Investigation the Effects of Utility Unbalance Voltage on Adjustable Speed Drives and Induction Motors

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ABSTRACT   *This paper endeavors to present a comprehensive summary of the causes and effects of voltage unbalance and to discuss related standards, definitions. Several causes of voltage unbalance on the power system and in industrial facilities are presented as well as the resulting adverse effects on the system and on equipment such as induction motors and power electronic converters and drives. Power electronic converters serve as the interface for many large electronic loads ranging from three-phase uninterruptible power supplies (UPSs) to motors operating at variable speeds through the use of adjustable speed drives (ASDs). Most of these converters contain diode rectifier front-end. Under the conditions of utility voltage unbalance, the input current harmonics are not restricted to the converter characteristic harmonics, and uncharacteristic triple harmonics can appear such as the 3rd and 9th harmonics. The more details of effects of unbalanced voltages on ASD are investigated follows.*

2. Introduction

Power quality problems and survey results have been reported in many publications [1-3]. The affected industry and businesses include automobile manufacturing plants, medical centers, and semiconductor manufacturing plants, broadcasting facilities, and industrial and commercial buildings. It is estimated that industrial and digital economy companies collectively lose much billion a year to outages and to power quality phenomena.

3. Unbalance Voltage

The unbalanced voltage gives a bad influence for the power quality. If the unbalanced power is applied to the electric apparatuses, it gives a difficult problem to them, especially the electric motors [4]. The unbalance voltage is caused by unsymmetrical transformer windings or transmission impedances, unbalanced loads, or large single phase loads. Voltage unbalance exists in almost all three-phase power system networks. The level of unbalance is considerably large in weak power systems and also those supplying large single phase loads. Based on the ANSI report, the voltage unbalance of 66% of the electrical distribution systems in USA, is less than 1%, and that of 98% of the distribution systems is less than 3%, whilst in the remaining 2% it is larger than 3% [5].

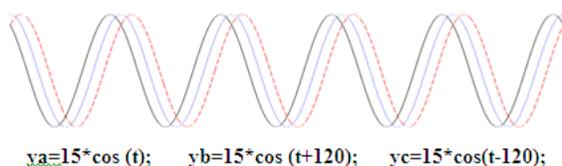In Figure 1 the instantaneous three phase balanced voltage are shown.

ya=15*cos (t);   yb=15*cos (t+120);   yc=15*cos(t-120);

Fig.1.The three phase balanced voltages

The unbalance voltages are two kinds. One is unbalanced due to difference in magnitude as shown in Figure 2 and another is unbalanced due to difference in phase angles (not 120 degree between phases) as shown in Figure 3. Surely, unbalanced could be occurred due to both difference in phase and magnitude.
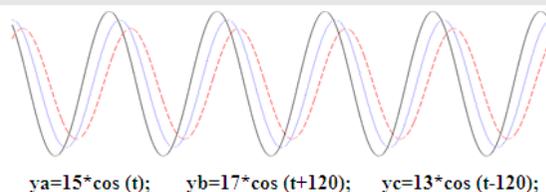

ya=15*cos (t);   yb=17*cos (t+120);   yc=13*cos (t-120);

Fig.2.The three phase unbalanced voltage due to difference in magnitude

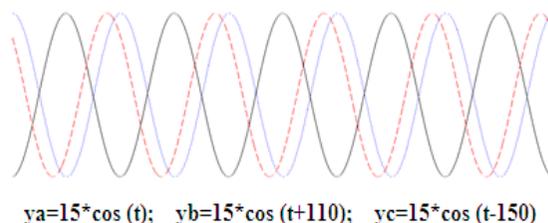ya=15*cos (t);   yb=15*cos (t+110);   yc=15*cos (t-150)

Fig.3.The three phase unbalanced voltage due to difference in phases

Reasons for unbalance are
- Incomplete transposition of transmission lines
- Open delta transformer connections
- Single phase loads
- Blown fuses on capacitor banks
- Railway traction loads

4. Definition of Voltage Unbalance:

There are two general definitions for measuring the voltage unbalance, given by international standards NEMA [6] and IEC [7]. NEMA defined the unbalance voltage by means of the "percent voltage unbalance" (PVU):

$$PVU = 100\% \frac{MVD}{V_{Avg}} \quad (1)$$

Where MVD is the maximum voltage deviation from the average line voltage magnitude and VAvg is the average line voltage magnitude. The IEC standard [7] adopts the "voltage unbalance factor" (VUF) as defined by the method of symmetrical components:

$$PVU = 100\% \frac{V_2}{V_1} \quad (2)$$

Where, V1 and V2 are the amplitudes of positive and negative sequence voltages, respectively.

