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Assessment of the Impact of MMC-VSC Intrinsic Energy on Power System Stability

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Abstract — Synchronous generation is increasingly being displaced by renewable energy sources and HVDC interconnectors that both have dissimilar characteristics and operating principles compared to synchronous generators. These factors will lead to a diminishing provision of ancillary services that are normally used to provide network support and grid stabilisation. Conventional services tendered to provide network support rely on the availability of synchronous generation and because of this, future power system operators will have to develop new ways to obtain the ancillary services required. A technology rapidly gaining in popularity for the connection of wind power plants and interconnectors is voltage source converter (VSC) based HVDC. Further advances in the technology have led to the modular multilevel converter (MMC). Due to the design of an MMC there is intrinsic electrostatic energy that could potentially be utilised to provide ancillary services. This paper determines the electrostatic energy available from a typical grid-scale MMC VSC for network support during disturbances and for power oscillation damping. Supporting simulations are provided to ascertain the impact that this electrostatic energy could have on network performance if utilised. Findings in this paper display that although an MMC possesses intrinsic energy, utilising it for frequency response would provide negligible system benefits. However, for POD, the available intrinsic MMC energy did improve system stability which leads to the potential of using multiple MMCs to increase the level of energy and further improve system stability.

Index Terms — Interconnectors, MMC, power oscillations, small-disturbance stability, VSC-HVDC.

I. INTRODUCTION

An energy evolution is underway leading to the incorporation of new technologies into the existing power system, in an attempt to increase sustainability while retaining the same levels of operability. A consequence of these changes will be reduced conventional synchronous generation in favour of power-electronics interfaced renewable generation and interconnectors. This will have an effect on the way in which system stability is maintained, as present methods for providing balancing services become less effective. Existing balancing services are reliant on conventional synchronous generators (SG) that provide the system inertia. This will lead to the requirement for more flexibility from renewable generation and interconnectors [1], in order to maintain system stability, as highlighted by many recent industrial projects such as [2].

In order to facilitate the connection of renewables and interconnectors, voltage source converters (VSC) are a growing technology option, and in the United Kingdom all proposed interconnectors will use VSC technology [3]. Advances in VSC technology have led to the modular multilevel converter (MMC). Due to the characteristics of MMC technology, there may be additional features that could be added to the control system that enable the MMC to provide network support for frequency response or power oscillation damping. The utilisation of intrinsic electrostatic energy may be able to provide support and damping in these areas if power can be injected into the network quickly and without disturbing the additional energy source connected.

The traditional response to disturbances caused by events such as loss of generation, requires large short term system support which is initially provided through the inertia of rotating components (mainly generator shafts), followed by primary frequency containment schemes. Previous research presented in [4-6] investigates the potential impact that VSCs could have on frequency response. In [4] and [5] the aim is to utilise the stored capacitive energy of the DC link to provide frequency support. In [5] the method introduced extracts electrostatic energy using a supplementary control loop that manipulates the DC voltage reference input value to the VSC control system. The use of the intrinsic electrostatic energy was shown to have a positive effect for frequency response; however this system was not based on an MMC topology that would have a different level of stored energy. A multi-terminal MMC-HVDC system is investigated in [6], and frequency response is provided using the stored electrostatic capacitive energy of the submodules (SMs) instead of the DC link capacitors. Conclusions provided in [6] highlight that this method of frequency response is faster than other connected non synchronous energy sources and reduced the rate of change of frequency (ROCOF) following a disturbance. However, the quantity of energy required to produce a significant impact is undefined.
Power oscillations are conventionally counteracted using power system stabilisers (PSS) that are incorporated into the control system of SG. Displacement of SG by RES and HVDC will also lead to displacement of PSSs requiring alternative methods to be implemented. There has also been a rise in FACTS based devices such as SVCs with supplementary control loops designed for power oscillation damping (POD) where the active power is regulated [7]. VSC-HVDC POD has been investigated in [8-10] where it has been shown to be effective. These methods rely on the availability of an energy source connected in order to modulate the level of active power injected into the AC network. Utilising the interconnected energy source could induce unwanted oscillations into the system or network at the other end of the VSC-HVDC line. An alternative method investigated in [11] provides POD through dynamic operation of MMC (SMs). By allowing the SMs to inject or absorb active power, damping of system oscillations was shown to be improved through simulation.

