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A Research on DC Voltage Offsets Generated by PWM-Controlled Inverters

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***Abstract*—**The increasing penetration of Distributed Generation and storage connected to the distribution network via PWM converters increases the possibility of a DC-component (offset) in voltage or current flowing into the grid. This occurs when even harmonics are present in the network voltage. DC-components can affect the operation and safety of several grid components. Therefore, an investigation of the way they are produced is important in order to take appropriate measures for their elimination. Further research on DC-components that appear on output voltage of converters is performed for different parameters of PWM technique and characteristics of even harmonics.

***Keywords*—**Asymmetric even harmonics, DC-offsets, distributed generation, electric machine drive systems, power quality.

I. INTRODUCTION

THERE have been several publications reporting the generation of DC-components in the current or voltage waveform. In [1]-[7] geomagnetically-induced currents are reported to introduce DC-offsets. DC-components may be produced by HVDC systems, when AC and DC transmission lines are in close proximity [8], [11]. DC-components may be also produced by Static Var Compensators [6], or in general, in cases where anti-parallel power electronic switches are used [12]. There are also references where single-phase [9] and half-wave rectifiers [7] are reported to produce DC-components when supplied with asymmetrically distorted voltage waveforms.

In this paper the generation of DC-components by PWM converters when even harmonics are present in the network voltage [9], [10], is investigated. Possible sources of even harmonics are presented in [9].

II. EFFECTS ON GRID COMPONENTS

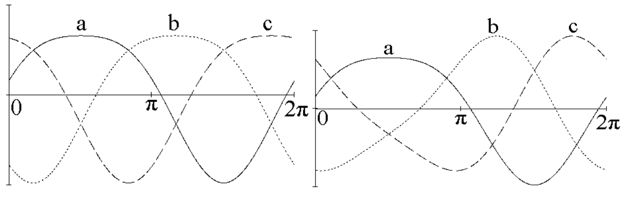
DC-components can influence the operation of several grid components, predominately transformers. In particular, converter transformers are DC-magnetized, when the converter output voltage contains DC-components. This means that DC current flows as transformer magnetizing current and offsets the knee of the flux-current characteristic and, if excessive, causes DC (or half-cycle or asymmetrical) saturation of the converter transformer [1]-[7], [10]-[16].

Other undesirable effects of DC-components on transformers and other grid components are:

1) Protective shutdown of the converter. When DC-magnetization of converter transformer progresses and reaches saturation level, results in an overcurrent and a protective shutdown of the converter [8].
2) Production of odd and even harmonics by transformers [1], [8] and nonlinear loads [9].
3) Power losses, possible loss of life expectancy, increase in reactive power consumption and audible noise by transformers [8], [11].
4) Inaccurate measurements. DC-components can cause inaccurate measurements because of saturation of current transformers on the AC side. Thus, control and protection systems (and protective relays) that depend on these measurements will not function properly [4], [7], [8], [11].

III. DC COMPONENTS BY PWM CONVERTERS

PWM converters produce DC-components when “asymmetric” 3-phase even harmonics are present in the network voltage. Asymmetries are typical in power networks, so “asymmetric” even harmonics are also very likely to appear. The word “asymmetric” means that together with the normal phase sequence of a harmonic, an amount of opposite phase sequence exists i.e., a positive-phase sequence for a 2nd harmonic, a negative-phase sequence for a 4th harmonic, and so on. A 3-phase voltage system consisting of the fundamental component and a negative (normal phase sequence) or a positive (opposite phase sequence) 2nd harmonic is shown in Figs. 1 (a) and (b) respectively. The large asymmetry between the three phases is obvious in the second case.



(a) (b)

Fig. 1 Fundamental with a: (a) negative-, (b) positive-2nd harmonic

When the network voltage contains harmonics, a percentage of these harmonics will also be contained in the reference waveform (control signal). In Fig. 3, the PWM pattern for a 6-pulse voltage source converter (Fig. 2) is shown when the reference waveform contains an 8th positive-sequence harmonic. For better visibility, the Harmonic Percentage (HP) is set high and the Modulation Frequency (MF) index low. The Modulation Amplitude (MA) index is arbitrarily set to 0.8

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and the Harmonic Angle (HA) is set to 60^0.

