THE EFFECT OF ELECTRICAL HARMONIC DISTURBANCES ON CURRENT- AND DEMAND REQUIREMENTS

Dirk AJ van der Bank.
ADA energy efficiency, South Africa.

ABSTRACT

The implementation of non-linear electrical loads on an electrical distribution system holds implications related to power quality (PQ) parameters, both for equipment in one's own facility but possibly also for those of a neighbouring premises. This paper discusses the importance of true rms measurements in order to appreciate the impact of harmonic distortion on current (I) - and demand (kVA) requirements, and the positive effect of proper PQ mitigation. Comparative computer simulation studies for a number of typical cases are presented; this for a VSD load application (with and without harmonic mitigation), a power factor correction (PFC) implementation (with and without harmonic mitigation), Utility versus Generator feed implications for unmitigated non-linear loads, and finally the differences between a harmonic mitigated versus an unmitigated facility on a neighbouring premises.

All these case studies showed that unmitigated harmonic loads (depending on the percentage non-linear loads and facility specific impedances) can give rise to high true rms current consumption, high voltage distortion effects and non-optimised apparent power values. It is also demonstrated that as facilities are unique in their electrical layouts, a one-size-fits-all approach to harmonic mitigation is not viable – this leading to the suggestion that site specific measurements are usually required, this being performed with the proper measurement equipment.

1. INTRODUCTION

The impact of electrical power quality (PQ) deficiencies is increasingly being recognized as an important consideration wherever electrical energy is consumed. PQ relates to a number of phenomena, including power sags, power surges, voltage imbalances and as further discussed in this paper, also the presence of harmonics. Unfortunately, standard energy metering in industry does not always represent harmonic content measurement and the presence and effect of such therefore doesn't get recognized adequately. This paper gives a brief explanation of harmonics and the internationally recognized limiting standards for such. It also discusses a number of typical real life cases of harmonic generation, and the resulting negative effect of such on true power factor (PF), demand /apparent power (kVA) and true rms load current requirements.

2. WHAT ARE ELECTRICAL HARMONIC DISTURBANCES?

The advent of power electronics in the electrical industry brought many advantages, but it also introduced distortion of the traditional sine wave voltage and -current waveforms. For an example: one of the popular devices used in industry today is the variable speed drive (VSD); used in order to obtain economical operation of electrical motors if operating at less than full speed.

Table 1 represents the characteristic current consumption curve of a typical six pulse front-end VSD, without a line reactor or internal choke [1]. Besides the fundamental current (a sine wave at 50Hz), some further harmonic content is present, mainly at the 5th and 7th orders (250Hz and 350Hz) as can be seen from the data.

Amplitude values are normalized as a per unit value to give representation of any size of load. These individual harmonic currents are graphically shown in the time domain view in Fig. 1a, and the mathematical summation of all of these (fundamental plus harmonic orders) in Fig. 1b. As can be clearly seen in this demonstration, the resulting current curve in Fig. 1b is nowhere near the standard 50Hz sine wave as obtained for linear devices (such as for a motor load driven without a VSD).

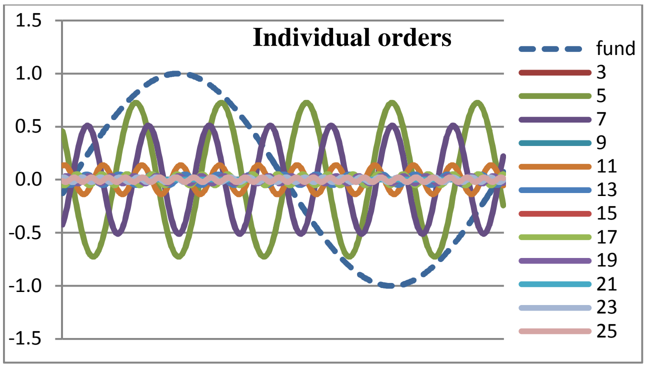

Fig. 1a. Time domain view of all separated individual orders as in Table 1.

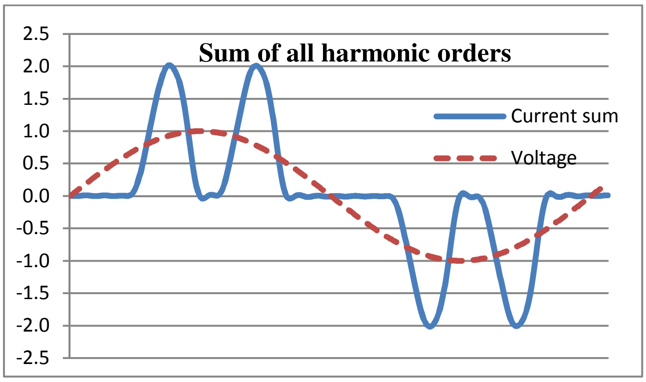

Fig. 1b. Time domain view of the combination of all individual orders from Fig. 1a.

