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A Current Reinjection Scheme That Adds Self-Commutation and Pulse Multiplication to the Thyristor Converter

Jos Arrillaga, *Fellow, IEEE*, Y. H. Liu, Lasantha B. Perera, and Neville R. Watson, *Senior Member, IEEE*

***Abstract*—An old concept proposed to double the pulse number of a line commutated converter and designated "dc-ripple reinjection," is made more effective by the use of self-commutating reinjection switches, such as GTO or IGCT. It is shown that the self-commutating reinjection switches can be controlled to force the thyristor valve currents to commutate independently from their respective line voltages. EMTDC-PSCAD simulation is used to verify that this effect adds reactive power controllability, as well as pulse multiplication, to the conventional thyristor converter.**

***Index Terms*—Current source conversion, harmonics, self-commutation.**

I. Introduction

A THIRD harmonic injection via the transformer neutral and returning through the conducting rectifier valves [1] has been shown to reduce the harmonic content in line-commutated three-phase current source converters (CSC). Its main shortcomings are the need of an external third-harmonic current generator, the difficulty of adjusting such source under varying operating conditions and poor efficiency. These problems are eliminated in the dc-ripple reinjection scheme [2], a solution equally applicable to the rectification and inversion processes, where the dc-ripple voltage is used as the commutating voltage for a single-phase thyristor controlled bridge connected in series with the dc line. This circuit injects a voltage component on the dc side and a current component on the ac side of the converter bridge that double the converter pulse number. The original dc ripple reinjection concept has been generalized to achieve pulse multiplication [3] using several reinjection transformers, or multitapped transformer secondaries, and a correspondingly increased number of reinjection switches.

Recent contributions [4], [5] have also described the application of multilevel reinjection techniques to both, self-commutating voltage and current source converters.

In the case of multilevel current reinjection, this paper shows that the magnitude and duration of the reinjection current pulses, used to minimize the harmonic content, can be adjusted to ensure that the modified valve currents are forced to zero during the commutations. This possibility has the important implication that the converter valves do not need to rely on the line voltage to commutate. Taking advantage of this fact, an advanced reinjection scheme is proposed that achieves pulse multiplication and reactive power control using conventional thyristors for the converters and self-commutating switches for the reinjection circuit.

Similar performance could have been achieved with a GTO or IGCT-based multibridge configuration. However, this solution would require the use of many transformer/converter groups and complex winding connections (as compared with the simplicity of the double bridge alternative, which relies solely on the natural phase-shift provided by the star and delta winding arrangement); moreover, the transformers of the outer bridges would require a higher level of isolation from ground as they are connected to larger dc voltage levels.

By keeping the reinjection circuit separate from the main converter bridges, the standard HVDC converter design can be used for the power circuit. Moreover, the risk of commutation failure is greatly reduced due to the cancellation of valve current during the commutation, which eliminates the (current-dependent) overlap, making the time left for the valve to recover its dielectric strength more predictable. The proposed scheme constitutes an important breakthrough that should further increase the field of applicability of the thyristor- based HVDC transmission technology.

II. Basic DC Ripple Reinjection

The line commutated three-phase ac–dc converter bridge complemented by the original dc-ripple reinjection circuit is shown in Fig. 1. The converter transformer is star connected (with accessible neutral point) on the bridge side and delta connected on the primary side (the latter is not shown in the diagram). The reinjection circuit consists of two single-phase transformers (T1 and T2) connected across the bridge through two dc blocking capacitors (C). Their two reverse-connected secondary windings are placed in series with the dc line via a single-phase thyristor bridge.

With respect to the star point of the converter transformer, each dc pole of the three-phase bridge has a nonsinusoidal ripple voltage of period 1/3T (i.e., a triple frequency voltage). This voltage has the same phase relationship on each dc pole and is referred to as the common mode dc ripple voltage.

