Combined DC–Filter and optimized Modulation to Absorb DC–Link Oscillations of Cascaded H-Bridge Converters

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***Abstract*--Cascaded H–bridge converters can be employed suitably for applications that need higher voltages, avoiding series connection of semiconductor switches. However, DC-link oscillations are a practical issue when converters operate under three-phase unbalance condition and/or single phase operation. Resultant low frequency oscillations would affect the harmonic performance as well as efficiency of the converter. This paper proposes four various external DC active filter circuits, aiming at cancelling these oscillations. Proposed circuits are simulated, and their performances on compensation of oscillations are compared to select the best choice. Furthermore, an optimized switching pulse train is developed to attenuate the harmonics objectively. The solution is then combined with the selected DC active filter circuit to limit the peak of the oscillations. The combined method can be applied to modular AC–AC multilevel converter as an application of the suggested technique. Simulation results confirm that the combined method limits the DC–link oscillations of cascaded H-bridges more suitably compared to other proposed circuits, and can be employed for single-phase applications as well as unbalanced three–phase systems.**

***Index Terms*— Active DC-filter, cascaded converters, DC-link oscillations, combinatorial minimization, optimized modulation.**

I. INTRODUCTION

MULTILEVEL converters can potentially overcome the practical issues concerned with the series connection of semiconductor switches to increase the system voltage [1]-[3]. Figure 1(a) shows a typical cascade H-bridge converter in which the harmonic performance is expected to be improved in addition to raising the output voltage. However, each H-bridge sub-module exchanges active power between the electrical network and the load through the other H-bridge converters. This power exchange depends on the magnitude of the fundamental voltage of each H-bridge converter, as well as the magnitudes of low order harmonics.

Furthermore, the exchanged power would affect considerably on the DC–link voltage of the H-bridge converter, causing low frequency oscillations. Further, when H-bridge converters introduce different power exchanges from each other, then balance of capacitor voltages is a major concern that could possibly lead to instability.

This paper proposes a DC-filter to be connected across the DC–link capacitor, resulting in compensation of the voltage oscillations. The suggested method is then examined and simulated with MATLAB to assess its performance along with suitability for the cascaded H-bridge converters. Moreover, the method is modified to get better performance on attenuating the DC–link oscillations. Then a conventional optimized switching technique is combined with this modified circuit to damp significantly the DC–link oscillations. Simulation results confirm that this latter combined proposal presents considerable improvement in adsorption of the DC–link oscillations.

II. PROPOSED DC-FILTER

Here we examine connection of various DC passive/active filtering circuits [8] across the DC capacitor to compensate its low-frequency oscillations imposed by the exchange of active power. Predominant frequency of these oscillations is 100/120 Hz when power system operates at 50/60 Hz. Figure 1(a) shows an uncompensated cascade converter (two H-bridges), which is simulated with SIMULINK. A PI controller is employed to control the phase of the H-bridges output voltages such that the average DC-voltage remains fixed at 150 V. Switching pulses are swapped between the two H-bridges to force both capacitor voltages vary similarly. Figure 1(b) illustrates the DC capacitor variations when no filter is designed to absorb the oscillations.

It is clear from Fig. 1 that the oscillations cannot be significantly damped (peak-to-peak variation is about 16V or 10.67%). Hence, the following sub-sections suggest and examine new designs that use active filters to damp the oscillations effectively.

