Comparison of Sinusoidal and Resistive Modulation Strategies for Single Phase Four Quadrant Converters

Gergely György BALÁZS , Miklós HORVÁTH , István SCHMIDT *

Abstract

Growing numbers of consumers distort AC networks with harmonics. Therefore, suppression of the network pollution should be considered. This problem can be solved by using "network-friendly" converters. In our study we examined two modulation strategies of single phase four quadrant converters. If these methods are used, converters behave like sinusoidal, or resistive current loads of the network, which enables "network-friendly" operation. The examined sinusoidal and the resistive modulation strategies are known, but the differences between the two methods have not been studied before. This paper deals with the comparison of these two strategies. By comparing their consumed RMS currents we defined a coefficient (k[%]), which depends only on the total harmonic distortion of the network voltage (THD_u). We demonstrated that at high THD_u resistive modulation method is more favorable.

Keywords: converter control, harmonics, modulation strategy, optimal control, power quality, pulse width modulation (PWM)

1. Introduction

Nowadays, high amount of electric energy is converted by power electronic devices. DC-link converters are widespread, e.g. in controlled electric drives, household appliances, welding equipments, computer systems, compact fluorescent lamps [CFLs], entertainment electronics, etc. Today, most of these equipments contain simple diode rectifiers.

In one period of the AC network voltage, the current consumption of these rectifiers is discontinuous (discontinuous-conduction mode, DCM). The periodically discontinuous current load causes distortion in the network, because the harmonic content in the consumed current is high. Therefore, the RMS (root mean square) current load of the AC network substantially grows. Extra losses reduce the electric energy transmission capacity of the network. The distorted current is full of harmonics, so the originally sinusoidal voltage waveform on the consuming points may become trapezoidal.

Eventually, qualitative parameters of the energy supply are affected: potential difficulties include various kinds of economic and technological problems, breakdowns, switching surges, overheating, and electromagnetic disturbances. [1]

Because of the increasing number of consumers who pollute the network with harmonics, both the suppliers and the consumers have to face dangerous phenomena.

To solve this problem, electric consumers should be equipped with "network-friendly" converters. The most common way of implementation is the use of high frequency pulse-width modulated (PWM) converters. [2, 3]

2. Typical "network-friendly" converters

Several types of power converters are capable of "network-friendly" operation. Simple converters (like the widespread BOOST or BUCK) allow unidirectional power flow. Such one-quadrant converters contain much fewer semiconductor elements than four-quadrant full-bridge converters (4QS).

In all these constructions the consumed current of the converters can be proportional to the AC network voltage waveform or its fundamental by the use of PWM controlled semiconductor switching elements (e.g. IGBTs). High-frequency harmonics caused by switching should be filtered.

In this study, we used full-bridge

* Gergely György BALÁZS, PhD Stud.; Dr. István SCHMIDT, Prof. PhD – Department of Electric Power Engineering, University of Technology and Economics, Budapest, Hungary /Miklós HORVÁTH, DiFilTON-ARC Ltd., Budapest, Hungary

four-quadrant converters (4QS) connected to the one-phase AC network. [4]

3. The 4QS converters

Figure 1 represents the schematic circuit diagram of a full-bridge four-quadrant converter.

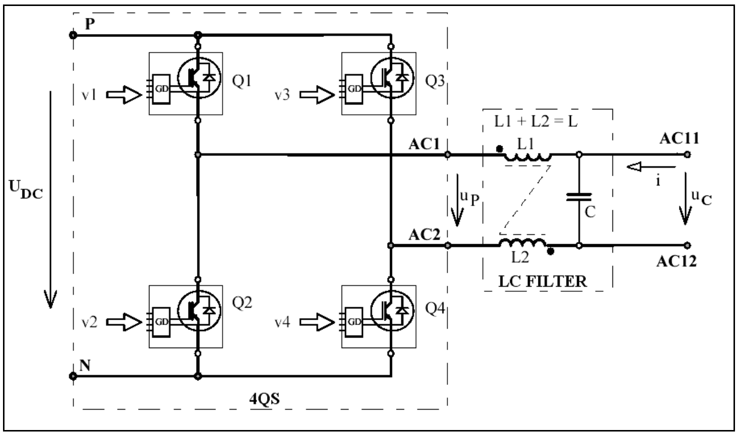


Figure 1. 4QS Schematic circuit diagram

Figure 2 shows the PWM control signals and the typical waveforms of the 4QS. The alternative control is used, it allows switching between three voltage values on the AC side of the converter (u_p=0, +u_{DC}, – u_{DC}).

