IEEE STD 519 RECOMMENDED PRACTICES FOR APPLICATIONS WITH VARIABLE FREQUENCY DRIVES

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***Abstract* – This work presents the study of some techniques used in the industry to mitigate the harmonic components of the input current produced by variable frequency drives (VFDs) and how to meet IEEE STD 519 requirements. The study is focused on the application of the *multipulse* rectifiers, with theoretical and experimental results and a simple method to verify if a system meets IEEE STD 519 is presented.**

***Keywords* – Power quality, variable frequency drives (VFDs), multipulse rectifiers, harmonics mitigation, IEEE STD 519.**

I. INTRODUCTION

The indirect frequency converters or variable frequency drives (VFDs) are usually composed of an input diode rectifier stage. The three-phase full-wave bridge rectifier, also known as Graetz Bridge or 6-pulse rectifier is one of the most used configurations for the input stage of VFDs. The currents drained by this converter are non-sinusoidal, containing low-order harmonics that may cause voltage harmonic distortion to the electric power supply system where VFDs are connected. The voltage distortion is related to the magnitude of the current harmonics of the electrical equipment and also to the network impedance, i.e., to the network capacity and to the ratio between the capacity of the installed drives and the network capacity.

In several applications, the 6-pulse variable frequency drive with an input line reactor or a DC reactor may perfectly meet the IEEE STD 519 recommendations. When it is not possible, the following options are available to reduce the harmonic currents:

- Increase the number of pulses of the input rectifier using 12, 18 or even 24-pulse.
- Passive tuned and active filters.
- Use an active front-end rectifier, also called regenerative drive.

This paper intends to review the basic concepts related to the reduction of the harmonic components in three phase rectifiers using *multipulse* configuration. Some theoretical and experimental results are shown and a simple method to verify if a system meets IEEE STD 519 is presented.

II. MULTIPULSE CONFIGURATION

A. The idea of Multipulse Configuration

In the industry, the term *multipulse*, when related to frequency converters, means the association, in series or in parallel, of 6-pulse three-phase rectifiers and the utilization of phase-shifting transformers to feed the rectifiers. The fundamental idea of the *multipulse* configuration can be understood as the interconnection of 6-pulse rectifiers so that the characteristic harmonics generated by these rectifiers are cancelled by the harmonics generated by other sets of rectifiers. This mitigation is performed by the appropriate design of the phase-shifting transformer with multiple secondaries. The harmonics of the 6-pulse rectifier that are present on the secondary of the transformer will be cancelled and will not appear at the primary of the transformer that is connected to the utility. In a *multipulse* rectifier the generated characteristic harmonics are given by:

$$h = P.n \pm 1 \qquad (1)$$

Where:

n - is an integer (1, 2, 3, 4, ...∞).
h - is the harmonic order.
P - is the number of pulses of the rectifier.

A deep treatment of multipulse methods and phase-shifting transformers is available in [1].

B. Simulation of Multipulse Configuration

It was considered a system as shown in Fig. 1. This system was modelled as: power electric system, input impedance, a non-linear load formed of input reactors or of phase-shifting transformers plus rectifiers with capacitive filter and load. The waveforms of the system input currents and their harmonic spectrum are presented in Fig. 2. These data were obtained by means of numerical simulation with PSPICE platform.

As the objective of this simulation was to show the qualitative aspects of increasing the number of pulses of the input rectifier, the values of the parameters involved were omitted.

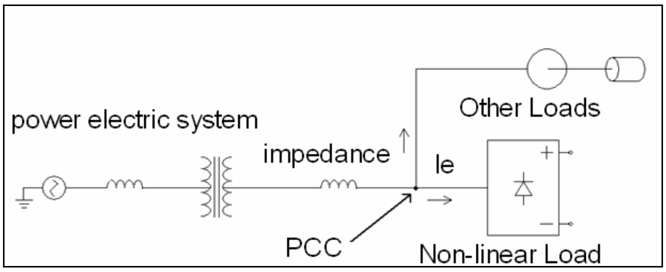
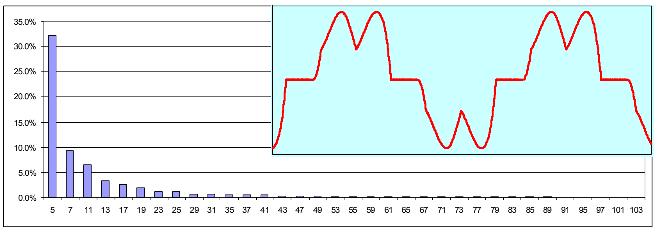


Fig. 1. Diagram of the simulated system.