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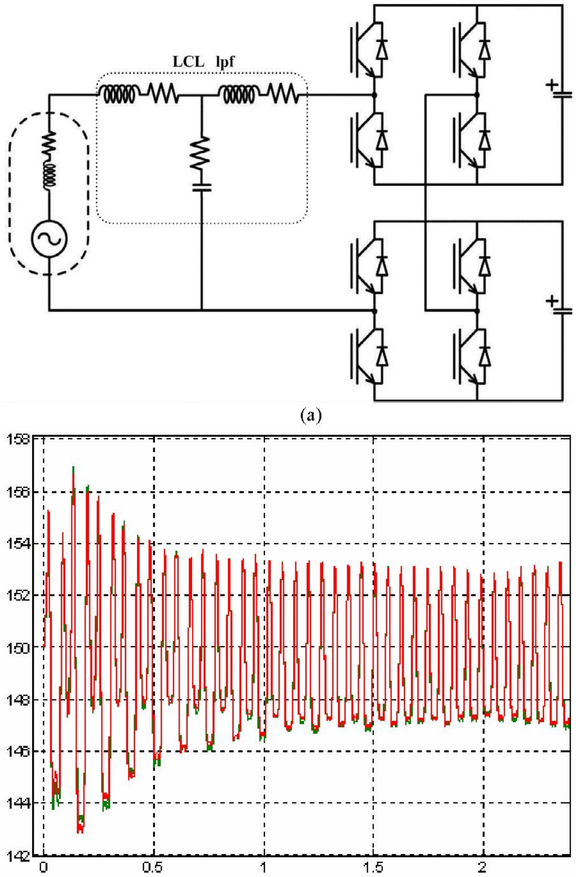


(b)

Figure 1. (a) Cascaded two H-brige converter without any compensators, (b) DC-link oscillations excluding any DC-link filters.

The low-frequency oscillations of the DC-link can also be filtered using a tuned LC passive filter that its natural frequency is 100 Hz. This would effectively reduce the oscillations. Nevertheless, the disadvantage of the PLC method is that the 100 Hz passive LC filter has big parameters, and occupies huge space.

A. Independent DC source (IDC): Proposition 1

Design of Fig. 2(a) uses the idea of passive LC-filter to damp the oscillations out; but, the inductance of the passive filter is replaced with the primary winding of a transformer. The secondary of transformer is connected to a low-power low-voltage H-bridge converter through a passive low-pass *LCL* filter. The suggested design provides much more satisfactory attenuation of DC-link oscillations compared to the PLC. Thus, the control and operation of this proposal is examined in detail.

First, the oscillations of DC-link voltage (V_f) is extracted by subtracting the average value from the exact value of the DC-link voltage like it is depicted by Fig. 2(b). Using the zero-order hold (ZOH) function of SIMULINK, the 10 kHz sampled signals are converted to continuous-time signals for analyzing the sampled continuous-time system. Then, the volt-second balance law is applied to each switching period (100 μs) to find the duty ratio of each switch as follows:

$$V_{dc} \times t_{on} = V_f \times 100(\mu s) \quad (1)$$

Where the source V_{dc} is the DC voltage of the compensating H-bridge converter, and t_{on} is the on-time duration of each switch. Computing t_{on} of the switches, they are applied to the extra H-bridge converter. The whole design is simulated with MATLAB, where Fig. 3(c) shows both voltages of primary and secondary windings of the transformer with a turn ratio slightly bigger than one. Also, Fig. 3(d) illustrates the compensated DC-link oscillations, which is considerably attenuated up to about 2.5 V peak-to-peaks (or 1.67%).

It is noticeable that the compensating elements including the DC source, transformer, low-pass filter and switches operate under low-voltage low-power conditions. This also makes low extra-cost to the cascaded converter. However, in practice, as the magnitudes of oscillations are being lowered, using (1), duty ratios of switches are being decreased as well. This implies a limit on reduction of magnitudes of oscillations as a drawback of the method. To remedy this issue, the voltage V_{dc} is needed to be decreased when the oscillations are going to be considerably attenuated. This also will add extra-cost to the converter for developing regulated controllable DC voltage (V_{dc}).

B. Variable DC source (VDC): improvement of proposition 1

One disadvantage over the proposition 1 is that presence of a variable DC source would allow damping of the oscillations down to a desirable level. This issue can be overcome by replacing the independent DC source V_{dc} with a full-bridge rectifier that is supplied through the capacitor C_5 in Fig. 2(d). Capacitor C_5 absorbs the DC value of the DC-link voltage, where the oscillations are transferred to the rectifier. Thus, the average DC value of capacitor C_7 depends directly to the magnitude of DC-link oscillations. This way provides a controllable DC source, which in turn can compensate even low magnitude oscillations by having the possibility of proper switching pulse width modulation according to (1).