The basic operating principle is best explained with reference to one half of the bridge (the common cathode side), which is shown in Fig. 2 together with the reinjection circuit. The latter

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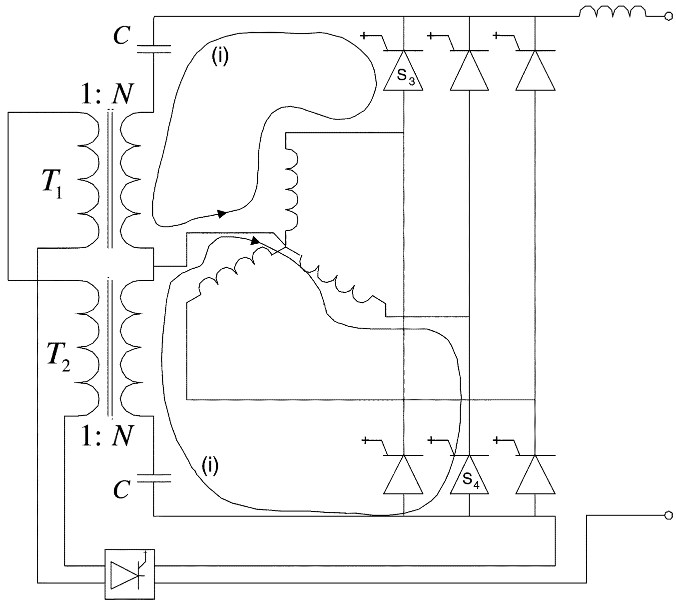

Fig. 1. Bridge rectifier with dc ripple reinjection.

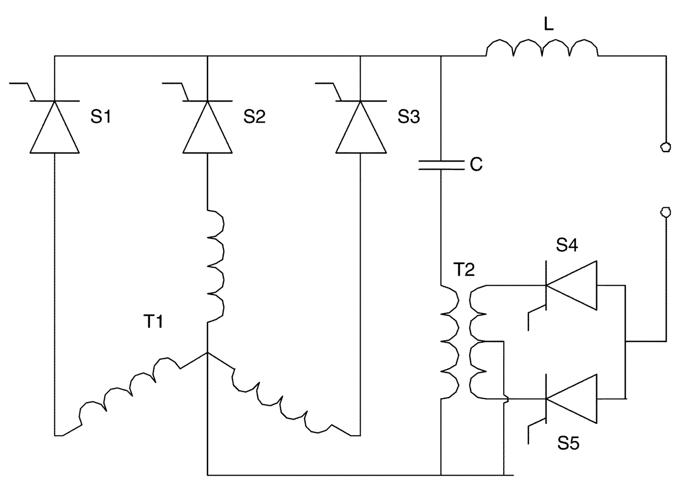

Fig. 2. Basic circuit to describe the reinjection principle.

includes transformer (T2), excited by the dc ripple voltage and a thyristor pair $(S_4–S_5)$.

A. Modified AC Current Waveform

The reinjection circuit acts as a current source, controlled to derive a two level alternating (triple frequency) current proportional to the dc current, the proportionality being determined by the reinjection transformer ratio. Thus for the ideal case of a perfectly smooth direct current, the reinjection current is a rectangular waveform, as shown by (i) in Fig. 3(a).

The reinjection waveform (i) must be phase-shifted by 30° with respect to the corresponding main converter valve [as shown by (ii) in Fig. 3(a)]. With this phase-shift the addition of current waveforms (i) and (ii) produces the modified phase current shown in (iii) for the 120° duration of the conducting region of the valve; outside this region the addition would result in a negative current, which cannot flow through the semiconductor. Similarly, waveform (iv) in Fig. 3(b) shows the current in a second phase of the converter transformer, but displaced by 60° (instead of 120°) with respect to (iii), so that the addition of (iii) and (iv) produces the phase current on the primary side of the converter transformer. Using the reinjection current amplitude calculated in Appendix A the output current, shown in Fig. 3(c), is clearly a twelve-pulse waveform. So the use of a two-level reinjection current doubles the converter pulse number.

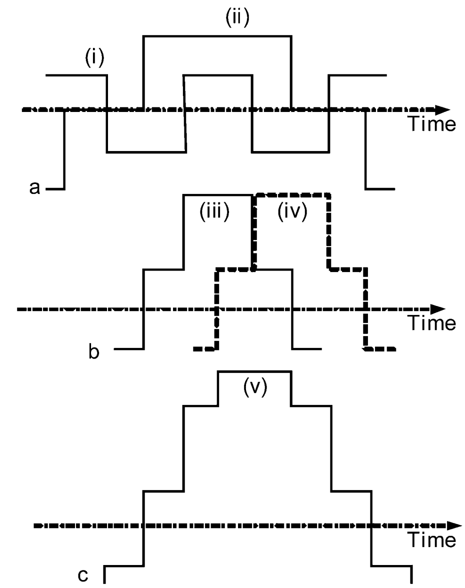

Fig. 3. Synthesis of the 12-pulse current waveform (i) triple-frequency injected waveform (ii) converter current before modification (iii) modified phase current of the converter side winding (iv) second phase (displaced by 60°) (v) resultant phase current on the transformer delta primary.