5. Unbalanced voltage and induction machine

In order to prevent the motor overheating due to unbalanced voltages the motor has to be operated below its rated output power which is called derating of the induction motor. As per NEMA guidelines, operating a motor for any length of time at voltage unbalance above 5% is not recommended. Any amount of unbalance makes a motor run hotter. The NEMA standard says that once unbalance reaches 5%, the temperature begins to rise so fast that protection from damage becomes impractical. The simplest protection as proposed by the NEMA standard, is to derate the motor-to reduce its output horsepower load so it can tolerate the extra heating imposed by the unbalanced supply.

When voltages are unbalanced, the percent increase in temperature rise equals about twice the square of the percent voltage unbalance. This can be defined by the following relation:

$$1 + \frac{2[PVU]^2}{100} = \left[\frac{Percent\ Load}{100} \right]^{-1.7} \quad (3)$$

The above relation can be used to find the percent load for operating under various unbalanced conditions (percent unbalance).the derating necessary to hold the temperature rise to the machine specifications can be determined. This derating curve for unbalance is given in Figure 4. At 5% unbalance for example the motor should not operate at more than 75% of its rated output.
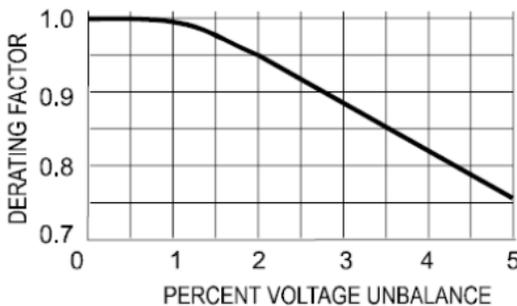

Fig.4.Voltage divider model for computing voltage sag in a radial distribution system

6. Effects of Voltage Unbalance on Power Electronic Converters and Drives

Power electronic converters serve as the interface for many large electronic loads ranging from three phase uninterruptible power supplies (UPSs) to motors operating at variable speeds through the use of ASDs. Most of these converters contain a diode rectifier front-end, as shown in Figure6, and dc-link capacitor to convert the incoming ac voltage to a low-ripple dc voltage. In Figure 5, the pulse-width modulated (PWM) inverter converts the dc voltage back to variable three-phase ac. The magnitude and frequency of the PWM inverter output control the motor speed.

Three-phase converters with diode rectifier front-ends draw non sinusoidal currents rich in odd harmonics. For rectifier systems supplied by balanced utility voltages, the input current characteristic harmonics are determined by [8]:

$$h = kq \pm 1 \quad (4)$$

Where, h is order of the harmonics, q is number of pulses of the rectifier system and k=1,2,3,....
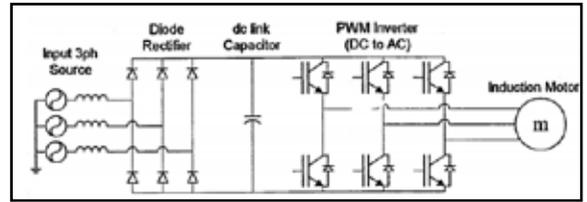

Fig.5.Typical adjustable speed drive (ASD) system

Under the conditions of utility voltage unbalance, the input current harmonics are not restricted to the converter characteristic harmonics, and uncharacteristic triple harmonics can appear such as the 3rd and 9th harmonics.

The more details of effects of unbalanced voltages on ASD are investigated follows.

Notice that as the ASD input voltage unbalance increases, the input current becomes significantly more unbalanced and changes from a double-pulse wave form to a single-pulse wave form due to the asymmetric conduction of the diodes. The voltage unbalance may cause excessive current in one or two phases, which can trip overload protection circuits [9]. The increased current can also cause excess heating of the diodes and decrease the life of the capacitor or require the use of a larger capacitor. Note the increase in the percent of the 3rd harmonic much increases as the voltage unbalance increases. The significant 3rd harmonic can increase harmonic and resonance problems on the system as well as require larger filter ratings.

