The Smoothing Transformer, a new concept in dc side harmonic reduction of HVdc schemes

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Abstract—Direct connection schemes have been a subject of recent investigation, offering operational flexibility and substantial reductions in ac components. In these schemes the use of active dc filters has been suggested to replace the conventional tuned passive filter design. This paper presents the smoothing transformer as a new means for reducing dc harmonics at characteristic and non-characteristic frequencies using only passive components. A realistic smoothing transformer design is examined using the New Zealand HVdc system operating in the direct connection mode. The steady-state and transient performance of the smoothing transformer design is compared with that of the existing dc smoothing reactor and filter bank.

I. INTRODUCTION

Unlike ac filters, which provide reactive power compensation to the converter, dc filters have no use except in the reduction of interference caused by dc side harmonics to external equipment. Therefore the design of dc side filters, although a complex exercise[1] permits greater flexibility in the selection of filter components to try and minimise the cost of the converter plant.

The direct connection[2] offers the advantages of compact HVdc as well as variable generator operating frequency. If the ac frequency supplying the converter is variable then the effectiveness of tuned dc side filters reduces. Recently it has been shown that the variation of harmonic voltages in the dc system will cause the conventional filters to function ineffectively[3] and that active or on-line tuning filters are required.

Active dc filters have been considered as an alternative to the conventional passive component design[4]. The active filter injects harmonic current back into the converter to “neutralise” the harmonics currents produced by the converter. Active filters are more complex than passive filters and they require accurate detection of harmonic voltage magnitude and phase, at the transmission line terminals. Moreover the rating of the active harmonic source is not trivial, it must be rated at a similar level to the harmonics produced by the converter.

This paper presents the smoothing transformer principle and initial feasibility investigations. The primary aim of the smoothing transformer is a reduction of the dc side harmonic content at nominal and off nominal ac system frequencies.

II. THE SMOOTHING TRANSFORMER

The smoothing transformer operation is easily described with reference to the circuit of Fig. 1, using ideal components. During steady-state the dc side capacitor \(C\) is charged to \(V_{C}\). If \(C\) is infinitely large then all harmonic voltages \(V_h\) produced by the converter are developed across the primary winding of the smoothing transformer (the capacitor winding). If the transformer ratio is set to unity and the coils connected oriented as shown, then the harmonic voltages \(V_h\) are developed across the secondary winding of the smoothing transformer (the dc line side winding). The resulting voltage at the terminal of the smoothing transformer is the dc component of the rectifier terminal voltage \(V_{dc}\).

If the smoothing transformer is ideal, with perfect coupling and no magnetising current, then no current will flow in the capacitor circuit. The ideal smoothing transformer operates without any harmonic load current and the Volt-Ampere rating of the primary winding and the capacitor is minimal. The converter harmonic voltages are cancelled out, rather than filtered from the transmission circuit. Fig. 2 displays how the conventional smoothing reactor may be modified with the addition of a low current primary winding to create the compact smoothing transformer.

The ideal smoothing transformer will eliminate all dc side harmonics because, unlike conventional filters, it is not tuned.
III. DESIGN CONSIDERATIONS

The viability of the smoothing transformer principle is dependent on its steady-state and transient performance using realistic components. Sizing the capacitor will affect performance. Many present HVdc filter designs use capacitance values exceeding one micro-farad [5]. The capacitor is the most costly element of conventional dc side filters [1] and is restricted in size. Even if the smoothing transformer capacitor can be designed to pass minimal harmonic current it is stressed by the total dc voltage in the same manner as the conventional filter.

One coil of the smoothing transformer carries the full dc line current. This current would force a steel core transformer deep into saturation and may not provide suitable coil coupling for the harmonic voltage cancellation. An air cored transformer will not saturate, but will offer poorer coil coupling. As the smoothing transformer essentially operates on no load, poorly coupled coils may be sufficient to provide harmonic voltage cancellation. For this example, the self inductance of the coil carrying the dc line current is set to 0.16H, this is equal to the NZ HVdc Pole 2 smoothing reactor inductance.

