A Novel Combined Control of Ground Current and DC-pole-to-Ground Voltage in Symmetrical Monopole Modular Multilevel Converters for HVDC Applications

Pablo Briff, Amit Kumar
GE Renewable Energy
Stafford, United Kingdom
Corresponding authors: {pablo.briff, amit.g.kumar}@ge.com
URL: http://www.ge.com

Abstract

This paper investigates the reduction in converter trips in the symmetrical Modular Multilevel Converter (MMC) by regulating the dc term of the valves' voltages, while allowing the dc pole-to-ground dc voltages to fluctuate within acceptable limits. Moreover, the control method proposed in this work serves two purposes: i) to regulate the pole-to-ground dc voltages of a symmetrical Modular MMC when the voltage of either of the poles at the dc side exceeds a predefined threshold; and ii) to control the ground current within acceptable limits. This results in an extended converter availability by avoiding unnecessary converter trips. The benefits of the proposed method is validated by simulation results for a symmetrical monopole MMC VSC-HVDC configuration.

Keywords: «modular multilevel converter», «ground current», «converter control».

Introduction

In HVDC power transmission networks, ac power is converted to dc power for transmission via overhead lines, under-sea cables and/or underground cables. This conversion removes the need to compensate for the ac capacitive load effects imposed by the transmission line or cable, and reduces the cost per kilometre of the lines and/or cables. Thus, dc transmission becomes cost-effective when power needs to be transmitted over a long distance [1], [2].

Fast and stable controllability of power is a major advantage of HVDC transmission over conventional ac transmission systems. Conventional thyristor-based line-commutated converter (LCC) HVDC systems have been a well-established technology for more than 60 years [3], especially when bulk power needs to be transferred over a long distance. However, when weak systems like wind or solar power plants need to be connected to the grid, Voltage Sourced Converter (VSC)-HVDC systems are the preferred solution [4]. During the past two decades, VSC-HVDC technology has undergone a series of evolutionary milestones until it finally reached the current state-of-art with the modular multilevel converter (MMC) technology. Most of these milestones were aimed at making the switching losses comparable to LCC HVDC systems, increase the rating of VSC converters and to reduce the harmonics emission of the converters [3].

A major topic in HVDC – being part of transmission infrastructure – is the availability of the converter stations. These are usually impaired by unplanned trips arising from protective actions. Examples of protection algorithms in VSC-HVDC are those which monitor the amount of ground current circulation and dc voltage to ground imbalance. While [5] addresses the issue of operation of MMC under dc pole imbalances, it does not investigate the problem of unexpected trips due to high ground current circulation and its impact on industrial applications.

More recent works such as [6–8] study the topic of dc voltage balancing in both pole and bipole configurations in great detail. However, these works do not address the issue of dc pole to ground voltage balancing combined with ground current control, and the prioritisation logic that must take place between these two controllers.

For a power transmission network, one of the major performance criteria are its reliability and availability. These form the basis of some of the key parameters an HVDC manufacturer considers while designing their VSC-HVDC scheme. At the same time, fitting a scheme with excessive design margins makes it uneconomical. By applying supplementary fast controls, the VSC-HVDC converter design can be optimised, while satisfying the reliability and availability targets.

This paper focuses on the symmetrical monopole MMC VSC-HVDC, which constitutes, at present, the most widely used dc circuit configuration in commercial HVDC projects. Compared to asymmetrical monopole or bipole, this configuration has the advantage that only two conductors (overhead transmission line or cable), each with only 50% of the total converter station dc voltage rating, are required.

This paper proposes a control method that serves two purposes: i) to regulate the pole-to-ground dc voltages of MMC when the voltage of either of the poles at the dc side exceeds a predefined threshold; and ii) to control the ground current within acceptable limits is also attained by regulating the dc term of the valves' voltages, while allowing the dc pole-to-ground dc voltages to fluctuate within acceptable limits. With the presented control method, the availability of the converter is extended by avoiding unnecessary converter trips. The potential of the method is validated by simulation results for a symmetrical monopole MMC for VSC-HVDC applications.