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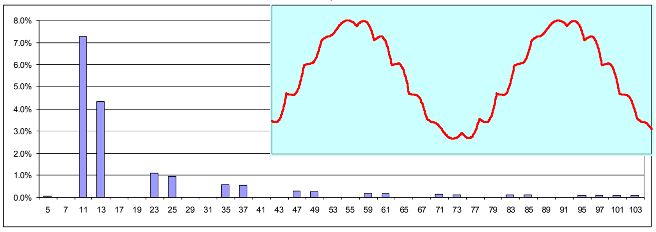

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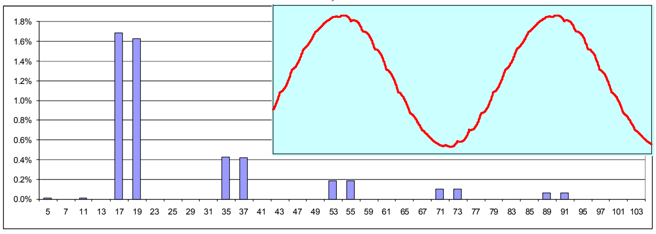

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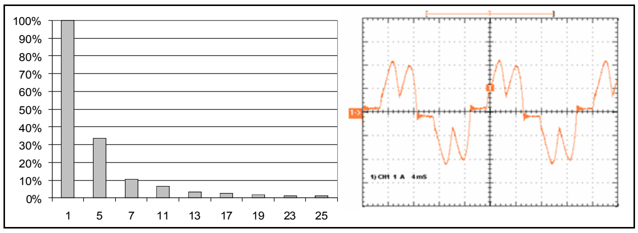
Fig. 2. Waveforms of simulated currents at input of the systems (Ie) and **characteristic** harmonics as a percentage of their fundamental components. (a) 6-pulse rectifier with input line reactor. (b) 12-pulse rectifier with phase-shifting transformer. (c) 18-pulse rectifier with phase-shifting transformer.



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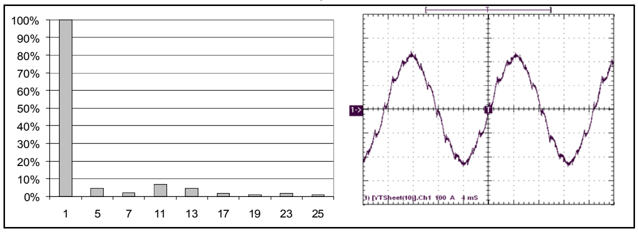

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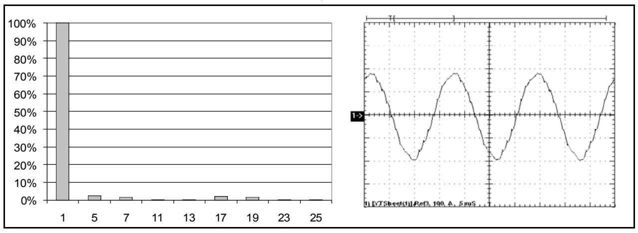

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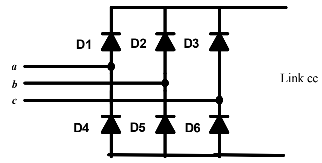
Fig. 3. Waveforms of measured currents at input of the systems (Ie) and measured harmonics as a percentage of their fundamental components. (a) 6-pulse rectifier with input line reactor. (b) 12-pulse rectifier with phase-shifting transformer. (c) 18-pulse rectifier with phase-shifting transformer.