Table 1. Magnitude (per unit) and phase (degrees) values of a typical 6 pulse VSD. [1]

Current spectra	Harmonic order	1	3	5	7	9	11	13	15	17	19	21	23	25
VSD	Magnitude (pu)	1	0	0.725	0.51	0	0.138	0.05	0	0.053	0.035	0	0.022	0.022
without reactor	Phase (deg)	-7.4	0	-219	-56	0	-285	-172	0	-114	-334	0	-289	-153
VSD	Magnitude (pu)	1	0	0.348	0.107	0	0.063	0.032	0	0.025	0.019	0	0.012	0.011
with 3% reactor	Phase (deg)	-15.5	0	-269	-177	0	-149	-119	0	-54	-36	0	-332	-309

Of note is that the current peak value of the combined curve in Fig. 1b extends to twice the peak of the linear equivalent load (or 50 Hz fundamental current), and it also results in peaks in the current profile as opposed to a rather smooth sine wave. It is importance to realize that (as with pure reactive current), the harmonic current component also possess a phase offset component. The total amount of distortion is expressed commonly as a percentage figure for total harmonic distortion (THD), defined as (considering here only uneven harmonics):

$$THD_{current} = \frac{\sqrt{(I3^2+I5^2+I7^2+I9^2+\dots)}}{Ifund} *100\ \% \quad (1)$$

For the above curve of a typical 6 pulse unmitigated VSD drive, this relates to a distorted current curve with a THD$_{current}$ value of **90%.**

Unique but similar non-linear (i.e. non sinusoidal) current profiles are drawn from a supply for all types of non-linear devices such as furnaces or welding operations, and most electronic incorporated devices (including CFL's, data center equipment, hospital equipment, telecom installations, forklift battery chargers, and many more). The net effect of a harmonic component in the true RMS current can be expressed as:

$$I_{rms} = I\,fund * \sqrt{1+THD^{\ 2}} \quad \text{Ampere} \quad (2)$$

In the example of a typical 6 pulse unmitigated VSD as above operated at full speed, this relates to a true RMS current of **1.35 times** the fundamental only current (as the case would have been when this motor load was driven directly without a VSD). Clearly this has implications for sizing of wiring, -transformers and -circuit breakers, metering equipment and many other parts of the installation.

The effect of current harmonic distortion (I_h) at any harmonic order reflects in a voltage distortion (U_h) on the feeder supply lines. This depends on the installation's relevant source- and feeder lines impedances (Z_h) according to Ohm's law:

$$U_h = I_h \; x \; Z_h, \quad \textit{(with h the harmonic order).} \quad (3)$$

As each installation is unique with respect to specific cable size/lengths and source transformer characteristics, (all determining factors of installation impedance), the net effect of harmonic voltage is therefore also unique per specific installation and measuring point.

It has been recognized in industry that once certain levels of both current- and voltage harmonic distortion are exceeded, severe negative effects can be experienced and some form of harmonic mitigation is then generally required.

3. POWER VECTOR CONFIGURATION

In the presence of harmonic loads, the power vector configuration can be graphically expressed as in Fig. 2. This indicates the addition of a harmonic reactive power component to the two-dimensional real- and reactive (capacitive/ inductive)-only components as applicable for linear loads.

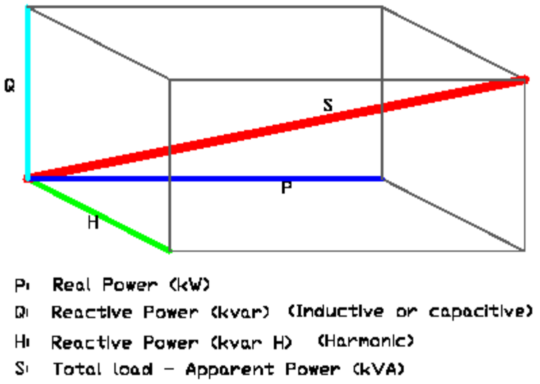

Fig. 2. Power vector configuration (non-linear loads)

The (true) apparent power (or total demand) required from a source in this case is thus hereby increased by the harmonic component, and can be expressed as:

$$S = \sqrt{(kW^2 + kvar^2 + kvar\,H^{\,2})} \quad \text{kVA} \quad (4)$$

The harmonic contribution, as is the capacitive /reactive contribution to demand requirements, does not contribute to useful work and as such does not normally feature in electrical energy measurement as expressed in kWh. Unless true rms recordings are taken, it also does not feature in demand readings, although it may well have adverse implications for sizing of electrical components in an installation.

4. WHAT ARE THE STANDARDS?

A number of industry bodies have documented standards related to the maximum allowable harmonic distortion levels. One which is widely recognized is the IEEE 512 - 1992 standard [2]. In this, some maximum recommended limits are set for both voltage and current distortion levels. These are shown in Tables 2 and 3.

Table 2. Voltage distortion limits from IEEE 519-1992

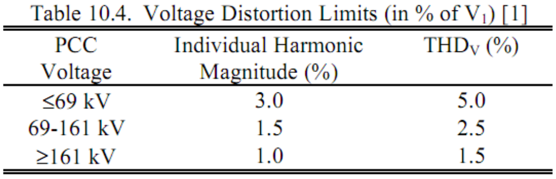

Table 10.4. Voltage Distortion Limits (in % of V_1) [1]

PCC Voltage	Individual Harmonic Magnitude (%)	THD_V (%)
≤69 kV	3.0	5.0
69-161 kV	1.5	2.5
≥161 kV	1.0	1.5