As shown in Figure 6 with replacing the diode rectifier with an active PWM rectifier has the following advantages [8-9]:

- Regulated dc-bus which offers immunity to voltage sags and transients
- Unity power factor with low input current harmonics (near sinusoidal)
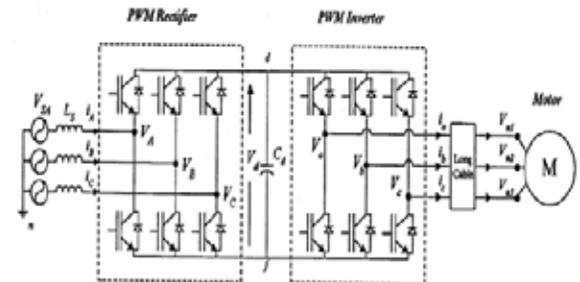- Power flow in both directions which enables regenerative braking.

Fig.6.ASD with PWM rectifier

7. Simulations and Results

In this section the influence of unbalanced voltages on adjustable speed drive is analyzed. As shown in Figure 7 the MATLAB-SIMULINK simulation tool was used to develop a model that allowed the simulation and testing the theory calculations.
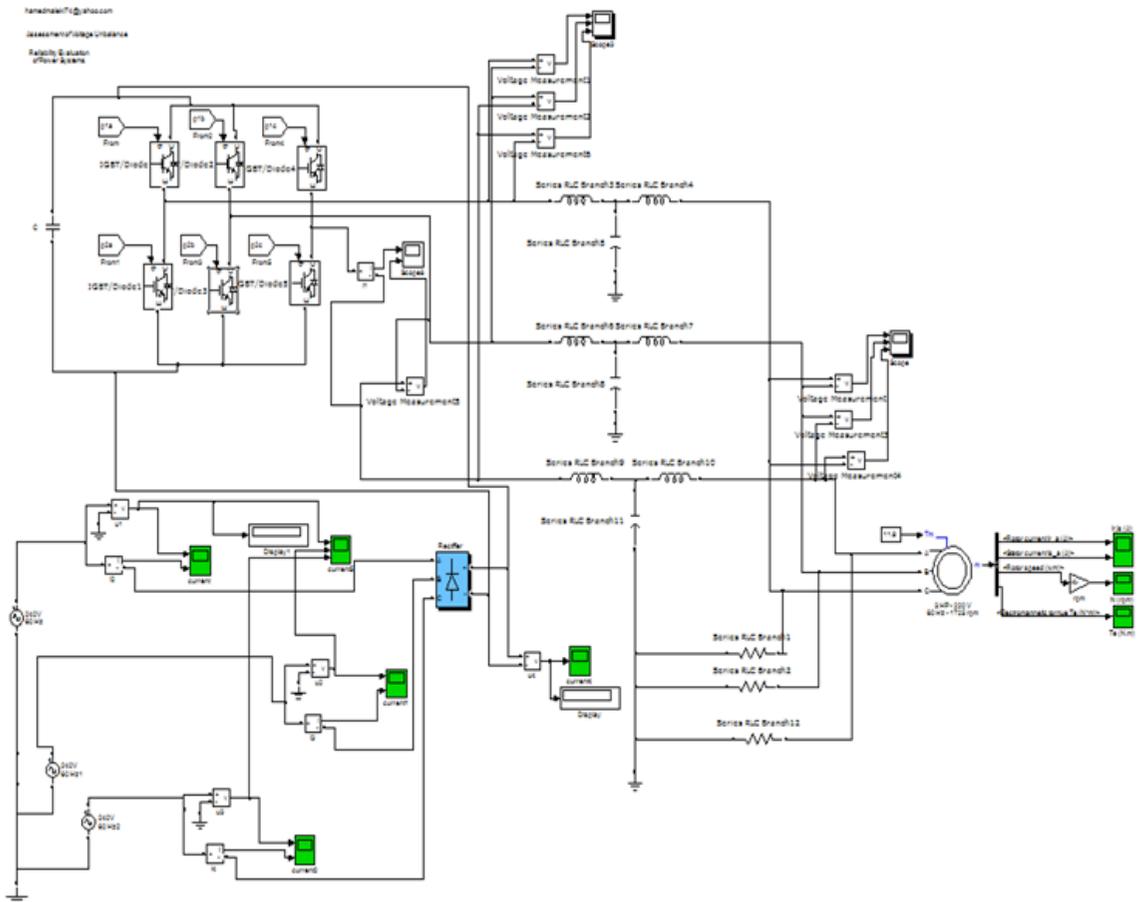
Fig.7.The MATLAB/SIMULINK model of typical adjustable speed drive which feed with unbalanced voltages