Also, the control algorithm is like that of the IDC method stated by (1) as shown by Fig. 3. However,

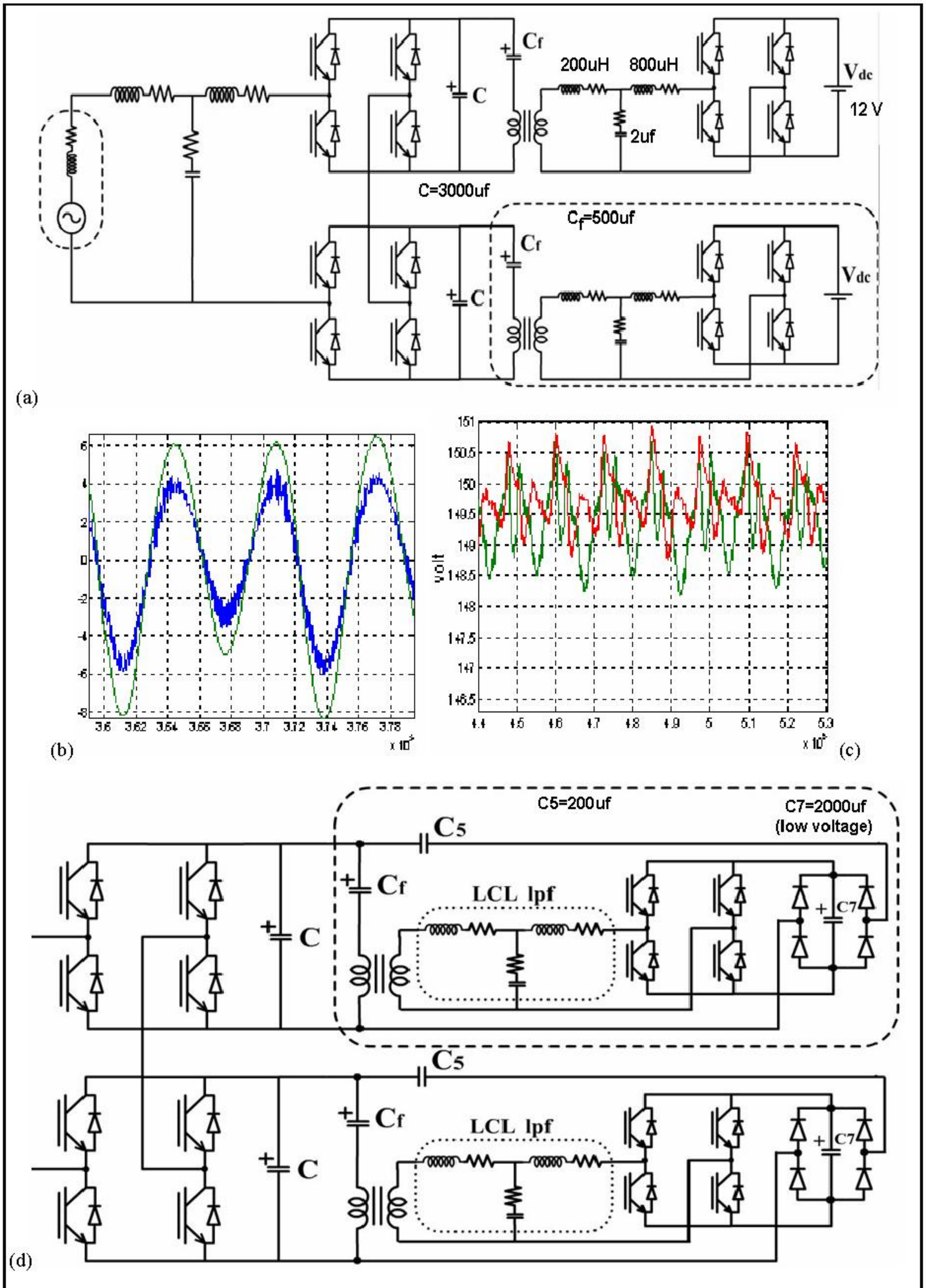


Figure 2: (a) The DC-links of two cascaded H-bridge converters are regulated by the suggested topology of IDC, (b)–(c) simulation results concerned with voltages of the two DC-link capacitors, and (d) the modified proposed method of the VDC.

the only modification is that V_{C7} is used for sampling instead of V_{dc}. Figure 3 illustrates how the DC-link oscillations are extracted out of the capacitor voltage V_{C7}. It also calculates the on-time durations t_{on}, and eventually generates the switching pulses required for the auxiliary H-bridge converter.