C. Experimental Results

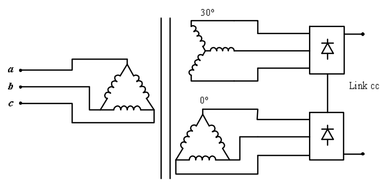
Experiments and measurements have been conducted on commercial VFDs of CFW-09 and MVW-01 series produced by WEG Automação Ltda. The objective of these measurements is to compare them with the simulation results in terms of current waveform quality. The diagrams of the Fig. 4 show the association of the phase-shifting transformers, for 12 and 18 pulses using series-connection of a 6-pulse rectifier. The obtained waveforms of the input currents can be viewed in Fig. 3: (a) 6-pulse rectifier with ac line reactance to produce around 4% of voltage drop (Measured THD = 36 %), (b) 12-pulse rectifier fed by a transformer with 2 secondaries in delta/wye connection to produce a shift of 30º (Measured THD = 8,5 %) and (c) 18-pulse rectifier fed by a transformer with 3 secondaries in delta/delta, delta/+20° delta, delta/-20° delta connection to produce a shift of 20º (Measured THD = 4,5 %). Both transformers had around 6 % of per unit impedance.

D. Practical Aspects

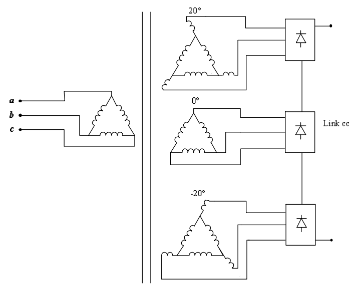
It can be viewed, in Fig. 3, that there are some residual non-characteristic harmonics like 5th and 7th in 12 and 18 pulse topologies. It is due to the non-ideal behavior of the transformer, causing angle phase errors. These harmonics are not perfectly canceled in the primary, affecting the expected result. Also, an already existing presence of voltage distortion on the power electric system may increase the values of these non-characteristic harmonics.



a) 6-pulse rectifier.



b) 12-pulse rectifier with delta/wye transformer.



c) 18-pulse rectifier with delta/delta, delta/+20° delta, delta/-20° delta transformer.

Fig. 4. Rectifiers and transformers connections.

III. IEEE STD 519 - RECOMMENDED PRACTICES

The non-sinusoidal drive input current, shown in previous section, results in a voltage drop, caused by the input impedance of the system, which distorts the voltage at the point of common coupling (PCC) which is defined as the electrical connecting point or interface between the utility distribution system and the customer's or user's electrical distribution system. This distortion can be evaluated by the current TDD, which is the total demand distortion, and by the voltage THD on the point of common coupling. The TDD and THD calculations will be presented later.

The IEEE STD 519 [2] is a set of recommended practices prepared by IEEE that describes the main factors that may cause harmonic distortion, indicates the measurement methods and states the distortion limits.

According to [3], the scope of these recommended practices is to analyze the harmonic distortion caused by all the loads (linear and non-linear) at the Point of Common Coupling (PCC) and not the distortion caused by one individual device. The main concern of IEEE is what the installation reflects to the other consumers connected to the same power supply and not what occurs within the installation.

The distortion limits are different according to the voltage and short-circuit levels at the PCC. The higher the short-circuit current (Isc) in respect of the load current, the higher the admissible current distortion, since they will cause a lower voltage distortion at the PCC. As the voltage level increases, the acceptable limits decrease.

The TDD – Total Demand Distortion – is defined as the current harmonic distortion, in percentage of the maximum demand load current (15 or 30 minutes demand). This means that the TDD shall be measured at the peak consumption.

Tables 10.2 and 10.3, obtained from IEEE STD 519, show the recommended limits for the THDv (Total Voltage Harmonic Distortion) and for the TDD (Total Demand Distortion).