If the δT pulse width of the switching elements' control signals are modulated with sinusoidal wave, the mean value of the consumed or the regenerated *i* current will be sinusoidal, providing the modulation is synchronized with the network voltage waveform.

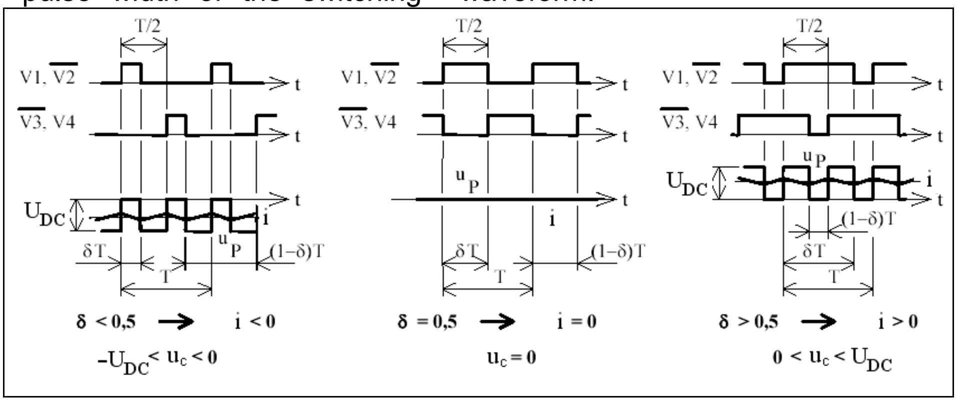


Figure 2. PWM control signals and typical waveforms of 4QS

Figure 3 shows the operation of the 4QS by presenting an example for sinusoidal modulation.

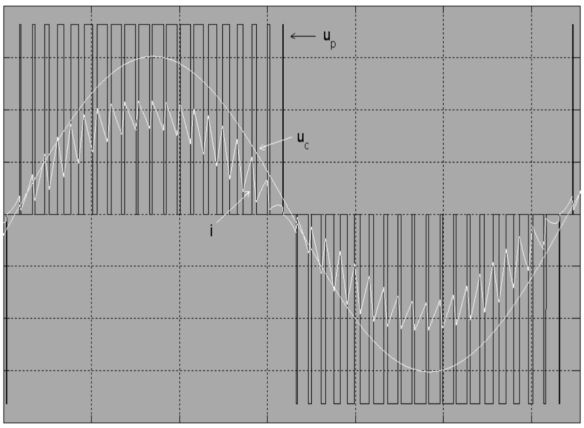


Figure 3. Example for sinusoidal modulation

As this converter is capable of four-quadrant operation, the power flow can be bidirectional between the load (connected to P-N terminals) and the AC network (connected to AC11-AC12 terminals).

If the network supplies power, the converter operates as a "network friendly" rectifier, in the other case, it operates as a regenerative inverter. The control circuit of the 4QS is not represented in Figure 1. [5, 6]

Study the case when several other consumers distort the network voltage waveform, which feeds the 4QS converter. At every time instant, if the current [*i(t)*] is controlled to be proportional to the network voltage instantaneous value [$u(t)=u_C(t)$], the *u(t)*/*i(t)* ratio will be constant. It means that the converter behaves like a resistive load.

For the adequate operation, the modulation signal should be proportional to *u(t)*. This is the resistive modulation method.

According to another modulation strategy, the PWM modulation enforces sinusoidal network current, which is proportional to the fundamental of the distorted network voltage waveform [$u_1(t)$]. In this case, the converter operates as a sinusoidal load. The modulation signal should be proportional to $u_1(t)$. It is called sinusoidal modulation method.

The question is, which control method is more favourable?