Unbalance voltage degree measurement for evaluating the percentage value of unbalance voltage is shown in Figure 8.
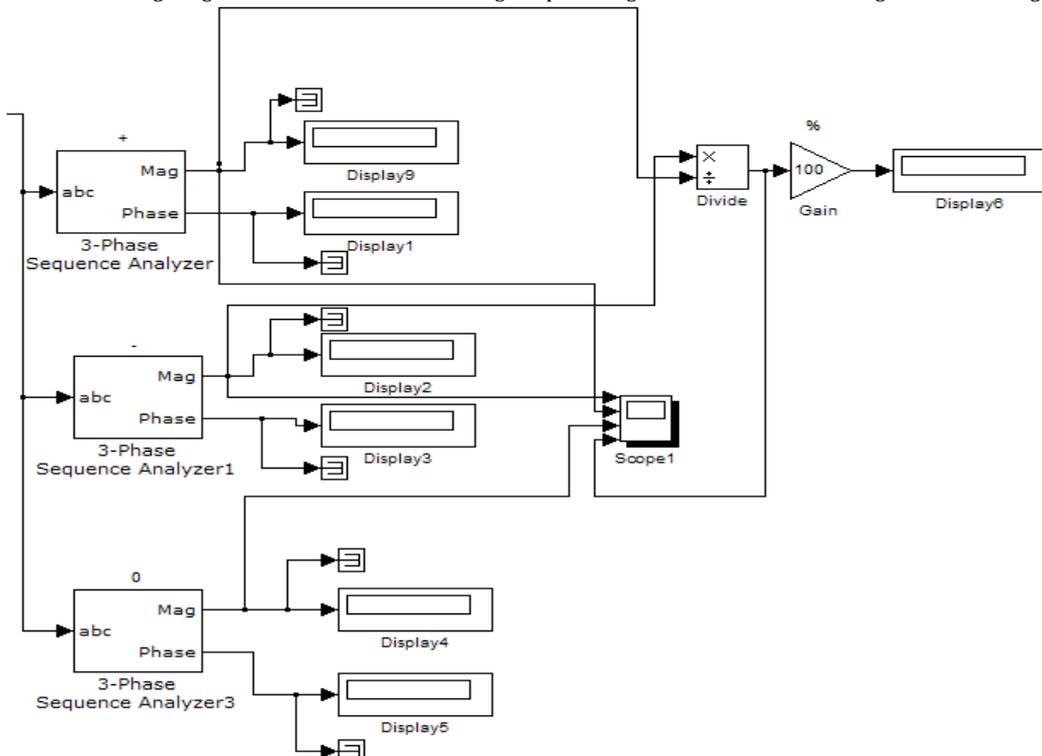

Fig.8.Unbalance voltage degree measurement

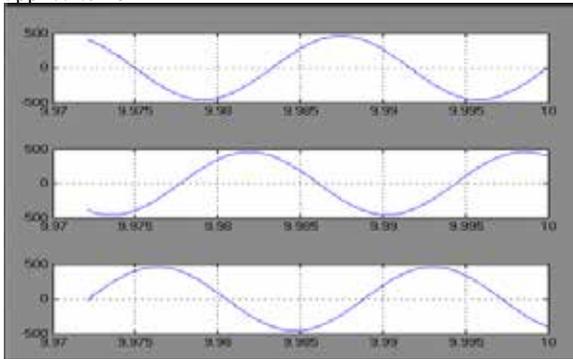At first, as shown in Figure 9 the three balanced voltage are applied to ASD.