Table 3. Current distortion limits from IEEE 519-1992

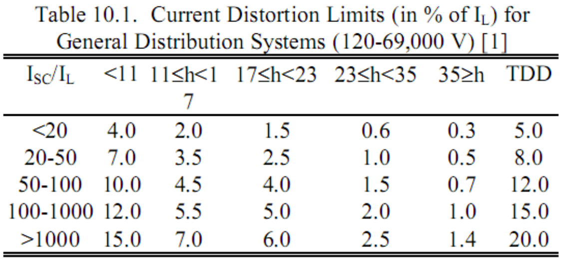

Table 10.1. Current Distortion Limits (in % of I_L) for General Distribution Systems (120-69,000 V) [1]

I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

The recommended maximum values above refer to measurements at the point of common connection (PCC), this being the point where a user is connected to the grid (or other users). For a user which receives mains supply at 11kV, this in reality means measurement at the 11kV side of his distribution transformer. In practice however, the PCC is commonly taken as the point at the distribution transformers secondary terminals, at 400V levels, as is the case for customers receiving power directly at a 400V voltage level. (This inter alia also ensures conformance at a medium voltage PCC)

Furthermore, the limiting current distortion levels are expressed as a total demand current distortion (rather than a momentary current distortion), this to ensure measurements at any given instance to be related to the maximum required current levels. For measurement at maximum load therefore, ***TDD*** equates to the ***THD*** $_{current}$.

It is intended that a user should be responsible for limiting the *harmonic currents* originating from his load profile, and that the Utility would be responsible for (enforcing) the recommended limitations on *voltage harmonic* distortion levels.

5. SIMULATION OF TYPICAL CASE STUDIES

With the above recommended harmonic distortion limits in mind, following are a number of case studies to demonstrate the effect of non-linear loads in an electrical distribution environment. The simulations presented here are done with the aid of commercially available PQ harmonic simulation software.

5.1 CASE STUDY 1

In Case 1 (Fig. 3), two electrical distribution lines are presented within a given facility. Each line represents a standard industrial electrical layout in the most basic format, i.e. power fed from the Utility at 11kV, towards a user distribution transformer for lowering the voltages to 400V, and finally a single load being an electrical motor driven via a VSD.

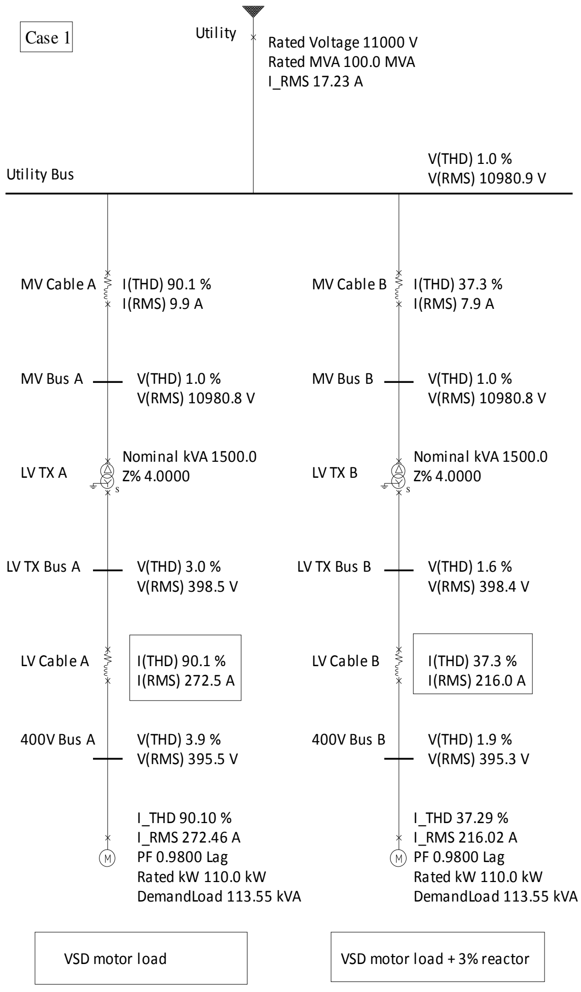

Fig. 3. VSD only load versus VSD-plus-3%-line-reactor load

The two lines are physically identical (left and right in the diagram) in all aspects (transformer, cabling and load characteristics) except for one aspect: while the left line load (electrical motor) is driven via a VSD without a line reactor or internal choke, the right hand side additionally also incorporates a *3% line reactor* in series with the VSD, this being a very simple and economic method of harmonic mitigation for VSD’s. (Refer to data from table 1.) The VSD speed (Hz) output setting is taken at 80% of full speed (i.e. 40Hz) for this simulation, and the motor load is taken as a *constant impedance* type of load.

The resulting true rms currents and -voltages, as well as current- and voltage distortion levels are indicated (in blocks) on the diagram in Fig. 3. It can be seen that while the left hand line (VSD only) results in a **90%** current harmonic distortion and a resulting **272 A** (true rms requirement), the mitigated line on the right hand side reflects a reduced current harmonic distortion of **37%** and an effective rms current requirement of only **216 A**.

This simple passive reactor inclusion therefore represents a reduction of **21%** in true rms load current (and effectively in the demand requirement).

The current waveforms and spectra of the two lines (with and without a line reactor) are represented in Figs. 4a and 4b respectively. The damping effect of the line reactor, resulting in lower peak current is evident in the blue curve in Fig. 4a. Similarly, when broken down into the individual harmonic orders, the lower amplitudes at all the harmonic orders for the mitigated line can be seen in blue in Fig. 4b.

