig. 4 presents the V-I characteristics of the neutral insulation fault at different locations (straight lines) overlaid on the experimental V-I characteristics of the arcing horns (curves) [3]. The 0.3 m gap characteristics were extrapolated from the experimental data. If the fault V-I characteristics pass below the arc characteristic, the dc arc has diminished spontaneously; otherwise, a stable dc arc is established at the right hand intersection with the arcing horn characteristics.

The arcing horns have to be of significant dimensions to clear the faults on the neutral insulation over the whole line length. Table 2 shows the relative lengths of the transmission line where arcing horns of certain dimensions would not be able to clear the neutral-to-ground faults under different power transfers and different tower grounding conditions.

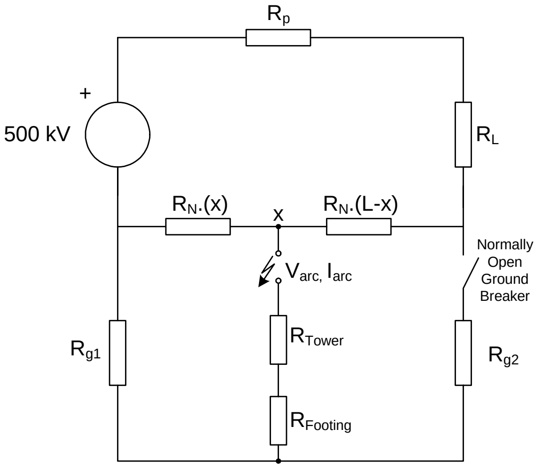

Figure 3. Neutral fault equivalent of the HVDC system

Neutral insulation faults that occur at the locations where arcing horns are inefficient can be cleared by closing the grounding breaker. Fig. 5 presents a case similar to that in Fig. 4, but with a grounding breaker closed. None of the V-I characteristics of neutral-to-ground faults intersects with the V-I characteristics of the arcing horns, which indicates successful fault clearing over the whole line length.

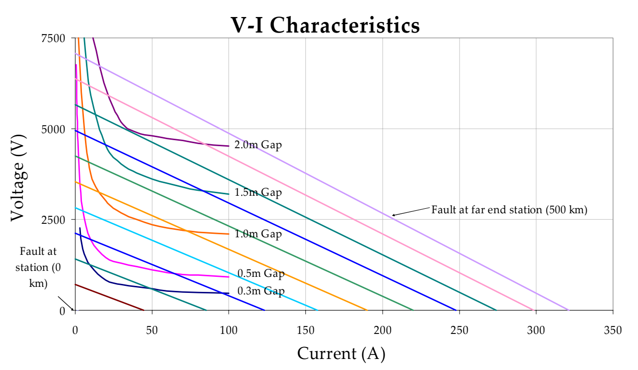

Figure 4. Arcing horns fault clearing efficiency (grounding breaker open, 15 Ω tower footing resistance, 500 MW power transfer)

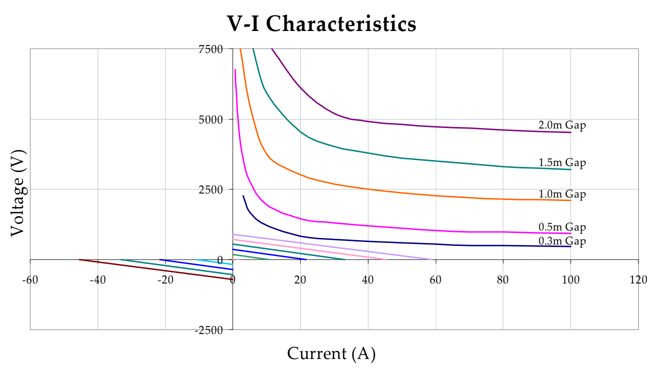

Figure 5: Arcing horns fault clearing efficiency (grounding breaker closed, 15 Ω tower footing resistance, 2000 MW power transfer)

Table 2. Relative Line Lengths for the Line for which Arcing Horns are Inefficient

Power Transfer (MW/pole)	**Tower Footing Resistance (Ω)**	**Arcing Horn Gap Length (m)**			
		0.3 m	***0.5 m***	***1.0 m***	***1.5 m***
2000	20	96%	94%	90%	86%
	15	98%	96%	90%	86%
	10	98%	96%	92%	88%
	5	98%	96%	92%	88%
1000	20	92%	88%	78%	68%
	15	92%	88%	80%	70%
	10	94%	90%	80%	72%
	5	94%	92%	82%	74%
500	20	82%	74%	54%	34%
	15	84%	76%	56%	36%
	10	86%	78%	58%	40%
	5	88%	80%	62%	44%

VIII. HVDC System Outage Rate due to Flashover on the Neutral Insulators

The HVDC converter controls will see pole insulation flashovers as ground faults and force the pole current to zero to clear the fault; they are usually set to attempt a restart in a short time (typically 300 ms to 1000 ms). If the line fault is transitory, (e.g., a lightning flashover), the attempt will usually be successful. The authors' interpretation of CIGRE statistics regarding the performance of HVDC systems indicates that up to 20% of pole restart attempts are not successful.