As the capacitor value is finite and restricted in size, the transformer winding ratio cannot be set to unity. The design for the capacitor winding is found using the steady-state equations of Fig. 3. The transformer secondary is open-circuit and applying Kirchoff's voltage law around the primary circuit gives

$$V_h = j\omega_0 L_{11} + \frac{1}{\omega_0 C}$$  (1)

where $\omega_0$ is the angular frequency of the harmonic voltage source.

Under no load conditions, the transformer primary voltage is related to the secondary voltage by

$$\bar{V}_1 = \omega \bar{V}_2$$  (2)

where $\omega$ is the transformer turns ratio.

Rearranging equation (1) to solve for the capacitor circuit current and multiplying both sides by $j\omega_0 L_{11}$ gives

$$j\omega_0 L_{11} = \frac{\bar{V}_h}{j\omega_0 L_{11} - \frac{1}{\omega_0 C}}$$  (3)

Utilizing $\bar{V}_1 = j\omega_0 L_{11}$ and equation (2), equation (3) can be rewritten as

$$\omega \bar{V}_2 = \frac{\bar{V}_h}{j\omega_0 L_{11} - \frac{1}{\omega_0 C}}$$  (4)

For harmonic voltage cancellation to occur

$$\bar{V}_2 = \bar{V}_h$$  (5)
Substitution of equation (5) into (4) gives

$$aV_h = \frac{\varphi_h j\omega_0 L_{11}}{j\omega_0 L_{11} - \omega_0 C}$$

(6)

The transformer turns ratio $a$ can be defined in terms of primary and secondary self inductance.

$$a = \sqrt{\frac{L_{11}}{L_{22}}}$$

(7)

Substitution of equation (7) into equation (6) gives a quadratic equation in terms of the primary winding self inductance $L_{11}$

$$q = L_{11} + \left[-L_{22} - \frac{2}{\omega_0 C}\right]L_{11} + \frac{1}{\omega_0 C^2}$$

(8)

where the two solutions of equation (8) (ie $q=0$ in Figure 4) provide possible values for the self inductance of the smoothing transformer primary winding. With the self inductance of the secondary winding $L_{22}$ set at 0.16H, the quadratic equation (8) is plotted in Fig. 4 for various capacitor values.

The two solutions for the quadratic equation (8) are given by

$$L_{11} = \frac{L_{22} + \frac{2}{\omega_0 C} \pm \sqrt{\left(L_{22} + \frac{2}{\omega_0 C}\right)^2 - \frac{4}{\omega_0 C^2}}}{2}$$

(9)

In the case of the positive root, $\frac{1}{\omega_0 C} < \omega_0 L_{11}$ and the current $\bar{i}$ will lag the voltage $\bar{v}_h$ by 90° (the inductive solution), the phasor diagram for this solution is shown in Fig. 5(a). $L_{11}$ will always be greater than $L_{22}$ and the transformer ratio $a$ will be greater than unity. As $C \to 0$, it is simple to show that $L_{11} \to \infty$ and as $C \to \infty$, $L_{11} \to L_{22}$.

In the case of the negative root, $\frac{1}{\omega_0 C} > \omega_0 L_{11}$ and the current $\bar{i}$ will lead the voltage $\bar{v}_h$ by 90° (the capacitive solution), the phasor diagram for this solution is shown in Fig. 5(b). As $C \to 0$, $L_{11} \to \infty$ and as $C \to \infty$, $L_{11} \to 0$.

Utilizing the parameters $C=0.923\mu F$, $L_{22}=0.16H$ and $\omega_0$ set to the angular frequency of the NZ HVdc link 12th harmonic (50Hz-rated frequency), the inductive solution gives $L_{11}=0.2926H > L_{22}$, and $a=1.35 > 1$; the capacitive solution gives $L_{11}=0.0199H < L_{22}$, and $a=0.353 < 1$.

Once the capacitor and the self inductance of the secondary winding are selected, the choice remains between the capacitive or inductive solution. Both solutions provide total cancellation of a single harmonic voltage at angular frequency $\omega_0$. Rearranging equation (4) gives

$$\frac{\bar{v}_2}{\bar{v}_h} = \frac{1}{a} \frac{j\omega_0 L_{11}}{j\omega_0 L_{11} - \omega_0 C}$$

(10)

For harmonic voltage cancellation to occur the gain of equation (10) must be unity and the phase 0° or 180°, depending on the orientation of the secondary coil. The solutions of quadratic equation (8) guarantee the correct gain and phase for a single harmonic voltage at angular frequency $\omega_0$. Consideration must be given to the smoothing transformer operation at other frequencies; reinforcement of characteristic converter voltage harmonics would be unacceptable. Fig. 6(a) and Fig. 6(b) display the gain and phase plots for the inductive and capacitive designs using the NZ HVdc Pole 2 parameters. The angular frequency $\omega_0$ is set at the 12th harmonic.