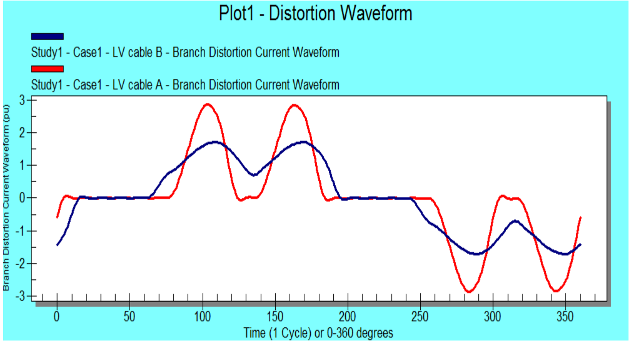

Fig. 4a. Current waveform (one cycle) for VSD only versus VSD plus 3% in-line reactor

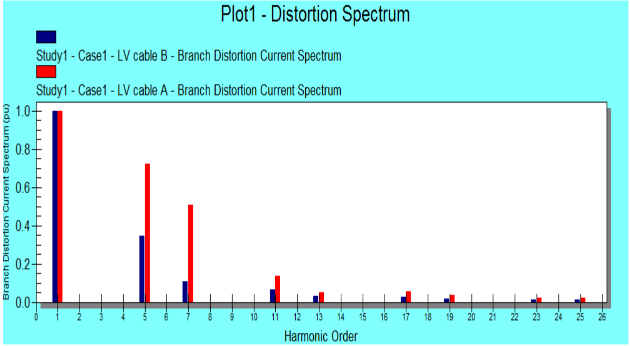

Fig. 4b. Current spectrum for VSD only versus VSD plus 3% in-line reactor

5.2. CASE STUDY 2

In Case 2, again two identical lines in a facility are simulated as shown in Fig. 6. This time each line also includes a power factor capacitor (PFC) bank sized to suit the reactive load. Both lines include a VSD load as before, but with no harmonic mitigation applied directly at any of the VSD's. In addition to the VSD load, a 100kW linear load at 0.75 displacement power factor (DPF) is added to both lines. The only difference in the lines are harmonic filtering applied at the PFC bank at the right hand side line– in this case a simple *tuned in-line reactor* within the capacitor bank feed line (detuned PFC).

In the pure PFC line (left side), current harmonic distortion of **79 %** and rms current consumption of **437 A** can be seen, whilst in the mitigated PFC line (right hand side), current distortion of only **35 %** and true rms current requirement of only **362 A** is evident- this a reduction in true rms current requirement of **17 %**.

The corresponding waveforms, current spectrum and impedance magnitudes are shown in Figs. 5a, b and c, with the red curves each time presenting the case for the mitigated setup. A typical resonance condition can be seen at 640Hz (around 17th harmonic order) in the unmitigated PFC line (blue curve), causing the additional harmonic current component. In the red curve, the successful mitigation of such is evident.

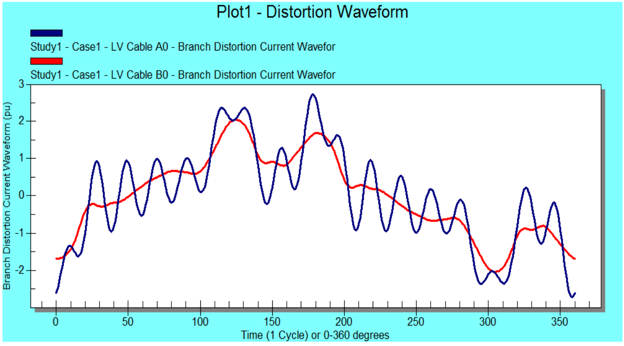

Fig. 5a. Current waveform comparison for a PFC versus detuned-PFC bank

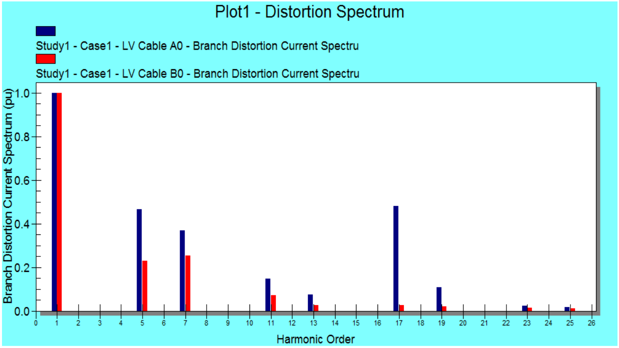

Fig. 5b. Current harmonic spectrum comparison for a PFC versus detuned-PFC bank

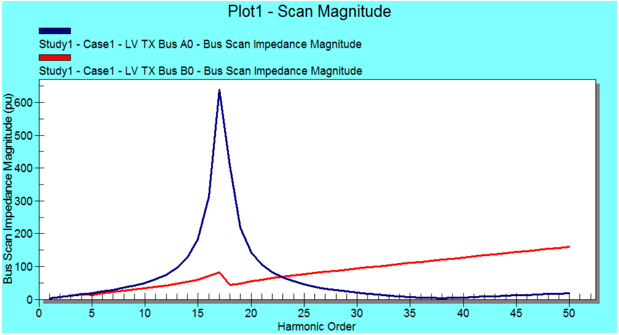

Fig. 5c. Impedance magnitude scans comparisons for a PFC versus detuned-PFC bank.