Ground Current and DC Pole to Ground Control

Model Statement

Fig. 1 shows a typical connection of an ac system to a VSC-HVDC, which is then connected to a dc line.

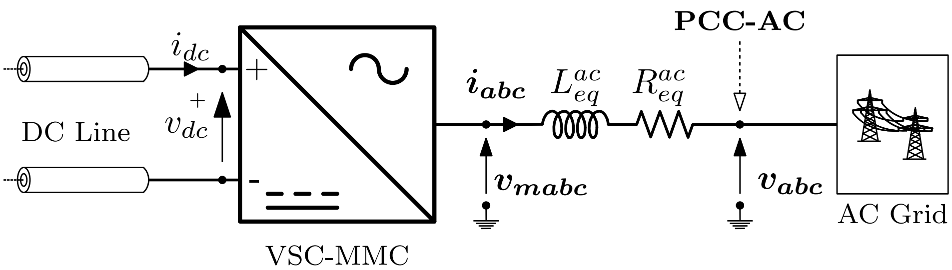

Figure 1: AC system connected to a VSC.

In particular, this paper focuses on the symmetrical monopole configuration of half-bridge (HB) MMC, where each valves' total voltage is in the range of $0 \rightarrow V_{dc}$ volts, where V_{dc} is the pole-to-pole voltage. A sample equivalent circuit of this topology configuration is shown in Fig. 2. While the concepts presented in this paper are applicable to both star-star and star-delta transformer connections, as an example, this paper investigates the application to the star-delta transformer configuration only. In a star-delta-connected transformer, the ground reference at the secondary side of the transformer is usually provided by inductors L_g with equivalent resistance R_g connected to ground. At the dc side, a virtual ground v_{gnd} with zero voltage potential is provided by means of the dc side equipment such as insulators, surge arresters, water cooling circuit, voltage divider and transmission line present at the positive and negative poles. Ultimately, an electrical connection between the solid ground provided by the grounding circuit and the virtual ground exists. Hence, a ground current i_g can flow at the star-point connection of the star-connected inductors.