B. Modified DC Voltage Waveform

As explained above with reference to the ac current development, the reinjection switches are fired 30° after the corresponding main converter valves. Having removed the dc component by means of the blocking capacitor C, the phase-shifted dc ripple voltage, transferred across the reinjection transformer and added in series with the dc voltage output, also doubles the ripple frequency, i.e., the pulse number of the dc voltage waveform.

This effect has been verified in a scaled down experimental converter based on the circuit of Fig. 1. Fig. 4 shows the experimental dc voltage waveforms without (a) and with (b) reinjection, for a firing delay $\alpha = 30°$. The respective six-pulse and twelve-pulse converter behavior is evident in the experimental waveforms.

III. Reinjection Concept in Self-Commutating Conversion

The pulse doubling effect achieved by the dc-current reinjection principle described in the previous section avoids the need for passive filters in line commutated conversion. The latter, however requires substantial reactive power compensation for its operation, much of which is provided by the filters and this fact makes the original reinjection proposal unattractive.

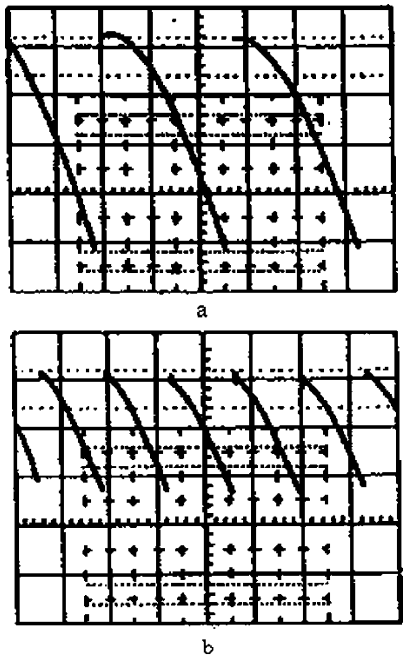

Fig. 4. Direct voltage waveforms for $\alpha = 30^\circ$: (a) without reinjection and (b) with reinjection.

If the reinjection circuit is used with a self-commutating converter, the firing angles of the main valves can be placed at will as they do not need the help of line voltages for their commutations; similarly the firings of the reinjection switches do not depend on the presence of dc-ripple voltage for their commutations. Thus the self-commutated converter can act as a source or sink of reactive power and, therefore, the elimination of the harmonic filters has greater justification in this case.

Moreover, as explained in Section IV, the use of a multilevel, instead of two-level reinjection scheme, adds further economic incentive by providing self-commutation to the conventional (i.e., thyristor based) converter.

IV. Multilevel Current Reinjection

It has been shown in Sections II and III that a two-level current reinjection waveform doubles the pulse number, both in line-commutated and self-commutated three-phase converters. An extension of the analysis to multilevel current reinjection [6], shows that it is possible to multiply the bridge pulse number in proportion to the reinjection level number and that the multiplication factor applies equally to the double bridge configuration. This is an attractive solution for large power converters such as those used in hvdc transmission.

Fig. 5 shows the circuit implementation of the multilevel reinjection theory in the series-connected double bridge configuration. The primaries (N_p) of the two single phase transformers are connected across the bridges terminals through dc blocking capacitors (Cj) and each of their multitapped secondaries (N_k) is periodically connected in series with the dc line; this is achieved by firing simultaneously two opposite-conducting switches (shown in the figure as GTOs) of the symmetrically placed taps on both sides of the reinjection transformer secondaries (e.g., S_{pj1} and S_{nj1}).

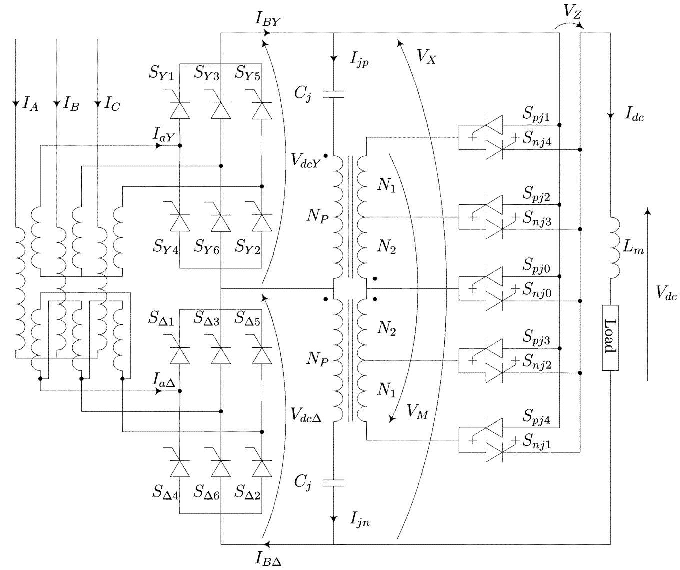

Fig. 5. Five-level reinjection in the self-commutating configuration.

