Ripple Reduction in DC Line of a PWM Drive by Direct Reinjection

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Abstract—This letter describes an alternative solution to passive and active filter arrangements on the dc side of the converter. The circuits of dc-side ripple elimination are based on direct reinjection of the ripple in series with the dc line.

Index Terms—Drives, harmonics, ripple.

I. INTRODUCTION

Substitution for dc motors by pulsedwidth modulation (PWM)-inverter-fed drives leads to high harmonics levels in the dc side of the converters. Higher order harmonics can be a source of electromagnetic interference and often need to be filtered. The conventional solution for the reduction of dc side ripple is the passive filter. It is an easy solution, but, unfortunately, the required reduction of ripple results in a filter of excessive size and weight [1]. It is also an expensive solution [2]. The use of an active filter in combination with a passive has recently been successful in reducing higher harmonics. The letter analyzes the operation of the proposed scheme and provides experimental verification of a six-pulse model of an ac/dc converter link to a PWM inverter. In many cases, a smoothing reactor is used in the output of a rectifier to eliminate the current harmonic. Typically, this reactor is connected in series with the rectifier and a load, or a power inverter to feed an ac machine. When our proposal is operating, there is no commutation, unlike the earlier dc-side filters. Therefore, it is considerably simpler than the above alternatives since it does not involve any switching devices. The proposal uses a transformer whose secondary is connected in a similar way to the smoothing reactor mentioned previously [3]. The secondary conducts the direct current and also the ripple current, but is phase opposed, with the result of reducing harmonics. In the filter, it is also necessary to include a capacitor in the transformer primary circuit in order to block the dc voltage [see Fig. 1(a)].

II. DESCRIPTION OF THE REINJECTION SCHEME

The reinjection circuit [Fig. 1(a)] consists of a 1:1 ratio reinjection transformer T with its primary winding in series with a capacitor C and the secondary winding in series with the dc output. If C is sufficiently large, most of the ripple will be transferred to the reinjection transformer, which will, in turn, provide an opposing voltage source in series with the dc output. It must be understood that the transformer secondary winding, being in series with the dc output, will carry the full dc current, therefore, its core must be dimensioned to avoid saturation. Fig. 1(b) shows the circuit formed by a rectifier, a series inductor, a filter, and the load. This load is formed by a capacitor, the induction motor inductances, the resistances, the transistors, and the diodes of the bridge. The load impedance is not linear, and the resultant harmonics can produce the electromagnetic interferences that we seek to eliminate. Fig. 1(c) shows the substitution of the PWM control and motor load of Fig. 1(b) for the harmonic source $V_h$. Considering only the ac components, since the dc voltage is blocked by the capacitor [Fig. 1(c)], we obtain

$$V_{id} = V_h - V_a$$
$$V_{id} = V_c + V_a$$
$$V_{id} = V_c - V_a = V_c.$$  \(1\)  \(2\)  \(3\)

Equation (3) indicates that the unfiltered harmonics content is equal to the capacitor voltage drop and should, therefore, be reduced in proportion to the increasing capacitor size.

If the voltage in the load $V_{id}$ reduces to zero, it will also reduce the harmonic current to zero. For this, the capacitor voltage is reduced to the smallest level practical.

III. ANALYSIS OF REINJECTION CIRCUIT

On the assumption that the dc current has no effect on the reinjection circuit, the Laplace formulation provides the following expressions for the circuit of Fig. 1(c):

$$V_h = \left(\frac{1}{C} + Ls\right)I_C(s) + MsI_{hb}(s)$$
$$V_h = MsI_C(s) + [Ls + Z_h(s)]I_{hb}(s).$$  \(4\)  \(5\)

$Z_h$ is formed by the sum of the series inductance and the impedance of the rectifier. Solving (4) and (5) gives the line current $(I_{hb})$

$$I_{hb} = V_h(s)\cdot\frac{1}{C} + Ls - Ms$$
$$\left[\frac{1}{C} + Ls\right][Ls + Z_h(s)] - (Ms)^2.$$  \(6\)