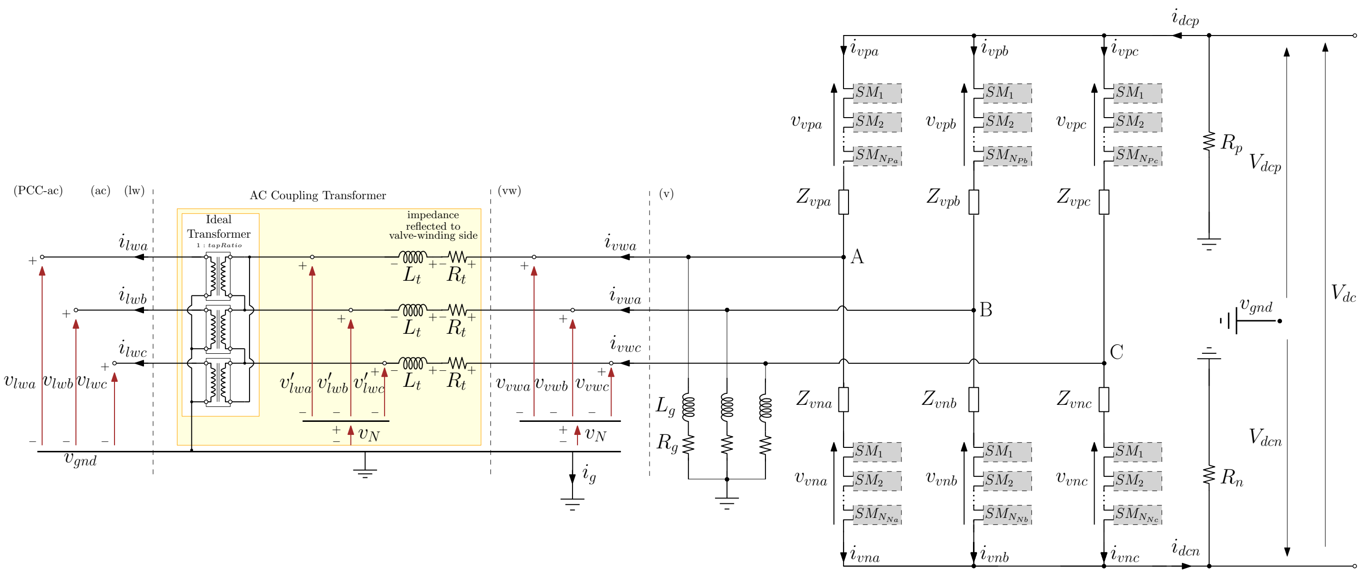

Figure 2: Single line diagram of MMC VSC-HVDC.

Tolerances in dc-side equipment such as surge arresters and insulators may alter the voltage reference at the V_{dcp}, V_{dcn}

terminals. Surge arresters and insulators in an overhead line usually present a dc resistance in the order of mega-ohms. If the value of such resistors varies with respect to each dc pole, an asymmetrical pole-to-ground dc voltage will be present since the pole-to-pole V_{dc} voltage will be unequally distributed by the resistive divider formed by the high resistance connected to each pole to ground.

Furthermore, if the pole-to-ground dc voltage exceeds a permitted maximum value, a protective action will be initiated, thus tripping the converter to avoid damage of equipment due to over-voltage.

An imbalance in the dc side conductance creates a current flow through the grounding circuit, and depending upon the grounding circuit resistance, this creates an imbalance in the pole to ground voltage, i.e. one of the pole-to-ground voltages increases with respect to the other pole. Other reasons for an imbalance of the pole-to-ground dc voltage include: manufacturing/ageing effect tolerance of voltage divider and surge arresters, difference in resistance of positive and negative pole conductor, dc current measurement error in the limbs, insulators degradation, to name a few. In addition to this, an imbalance in the pole-to-ground voltages will drive the ground current i_g. Such current can be measured accurately with a dc current transformer (DCCT) and it can be used as a measure of the amount of imbalance present at the dc poles. Moreover, if either the dc pole-to-ground voltage or the current through grounding circuit should exceed a permitted maximum value, then a protective action will be initiated.

Ultimately, the benefits of the proposed method relies on the extended operation of the converter by keeping both the pole-to-ground dc voltages and the ground current within acceptable limits. The main benefit is, therefore, an extension of the converter's availability, as well as the minimization of the liquidated damages due to excessive converter trips arising from excessive ground current circulation or over-voltage on the dc lines. What is more, these benefits are attained at no extra hardware costs.

Control Strategy

The pole-to-pole dc voltage is defined as $V_{dc} \triangleq V_{dcp} - V_{dcn}$. Under balanced operating conditions, the positive and negative valves' voltages, v_{vpx} and v_{vnx} respectively, for the MMC circuit shown in Fig. 2 are given by

$$\begin{aligned} v_{vpx} &= \frac{V_{dc}}{2} - v_x - v^{\Sigma}_{ctrl,x} \quad , \\ v_{vnx} &= \frac{V_{dc}}{2} + v_x - v^{\Sigma}_{ctrl,x} \quad , \end{aligned} \tag{1}$$

where $x = \{a, b, c\}$, $[v_a v_b v_c]^T$ is the three-phase equivalent converter's ac output voltage, and $v^{\Sigma}_{ctrl,x}$ is a common-model control voltage term that relates to the valves energy control. In general, the dc term of the valves voltage is $v_{zx,dc}$, where $z = \{p, n\}$.

The dc equivalent circuit of Fig. 2 is shown in Fig. 3. Consider the situation where the positive pole-to-ground dc voltage exceeds its maximum steady-state value by an amount ΔV_{dcp}, as shown in Fig. 4 . In order to reduce the pole-to-ground voltage on the positive dc rail, the dc voltages of the positive valves shall be reduced by ΔV volts, and typically $\Delta V \approx \Delta V_{dcp}$ volts.