Fig.9.The instantaneous balanced voltage applied to ASD

Under balanced feed voltage, the operation of PWM inverter is obtained as presented in Figure 10.
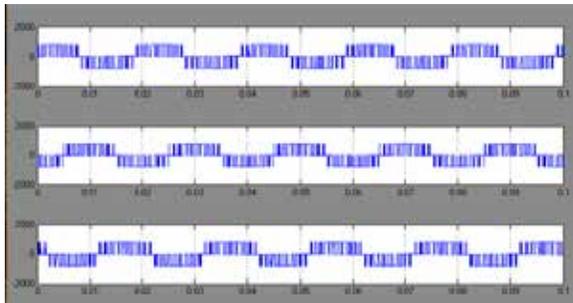

Fig.10.The output of inverter under balanced voltage

The voltage and current of phase 'a' under balanced voltages is shown in Figure 11.
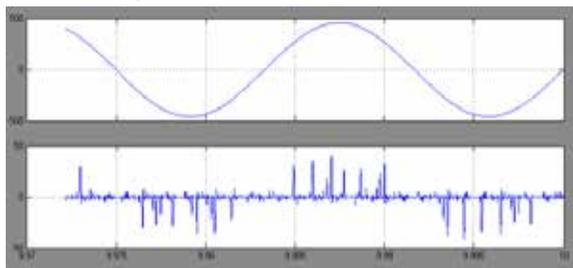

Fig.11.The instantaneous voltage and current of phase 'a' under balanced voltage

The FFT analysis of input current harmonics under utility voltage unbalance demonstrates this matter which is shown in Figure 12.
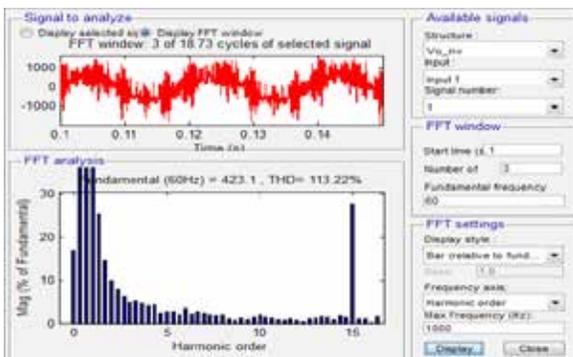

Fig.12.FFT analysis of input current harmonics under balance voltage

At second case study, the three unbalanced voltage are applied to ASD. Three unbalanced applied voltage to ASD is shown in Figure 13. The inverter output under this condition is shown in Figure 14.
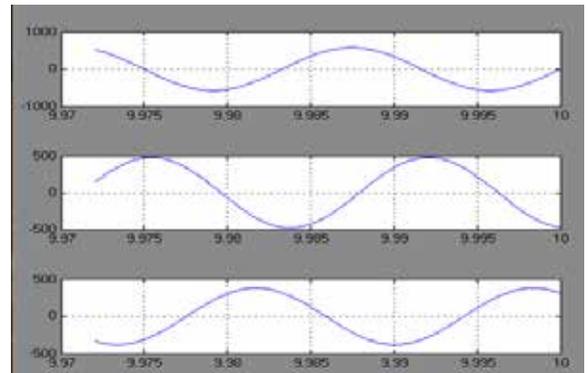

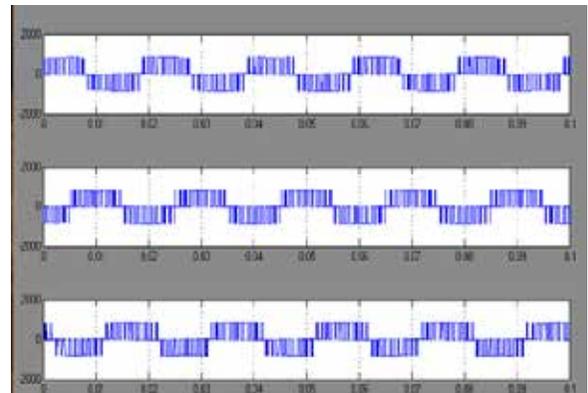**Fig.13.The instantaneous of unbalance voltage applied to ASD**

Fig.14.The output of inverter under unbalanced utility voltages

The voltage and current of phase 'a' under unbalanced voltages is shown in Figure 15.
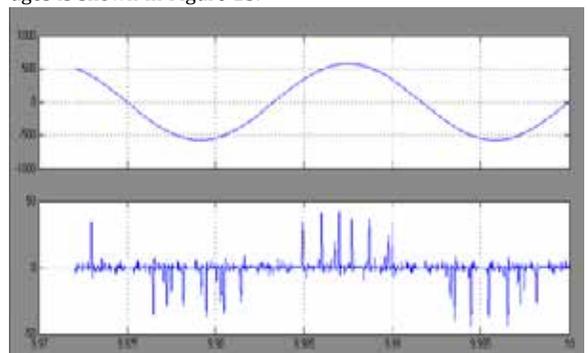