The voltage $V_{id}$ can be expressed as

$$V_{id}(s) = I_{hb}(s)Z_h(s)$$

and, therefore, the transfer function becomes

$$V_{id}(s) = \frac{Ls + Z_h(s)}{Z_h(s) + [Ls + Z_h(s)] - M^2s^2}.$$  \(7\)

For the two extreme cases of zero and infinite blocking capacitance, the transfer function becomes

$$\frac{V_{id}(s)}{V_h(s)}\bigg|_{(C=0)} = \frac{Z_h(s)}{Ls + Z_h(s)}$$
$$\frac{V_{id}(s)}{V_h(s)}\bigg|_{(C=\infty)} = 0.$$  \(8\)  \(9\)

In this last case it is necessary to suppose that the elements are ideal (zero resistance and perfect coupling).

When $s = j\omega$

$$X_1 = j\omega L_X = j\omega M_Xc = j\omega L_C Xc = -\frac{j}{\omega C}$$

and solving (4) and (5) for $I_{hb}$ when

$$j\omega L = \frac{j}{\omega C}.$$  \(11\)  \(12\)
This can be a large current, considering that $X_m$ (the transformer mutual coupling reactance) will be a relatively low value as compared with the impedance of the dc transmission link. According to (3), a complete harmonic cancellation would require infinite capacitance. For a cost-effective solution, the harmonic levels must stay below certain specified limits. To meet this condition, the natural resonance offered by the combination of the capacitor and the reinjection transformer must occur at a frequency well below that of the lowest
expected characteristic harmonic. The criterion used here for the selection of the capacitor is to prevent the amplification of any harmonic frequency down to the fundamental, which is achieved when

\[ C > \frac{1}{\omega_r^2 L} \]  

(14)

where \( \omega_r = 2\pi f \) and \( f \) is the fundamental frequency of the ac system.

Using the parameters of the system described in the following section, the above condition is satisfied with a 112.5-\( \mu \)F capacitor. The selection of the capacitor depends on the lowest frequency at which the drive operates. In this letter, the frequency of operation is 50 Hz. To assess the sensitivity of the transfer function to variations in the blocking capacitor value, (8) has been solved for a test system using PSPICE with a source of 100 V peak. The results are shown in Fig. 2(a) for capacitor values from 100 to 500\( \mu \)F. In the simulation, \( L \) consists of 112.5\( \mu \)F and \( C_f \) = 24\( \mu \)F, according to the circuit of Fig. 1(b). At very low frequencies, the use of a capacitor below 112.5\( \mu \)F amplifies slightly the initial voltage. However, the transfer of the harmonic voltages shows rapid attenuation for increasing frequencies. The use of a larger capacitor further increases the attenuation.

IV. EXPERIMENTAL VERIFICATION

The operating principle of the reinjection scheme has been verified in a six-pulse rectifier. The inductance and resistance of the two reinjection transformer windings are 0.09 H and 40\( \Omega \) and its core was designed to provide a linear magnetizing characteristic for a 500-V peak voltage level. As discussed in the previous section, the blocking capacitor required to avoid any ripple amplification down to the 50-Hz frequency has a value of 112.5\( \mu \)F and the actual capacitor selected for

the test system is 141\( \mu \)F. Fig. 3 illustrates the harmonics current measured with and without the reinjection circuit. Considerable reductions are noticed with the reinjection circuit in service, particularly at the larger harmonic frequencies. The current \( I_{hi} \) has been measured with a resistance shunt (3\( \Omega \)) installed between the series inductance and the filter. Referring to the frequency spectra [Fig. 3(b) and (d)] and, in particular, to the 50 Hz (the first characteristic harmonic) the ripple voltage reduces to approximately 9%, a value that coincides with the simulated results (Fig. 2) derived earlier with the PSPICE program.

V. CONCLUSIONS

A direct reinjection of the harmonics content has been shown to provide an effective alternative to the conventional passive and active filters. Theoretical and experimental results have demonstrated the ability of the scheme to eliminate harmonics. Its effectiveness improves with increasing frequencies, while at the low end of the spectrum the reduction requires large sizes. The ripple reinjection scheme proposed can provide an ideal solution for variable-frequency unit-connected schemes.

REFERENCES