III. OPTIMAL SWITCHING TECHNIQUE

Conventional multilevel PWM schemes produce fundamental voltages for all H-bridges within the cascaded converter, which are different. This would cause real power exchange between the H-bridges themselves as well as the cascade converter and the network, making voltages of the H-bridges unbalanced. To remedy this issue, an optimization problem is arranged to find the best switching instants [4]-[7].

Assume N cascade H-bridge converters in which each H-bridge is switched such that its output voltage introduces both half-wave and quarter-wave symmetry. Thus, the Fourier series include only odd sinusoidal terms ($\sin(n\omega t)$). Figure 4(a) presents an example for N = 4, where determination of five switching instants is enough to recognize the whole period. Also, Fig. 4(b) gives the resultant output voltage of the whole cascade converter, where the general description of the nth harmonic voltage using the Fourier series for N H-bridges and K switching instants within each quarter-wave is calculated as below:

$$V_{a-n} = \frac{4}{n\pi}\sum_{i=1}^{N}\sum_{j=1}^{K}(-1)^{k+1}\cos(n\alpha_{ij}) \qquad (2)$$

Where the angle α_{ij} is the jth switching instant of the ith H-bridge converter, and V_{a-n} is the nth harmonic of the cascade converter voltage.

It should be noted that the Fourier series (2) indicates half-wave symmetry in the voltage waveform. Now we can arrange an optimization problem with an objective of minimizing the remaining odd harmonics starting from the third up to $2NK-1$ [5]. This also is subjected to several constraints. For example, one necessary condition is needed to be satisfied. The fundamental components of the AC output voltages for all the H-bridges of the cascade converter have to be identical. Also, obvious conditions on angles α_{ij} have to be maintained satisfy as follows:

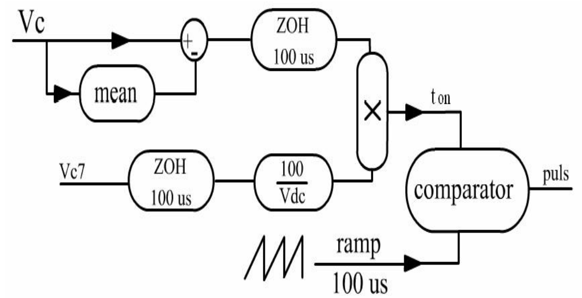


Figure 3. Control of on-duration pulses for the auxiliary H-bridge converter based on the extracted oscillations.

$$\text{Minimize} \sum_{\substack{n=3 \\ (n \text{ is odd})}}^{2NK-1} V_{a-n}^2$$

$$\text{Subject to:} \begin{cases} \frac{4}{\pi}\sum_{j=1}^{K}(-1)^{k+1}\cos(\alpha_{ij}) = \frac{|V_{a-1}|}{N}, & \text{for } i=1,2,\ldots,N \\ 0 < a_{i1} < a_{i2} < \cdots < a_{iK}, & \text{for } i=1,2,\ldots,N \end{cases} \qquad (3)$$

The above optimization problem is considered to be combined with the variable DC source compensation proposal to damp the DC-link oscillations. Nevertheless, we added other conditions to the optimization problem to make sure that the *pulse widths are bigger than a certain value* (e.g. 10 μs) for implementation purposes. This value depends on the switch specifications, including the on and off times that limits the switching frequency. Moreover, two adjacent switching instants need to be bigger than a certain value as well. Table I lists the resultant switching instants described by angles in degrees. These switching angles are repeated for other parts of the waveform because of the assumed quarter-symmetry as well as half-wave symmetry of the voltage waveform.