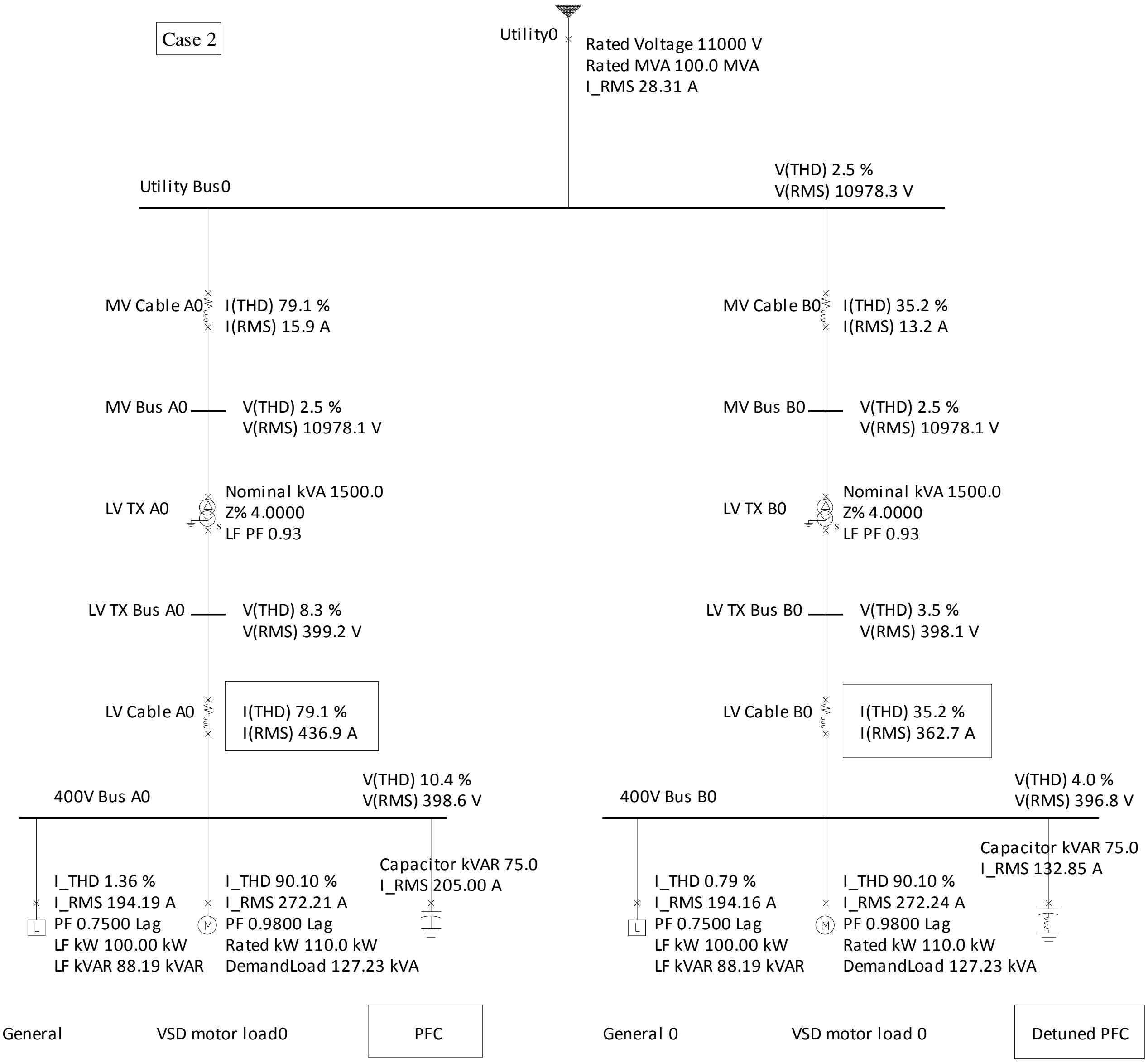

Fig. 6. PFC bank with VSD (PFC-only versus detuned-PFC)

5.3 CASE STUDY 3

In Case 3, identical distribution systems are compared when non-linear loads are being fed from either the **Utility** or a local **Generator** (as in power backup situations).

Identical size sources (each 1500kVA) are simulated, the only difference being the inherent difference in impedance of a typical transformer (Z=4%) versus that of a generator (X"=19%). The load represents a 50% portion non-linear (VSD) load at 0.98 DPF and a 50% linear load at a 0.75DPF. In this simplistic case, no power factor correction is included, in the simulations.

The comparative layouts and simulations are shown in Figs. 7a and 7b.

It can be seen that the voltage harmonic distortion figures increased from a value of 2.8% to **9.6 %** when switching the facility to a generator fed source, an increase of more than **3 fold**; this pushing the voltage distortion limits beyond those recommended in the IEEE 519 standard (where THD voltage max = 5%).

This resulting additional voltage distortion is applied to the common feed of all users at such a facility. The effect is highly dependent on a particular user's electrical layout and characteristics, but it is often seen that capacitor banks in combination with a generators' relative high impedance can result in resonance conditions - this leading to high current consumption and resulting blowing of fuses, damages to capacitors and many other undesirable effects.