A pole insulation flashover will almost certainly cause a simultaneous flashover on the neutral insulation. If the dc arc parameters are within the capabilities of the arcing horns, they will clear the fault and monopolar operation will continue without interruption. However, arcing horns are not efficient over the whole length of the line, as shown in Table 2. An arc that persists can be cleared by the grounding breaker. If the fault still persists, the remaining converter pole may be force retarded, with or without an attempt to restart.

The results presented in the previous section provide enough information to determine the outage rate due to the ground faults on the neutral insulation of the entire bipole.

A bipolar outage rate that is a result of the insulation fault $BPOR_N$ can be calculated by applying Equation 1. The equation assumes the system is in a bipolar mode for a relative duration T_B during the year; FOR_P is the flashover rate of the pole insulation (the lightning component in Table 1), P_{AH} is the relative length of the line where the arcing horns are not effective (from Table 2), P_{GB} is the probability of the ground breaker not clearing the fault for any reason, and P_R is the probability of the converter controls not restarting the affected pole.

The monopolar outage rate $MPOR_N$, a result of the neutral insulation fault during monopolar operation with the neutral conductor in use, can be calculated by applying Equation 2. T_{MN} is the relative duration of operation of the system in a monopolar mode with the neutral conductor in service.

$$BPOR_N = T_B \cdot FOR_P \cdot P_R \cdot P_{AH} \cdot P_{GB} \qquad (1)$$

$$MPOR_N = T_{MN} \cdot \left(FOR_N - FOR_P\right) \cdot P_{AH} \cdot P_{GB} \cdot P_R \qquad (2)$$

Table 3 presents the rate of bipolar outages caused by a failure to clear a fault on the neutral insulation due to lightning strikes. Pollution flashovers are in addition to the presented values. The different levels of fault clearing in Table 3 represent the neutral-to-ground fault clearing methods in the sequence of their application. For example, Table 3 shows that if no neutral-to-ground fault clearing method is applied and the converter controls are not set to attempt a restart, all single-pole ground faults will cause ground faults on the neutral, and consequently, the second pole will have to be shut down. In such a case, the neutral conductor is useless because almost every single-pole fault causes bipolar outage.

Enabling the controls to attempt to restart the faulted pole reduces the bipolar outages proportionally to the restart failure rate, in our case to 20% of the initial value. The faults not cleared can be handled by the arcing horns, although their success rate dramatically decreases with the increase of line length and power transfer. Eventually, the great majority of the remaining neutral-to-ground faults can be cleared by the grounding breaker, with assumed success rate of 90%.

Table 3. Annual Bipolar Outage Rate due to Simultaneous Faults on the Pole and Neutral Insulators, 15 Ω Tower Footing Resistance and $T_B = 1$

Power Transfer (MW/pole)	**Levels of Fault Clearing**			
	None	***Attempt to Restart***	***Arcing Horn***	***Ground. Breaker***
2000	1.55	0.31	0.30	0.030
1000	1.55	0.31	0.29	0.029
500	1.55	0.31	0.26	0.026

Table 4. Monopolar Outage Rate due to Faults on the Neutral Insulators, 15 Ω Tower Footing Resistance and $T_{MN} = 0.02$

Power Transfer (MW/pole)	**Levels of Fault Clearing**			
	None	***Arcing Horn***	***Ground. Breaker***	***Attempt to Restart***
2000	3.18	3.11	0.31	0.062
1000	3.18	2.92	0.29	0.058
500	3.18	2.67	0.27	0.054

The rate of converter failure to restart, $P_{R,}$, was assumed to be 0.2, the P_{AH} for a 0.3 m gap were taken from Table 2, and the failure rate of the grounding breaker, P_{GB}, was assumed to be 0.1. Results for the monopolar outage rate are presented in Table 4. This table assumes the system is in monopolar operation with the neutral conductor in service for one week during the year or 2% of the time.

It can be noted that the satisfactory performance of an HVDC transmission line with a neutral conductor can be achieved if a grounding breaker is installed and converter controls are enabled to restart.

IX. Conclusion

A neutral conductor can affect the outage performance of an HVDC system and compromise pole independence. To maintain the desired performance, neutral-to-ground faults have to be cleared efficiently and reliably. Arcing horns are effective on relatively short low-capacity HVDC lines. This work shows that arcing horns installed on relatively long or high capacity HVDC lines have little effect (except that they keep the arc away from the insulator). For such configurations the use of arcing horns may not be justified and a grounding breaker has to be considered as a main neutral-to-ground fault clearing device.

X. References

[1] IEEE 1243-1997, "IEEE Guide for Improving the Lightning Performance of Transmission Lines".

[2] CIGRE WG01 SC33, "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines".

[3] Canellas, J., Clarke, C.D., Portela, C.M., "DC Arc Extinction on Long Electrode Lines for HVDC Transmission," International Conference on DC Power Transmission, pp. 127-133, Jun. 1984.