The main differences of multilevel reinjection with respect to the two-level system described in the previous section are shown in the following.

i) *Operating frequency*.
   The repetition frequency of the reinjection current and voltage waveforms is now six times (instead of three) the fundamental.
ii) *Location of the reinjection point*.
   The point of current reinjection for the upper and lower bridges is the midpoint connection between the two bridges, instead of the transformer neutrals.
iii) *Type of reinjection switch*
   The thyristor switches in the reinjection circuit are now replaced by semiconductors with turn-off capability. The relatively low switching frequency required (300 Hz for a 50 Hz supply or 360 Hz for a 60 Hz supply) favors the use of thyristor type devices, such as the GTO or IGCT. In this paper we are using the GTO throughout as a basis for the description.

A. Reinjection Control to Provide Self-Commutation to the Thyristor Converter

In the original pulse multiplication scheme [3] the magnitude and duration of the reinjection steps were optimized to achieve maximum harmonic cancellation. When applying this method to the five-level configuration shown in Fig. 5, for every pair of taps symmetrically placed with respect to the two reinjection transformer secondaries, the pulse number is doubled, with the midpoint tap and short-circuiting switch pair $(S_{pj0}–S_{nj0})$ adding an extra multiplication factor. Thus the five-level configuration can achieve sixty-pulse conversion [5] (reinjection level number) $\times$ 6(reinjection frequency ratio) $\times$ 2(number of main bridges).

However, to achieve complete current cancellation in the commutation regions requires the use of nonoptimal reinjection taps ratios [6]. This causes a reduction in the pulse multiplication factor (providing 48 instead of 60 pulse operation for the five level reinjection configuration of Fig. 5). It will be shown next, that with this

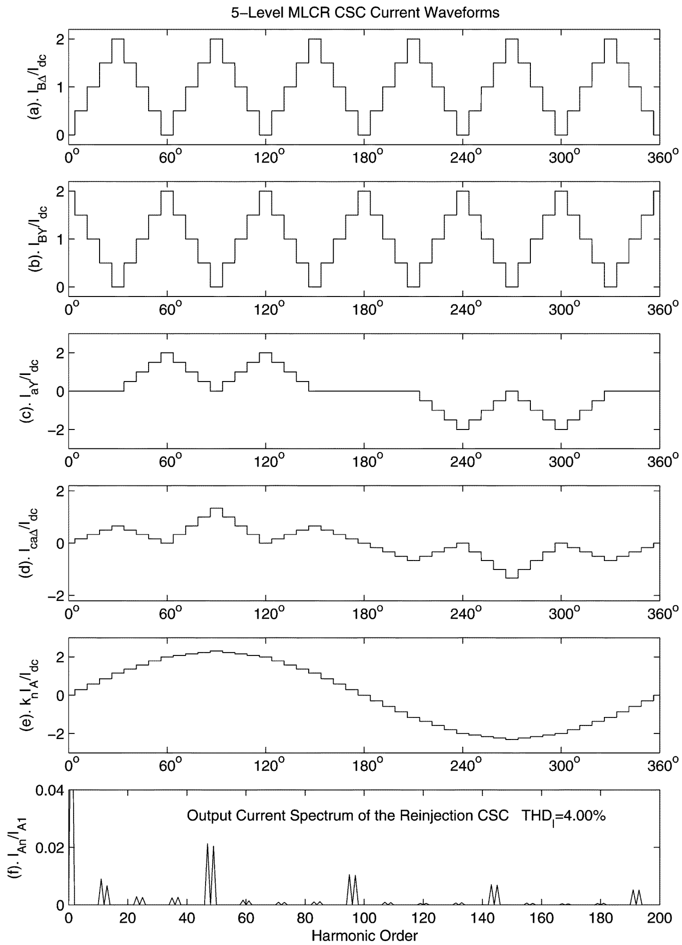

Fig. 6. Theoretical current waveforms of the five-level reinjection CSC.