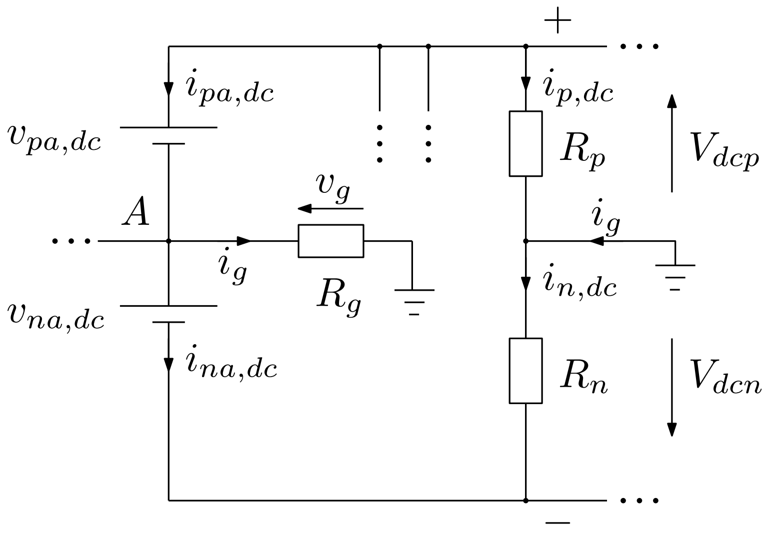

Figure 3: DC equivalent circuit of Fig. 2 for phase a.

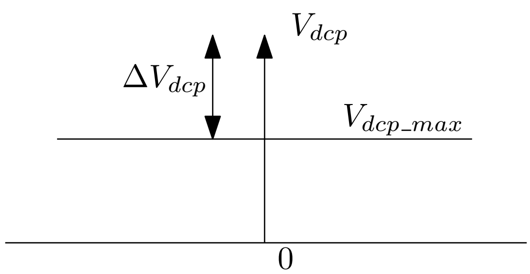

Figure 4: Pole-to-ground voltage V_{dcp} exceeding a threshold V_{dcp_max} by an amount ΔV_{dcp} at the positive dc pole.

An imbalance in the pole-to-ground dc voltages, defined as $\Delta V_{pn} \triangleq V_{dcp} - |V_{dcn}|$, is mainly due to an imbalance in the dc resistors R_p, R_n – these are usually in the order of mega ohms. If the ground current i_g is zero, then the voltage divider of R_p, R_n determines the values of V_{dcp}, V_{dcn} as follows

$$\begin{aligned} V_{dcp} &= V_{dc}\frac{R_p}{R_p + R_n}, \\ V_{dcn} &= -V_{dc}\frac{R_n}{R_p + R_n}. \end{aligned} \tag{2}$$

Naturally, if $R_p \neq R_n$ then $V_{dcp} \neq |V_{dcn}|$, or equivalently $\Delta V_{pn} \neq 0$, unless some control action is performed. The imbalance in V_{dcp}, V_{dcn} can be influenced by controlling the currents $i_{p,dc}$ and $i_{n,dc}$. What is more, if $i_{p,dc} \neq i_{n,dc}$, then $i_g \neq 0$. This means that a dc pole-to-ground imbalance will generate a ground current, and vice versa. However, the amount of voltage imbalance at the dc rails may not be as significant – in terms of protective actions – as the current imbalance observed at the ground connection. This means that a ground current imbalance may be prioritised over an imbalance at the dc rails.
From Fig. 3, relation between the ground current i_g the dc pole-to-ground voltage imbalance $|V_{dcn}|$ is given by

$$\begin{aligned} V_{dcp} &= v_{pa,dc} + v_g, \\ V_{dcn} &= -v_{na,dc} + v_g, \\ v_g &= R_g i_g, \\ i_g &= i_{n,dc} - i_{p,dc}. \end{aligned} \tag{3}$$

From (3), if $R_p > R_n$, then $V_{dcp} > V_{dcn}$. Meanwhile, $i_{n,dc}$ is increased by increasing i_g. The ground current i_g is increased by increasing v_g. And the voltage v_g is increased by increasing $v_{pa,dc}$. Consequently, this leads to decreasing $v_{na,dc}$ in order to keep V_{dc} constant.