TABLE I
Reproduction of part of Table 10.2 from IEEE STD 519

	Special Applications*	General System	Dedicated System**
THD (Voltage)	3%	5%	10%

* Special applications include hospitals and airports
** A dedicated system is exclusively dedicated to the converter load

TABLE II
Reproduction of Table 10.3 from IEEE STD 519

Isc / IL	< 11	11≤n<17	17≤n<23	23≤n<35	35≤n	TDD(%)
< 20	4	2	1,5	0,6	0,3	5
20 < 50	7	3,5	2,5	1	0,5	8
50 < 100	10	4,5	4	1,5	0,7	12
100 < 1000	12	5,5	5	2	1	15
> 1000	15	7	6	2,5	1,4	20

Maximum Harmonic Current Distortion in Percent of IL
Isc - maximum short-circuit current at PCC
IL - maximum demand load current (fundamental frequency component) at PCC

Table 10.3 is applicable to 6-pulse rectifiers and general distortion situations. However, when phase-shifting transformers or converters with pulse numbers higher than six are used, the allowed limits for the characteristic harmonic orders may be increased by a factor equal to: 1,414 for 12-pulse and 1,732 for 18-pulse.

Although the IEEE STD 519 is not a mandatory standard, its recommendations are being used as a reference to specify the harmonic distortion limits allowed by the utility companies and in the design of industrial power systems.

IV. CASE STUDY

The following case study aims to show how to obtain, in a simple way and with good precision, the Voltage Harmonic Distortion (THDv) and the Total Demand Distortion (TDD) values for a system (Fig. 5) composed of a main bus bar with known power and impedance, feeding a non-linear load with an input rectifier with the specified number of pulses and verify if this system meets IEEE STD 519.

The following aspects are not considered: already existing presence of harmonics on the power electric system, phase unbalance, transmission line impedance, influence of other loads connected to the PCC, imperfections in the transformers, system efficiency, etc. The values presented herein are useful for a preliminary analysis of the harmonic distortion level of the system. For a complete analysis, taking in account all the variables listed above, it is necessary to perform a complete numerical simulation of the system.

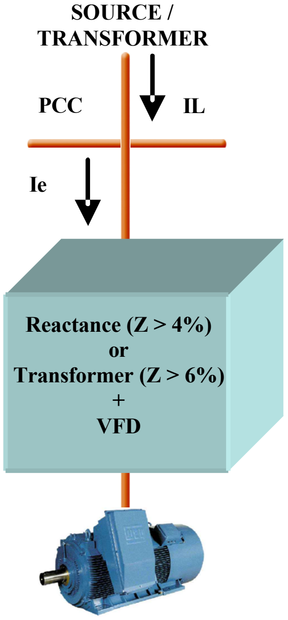


Fig. 5. System under study.

A. Requirements

Four requirements will be considered to meet IEEE STD 519:

1. THDv - according to table 10.2.
2. Individual limit of 3% for the voltage harmonics at the PCC.
3. TDD - according to table 10.3.
4. Individual limit of current harmonics as percentage of IL according to table 10.3.

B. Calculation Procedure

Considering that the fundamental is the only component that provides active power to the motor it is possible to calculate its value at the PCC by taking in account the typical motor displacement power factor-cos(ϕ). With the calculated fundamental component, the theoretical harmonic components of the current at the PCC can be known as a function of the number of pulses of the rectifier.

The THD_i (total harmonic distortion) of the current at the PCC is calculated by the following expression:

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_{(1)}} \qquad (2)$$

Where:

n - is an integer (2, 3, 4, ...∞).

I_n - are the harmonic components of the PCC current.

$I_{(1)}$ - is the fundamental component of the PCC current.

The I_n values can be obtained by numerical simulation. In [4] and [5] these values are presented as a function of the % voltage drop on the ac line reactance. The TDD is calculated as the current harmonic distortion at the PCC in relation of its demand current (IL):

$$TDD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{IL} = THD_i \times \frac{I_{(1)}}{IL} \qquad (3)$$

Where:

IL - maximum demand load current (fundamental frequency component) at PCC.

As $I_{(1)}$ depends only of the power processed by the VFD and IL depends of all loads connected to the system, the relation between these two currents represents a percentage of power used by the VFD in related to the demand.