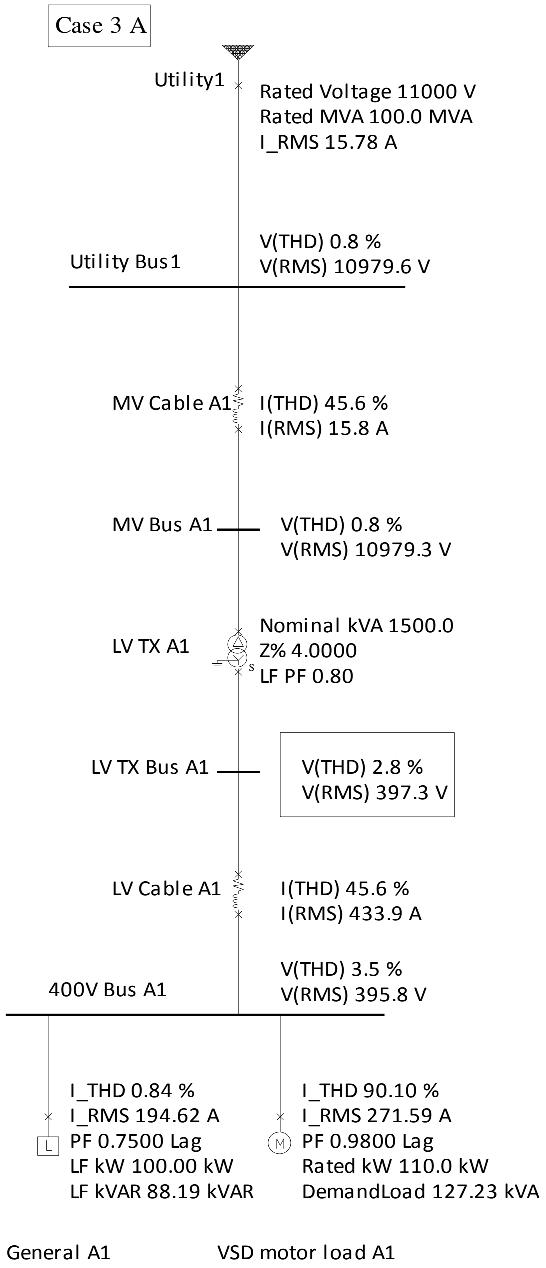

Fig. 7a. Utility supply to typical load

The resulting comparative voltage distortion figures for the above case setups are shown in Fig. 8, in the time domain.

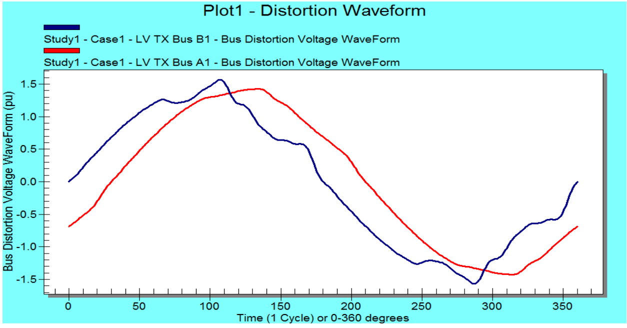

Fig. 8a. Voltage harmonic disturbances - utility versus generator supply -waveforms

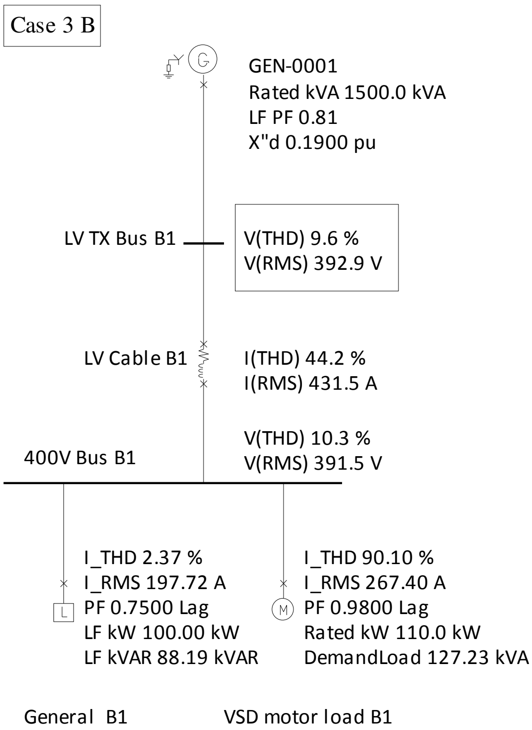

Fig. 7b Generator supply to typical load

5.4 CASE STUDY 4

In Case 4, the effect of harmonics generation from within a plant/premises on a neighbouring premises/user is demonstrated. The difference between non-mitigated and mitigated systems is compared in Figs. 9 and 10 respectively. Both facilities in this simulation have identical layouts and loads, whilst only one facility (left hand side) does make use of power factor correction. The effect of detuning of this PFC bank is illustrated on the neighbouring user's *imported* voltage harmonic levels. (For this case simulation, a 50MVA 3-phase Utility source is assumed).

From the simulations in Fig. 10 it can be seen that for this case the imported harmonic voltage distortion results in a **4.8%** **THDU** (within the IEEE 519 limits) if the neighbour (left-line) implements proper *detuning* (a form of mitigation) of his capacitor bank, whilst this voltage THD level rises to an unacceptable level of **7.1 %** if no such mitigation is applied (fig. 9). In this particular simulation, detuning was applied via a series reactor, tuned at the 4.7th harmonic order.

The resulting waveform and harmonic spectra of each case (mitigated versus non-mitigated) are presented in Fig. 11.