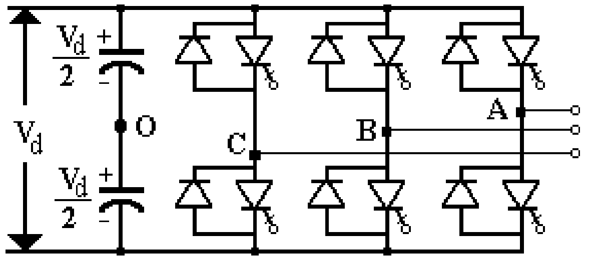

Fig. 2 Six-pulse voltage-source converter

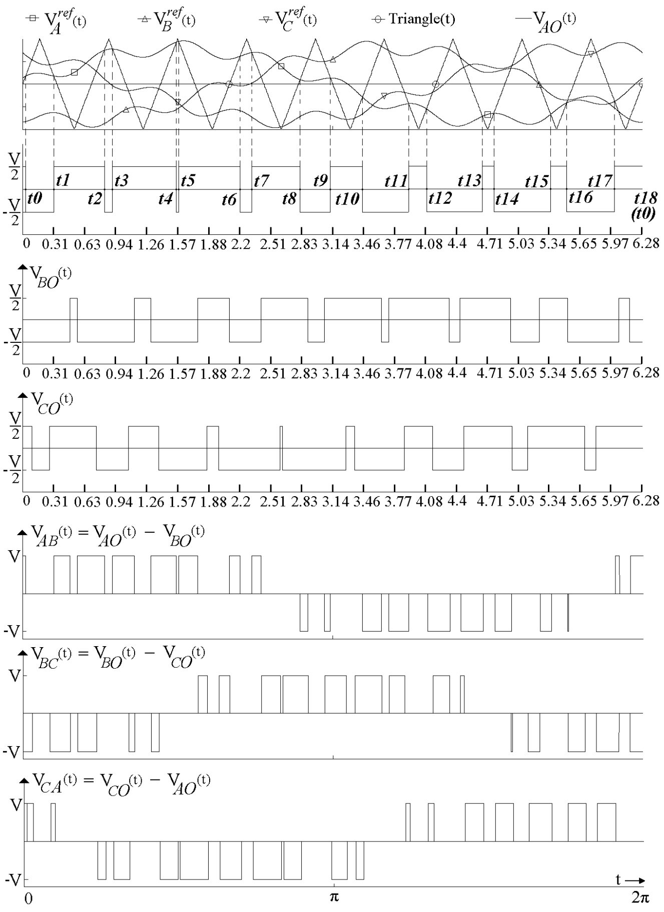

Fig. 3 PWM pattern when an 8^{th} harmonic is present on the reference waveform. HP=20%, MF=9, HA=60^0, MA=0.8

IV. Maximum DC Component of PWM Converters

A. One Even Harmonic on the Reference Waveform

The analytical method used for the calculation of DC-component that is contained in the three line voltages is described in [1]. It uses the intersection points between the three reference waveforms and the triangular pulse. An example is also given for the case shown in Fig. 3. After calculating the DC-component of each of the three line voltages, the maximum absolute value is eventually extracted.

The DC-component contained in the converter output voltage is influenced by the PWM pattern parameters and characteristics of the harmonics. These parameters are thoroughly investigated, in order to calculate the maximum level of DC-component that may be produced when even harmonics are present in the network voltage. These parameters are:

1) Modulation Frequency (MF) index. The MF index in a 6-pulse PWM converter is an odd multiple of 3 10].
2) Modulation Amplitude (MA) index. Values in the range 0.6 – 1 were used.
3) Harmonic Order (HO).
4) Harmonic Percentage (HP).
5) Harmonic Angle (HA). HA is the phase angle difference between fundamental component of the reference waveform and harmonics. The effective range for the HA is: $0 – 180^0$.

In Figs. 4 and 5, the maximum DC-component for MF = 9 (450 Hz for a 50 Hz system) and HO up to the 50^{th} is given.