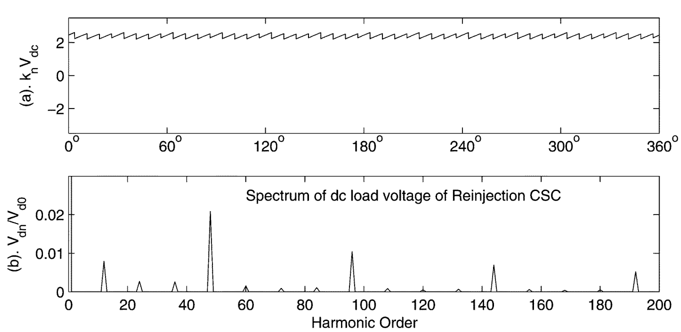

Fig. 7. Theoretical dc voltage of the five-level reinjection CSC.

relatively small sacrifice in the harmonic content, the reinjection current forces the converter valves to zero in the commutating regions; moreover, the zero current switching (ZCS) interval of the five-level reinjection scheme is about six degrees (or 300 μS at 50 Hz), which should be long enough to permit the outgoing thyristor to recover its blocking capability, thus giving the thyristor bridges the opportunity to self-commutate.

Let us consider the circuit of Fig. 5 in steady state with valve (S_{Y1}) conducting. When the reinjection current forces the current of valve S_{Y1} to zero (as will be shown in Fig. 6(d) to be described in Sections V), none of the valves connected to the common cathode (CC) conduct and the dc current will continue to flow via the reinjection path. However, the next step of the reinjection current should force a change in the dc current. This is prevented by the large dc reactor, that develops the necessary transient emf (with negative polarity on the bridge CC bus) to ensure that the anode of S_{Y3} becomes positive with respect to its cathode irrespective of the potential of the ac system voltage. Therefore, provided that valve S_{Y1} has by then recovered its blocking capability, it is possible to turn on valve S_{Y3} to provide a new path for the converter current. Thus the main converter can commutate without the assistance of a turn-off pulse or a line commutating voltage, i.e., it can be of the conventional thyristor type.

B. Theoretical Waveforms

The following theoretical waveforms (derived as described in Appendix B) are shown in Fig. 6 for the five-level reinjection scheme of Fig. 5 operating with a firing angle of -45° (i.e., supplying reactive power, even though the switches are thyristors, as explained in Section IV-A):

- (a) and (b): $I_{B\Delta}$ and I_{BY} are the dc currents of the bridge converters modified by their respective reinjection currents I_{jn} and I_{jp}.
- (c) and (d): $I_{ca\Delta}$ and I_{aY} are the phase "a" currents in the secondary windings of the delta and star connected windings respectively.
- (e): I_A is the phase "a" current on the primary side of the converter transformer (i.e., the output current of the converter).
- (f): I_{An}, is the harmonic spectrum of the output current. It shows that the 47 and 49 harmonic orders as prevalent, which indicates that the converter is on 48-pulse operation. The total harmonic distortion (THD) of the output current waveform, obtained from the formulation given in the Appendix, is 4%.

On the dc side the voltage ripple, transferred via the reinjection transformers and multiplied and shifted by the self-commutating reinjection switches, also increases the number of pulses of the voltage waveform by a factor of four (i.e., to 48 pulses per cycle). The dc output voltage waveform and its harmonic spectrum are shown in Fig. 7.

Regarding switching device duties, the proposed MLCR scheme shares the advantages of other multilevel configurations and in particular the reduced rate of change of current. The main converter valves switch at the fundamental frequency (like in Line Commutated Conversion) and the reinjection valves at either six or twelve times the fundamental frequency. Reinjection switch pairs (S_{pj1}, S_{nj1}) and (S_{pj4}, S_{nj4}) have an RMS current rating of 0.5222 times that of the main thyristors and the corresponding rating for the remaining reinjection switches is 0.7385. The voltage rating (reversed and forward) of the reinjection switches is 0.5176 times that of the main bridge thyristors.