Although in both cases at the 12th harmonic the gain is unity and the phase either 0° or 180°, the characteristics are very different. In both solutions equation (10) shows that as $\omega_0 \to \infty$, the gain approaches $\frac{1}{a}$. For the parameters used to create figure 6, $\frac{1}{a}=0.74$ and 2.83 for the inductive and capacitive solutions respectively. In this example, the capacitive solution is clearly not an acceptable design.

The gain of the inductive solution for harmonics above the 12th remains close to unity, and at worst becomes equal to the inverse of turns ratio, 0.74. This implies that a smoothing transformer with this design would remove 74-100% of
the harmonic voltage content above the 12th.

Both cases exhibit a resonance point. In the inductive solution resonance occurs at a non-characteristic frequency just above the sixth harmonic (300Hz). The angular resonant frequency is calculated from

$$\omega_R = \frac{1}{\sqrt{L_{11}C}}$$  \hspace{1cm} (11)

Combining equation (9) with (11) shows that as $C \rightarrow 0$ the resonant frequency $\omega_R \rightarrow \omega_0$. Fig. 7 displays the variation in inductive solution resonant frequency with different values of capacitance.

The resonant frequency can be altered with small variations in dc blocking capacitance. If the resonant point of the smoothing transformer excites a non-characteristic harmonic to an unsatisfactory level a series resistance $R_s$ can be added to the primary circuit to alter the gain of the smoothing transformer. Equation (10) is then replaced by

$$\frac{V_2}{V_0} = \frac{1}{\alpha j\omega_0 L_{11} - \frac{1}{\alpha C} + R_s}$$  \hspace{1cm} (12)

The gain and phase plots for the smoothing transformer with $R_s = 210\Omega$ are shown by the dash-dash line of Fig. 6. This gain reduction ensures that harmonic reinforcement will not occur, but the harmonic voltages on the secondary side of the smoothing transformer are phase shifted and harmonic cancellation at frequencies of interest is less effective.

### IV. Test System

Resonance and coil coupling effects are best quantified with simulation of a smoothing transformer in a realistic HVdc test system. Recently, a dynamic simulation model for group connected operation of the NZ HVdc link Pole 1A was verified with experimental data [6]. This test system has been selected for analysis of the smoothing transformer principle; all example solutions presented above are relevant to NZ HVdc link parameters and the group connection offers variable frequency operation. Moreover application of the NZ HVdc parameters presents a difficult design example, the use of more typical
smoothing reactor and capacitor values of 0.3H and between 2 and 5 pF would show the smoothing transformer to be more attractive.

The dc filters operating on Pole 1A and Pole 2 are identical. The Pole 1A smoothing reactor is of the old 0.8H iron-cored type and the Pole 2 reactor the newer air-cored design. This feasibility study aims to include the latest component designs and for this reason the Pole 2 smoothing reactor has been included in the Pole 1A test system. The generator, transformer and converter models utilized are as published in reference [6] and the transmission line parameters are given in Appendix A.

The smoothing transformer design selected in the previous section is used with the test system, i.e. \( L_{11} = 0.2926 \text{H}, L_{22} = 0.16 \text{H} \) and \( C = 0.923 \text{pF} \). The ideal coupling factor \( k = 0.96 \) used for best harmonic cancellation is unrealistic for a transformer with an air core. The coupling factor selected at \( k = 0.96 \) uses as a basis an air cored laboratory transformer that was tested to exhibit a coupling factor of this order.

A. Steady state performance

The Benmore test system was run to steady-state at full Pole 1A dc line voltage (270kV) and current (1000A) using the electromagnetic transient program PSCAD2-EMTDC [7][8]. Harmonic voltages were calculated at the rectifier wall bushing and at the start of the dc transmission line for two cases. Case A contains the Benmore 0.16H smoothing reactor and the dc side filters (the design for the Benmore Pole 1A dc line filters are given in Appendix B). Case B utilizes the smoothing transformer design selected above with the coil coupling factor \( k = 0.96 \). Table I presents the conventional filter and smoothing transformer primary circuit for the variable frequency operation.

