
General Properties of Multilevel Converters

Multilevel converters use many different topologies depending on the type of conversion, the power range, etc., but the basic properties are always the same. These properties are reviewed here.

1.1. Time-domain: multilevel waveform and apparent switching frequency

Standard two-level converters use the variation of the duty cycle of these levels to regulate the average power flowing between a current source and a voltage source, which is generally referred to as pulse width modulation (PWM). Multicell converters combine such two-level waveforms to create multilevel waveforms. This is illustrated in Figure 1.1 with three of these two-level PWM waveforms of the same duty cycle and frequency but with a phase-shift of 120° . When the duty cycle is less than $1/3$, the sum of the three is also a square voltage taking values 0 and 1. But when the duty cycle increases, the overlapping creates higher levels as shown in case of a duty cycle of 50% (right). In practice, since each cell handles a fraction of the power, the composition of PWM results generally in an average rather than a sum, and the

amplitude is then n times smaller. This property gave the name of multilevel converters that is in general used only for series connection and medium-voltage (MV) applications, although the same combinations of waveforms can be found on the current waveforms of parallel multicell converters used in low and very low-voltage (LV) applications.

In the same figure, we see that when the reference is constant the sum of the three signals is also a 2-level square voltage, but its frequency sometimes called “apparent switching frequency” is three times the frequency of each of the PWM signals. This property is interesting since higher switching frequency may reduce the size and weight of the filters, but it is generally obtained at the cost of increased switching losses; however multicell converters generate waveforms with a better trade-off between apparent switching frequency and switching losses. This property is generally highlighted for parallel multicell converters which are often called “interleaved converters”; interleaving or phase-shifting the PWMs is the key to generate higher switching frequency, but it is also found on voltage waveforms of a series multicell converter.

It can be seen that multilevel waveforms and higher apparent switching frequency are closely related and may apply to current and/or voltage waveforms of series and parallel multicell converters.

The PWM waveform generated by a commutation cell needs to be filtered. Filtering components act as integrators so the ripple is a triangular waveform and its amplitude reaches a maximum for a duty cycle of 50%. This property transfers to the sum of n PWM waveforms, but the maximum amplitude is reduced by a factor n^2 due to both the reduction in amplitude of the square voltage and the increase in the apparent frequency. Interleaving also creates an “apparent duty cycle” that is different from the individual duty cycle:

$$D_{\text{apparent}} = \text{mod}(n.D, 1) \quad [1.1]$$

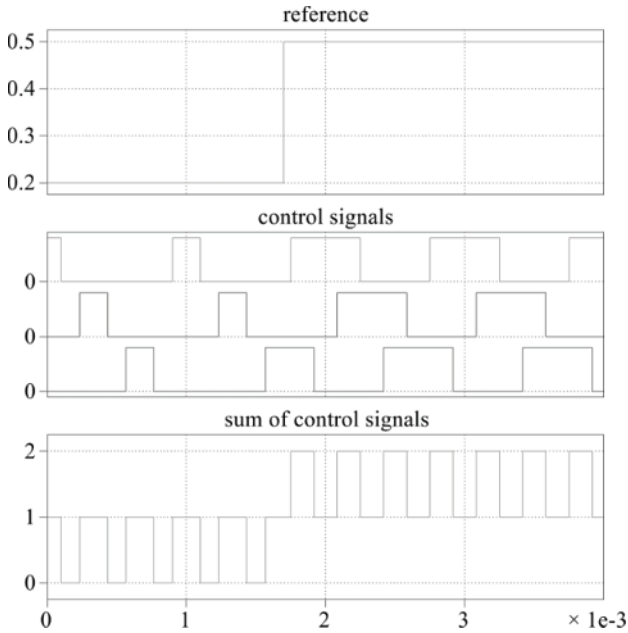


Figure 1.1. Time domain sum of PWM signals. For a color version of the figure, see www.iste.co.uk/meynard/vectorized.zip

The resulting ripple is shown in Figure 1.2. It can represent both the current ripple on the low-voltage side (LV side) of a series or parallel multicell commutation cell, and the voltage ripple on the high-voltage side of a parallel multicell commutation cell.