To answer this question we compared the sinusoidal and the resistive strategies by examining the root-mean square (RMS) value of the consumed AC network currents [I_{RMS}] in both cases, while keeping constant the DC-side power of the converter. (It is an important requirement of modern “network-friendly” converters to reduce the I_{RMS}.)

4. Features of Sinusoidal and Resistive Current Loads

The converter’s DC-side power mean value is equal with the AC-side power mean value, if we assume that the converter and the LC filter are ideal.

If infinite network is supposed, $u(t) = u_C(t)$ distorted network voltage and the fundamental are as follows:

$$u(t) = \sum_{i=1}^{n} U_i \sin(i\omega t + \varphi_i)\,,\; u_1(t) = U_1 \sin(\omega t) \quad (1.a,b)$$

where:

i=1,2…n harmonic numbers,

U_i: harmonic voltage amplitudes,

φ_i: phase angles of harmonics,

$\omega=2\pi f_1$,

f_1: fundamental frequency)

By using the sinusoidal modulation strategy, on the AC-side the converter enforces current ($i_{\sin}$) which is proportional to the instantaneous value of the network voltage fundamental ($k_{\sin}$ [A/V]: coefficient):

$$i_{\sin}(t) = i_1(t) = k_{\sin} \cdot u_1(t) = k_{\sin} \cdot U_1 \sin(\omega t) \quad (2)$$

If the instantaneous values are equal as in (2), then the amplitudes will be the following:

$$I_{1\_\sin} = k_{\sin} \cdot U_1 \Rightarrow U_1 = I_{1\_\sin} / k_{\sin} \quad (3a,b)$$

By using the resistive modulation strategy, on the AC-side the converter enforces current (i_{ohm}) which is proportional to the instantaneous value of the distorted network voltage (k_{ohm} [A/V]: coefficient):

$$i_{ohm}(t) = k_{ohm} \cdot u(t) = k_{ohm} \cdot \sum_{i=1}^{n} U_i \sin(i\omega t + \varphi_i) \quad (4)$$

If the instantaneous values are equal as in (4), then the amplitudes of each harmonic will be the following:

$$I_{i\_ohm} = k_{ohm} \cdot U_i \Rightarrow U_i = I_{i\_ohm} / k_{ohm} \quad (5a,b)$$

We assumed that the consumed powers of the two strategies are equal (at same DC-side load) [$P_{\sin}= P_{\text{ohm}}$]. It can be computed with the peak values:

$$P_{\sin} = \frac{1}{2} U_1 I_{1\_\sin} \overset{!}{=} P_{ohm} = \frac{1}{2} \sum_{i=1}^{n} U_i I_{i\_ohm} \quad (6)$$

Substituting (3a) and (5a) into (6):

$$P_{\sin} = \frac{1}{2} k_{\sin} U_1^2 \overset{!}{=} P_{ohm} = \frac{1}{2} k_{ohm} \sum_{i=1}^{n} U_i^2 \quad (7)$$

By using (7) and based on the definition of the RMS (Root Mean Square) values, we got:

$$k_{\sin} U_{1RMS}^2 = k_{ohm} U_{RMS}^2 \quad (8)$$

Substituting (3b) and (5b) into (6):

$$P_{\sin} = \frac{1}{2} \frac{I_{1\_\sin}^2}{k_{\sin}} \overset{!}{=} P_{ohm} = \frac{1}{2} \frac{1}{k_{ohm}} \sum_{i=1}^{n} I_{i\_ohm}^2 \quad (9)$$

By using (9) and based on the definition of the RMS, we got:

$$k_{ohm} I_{\sin\_RMS}^2 = k_{\sin} I_{ohm\_RMS}^2 \quad (10)$$

Based on (8) and (10):

$$\frac{k_{\sin}}{k_{ohm}} = \frac{I_{\sin\_RMS}^2}{I_{ohm\_RMS}^2} = \frac{U_{RMS}^2}{U_{1\_RMS}^2} = \frac{U_{1\_RMS}^2 + U_{harm\_RMS}^2}{U_{1\_RMS}^2} \quad (11)$$

By computing the square root of (11) and based on the definition of the total harmonic distortion ($THD_u=U_{harm\_RMS}/U_{1\_RMS}$), we defined a coefficient k[%]:

$$k[\%] = \frac{I_{\sin\_RMS} - I_{ohm\_RMS}}{I_{ohm\_RMS}} \cdot 100 = \left(\sqrt{1 + THD_u^2} - 1\right) \cdot 100 \quad (12)$$

In the case of sinusoidal modulation the current load of the grid is k [%]-times higher than at resistive modulation (Figure 4.)