Moreover, an important conclusion from (3) is that controlling both i_g and $|V_{dcn}|$ *simultaneously* is not possible. Only one of those variables can be controlled at any given time, and priority should be given to each of these controlled variables based on the protection levels defined by the converter design and its control strategy.

Defining the following

$$x = \begin{bmatrix} v_{pa,dc} \\ v_{na,dc} \\ V_{dcn} \\ v_g \\ i_{p,dc} \\ i_{n,dc} \\ i_g \end{bmatrix} \qquad b = \begin{bmatrix} V_{dc} \\ V_{dcp} \\ 0 \\ 0 \\ 0 \\ V_{dcp} \\ 0 \end{bmatrix} \qquad A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & -R_g \\ 0 & 0 & 0 & 0 & R_p & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & -R_n & 0 \end{bmatrix} \tag{4}$$

then the system of equations for the circuit of Fig. 3 is

$$A \cdot x = b \tag{5}$$

The solution of the system (5) is found by simple inversion of the matrix, i.e. $x = A^{-1} \cdot b$.

Furthermore, in order to leave the ac converter voltage unaltered, all the positive valves' dc voltages shall be *decreased* an amount equal to ΔV volts. This is because, in a delta-connected transformer, the ac voltage output is a differential output of either the positive or negative valves' voltages; hence, shifting all the positive (or negative) valves voltages simultaneously and by the same amount will not affect the differential output.

What is more, in order to leave the dc voltage unaltered, all the negative valves voltages shall be *increased* an amount equal to ΔV volts. This is summarised in (6):

$$\begin{aligned} v_{vpx} &= \frac{V_{dc}}{2} - v_x + (-\Delta V), \\ v_{vnx} &= \frac{V_{dc}}{2} + v_x + (+\Delta V). \end{aligned} \tag{6}$$

It is worth mentioning that the energy term in (1) has been neglected in (6), without loss of generality.

From (6), notice that $v_{vpx} + v_{vnx} = V_{dc}$, and $v_{vnx} - v_{vpx} = 2v_x + 2\Delta V$. Hence, the dc voltage remains unaffected, and thus the dc power is unaltered too. Meanwhile, the dc term of the differential voltage $(v_{vnx} - v_{vpx})/2$, i.e. ΔV, appears as common-mode voltage on the transformer's secondary windings with respect to ground. However, as the transformer is star-delta connected, there is no phase-to-phase dc voltage induced on the transformer windings. Hence, the difference $v_{vpx} - v_{vpy}$ contains no dc voltage, and the same holds true for $v_{vnx} - v_{vny}$, with $x, y = \{a, b, c\}$. Offsetting the valves voltages by ΔV volts has a small impact on equipment insulation levels, with the benefit of being able to control both the ground current and dc pole to ground voltages.

It must be noted that by altering (increasing or decreasing) the dc voltage term in each valve, the synthesized ac voltage peak, denoted as $\hat{v}_x$, is affected, as shown in Fig. 5. This is because, in a HB MMC topology, the maximum symmetrical swing of the synthesized ac voltage is limited by the dc term of each valve (excluding the application of triplen harmonic injection). For this reason, the proposed control strategy shall only be applied when either the relevant pole-to-ground dc voltage V_{dcp}, V_{dcn} or the ground current i_g has crossed a preset threshold associated with a preventive protective level. Applying the proposed method i normal operating conditions may have a negative impact on converter losses as well as it would limit its power delivery capability.

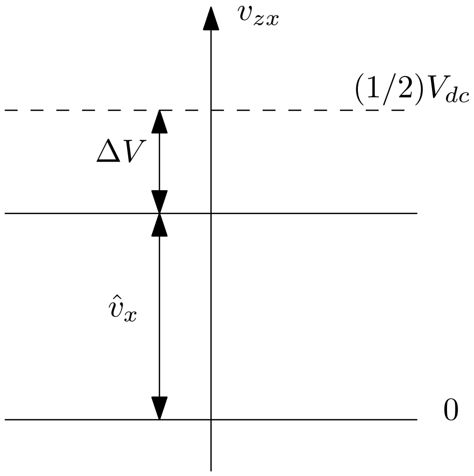

Figure 5: Reduced ac voltage swing due to a reduction in the valve's dc voltage for valve zx.