Given the power and impedance (%) it is possible to calculate the physical inductance (L) at the PCC and, therefore, calculate the voltage drops caused by the components of the current harmonics:

$$V_n = I_n.(2.\pi.F_n).L \qquad (4)$$

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_{(1)}} \qquad (5)$$

Where:

L - is the physical inductance at the PCC.

F_n - are the characteristic harmonic frequencies.

V_n - are the harmonic components of the voltage at PCC.

$V_{(1)}$ - is the fundamental component of the voltage at PCC.

C. Example

With the results of basic computer simulations and equations (2) to (5) the four previously cited requirements can be verified. Consider an electrical system as shown in Fig. 5 with the following characteristics:

Capacity and Demand:	8,00	MVA
Source reactance (%):	8,00	%
Voltage at PCC:	13800	Volts

Simulations were done for a VFD with different input rectifier configurations connected to this electrical system and varying the power level. Results are shown in Table III.

TABLE III
Results obtained with computer simulations

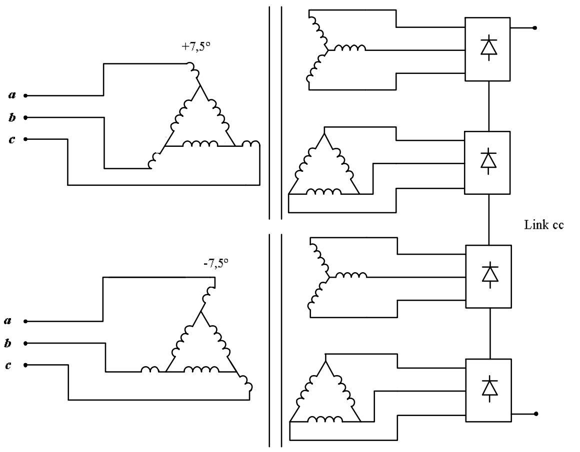
		Requirements								
		1.		2.		3.		4.		
VFD Rectifier	I(1)/IL	THDv - General System		Individual Limit for the Voltage Harmonics at PCC		TDD		Current Harmonics (table 10.3)		IEEE 519
6 PULSE (1)	13 %	2,06 %	Ö	< 3 %	Ö	4,20 %	Ö	< limits	Ö	OK
	16 %	2,41 %	Ö	< 3 %	Ö	4,93 %	Ö	> limits	X	NOT
	27 %	3,88 %	Ö	< 3 %	Ö	7,97 %	X	> limits	X	
	36 %	4,92 %	Ö	> 3 %	X	10,14 %	X	> limits	X	
	37 %	5,11 %	X	> 3 %	X	10,53 %	X	> limits	X	
12 PULSE (2)	65 %	4,11 %	Ö	< 3 %	Ö	3,88 %	Ö	< limits	Ö	OK
	79 %	4,60 %	Ö	< 3 %	Ö	4,30 %	Ö	> limits	X	NOT
	92 %	5,00 %	Ö	> 3 %	X	4,63 %	Ö	> limits	X	
	99 %	5,16 %	X	> 3 %	X	4,75 %	Ö	> limits	X	
18 PULSE (3)	100 %	2,25 %	Ö	< 3 %	Ö	1,29 %	Ö	< limits	Ö	OK

(1) 6-pulse plus a 4% ac line reactance.
(2) 12-pulse rectifier plus a phase-shifting transformer (Z = 6%)
(3) 18-pulse rectifier plus a phase-shifting transformer (Z = 6%)

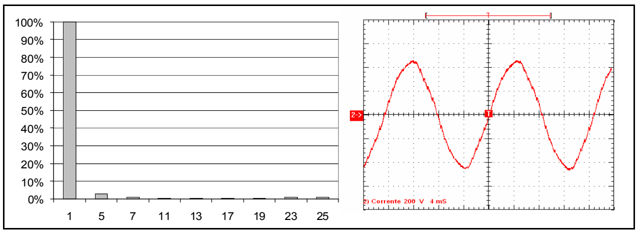
The results show that it is possible to meet IEEE STD 519 even with a 6-pulse rectifier, depending of the relation between the percentage of power used by the VFD in relation to the demanded power. In this example, considering the four requirements, the limit of this relation is 13 %, for a 6-pulse rectifier and 65 % for a 12-pulse rectifier. Considering only the main recommendation, that is, the THDv, this electrical system can be loaded up to 36% by a 6-pulse rectifier and 92% by a 12-pulse rectifier. An 18-pulse rectifier met all IEEE STD 519 requirements for all range of power used. It is important to emphasize that only the characteristic harmonics were considered in the simulation.