The remainder of this paper discusses the construction and operation of an MMC as a basis for determining the level of stored electrostatic energy within an MMC available for fast frequency support and POD. Simulations are provided to illustrate the effect that releasing MMC electrostatic energy could provide for POD before conclusions and recommendations are presented.

II. MMC DESIGN AND OPERATION

An MMC uses VSC technology and is built up using submodules (SM) in a modular construction allowing easy scalability [12]. The number of SMs is determined by the required levels in the output voltage. Each half bridge SM is a two-level VSC converter and contains two IGBTs and a single parallel capacitor. For safety, each SM contains a bypass switch to remove it from the circuit following a component fault [13]. Each phase of an MMC is made up of one leg which consists of two arms as depicted in Fig.1. An inductor is connected in each arm to supress circulating currents, reduce switching ripples, and limit fault current [14].

The voltage across each SM depends on which state it is being operated in. A SM capacitor may be charging, discharging, or bypassed, depending on the switching arrangement of the IGBTs and the direction of current flow. If arm current is positive and IGBT1 and IGBT2 are Off, then the SM will charge as displayed in Fig.2a. If arm current is negative and IGBT 1 is On and IGBT 2 Off then the SM will discharge as shown by Fig.2b. The SM will be bypassed if arm current is positive and IGBT1 Off and IGBT2 ON or if arm current is negative and IGBT1 OFF and IGBT2 OFF. A comprehensive review of operation is provided in [15] and discusses all SM operating states.

In an MMC VSC-HVDC system, one terminal typically acts to control active power and frequency while the other terminal controls DC voltage and reactive power. The DC voltage at the inverter end \(V_{dc}\) is determined by the sum of voltages across all SMs that are turned on (discharging) as given by \(V_{sm, on}\) in that specific arm, as given by equation (2) where \(l\) and \(u\) denotes the lower and upper arms. The output voltage produced per phase is given in (3). The sum of active SMs per arm has to be able to produce the required output AC voltage. An advantage of VSC and MMC over line commutated converters (LCC) is the ability to control real and reactive independently. During steady state operation, SM voltage deviates and this change in voltage through operation leads to an energy deviation. The difference in energy for each SM is controlled to a nominal value through the voltage balancing controller.

\[
V_{dc} = \sum V_{sm, on} \quad (1)
\]
\[
V_{lu} = n_{on} l_u V_{cap} \quad (2)
\]
\[
V_a = \frac{V_l - V_u}{2} \quad (3)
\]

III. INTRINSIC ELECTROSTATIC ENERGY

Energy is predominantly stored in power systems within the rotating shafts of SG and briefly electrostatically in cables. This energy is directly coupled to the AC network and when
an imbalance between generation and supply occurs, the kinetic energy within the rotating shafts is used as a buffer whilst the controls adjust and regulate the machines. The kinetic energy reduces the rate of change of frequency within the AC network following an imbalance by releasing or absorbing energy. This form of response is an inertial response where no control interaction is needed as it occurs immediately and naturally. The level of system inertia will diminish as SG reduces, leading to ROCOF and frequency limits being exceeded following major disturbances. Alternate forms of energy stored within AC and DC systems could provide suitable network support depending on the value of useful stored energy. This raises the prospect of using electrostatic energy that is stored intrinsically within an MMC-HVDC system as a means to provide system support.

An MMC-HVDC system has intrinsic energy stored within the SM capacitors and the HVDC cable. Energy extracted from an MMC-HVDC system would not be an inertial response as additional sensing and control would be required, but could potentially be extracted quickly and could present an opportunity to enhance AC network support. In an MMC system, the value of stored energy is continually changing depending on the voltage of each SM and how accurately the control systems maintain the nominal voltage. Control systems are required to manage the circulating currents and charging/discharging of the SMs through balancing controls. A SM is operated to be charging/discharge based on its level of charge. A certain amount of energy is required in order for the MMC system to provide the required voltage and active power levels to the AC system. The electrical energy stored within a SM of an MMC can be seen as analogous to the kinetic energy of a generators rotating shaft. Total MMC energy may be given by (4), where \( C_{sm} \) is SM capacitance and \( V_{sm} \) is SM voltage. These are multiplied by the number of SMs per arm(\( n_{sm} \)) and number of arms per converter (\( n_{arms} \)).

\[
E_{mmc} = n_{arms} n_{sm} \left( \frac{1}{2} C_{sm} V_{sm}^2 \right)
\]