The control strategy proposed in this paper is shown in Fig. 6. This combines the control of pole-to-ground dc voltage and ground current with a prioritisation logic. The parameters of the deadband are settable by the control designer, either by offline or online methods.

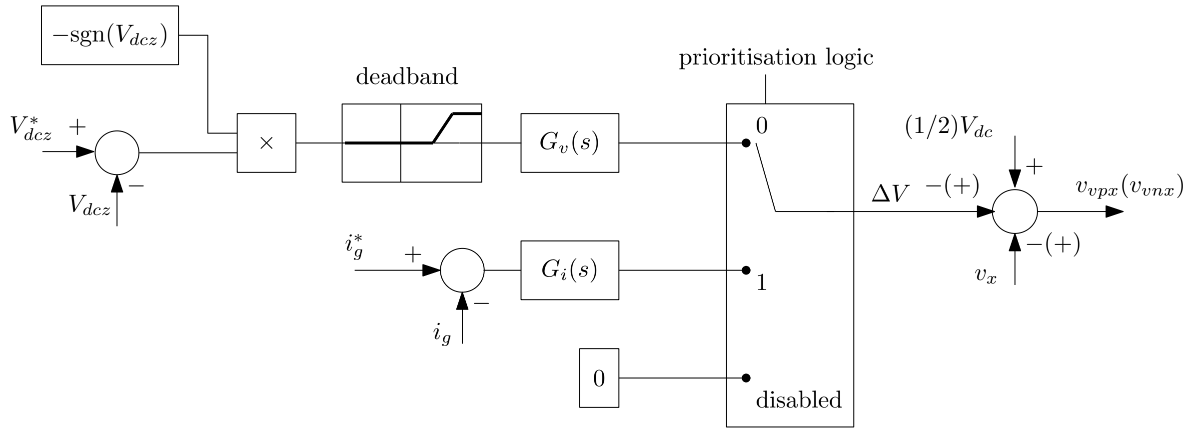

Figure 6: Strategy of pole-to-ground dc voltage feedback control using voltage and current measurements.

Fig. 6 shows how the positive (negative) valves voltages are modified when the pole-to-ground voltage V_{dcz} exceeds a predefined upper limit. The ground current measurement i_g allows the designer to control such current within acceptable limits by varying the dc term of the valves' voltages according to (6). The ground current reference i^*_g can be derived, e.g., by estimating the values of the resistors R_p, R_n and solving for (3). The controller gain $G_i(s)$ for the closed-loop control on i_g has the form of a negative (positive) resistance for over-voltages of the positive (negative) dc pole. More specifically, $G_v(s)$ and $G_i(s)$ are implemented using proportional-plus-integral (PI) controllers with harmonic filtering capability, in order to regulate the dc term of the error and hence bring its nominal value to zero. The prioritisation logic block implements enables the regulation of the ground current i_g over the relevant dc pole-to-ground voltage V_{dcz}, or vice versa; this block operates based on the measured quantities i_g and V_{dcz}, in combination with the converter's protection setting levels and trigger levels, V_{dcz_trig}, i_{g_trig}.

Simulation Results

In this section, the proposed control strategy is validated under different imbalance scenarios. The converter topology is a symmetrical monopole MMC with V_{dc} = 640 kV. The proposed control algorithm is implemented in MATLAB/Simulink.

The protection trip levels are shown in Table 1. The numerical results for various parameter combinations are shown in Table 2.

All figures and values shown below are approximate figures and values and are not definite in nature.

As it can be seen in Table 2, when R_g = 7.5 kΩ and there is a 20% imbalance between R_p, R_n, operating at the rated

Quantity	Trip level
V_{dcp}	1.05×320 kV
$\|V_{dcn}\|$	1.05×320 kV
i_g	250 mA

Table 1: Converter trip levels.