Fig.15.The instantaneous voltage and current of phase 'a' under unbalanced voltage

Under the conditions of utility voltage unbalance, the input current harmonics are not restricted to the converter characteristic harmonics, and uncharacteristic triple harmonics can appear such as the 3rd and 9th harmonics. The FFT analysis of input current harmonics under utility voltage unbalance demonstrates this matter which is shown in Figure 16.
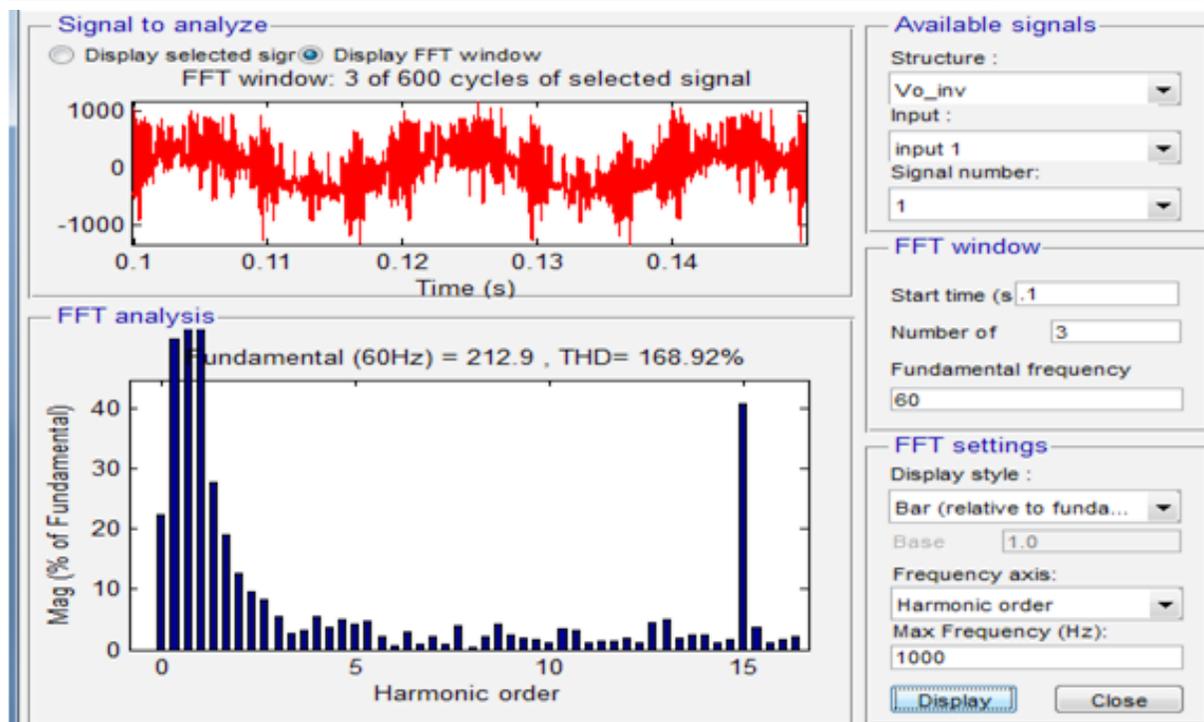
Fig.16. FFT analysis of input current harmonics under utility voltage unbalance

8. Conclusion

This paper deals with investigation the effects of unbalanced voltage of utility grid and resulting adverse effects on induction motors and adjustable speed drives. Standards addressing voltage unbalance were discussed and clarified. In this research two case study were analyzed. At first the behavior of ASD under balanced voltage are investigated. And second case, the influence of unbalanced voltage analyzed. The FFT analysis of input current harmonics under utility voltage unbalance demonstrates this matter which the THD could be increased from 113% under balanced voltage to 165% under unbalanced voltage. Under the conditions of utility voltage unbalance, the input current harmonics are not restricted to the converter characteristic harmonics, and uncharacteristic triple harmonics can appear such as the 3rd and 9th harmonics.

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