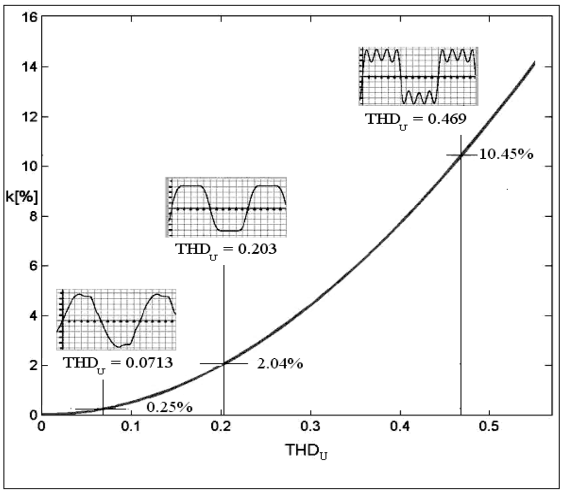


Figure 4. The relative deviation of sinusoidal and resistive loads (with same typical voltage waveforms)

5. Conclusions

The main requirement of the "network-friendly" converters is to eliminate network current harmonics. Two appropriate modulation strategies were demonstrated. Neither the sinusoidal, nor the resistive current load produces additional harmonics.

An increasing proportion of "network-friendly" converters mean less harmful network pollution and an improved THD_u value of the network voltage. The waveform approaches the sine wave, the additional current load of the network decreases. If the network voltage waveform is distorted, the resistive modulation method is more favourable than the sinusoidal. Stark differences can be observed at high THD_u values (see Figure 4).

It is easier to build control electronics in the case of resistive modulation, because we do not need to know the fundamental frequency of the network voltage. It is enough to map the network voltage waveform to obtain an adequate modulation signal. On the other hand, reactive current control can be appropriately realized by sinusoidal modulation.

References:

[1] HORVÁTH M., BORKA J., "Long-range Concept for Improving the Quality of Electric Power in the Public Utility Line, by Applying DC Voltage Energy Distribution Electric Power Quality and Utilisation", in *Magazine*, Vol.I, No.2, 2005, p. 27-36.

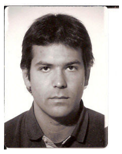
[2] HORVÁTH M., BORKA J., "Welding technologies and up-to-date energy converters", in *EDPE 2005-13th international conference on electric drives and power electronics*. Dubrovnik, 2005, p. 1-8.

[3] PAKU R., POPA C., BOJAN M., MARSCHALKO R., "Appropriate Control Methods for PWM ac-to-dc Converters Applied in Active Line-Conditioning", in *EPE-PEMC 2006*, Portorož, Slovenia, p:573-579.

[4] van der WEEM J., BOLLN H., "Measurement and Analysis of Line Interference Currents generated by an IGBT Four Quadrant Converter", in *EPE 2005*, Dresden, ISBN 9075815085 (CD), p:1-9, paper: 316.

[5] BALÁZS G.G., SCHMIDT I., HORVÁTH M., "Control Methods of Alternating Voltage-Fed Vehicles' Modern Line-Side Converters", in the *2nd International Youth Conference on Energetics*, Budapest, Hungary, 2009. ISBN 9789634209836 (CD), p:1-7, paper 447.

[6] BALÁZS G.G., SCHMIDT I., "Network Friendly Operation of Alternating Voltage Fed Vehicles" (in Hungarian), in *Elektrotechnika*, Jan 2009, p. 9-12.



Gergely György BALÁZS
PhD student, Budapest University of Technology and Economics,
Department of Electric Power Engineering,
Budapest, Hungary

Miklós HORVÁTH
DiFiLTON-ARC LTD., Budapest, Hungary

Dr. István SCHMIDT
Professor, Budapest University of Technology and Economics,
Department of Electric Power Engineering,
Budapest, Hungary