V_{dc} [kV]	R_p [kΩ]	R_n [kΩ]	R_g [kΩ]	$v_{pa,dc}$ [kV]	$v_{na,dc}$ [kV]	V_{dcp} [kV]	V_{dcn} [kV]	i_g [mA]
640	300	$0.8R_p$	7.5	320	320	1.006×320	-318	252
640	300	$0.8R_p$	7.5	328	312	1.03×320	-310	195
640	300	$0.8R_p$	175	320	320	1.06×320	-300	115
640	300	$0.8R_p$	175	310	330	1.05×320	-304	146

Table 2: Application example for different parameter values of Fig. 3.

dc valves' voltage of $(1/2)V_{dc} = 320$ kV does not produce a significant voltage difference at V_{dcp}. However, in this case the ground current i_g goes beyond the trip limit of 250 mA (marked in red). Hence, the valves voltages shall be modulated as shown in the second row of the table to avoid the converter to trip.
The third row of the table shows an increase in the ground resistor $R_g = 175$ kΩ (shown in blue) for the same values of the remaining parameters. It can be noticed that now the voltage V_{dcp} has gone beyond the 5% allowable limit (shown in red), which can trip the scheme, thus reducing the system availability and reliability. To stabilise the system, the valves voltages shall be regulated as shown in the fourth row, where all parameters are controlled within acceptable limits.
To confirm the results shown above, a point to point VSC HVDC scheme has been simulated with an imbalance of $R_n = 0.8R_p$, and $R_p = 300$ kΩ. It is expected that this configuration of parameters trigger a ground current protection, and not a dc pole-to-ground protective action. Hence, ground current control takes priority over dc pole-to-ground voltage control in Fig. 6.
When the control of the ground current i_g is disabled, the ground current goes out of control, thus crossing the protection boundary of 250 mA, as shown in Fig. 7. When the i_g current control is activated, the ground current is controlled to a peak value below 7 mA, as shown in Fig. 8.
Based on the results obtained in this example, the adjustments required to control the ground current and/or pole-to-ground dc voltages are attained at minimal modification of the dc voltages at the valves (< 3% of the rated valves' dc voltage). Therefore, by using this technique no significant increase on the number of connected submodules per valves is expected. In summary, regulating the dc valves' voltages can serve the purpose of both regulating the pole-to-ground dc voltages as well as the ground current to avoid an unnecessary trip in the scheme.

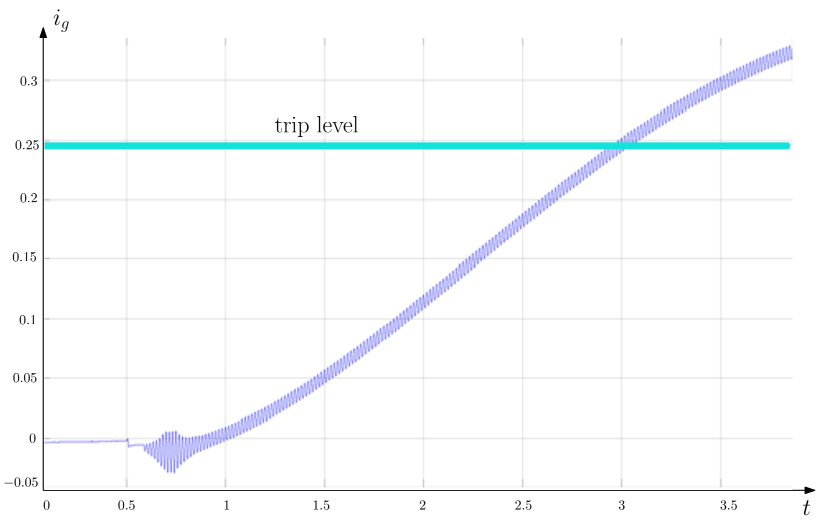

Figure 7: Uncontrolled ground current i_g as a function of time. The trip level is marked in green.