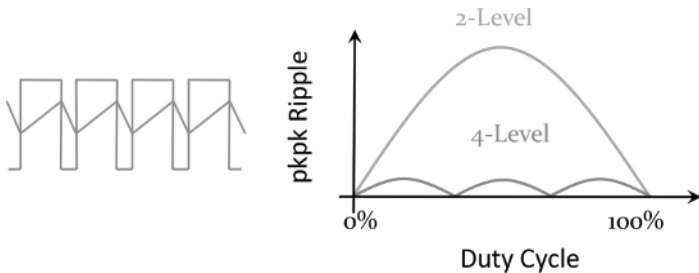


Figure 1.2. Ripple as the integral of a PWM waveform. For a color version of the figure, see www.iste.co.uk/meynard/vectorized.zip

1.2. Frequency domain: harmonic cancellation

Using the term phase-shifted PWMs is not the best way to describe interleaved control especially to understand how harmonics compose in multicell converters; it would be more appropriate to speak of time-delayed PWM signals because the consequence on phase is different for each rank. If s_1 is a signal of period T with amplitudes and phases of harmonics equal to a_n and ϕ_n , and s_2 is equal to signal s_1 of period T but delayed by T_d , we get:

$$s_2(t) = s_1(t - T_d) = \sum_{n=0}^{\infty} a_n e^{j\left(\frac{2\pi}{T}(t - T_d) + \phi_n\right)} = \sum_{n=0}^{\infty} a_n e^{j\left(\frac{2\pi}{T}t + \phi_n - n\frac{2\pi T_d}{T}\right)} \quad [1.2]$$

Therefore, it can be seen that the phase of each harmonic in s_2 is the phase of s_1 augmented by the phase-shift of the fundamental multiplied by the harmonic rank. The vector diagrams corresponding to three PWM signals delayed by 1/3 of period are shown in Figure 1.3: the first diagram corresponding to the fundamental rank gives a zero-sequence, the second diagram related to rank 2 is a negative sequence and the third diagram corresponding to rank 3 is a zero-sequence. This means that if the three PWMs have the same amplitudes and duty cycles, the amplitude of the first and second harmonic of the sum will be zero, and the third will be the sum of those of the three signals.

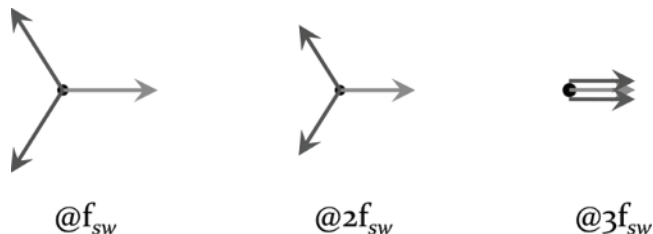


Figure 1.3. Harmonic composition of time-delayed signals. For a color version of the figure, see www.iste.co.uk/meynard/vectorized.zip