It follows that the conventional series-connected double bridge converter with the assistance of a much lower rated self-commutating reinjection scheme, not only transforms the conventional waveforms into multi-step ac current and multi-pulse dc voltage waveforms, but also provides controllable reactive power. This applies equally to rectifier and inverter operation and to variable frequency supplies. The

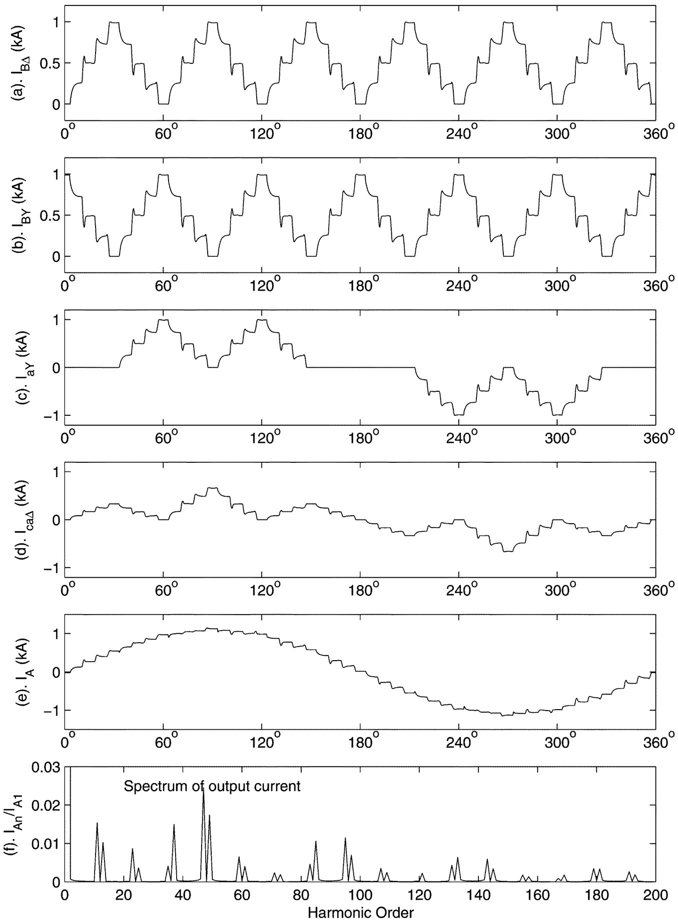

Fig. 8. EMTDC simulation of the current waveforms.

power conversion efficiency is high, because the rectified harmonic power is reinjected into the dc system. Moreover the increased number of taps of the multilevel arrangement does not alter the total current rating of the reinjection switches, as the individual switches share of the dc current reduces in inverse proportion to the number of switches.

V. EMTDC Verification

The scaled down physical model used in Section II for a qualitative verification of the dc voltage waveform of the basic reinjection system, can not be relied upon to provide realistic quantitative verification of high power conversion; in particular, the unrealistically high magnetising current of the scaled down converter transformer heavily distorts the output current waveform. Electromagnetic transients simulation is a better alternative in this respect. Accordingly, the converter system shown in Fig. 5 has been modeled in the PSCAD/ EMTDC package. The main parameters used in the test system, are 5% leakage reactance (based on 100 MW/100 kV) for both the main and reinjection transformers, a smoothing inductance of 2 H and a load resistance of 1 Ω. The converter transformer is connected to an ideal three-phase voltage source. As in the theoretical model described in Section IV, the reinjection ratios are controlled to ensure valve current cancellation in the commutation regions.

Figs. 8 and 9 show the results of the simulation when the converter is absorbing 100 MW and generating 100 MVAr (which corresponds to a firing angle of -45°). Like in the theoretical case [Fig. 6(e)], the simulated output current [Fig. 8(e)] and its spectrum [Fig. 8(f)] show predominantly 48-pulse operation, with a THD of 4.65%, as compared with the 4% of the theoretical waveform. Similarly, Fig. 9 illustrates the predominantly 48-pulse behavior on the dc side of the converter.

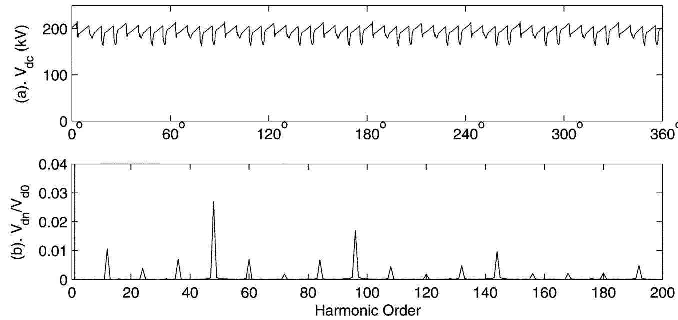

Fig. 9. EMTDC simulation of the dc voltage.