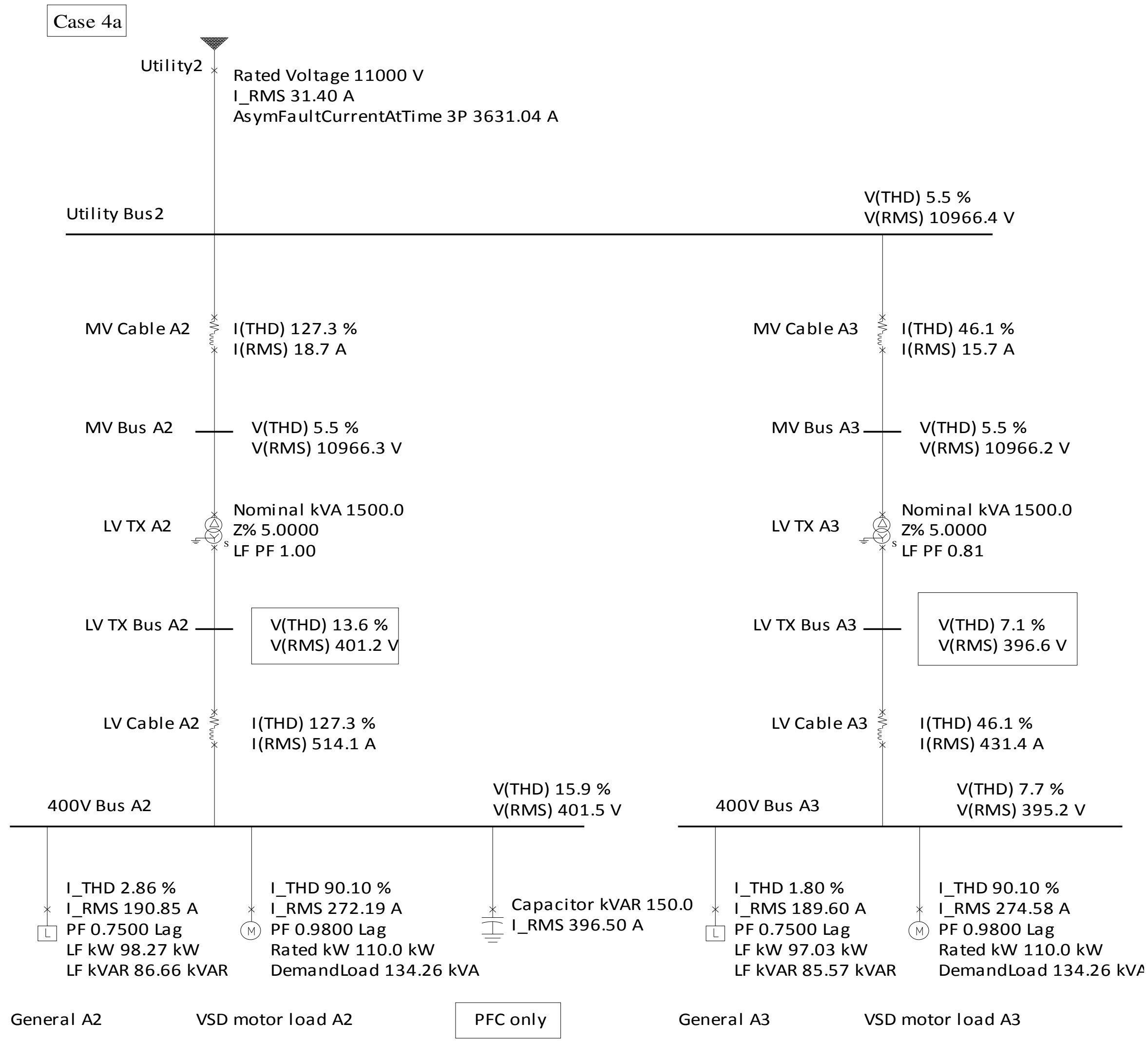

Fig. 9. Neighbour (left side) implemented PFC without detuning

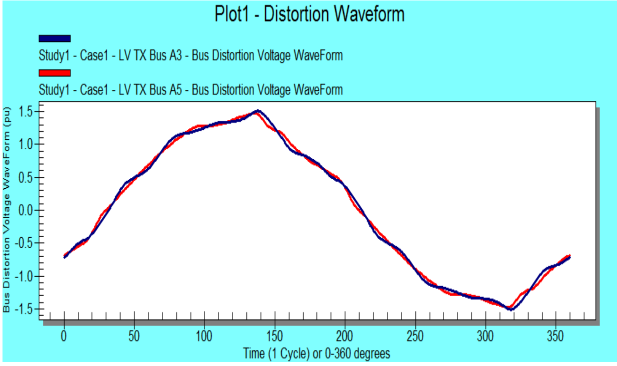

Fig. 11. Comparison of bus voltage distortion due to neighboring mitigation actions- waveform.

6. CASE STUDIES SUMMARY

The above 4 cases clearly demonstrate some of the negatives associated with high levels of THD, notably the higher true rms current requirements as well as an increase in apparent power or the load demand (kVA). It is also demonstrated that harmonic distortion and - propagation are site specific, and therefor also deducted that a one-size-fits-all mitigation methodology does not apply. It is seen that adverse effects can even be obtained due to neighbouring users on the grid which does not adhere to proper harmonic mitigation practices. Although the cases presented here all made use of only a very basic level of mitigation devices (such as correctly specified in-line reactors), already the substantial benefits of such is demonstrated.