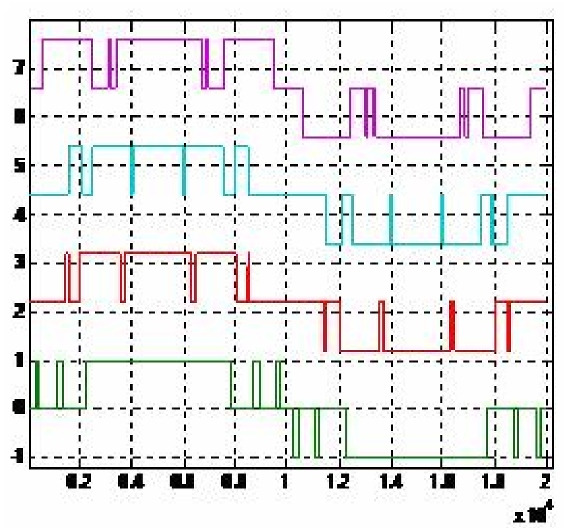
TABLE I
CALCULATED SWITCHING INSTANTS OF A CASCADED CASE FOR N = 4.

Cascaded H-Bridge No.	1	2	3	4
Switching Instant 1 in DEG	5	25	27	10
Switching Instant 2 in DEG	7	27	38	44
Switching Instant 3 in DEG	20	35	45	55
Switching Instant 4 in DEG	23	64	72	56
Switching Instant 5 in DEG	40	67	73	60

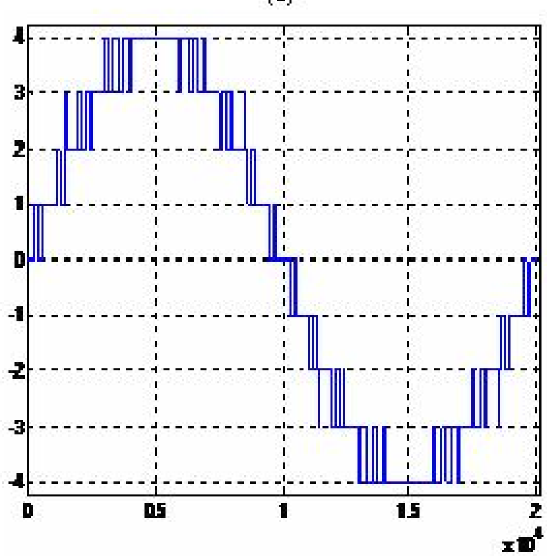
Table II summarizes the simulation results obtained by the suggested methods, including the uncompensated case, the IDC, the VDC and combination of optimal switching plus the VDC.

TABLE II
SIMULATION RESULTS CONCERNED WITH THE PEAK-TO-PEAK OSCILLATIONS OF THE DC-LINK OF H-BRIDGE CONVERTERS.

Compensation Method	Oscillations (maximum Peak-to-Peak)	Oscillations (average Peak-to-Peak)
IDC	2.0%	1.5%
VDC	2.0%	1.5%
VDC + optimized modulation	1.5%	1.2%
Uncompensated	10.67%	8.9%



(a)



(b)

Figure 4. (a) Optimized solutions for a cascaded converter including four H-bridges, and (b) resultant output voltage of the cascade converter.

IV. CONCLUSIONS

This paper describes the DC-link oscillations concerned with H-bridge cascade converters when the number of H-bridges is smaller than four. While an uncompensated simulation with two H-bridges show considerable oscillations on the DC-link, an active DC-filter method is proposed and examined to lower peak-to peak of the oscillations. This method is called independent DC-source (IDC) in which there would be a limit in reduction of the magnitude of the oscillations. Thus, the method is improved by proposing variable DC source (VDC) method. Furthermore, an available optimized switching technique is programmed, and combined with the improved proposal VDC to manage harmonic cancellation along with filtering the DC–link oscillations. These methods are all simulated with SIMULINK to compare their performance on lowering the DC-link oscillations. Simulation results show that these methods successfully control the oscillations; among them the combined optimized modulation along with the VDC performs as the best solution.

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