V. ALTERNATIVE TOPOLOGIES

There are other techniques to mitigate the harmonic components of the VFD input current like diode rectifiers with more than 18 pulses, passive tuned filters, active filters or active front-end rectifiers. Fig. 6 shows: (a) the arrangement of a 24-pulse rectifier with two phase-shifting transformers and (b) the measured current at the primary of each phase. This current has THD = 3,5 %. When compared with the 18-pulse solution, the THD reduction was not so significant. Fig. 7 (a) shows the basic power diagram of an active front-end rectifier (AFE). In this converter, it is possible to control the input current (Is) to follow the input voltage. As the harmonics are produced by the switching frequency of the controlled switches at the input bridge, with a small filter it is possible to get currents with THD levels around 3 %. The current in Fig. 7 (b) was measured at the input of a CFW-09 AFE converter produced by WEG Automação Ltda.

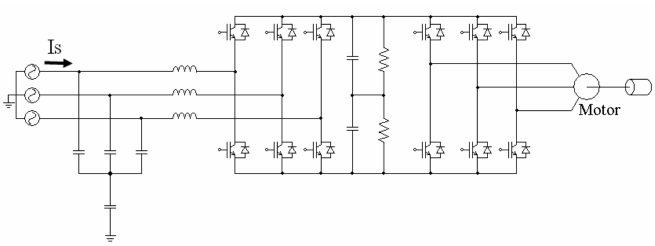


a) 24-pulse series rectifier with 2 transformers shifted at primaries.

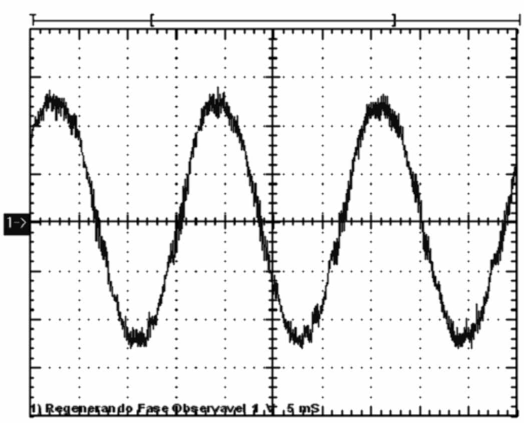


b) Waveform of measured current at input of the primaries (Ie) and measured harmonics as a percentage of their fundamental component.

Fig. 6. Example of a 24-pulse arrangement.



a) AFE basic power diagram.



b) Waveform of measured current at input of an AFE (Is).

Fig. 7. Example of an AFE arrangement.

VI. CONCLUSION

The maximum allowable distortion depends on the relevant applicable standards. There are various techniques available to decrease the harmonic distortion, such as the use of input reactors, external passive filters, 12 or 18-pulse rectifiers, active-front end converters or active harmonic filters. Choice of technique should be made based on the following engineering parameters: impact on power quality, cost, maintenance, overall efficiency of the system and maximum THD level.

As shown, when the number of pulses of the rectifier is increased above 18-pulses, significant gains in terms of THD reduction were not produced despite the higher investment on that arrangement caused by increasing the number of semiconductors (diodes), electrical connections and the difficult to design phase-shifting transformer.

As presented, it is possible to meet IEEE STD 519 requirements depending on the percentage of power used even with a 6-pulse rectifier.

AFE converter can also be used to reduce the harmonic components of the input current, but the obtained THD with these converters is close to an 18-pulse solution. Active front-end converter is more suitable for application where it is needed repetitive braking and the economy obtained, regenerating the energy back to the power supply, justifies the investment of this solution.

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