The observed small content of 12-pulse related harmonic content (i.e., 11 and 13 orders on the ac side and 12 on the dc side) were also present in the theoretical results. Their levels, however, are small enough (in the region of 1%) to fall within present harmonic standards.

The main differences between the theoretical and simulated waveforms relate to the presence of snubber components in the PSCAD converter model, which tend to distort the waveforms with high frequency content in the regions where the switchings take place. No attempt has been made to optimize the snubber circuits to suit the proposed configuration.

Clearly the PSCAD/EMTDC simulation confirms that the series-connected double bridge thyristor converter commutates naturally even at negative firing angles, that it is capable of generating reactive power and that the ac current and dc voltage waveforms are perfectly acceptable without the need for harmonic filters on either side of the converter.

VI. Conclusion

It has been shown that the use of a multilevel current reinjection scheme with turn-off switching capability can force the valve currents of an hvdc converter to zero in the commutation region for a sufficient time to permit the off-going thyristor to re-establish its voltage blocking ability. Therefore, the converter valves can be made to commutate without the assistance of the line voltage (i.e., they can be of the conventional thyristor type). Since the reinjection switches can be turned off at will, the converter valves can be switched on at negative firing angles. This provides the thyristor converter with reactive power control capability. It is achieved at the expense of a small reduction in the converter harmonic elimination capability. However, a five level reinjection scheme has been shown to provide 48-pulse operation, which is likely to satisfy harmonic standards without the need for passive filtering on either side of the converter. The theory has been verified by Electromagnetic Transients Simulation.

The proposed solution potentially shares the benefits and problems of the conventional line commutated current source conversion. The probability of commutation failure is substantially reduced due to the cancellation of valve current in the commutation regions; this effect eliminates the (current-dependent) overlap and, therefore, the time left for the valve to recover its dielectric strength is more predictable. Following dc line faults the proposed solution provides fast and reliable control of the dc current due to the presence of smoothing reactors.

With the addition of reactive power controllability and multi-pulse conversion, the proposed hybrid (thyristor valves and self-commutating reinjection switches) scheme provides a very effective solution that should encourage the continuing use of CSC-HVDC Transmission.

Appendix A
Derivation of the Reinjection Ratio to Double the Pulse Number

The current waveform of Fig. 3(b) (iii) is an odd function with half-wave symmetry and its general Fourier term is given by the expression

$$\begin{aligned} a_n &= \frac{4}{\pi}\left\{\int_{\pi/6}^{\pi/3}(1-\mathrm{FB})\sin(nx)dx + \int_{\pi/3}^{\pi/2}(1+\mathrm{FB})\sin(nx)dx\right\} \\ &= \frac{4}{\pi}\left\{\frac{(1-\mathrm{FB})}{n}[-\cos(nx)]_{\pi/6}^{\pi/3} + \frac{(1+\mathrm{FB})}{n}[-\cos(nx)]_{\pi/3}^{\pi/2}\right\} \end{aligned} \tag{1}$$

where $n = 1, 3, 5, 7, \ldots$ and FB is the ratio of reinjection current to the direct current (Fig. 10).

It can be shown that for $n = 5, 7, 17, 19, \ldots$ (i.e., the six-pulse characteristic harmonics)

$$a_n = \frac{4}{n\pi}\left\{\frac{-\sqrt{3}}{2} + \mathrm{FB}\left(\frac{\sqrt{3}}{2}+1\right)\right\}. \tag{2}$$

These harmonics will be cancelled when

$$\mathrm{FB}\left(\frac{\sqrt{3}}{2}+1\right) = \frac{\sqrt{3}}{2}$$

i.e.,

$$\mathrm{FB} = \frac{\sqrt{3}}{2+\sqrt{3}} = 0.4641.$$

Appendix B
Analysis of the Multilevel Output Current Waveform

Generalizing the reinjection system of Fig. 5 to multiply the pulse number by "m" instead of four, it can be shown [6] that the output line current $I_A(\omega t)$ in Fig. 6(e) is given by

$$I_A(\omega t) = \left(\frac{1}{k_n}\right)\left[I_{aY}(\omega t) + \sqrt{3}I_{ca\Delta}(\omega t)\right] \tag{3}$$