(4)

IV. APPLICATION

This section details how to determine the quantity of electrostatic energy within an MMC system. SM capacitor sizing is a trade-off between component physical size, ripple voltage and cost. According to [16], the average stored energy in the converter (\( E_s \)) required to produce a ripple voltage of ± 5% is 30-40 kJ/MVA. An estimate of the energy storage required per SM (\( E_{sm} \)) can be derived which allows the calculation of capacitor size. Nominal SM voltage (\( V_{sm} \)) is required which is given by (5) where the DC link voltage is \( V_{dc} \). SM energy is calculated using (6) where \( S_{mmc} \) is the converter rating. Based on the required energy storage value per SM, the SM capacitance (\( C_{sm} \)) can be determined by (7).

\[
V_{sm} = V_{dc}/n_{sm}
\]

(5)

\[
E_{sm} = \frac{E_s S_{mmc}}{n_{arms} n_{sm}}
\]

(6)

\[
C_{sm} = \frac{E_{sm}}{\frac{1}{2} V_{sm}^2}
\]

(7)

The DC cable connecting the rectifier and inverter has electrostatic energy stored due to the electric charge. Energy for a single pole (\( E_{cable} \)) can be calculated using (8) where \( V_{cable} \) is the DC voltage of the pole and (\( l \)) is the cable length with \( C_{km} \) the capacitance rating per km for the cable.

\[
E_{cable} = \frac{1}{2} C_{km} V_{cable}^2
\]

(8)

A. Frequency containment

The quantity of power available for frequency containment support depends on the available energy, which can be a combination of the SM energy and cable energy, and also on the time over which the energy is released. A longer sustained requirement for energy release leads to a reduced level of power attainable from the system.

B. Power oscillation damping

In order for an MMC to provide power oscillation damping by releasing and absorbing energy, the inverter must operate within pre-defined boundaries and the SM energy must not exceed the limits. A generic comparison between normal SM operation and POD SM operation is displayed in Fig. 3. Remember that no modulation of power at the other end of the HVDC system is required; energy is released and absorbed within the MMC itself to enable POD.

In order to determine the amount of energy available for POD, the allowable energy deviation must be calculated. The minimum DC link voltage (\( V_{dc min} \)) required to produce the desired AC output voltage can be determined by rearranging (3) and substituting \( V_a \) for the required AC output voltage amplitude. Minimum SM voltage (\( V_{sm min} \)) is determined using (9) where \( r \) is the ripple factor of the SM (usually ± 5%). SM energy difference (\( \Delta E_{sm} \)) is determined by (10) and is used to determine total MMC energy available for POD (\( \Delta E_{mmc} \)) in (11).

\[
V_{sm min} = (V_{dc min}/n_{sm}) r
\]

(9)

\[
\Delta E_{sm} = \left( \frac{1}{2} C_{sm} V_{max}^2 \right) - \left( \frac{1}{2} C_{sm} V_{min}^2 \right)
\]

(10)

\[
\Delta E_{mmc} = n_{arms} n_{sm} \Delta E_{sm}
\]

(11)
In order to provide POD, the additional energy is released and absorbed in a sinusoidal manner to counteract typically sinusoidal electromechanical oscillations. The maximum power injected and absorbed ($\Delta \dot{P}$) into the system is given by (12) and depends on the amount of available energy from the MMC and also on time and frequency.

$$\Delta \dot{P} \sin \omega t = \frac{d \Delta E_{mmc}}{dt} \quad \text{(12)}$$

C. Enhancement of power

To enhance the capabilities of an MMC for the purpose of improving power system stability, certain parameters may be adjusted. Obtaining the general solution of (12) for $\Delta \dot{P}$ and assuming that the energy would always be injected between 0 and $\pi$ produces (13). Equation (13) allows different system parameters to be adjusted to view the extent they have on energy available for POD. Financial implications may make certain parameter changes impracticable in reality.

$$\Delta \dot{P} = [0.5C_{sm} \left\{ (V_{nom})^2 − (V_{sm min})^2 \right\}] \frac{n_{sm} n_{arms}}{\pi f} \quad \text{(13)}$$