The harmonic current ratings of the smoothing transformer components can be less than that of the conventional filter. Table II presents the rms current flowing in the conventional filter and smoothing transformer primary circuit for the variable frequency operation.

![Harmonic Current Reduction Table](image)

The smoothing transformer has reduced the characteristic voltage harmonics produced at the rectifier wall bushing. At the 12th harmonic for 35Hz operation (420Hz) the smoothing transformer cancellation falls to 43%. This operating condition is near the primary circuit resonance point (306Hz) and in this example primary circuit resistance \( R_p \) has not been implemented to control the smoothing transformer gain. In comparison at this operating point the conventional filter results in a 155% reinforcement due to its own resonance between the smoothing reactor and dc blocking capacitor.

Over all operating frequencies examined the performance of the smoothing transformer is either equal or superior at the 12th harmonic and slightly poorer at the 24th and 36th as compared with the conventional filter. However the 12th harmonic is by far the dominant dc side component of HVdc converters at all generator operating frequencies.

As postulated previously, the harmonic current ratings of the smoothing transformer components can be less than that of the conventional filter. Table II presents the rms current flowing in the conventional filter and smoothing transformer primary circuit for the variable frequency operation.

B. Transient performance

The inclusion of the smoothing transformer on the dc side of a converter must not impair the transient performance of the HVdc link. A dc line-to-ground fault and restart has been selected to examine this performance. Fig. 8 and Fig. 9 display the simulated rectifier end dc line voltage and current respectively for a dc line-to-ground fault and restart for a 50Ω fault resistance.

The fault is initiated at time 3.0s. Utilizing a similar fault detection delay to that of Heffernan [9] the fault control begins at 3.02s, one cycle after the fault initiation. The rectifier firing angle is then advanced to 120° and the inverter left on constant current control, with a 100° limit to the firing angle advance. At time 3.5s a restart is ordered to the rated prefault conditions.

The replacement of the smoothing reactor and conventional dc filters with the smoothing transformer does not degrade the transient performance of the dc link under a dc line-to-ground fault. In each simulation peak fault currents and decay times are almost identical. The link restart to rated conditions is not slowed by the presence of the smoothing transformer. Moreover the smoothing transformer does not induce overvoltages.

![Harmonic Current Table](image)
or oscillations that are dissimilar from the conventional system at the converter wall bushing or on the dc line.

V. CONCLUSIONS

This paper presents preliminary investigations of the smoothing transformer as a means to reduce the cost and increase the operational flexibility of the HVdc terminal. The operating principle, simplified design technique and feasibility simulations have been presented. Unlike the conventional filters, the smoothing transformer achieves substantial harmonic cancellation at off nominal fundamental frequencies, an essential requirement in the direct connected schemes with adjustable speed.

Steady-state simulation studies using the experimentally verified NZ HVdc direct connected test system show that the resonance effects and poor coil coupling will not degrade the performance of the smoothing transformer. These studies also indicate that the current harmonic rating of the dc blocking capacitor is less in the smoothing transformer design in comparison with the conventional filter.

The transient response of the dc link to a dc short-circuit both in terms of peak fault current and recovery voltage, is practically the same as for a conventional filtering arrangement.

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VI. REFERENCES


Fig. 9: Fault initiation and recovery, Pole 1A, NZ HVdc link DC line current; (a) Case A, conventional system, (b) Case B, smoothing transformer \( (k=0.96) \)


Appendix A:

The data for the NZ HVdc transmission line was obtained from New Zealand Electricity. The per pole line resistance is made up of: Overhead line 10.95Ω per pole and submarine cable resistance 1.51Ω. The submarine cable capacitance is 0.333µF/km; a total capacitance of 13.331µF. The series inductance for the overhead line is 1.33mH/km, and the shunt capacitance 0.012µF/km. The submarine cable divides the overhead line into two segments; the South Island and North Island partitions are 530km and 40km respectively.

Appendix B:

Fig. 10. Benmore Pt A dc line filter design.

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