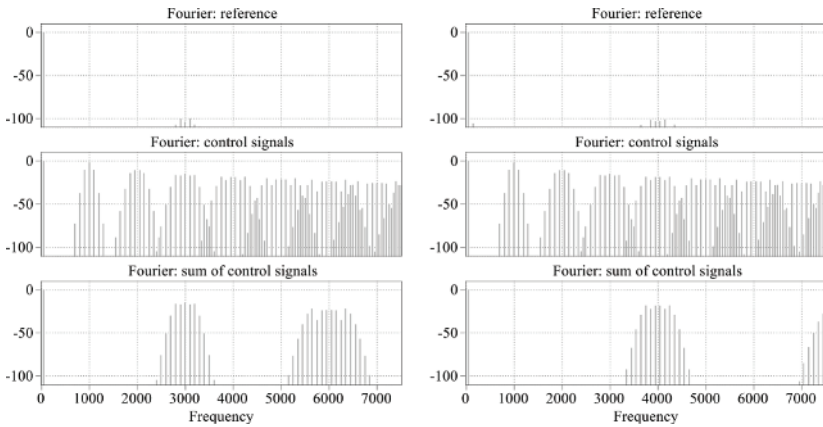


Figure 1.4. *Spectrum resulting of interleaved PWM*

This directly generalizes for the sum of n PWM signals that contain only harmonics at the multiples of $n.f$. When the PWM is modulated to generate an Alternating Current (AC) waveform, the property is maintained with a good accuracy if there is a sufficient difference between the modulation and switching frequency. This can be verified by looking at the waveforms in Figure 1.4.

1.3. Transient response

The dynamic response of converters is mainly influenced by the limitations of power semiconductors on the one hand, and by the energy stored in the filters on the other hand. Power semiconductors cannot accept more than a certain amount of switching losses, and cannot accept very short 'on' or 'off' pulses. For this reason, in two-level converters the switching frequency is generally precisely imposed by sampling the duty cycle reference at the switching frequency or at twice the switching frequency; that means that for a period, or half a period, the control cannot react to any perturbation and this is the first factor limiting the response

time. The square waveform generated by a two-level commutation cell needs to be filtered, and this 'inertia' is the second factor limiting the overall response time. If a second-order filter is used, the attenuation required determines its natural frequency directly. Output ripple must generally be limited to a very low value, and as a consequence, the transfer function and the response time of the commutation cell equipped with its filter is dominated by the filter. This is illustrated in Figure 1.5, the green curve corresponding to the sampling block and the blue line corresponding to a second-order filter with 1% ripple at the output. When multicell conversion is considered, the improved waveforms allow increasing the cutoff frequency of the filter, and as can be seen in the same figure, the influence of the sampling block rapidly becomes a the main limiting factor.

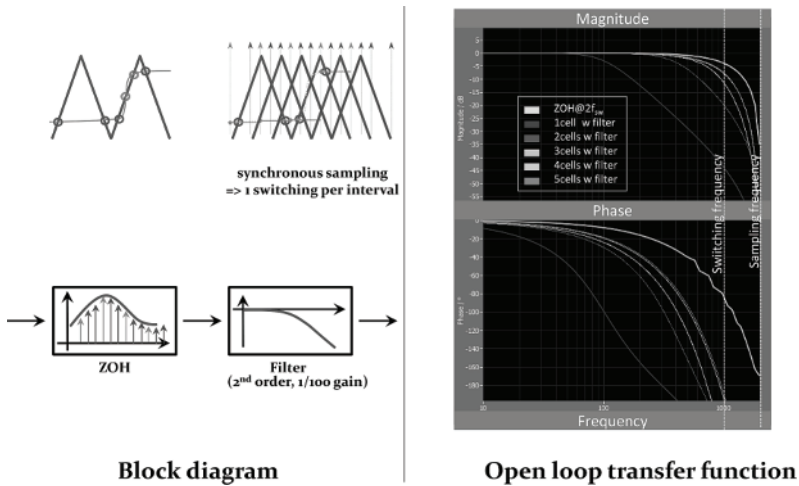


Figure 1.5. Factors limiting the dynamic performance. For a color version of the figure, see www.iste.co.uk/meynard/vectorized.zip

1.4. Conclusion

Multicell conversion has inherent advantages that makes it an increasingly attractive solution which can be considered

for any application. It provides more degrees of freedom to the designer, but it also makes design more complicated since many options can be considered. For this reason, it seems important to develop an approach that allows fast evaluation of several solutions with different numbers of series and parallel cells, the particular case of 1 cell in series and 1 cell in parallel corresponding to the case of standard two-level conversion. Exploring these degrees of freedom is the aim of this book and the models that are presented in it.