V. SYSTEM SUPPORT

In order for an MMC-HVDC system to provide network support to the AC system, there has to be sufficient power for the tendered service. To assess the level of intrinsic energy available within an MMC-HVDC system for network support, frequency response and POD scenarios were investigated. System parameters displayed in Table I based on the Transbay interconnector project have been used and an estimated SM capacitance value was determined using (5)-(7).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>400 MW</td>
</tr>
<tr>
<td>DC Voltage</td>
<td>400 kVdc (± 200 kVdc)</td>
</tr>
<tr>
<td>Number of SMs</td>
<td>200 per arm</td>
</tr>
<tr>
<td>SM capacitance</td>
<td>5 mF</td>
</tr>
<tr>
<td>Number of arms</td>
<td>6</td>
</tr>
<tr>
<td>Cable length</td>
<td>85 km</td>
</tr>
<tr>
<td>Cable capacitance</td>
<td>0.1908 μF/Km</td>
</tr>
<tr>
<td>RMS Output Voltage</td>
<td>115 kV</td>
</tr>
</tbody>
</table>

A. Frequency Response

This section determines the amount of power an MMC-HVDC system could theoretically and hypothetically provide during a disturbance. This section aims to highlight what impact the total intrinsic electrostatic energy could provide the network in terms of power injection. It is noted and fully appreciated that the extraction of all electrostatic energy would not be a practical solution as this would cause further detrimental system impacts. This is purely illustrative. The energy within the HVDC cable and the MMC are considered and combined to produce a total value of energy. Estimating the energy stored within the HVDC cable can be deduced from Table I and (8). Similarly, an estimate of MMC energy can be produced using (4). Total cable energy for both poles is 0.644 MJ and total converter energy is 12 MJ, producing a system total of 12.644 MJ.

A hypothetical situation is considered in which all of the energy within the converter is released in a uniform manner to provide network support. Power is determined by the speed of energy release, therefore, the longer the energy release the lower the available power as given using $dE/dt$. Taking the integral of $dE/dt$, the time over which energy is released ($\Delta t$) can be determined. E.g. power deliverable for 1 s is 12.644 MW as displayed in Fig.4.

Practical application of the stored energy within the converter to provide frequency support in this situation can be determined using minimum contracted support services tendered by National Grid (the Great Britain transmission system operator). If the converter was contracted for mandatory primary response, the power output must be sustainable for 20 s. An enhanced frequency contract requires a sustainable power output for 9 s [18]. Table II displays the level of power that would be provided by the system for both tendered services.

<table>
<thead>
<tr>
<th>Table II. Tendered service response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service</td>
</tr>
<tr>
<td>Mandatory primary response</td>
</tr>
<tr>
<td>EFR</td>
</tr>
</tbody>
</table>

![Fig.4. Power deliverable for specific time periods](image_url)

Under these illustrative assumptions where all of the energy within the converter system is extracted, it can be seen that there is a minimal amount of power available for system support. The extraction of intrinsic electrostatic energy from within MMC converters for the purpose of frequency containment following disturbances is therefore not possible without the addition of significant additional energy storage.

B. Power Oscillation Damping

In this section, the energy available for POD is quantified. The required control architecture is omitted from this research but could be investigated if found viable. The method entails injecting and absorbing power to and from the AC network by dynamically changing SM voltage operating points. By reducing SM voltages, stored energy can be gradually released until the SMs are operating at their minimum accepted voltage level. The minimum acceptable DC voltage level has to be capable of producing the desired output AC voltage. Once SM
voltages are at their minimum acceptable level, energy can be absorbed from the AC network by charging SMs back up to their maximum level. This method excludes the use of redundant SMs and does not take into account SM rotation in the switching sequence. This method would impact on the DC link potentially causing higher current to flow from the rectifier to the inverter and would impact the converters ability for AC fault ride through as nearly all the SMs voltage reserve would be used. This would have to be carefully considered against grid-code requirements.