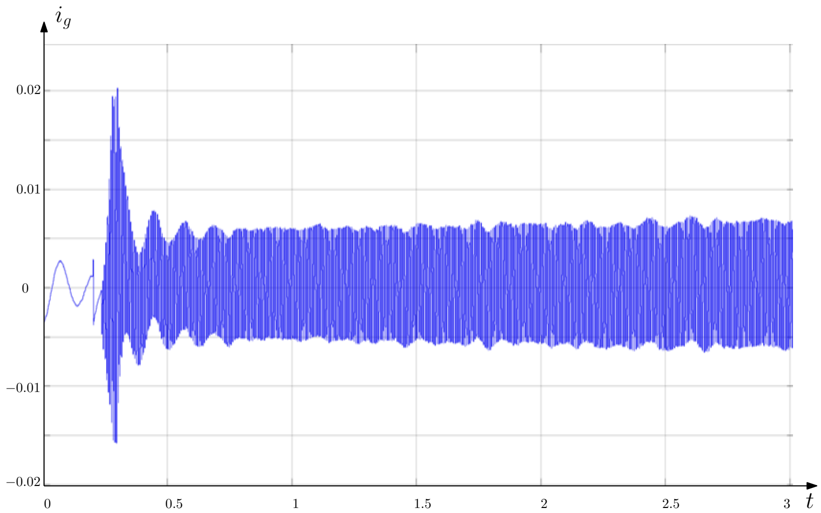

Figure 8: Controlled ground current i_g as a function of time.

Conclusions

This paper described a control method to regulate both the ground current and the pole-to-ground dc voltages of a symmetrical monopole modular multilevel converter, so that these do not exceed a pre-defined threshold. The paper has provided the mathematical modelling of the VSC HVDC converter voltage control, and a top level description of the proposed control algorithm. It has been discussed how, by controlling such voltages, the reliability and availability of the converter can be extended by avoiding unnecessary converter trips. To illustrate the effectiveness of the proposed control method, the control algorithm is applied to a typical VSC-HVDC system. The simulation results show the significance of the proposed method to improve the reliability and availability of the VSC HVDC system.

References

[1] O. Gomis-Bellmunt, J. Liang, J. Ekanayake, R. King, and N. Jenkins, "Topologies of multiterminal hvdc-vsc transmission for large offshore wind farms," *Electric Power Systems Research*, vol. 81, no. 2, pp. 271–281, 2011.

[2] I. Legorburu, K. R. Johnson, and S. A. Kerr, "Multi-use maritime platforms-north sea oil and offshore wind: Opportunity and risk," *Ocean & Coastal Management*, vol. 160, pp. 75–85, 2018.

[3] O. E. Oni, I. E. Davidson, and K. N. Mbangula, "A review of lcc-hvdc and vsc-hvdc technologies and applications," in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*. IEEE, 2016, pp. 1–7.

[4] A. Fernández-Guillamón, K. Das, N. A. Cutululis, and Á. Molina-García, "Offshore wind power integration into future power systems: Overview and trends," *Journal of Marine Science and Engineering*, vol. 7, no. 11, p. 399, 2019.

[5] A. Junyent-Ferre, P. Clemow, M. M. Merlin, and T. C. Green, "Operation of hvdc modular multilevel converters under dc pole imbalances," in *Power Electronics and Applications, 16th European Conference on*. EPE 14-ECCE Europe, 2014, pp. 1–10.

[6] Y. Zhao, W. Huang, and F. Bu, "Dc voltage balancing strategy of a bipolar-output active rectifier for more electric aircraft based on zero vector redistribution," *IEEE Access*, vol. 9, pp. 139 657–139 667, 2021.

[7] M. Wang, W. Leterme, G. Chaffey, J. Beerten, and D. Van Hertem, "Pole rebalancing methods for pole-to-ground faults in symmetrical monopolar hvdc grids," *IEEE Transactions on Power Delivery*, vol. 34, no. 1, pp. 188–197, 2018.

[8] M. Wang, J. Beerten, and D. Van Hertem, "Pole voltage balancing in hvdc systems: Analysis and technology options," in *2019 IEEE Milan PowerTech*. IEEE, 2019, pp. 1–6.