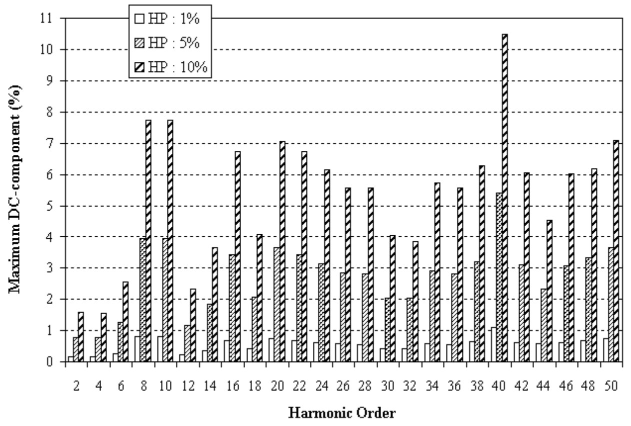

Fig. 4 Maximum DC-component for MF=9, HO ≤ 50, HP=1-10%.

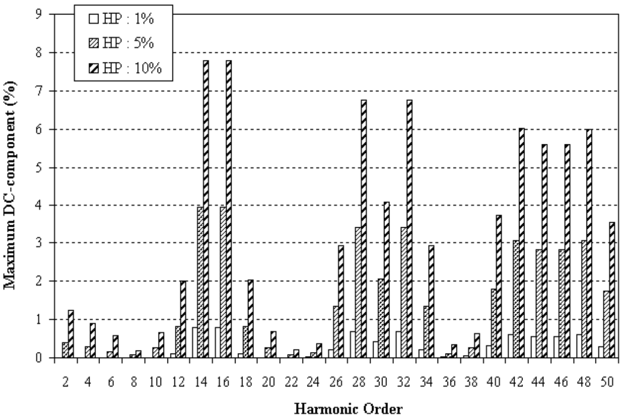

Fig. 5 Maximum DC-component for MF=15, HO ≤ 50, HP=1-10%

It can be seen that for all the harmonics, a quite large amount of DC-component exists, especially for some of the higher order harmonics. It becomes even higher than the HP for the 40^{th} harmonic, but for all the other harmonics is less than $0.8 \cdot HP$.

In Fig. 5, the maximum DC-component is presented for MF=15 (450 Hz). Again, higher order harmonics give the highest levels of DC-component.

It is found that for MF≥15 (21, 27, 33…), some harmonics follow a particular pattern as regards the maximum DC-component they lead to. This pattern regards the harmonics that lead a PWM converter to the production of the highest amounts of DC-component and it is presented in Fig. 6. It should be noted here that this pattern applies also for MF=9, but with a few small differences.

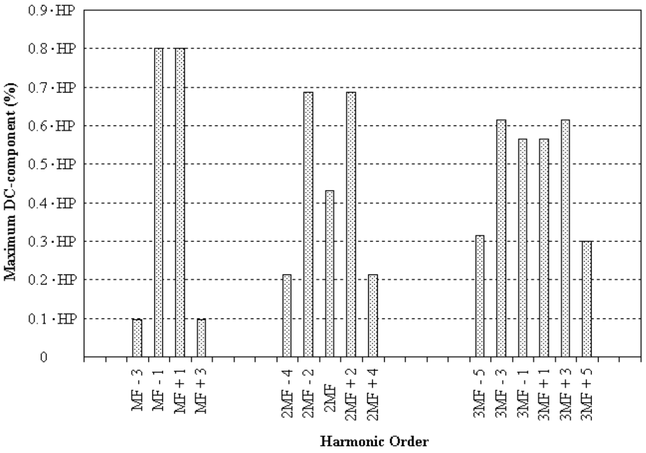

Fig. 6 General pattern for the harmonics that lead to the highest values of DC-components

There are pairs in the band of MF, 2MF, 3MF etc, that give high and about equal levels of DC-components. These pairs involve both the so-called "positive-" or "negative-sequence" (MF±1, 2MF±2, 2MF±4, 3MF±1, 3MF±5) and "zero-sequence" (MF±3, 2MF, 3MF±3) harmonics. The highest level of DC-components is taken for HO=MF±1 and HO=3MF±3 for the positive-negative- and zero-sequence harmonics respectively. It must be noted here that higher order harmonics than those presented in Fig. 6 lead also to high production of DC-components.