7. CONCLUSION

The effect of non-linear devices (such as VSD's, switched mode power supplies, CFL's, etc.) in a plant/facility is seen in the generation of current harmonics, as this translates into voltage harmonics according to a plant's unique impedance components, such as transformers, cable sizes- and lengths, source impedances, etc.

The phase offset between the voltage and current is generally well understood; this commonly being mitigated by power factor capacitors in order to minimize apparent demand (kVA).

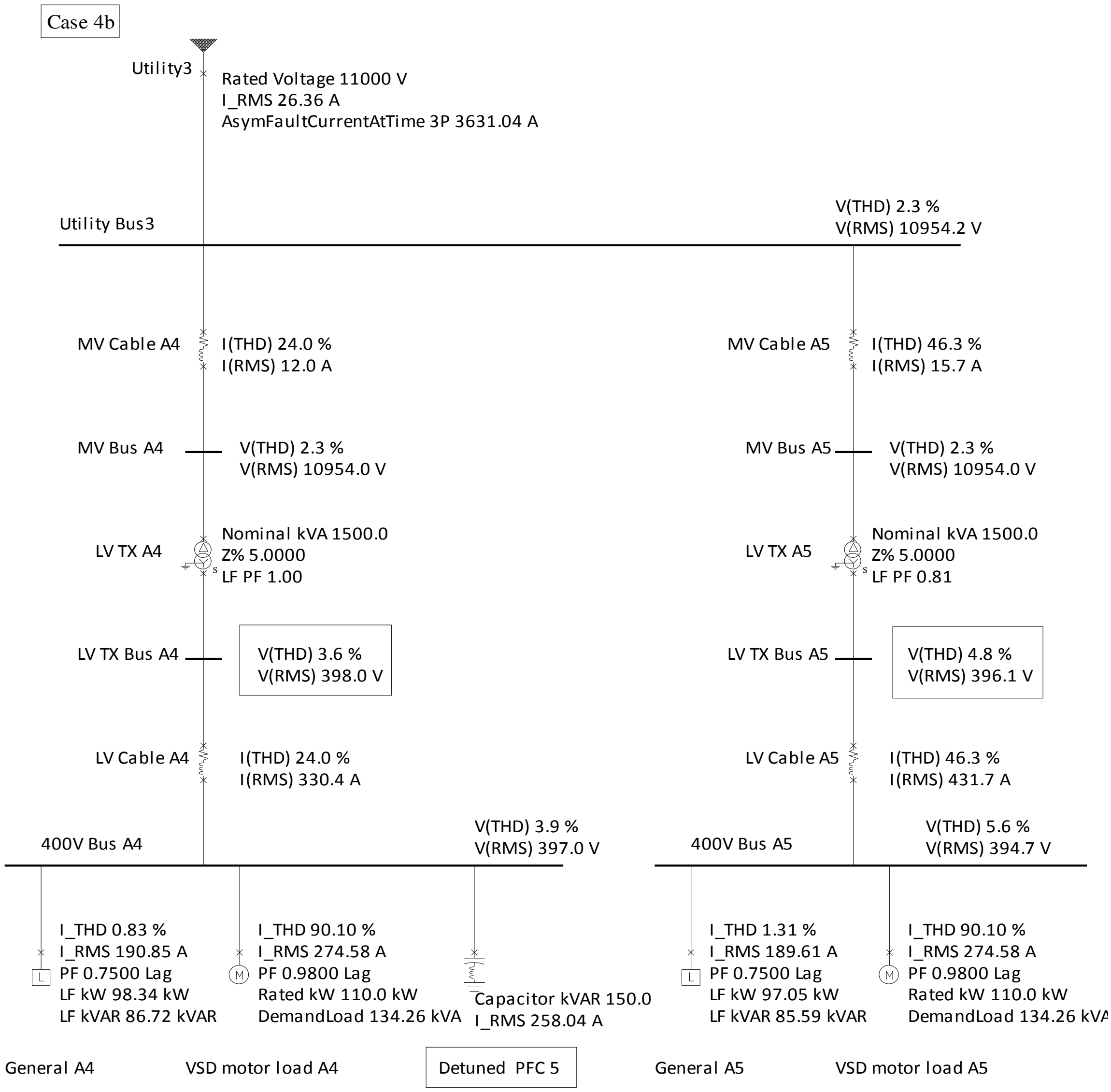

Fig. 10. Neighbour (left side) implemented PFC with detuning

However, the fact that harmonic order components also adds a further disturbed sine wave plus a current/voltage phase offset per harmonic order to the reactive components, are not commonly appreciated or metered.

In contrast to the metering commonly installed at a plant (real- or active energy and –demand quadrants only), in the existence of substantial percentage non-linear loads it is advocated that true rms measurements should rather be taken. This often leads to the realization of the dire need for harmonic mitigation, and consequently in the reduction of true rms current and –demand figures for an installation.

REFERENCES

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[2] IEEE Standard 519-1992, *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems,* The Institute of Electrical and Electronic Engineers, 1993.

Author:

Dirk AJ van der Bank holds a BEng degree in Electronic Engineering from the University of Pretoria and a MBL degree from the School of Business Leadership (UNISA). He also holds CEM and CMVP certifications via the AEE. At present he is a Professional Engineer, consulting on Power Quality at ADA energy efficiency.