The quantity of power available for injection and absorption is calculated using Table I and equations (9)-(11). The assumed peak AC output voltage based on an RMS voltage of 115 kV (and assuming a transformer turns ratio of 1:1) is 162 kV. The DC link voltage minimum is 324 kV. A SM ripple voltage of ±5% is also taken into consideration. The difference in energy per SM ($\Delta E_{SM}$) is calculated as 3.8 kJ and the total energy deviation of the MMC is calculated as 4.56 MJ. When this energy is applied to a 1 Hz power oscillation where power is injected over half of the period (0.5 s), maximum power injection is 14.32 MW as given by (12). This is the amount of power that could be injected and then absorbed from the AC network. As a percentage of the test scenario converter rating, this equates to 3.58%. The quantity of power injected or absorbed at a specific time can be determined using (14) and is displayed in Fig. 5.

$$P(t) = 14.32 \sin 2\pi (t) \quad (14)$$

![Fig.5. Power injected](image)

VI. SIMULATION TEST SYSTEM

To ascertain if the available energy from an MMC could improve POD, a set of simulations was undertaken. The test system chosen is a single machine infinite bus (SMIB) system, which allows easier interpretation of network dynamics. The test system has been implemented into DIgSILENT Powerfactory 15.2. The synchronous generator is set with constant excitation and does not incorporate any additional control; governor or power system stabiliser. The power from an MMC ($\Delta P$) is attached to bus1 using a controllable load and mimics the power system stabilising capabilities of the MMC and does not absorb or inject power during steady state. The controllable load power injection and absorption is the value of $\Delta P$ e.g. the 14.32 MW calculated and described in Section V. The timing signal offset of $\Delta P$ in relation to the power oscillation can be controlled as well as the amplitude.

VII. RESULTS AND ANALYSIS

The aforementioned test system has been used to determine what level of impact the electrostatic energy could provide for power oscillation damping. As the amplitude for $\Delta \hat{P}$ increases, it is expected that system damping would increase as it can absorb and inject higher levels of power to damp the oscillations. Five amplitudes for $\Delta \hat{P}$ were chosen and are based on the rating of system generation. A 1% value for $\Delta \hat{P}$ represents 1% of the installed system generation e.g. a 2 GW installed capacity would give $\Delta \hat{P}$ a value of 20 MW. The angular offset of the $\Delta \hat{P}$ in relation to the power oscillation was investigated to view how it influenced the damping factor. Results obtained from the angular offset analysis determined that to achieve greater levels of damping, the angular offset for $\Delta \hat{P}$ should be 90° leading the power oscillation. The average damping difference with respect to the natural system damping and rated power of the system is displayed in Fig.6. Similarly, Fig.7 displays the change in damping with respect to the short circuit level of the system.

![Fig.6. Damping factor versus $\Delta \hat{P}$ as a percentage of system rating](image)

![Fig.7. Damping factor versus $\Delta \hat{P}$ as a percentage of system rating](image)

Results in Fig.6 show a linear increase in damping as the amplitude of $\Delta \hat{P}$ increases as a percentage of the system rating. Fig.6 also displays that the damping increase does exist but is marginal. Although there is only a marginal increase from a single or a few converters, as more are eventually connected into the network, this will increase the impact they can provide for system stability. The impact of a 2% amplitude for $\Delta \hat{P}$ on power oscillation damping for the test system is compared against the natural system damping in Fig.8 and confirms that $\Delta \hat{P}$ has an effect on damping. The results obtained confirm that the use of the electrostatic energy deviation in an MMC can marginally increase system damping. However, the value of
damping increase is dependent on the energy deviation that the MMC can withstand and the number of them connected to the network.

![Graph showing comparison of natural damping versus controllable load providing 2% of system power](image)

**Fig. 8. Comparison of natural damping versus controllable load providing 2% of system power**

VIII. CONCLUSION

This paper has theoretically investigated the quantity of intrinsic electrostatic energy in an MMC. The available intrinsic electrostatic energy was determined based on two hypothetical situations for providing AC network support; frequency response and POD. When applied to frequency response situations, it is shown that even if all stored MMC energy was utilised to provide network support, the level of response would be negligible. Furthermore, when converter operating limits and considerations are incorporated, the level of support for frequency response would be greatly reduced. Therefore there is no feasible viability of using the intrinsic MMC energy to provide support in this area. For POD however, theoretical calculations suggest that from an AC system viewpoint, an MMC could assist with POD in a small way if internal submodule voltage variations are permissible. Using a simple SMIB test system, the use of the electrostatic energy and energy deviation within the MMC has been shown to increase damping. Although the level of damping is relatively small from a single MMC, a coordinated approach using multiple MMCs could increase the level of damping on the system. However, operating an MMC to provide POD using the intrinsic energy could cause undesired effects such as oscillating DC currents due to the difference in \( V_{dc} \) between rectifier and inverter [19] and this along with fault contingency would need to be addressed in future work.

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