Lower order harmonics and other harmonics apart from those shown in Fig. 6 e.g. 2, 4, 6, 8, 22, 24, 36, 38… (Fig. 5, for MF=15) produce an amount of DC-components, which have a non-proportional dependence on the HP. This amount is not greater than 0.1·HP except for the 2nd harmonic, which gives a maximum DC-component of about 1.25% for HP=10%. Moreover, the maximum DC-component of these harmonics takes about equal values even for higher values of MF.

The relationship of the maximum DC-component with the HA, follows again a particular pattern, especially for low values of HP. For higher values of HP, this pattern presents some differences mainly in the HA that gives the maximum DC-component. In Fig. 7, this pattern is shown and the opposite phase sequence is indicated in the brackets beside the harmonic order.

It can be seen that for positive or negative sequence harmonics, positive-sequence harmonics (e.g. 2nd, MF-1…) give the maximum value for HA=60^0 and negative-sequence (e.g. 4th, MF+1…) for HA=120^0. The variation of the maximum DC-component is exactly opposite for the positive- and negative-sequence harmonics. On the other hand, zero-sequence harmonics (6, 12, MF±3…) have the same characteristics with the positive-negative sequence harmonics but with the opposite order.

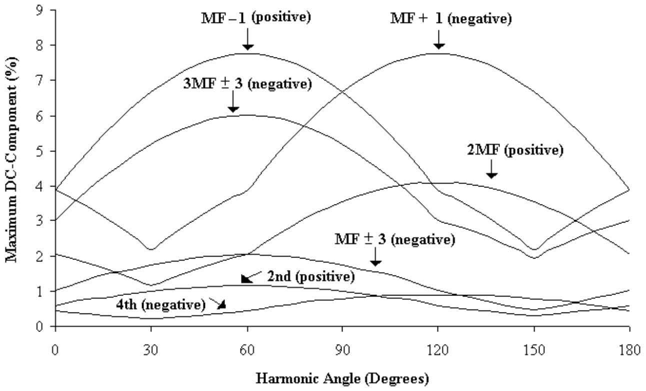

Fig. 7 Maximum DC-component versus HA for positive-negative and zero-sequence harmonics for HP =1%

As regards the influence of the MA on the maximum DC-component, there is also a common variation for some of the harmonics and for low values of HP. This is presented in Fig. 8 for HP=1%. It can be observed that the harmonics with the highest value of DC-components (MF±1, 2MF±2, 3MF±3), as Fig. 6 shows, present about the same variation. Another group with the same variation consists of the 2MF and 3MF±1 harmonics. The 2MF±4 and MF±3 harmonics form the third group. In this group, the 2nd, 4th and 6th harmonics are also included.

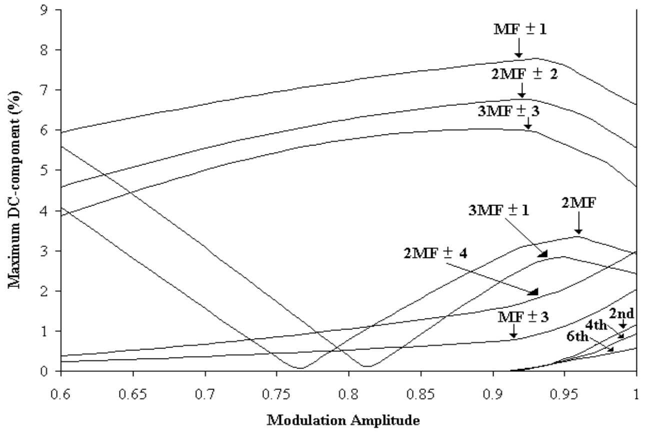

Fig. 8 Maximum DC-component versus MA for HP =1%

B. Combination of Even and Odd Harmonics

The cases where two even harmonics or one even and one "symmetric" odd harmonic are contained in the reference waveforms are also investigated. The maximum DC-component is calculated for equal values of HP for the two harmonics and compared with the maximum DC-component of each harmonic. The results for MF=27 and HP=1% are presented in Fig. 9. It is shown that the maximum DC-

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component for the combination of two harmonics is higher than the maximum DC-component of each harmonic. Obviously, this rule applies only for the maximum value, which means that the DC-component may be lower when two harmonics appear on the reference waveform.