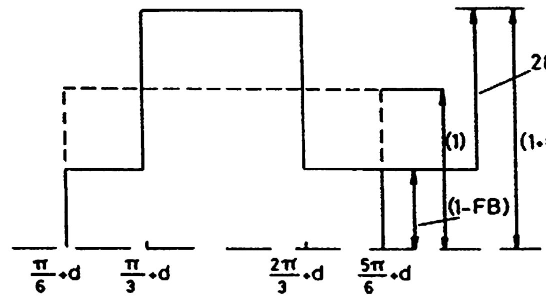

Fig. 10. Current waveform in the main thyristors, dashed line—unmodified current equal to 1 p.u., solid line—modified current waveform.

where k_n is the turns ratio of the converter transformer, and the Fourier components of the currents in phase "a" of the star and delta secondary windings are

$$\begin{aligned} I_{aYn} &= \frac{2}{\pi}\int_0^{\pi} I_{aY}(\omega t)\sin(n\omega t)d(\omega t) \\ &= \frac{16\left[1-(-1)^n\right]I_{\mathrm{dc}}}{n\pi(m-1)}\sin\left(\frac{n\pi}{12(m-1)}\right) \times \cos\left(\frac{n\pi}{6}\right)S_{An} \\ &\text{for } m \geq 3,\ n = 1, 2, 3, \ldots \end{aligned} \tag{4}$$

$$\begin{aligned} I_{ca\Delta n} &= \frac{2}{\pi}\int_0^{\pi} I_{ca\Delta}(\omega t)\sin(n\omega t)d(\omega t) \\ &= \frac{16\left[1-(-1)^n\right]I_{\mathrm{dc}}}{3n\pi(m-1)}\sin\left(\frac{n\pi}{12(m-1)}\right) \times \cos\left(\frac{n\pi}{6}\right)S_{Bn} \\ &\text{for } m \geq 3,\ n = 1, 2, 3, \ldots \end{aligned} \tag{5}$$

where

$$S_{An} = (m-1)\sin\left(\frac{n\pi}{6}\right) + \sum_{i=1}^{m-2} i\sin\left(\frac{n\pi}{3} + \frac{in\pi}{6(m-1)}\right)$$

$$S_{Bn} = (m-1)\sin\left(\frac{n\pi}{3}\right) + 2\sum_{i=1}^{m-2} i\cos\left(\frac{n\pi}{6}\right) \times \sin\left(\frac{n\pi}{3} + \frac{in\pi}{6(m-1)}\right).$$

The Fourier components of the output current $I_A(\omega t)$ are

$$I_{An} = \frac{16\left[1-(-1)^n\right]I_{\mathrm{dc}}}{\sqrt{3}k_n n\pi(m-1)}S_{Cn}S_{Dn}$$
$$\text{for } m \geq 3,\ n = 1, 2, 3, \ldots$$

where

$$S_{Cn} = \sin\left(\frac{n\pi}{12(m-1)}\right)\cos\left(\frac{n\pi}{6}\right)$$

$$S_{Dn} = 2\left(\cos\left(\frac{n\pi}{6}\right) + \frac{\sqrt{3}}{2}\right)S_{An}.$$

The fundamental peak value of the converter output current, derived from (6) is

$$I_{A1} = \frac{32\sqrt{3}I_{\rm dc}}{k_n\pi(m-1)}\sin\left(\frac{\pi}{12(m-1)}\right) \times \left[\frac{(m-1)}{2} + \sum_{i=1}^{m-2} i\cos\left(\frac{\pi}{6} - \frac{i\pi}{6(m-1)}\right)\right].$$

The converter rms line current output is

$$I_{A_{\rm rms}} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_A(\omega t)^2 d(\omega t)} = \frac{2\sqrt{4+\sqrt{3}}}{3k_n} I_{\rm dc}\sqrt{1 + \frac{11-6\sqrt{3}}{13(m-1)^2}}. \quad (6)$$

The THD of the output current for the five-level configuration of Fig. 5 is

$$\mathrm{THD}_I = \sqrt{\frac{2I_{A_{\rm rms}}^2}{I_{A_1}^2} - 1}\,\Bigg|_{m=5}. \quad (7)$$

Finally, the average dc voltage is given by

$$V_{\rm dc} = \frac{48\sqrt{3}V_m}{k_n\pi(m-1)}\sin\left(\frac{\pi}{12(m-1)}\right) \times \left[\frac{(m-1)}{2} + \sum_{i=1}^{m-2} i\cos\left(\frac{\pi}{6} - \frac{i\pi}{6(m-1)}\right)\right] \quad (8)$$

where α is the firing delay of the main bridge thyristors.

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