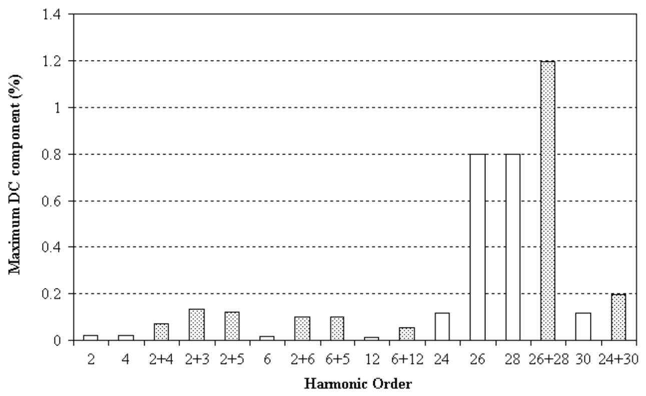

Fig.9 Maximum DC-component for some even harmonics and the combination of them with one other even or one "symmetric" odd harmonic with equal HP=1% (MF=27)

The maximum DC-component is taken for the case where the two harmonics with the highest values (0.8·HP) of DC-components are present (MF±1). In general, the combination of these two harmonics with equal HP gives a maximum value of 1.5·0.8·HP.

In Table I, the parameters (MA, HA_1 and HA_2) that correspond to the maximum DC-component for two harmonics are given.

TABLE I
PARAMETERS FOR THE MAXIMUM DC-COMPONENT

$HO_1 + HO_2$	MA	HA_1 (Degrees)	HA_1 (Degrees)
2+4	1	60	0
2+3	1	60	179
2+5	1	60	0
2+6	1	60	60
6+5	1	60	0
6+12	1	60	179
26+28	0.99	60	0
24+30	1	60	179

V. ELIMINATION OF DC COMPONENTS

It was shown in the previous analysis that for higher MF indices, the harmonics that may lead to high levels of DC-components are of higher order. However, it was also shown that lower order harmonics e.g. 2, 4 , 6, 8…, which are more common to appear in a power network, can lead to significant amounts of DC-components if their magnitude is high or other harmonics (even or odd) are also present.

The provision of a filter to remove even harmonics from the detected (measured) network voltage can only be used in steady-state operation of the converter. In transient conditions, filtering cannot be used as it makes the response of the converter very slow, so this solution should not be adopted. Moreover, in transient conditions, the asymmetries and the magnitude of even harmonics may be higher. Thus, a system for quick detection and control of DC-components need to be alternatively used for the elimination of DC-components [7] independently of the converter's MF index.

In cases of converters connected to the grid by means of a transformer, no DC-components will flow into the grid, as DC-components do not propagate through transformers. For transformer-less converters, acceptable limits for DC-components injection must be set in order problems not to be caused to other grid components. It can also be mentioned here that DC-components are damped by network resistance. Thus, higher resistances mean lower propagation of DC-components in large distances. Moreover, higher resistances mean smaller DC-currents for a given DC-voltage.

VI. CONCLUSION

In this paper, DC-components contained in the output voltage of a PWM converter, when even harmonics are present in the network voltage are investigated. A method for calculating analytically the maximum level of DC-component for various parameters of PWM pattern and harmonics is presented.

By extensive calculation of DC-component for all these parameters, it is found a common pattern for the critical harmonics that give the maximum DC-component in relation with the MF index. It is also shown that there is a typical relationship between the maximum DC-component and the HA for some of the harmonics and their phase-sequence. Typical variation applies also for the maximum DC-component and the MA index.

The presence of two even or one even and one odd harmonic with equal HP is also investigated. It is shown that the maximum DC-component can be quite high in relation with the maximum DC-component of each even harmonic. This means that lower order harmonics of high magnitude can cause problems when they are combined with other harmonics. Thus, independently of the MF index that a converter operates, measures must be taken to reduce the possible DC-component produced when even harmonics appear in the network voltage.

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