Harmonic Cancellation by Mixing Non-linear Single-phase and Three-phase Loads

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Abstract - **The voltage on the distribution line is in most cases distorted even at no load of the transformer. This is due to the "background" distortion on the medium voltage line caused by the large number of single-phase non-linear loads such as PC's, TV, VCR etc. This paper proposes a method to mix single-phase and three-phase non-linear loads and reduce the harmonic currents significantly. The dependence of the phase angle of the harmonic currents as a function of the short circuit impedance is investigated using SABER for the three-phase and the single-phase diode rectifier both with and without dc-link inductance. The phase angle of the 5th and 7th harmonic current of a three-phase diode rectifier is often in counter phase with the 5th and 7th harmonic current of a single-phase diode rectifier. This leads to the conclusion that adding three-phase rectifier load often lowers the voltage and current distortion at the transformer. This is also validated by a number of measurements.**

I. INTRODUCTION

The exploding use of personal computers and electric loads controlled by power electronic has lead to a severe increase of current harmonics drawn from the distribution line. These harmonic currents can in worst cases result in:

- Overheating or derating of transformer
- Overheating of wiring
- Damaging of capacitor banks
- Resonance
- Malfunction of electronic equipment
- Communication interference
- Distorted supply voltage.

Due to the impedance of the distribution line the harmonic currents lead to harmonic voltage distortion, which results in increased losses or damaging of parallel loads and in worst case to system instability. Because of the drawbacks mentioned, the interest in harmonic distortion has increased in both manufactures of electronic equipment and the power supply authorities. Some power supply authorities may even consider to increase the charge paid by the customers generating the distortion because of increased losses in transformer and transmission lines.

This paper deals with the effect of mixing the non-linear load of three- and single-phase diode rectifiers. Furthermore, the influence of the non-linear load regarding the voltage background distortion is investigated. The voltage distortion on the transformer secondary side has two origins: One part is coupled from the medium voltage (MV) side (background distortion) and the other part is generated by the voltage drop in the transformer itself caused by the harmonic currents of the load (load distortion).

Large ASD's (Adjustable Speed Drive) have often been accused of distorting the distribution line but this paper will show that large three-phase ASD's actually can enhance the resulting voltage distortion with respect to the voltage background distortion.

Because of different phase angles the addition of the harmonic currents and voltages must be vectorial and not arithmetical. This is shown by [1] and [2]. Ref. [2] has shown that the background voltage distortion can be reduced when connecting a six-pulse diode rectifier to the distribution line, while the distortion is increased when connecting single-phase diode rectifiers to the distribution line. A complete analysis of the influence of the harmonic currents phase angle from both single- and three-phase rectifier has not yet been done. This leads to the question of phase angle dependency of the harmonic currents regarding to the network impedance for both the single-phase and three-phase diode rectifiers.

Ref. [4] has made an investigation on the influence of the short circuit ratio and the dc-link capacitor on the percentage and the angular displacement of the harmonic currents regarding to the fundamental voltage of a six pulse diode rectifier. The influence of the dc-link inductance in the rectifier is not included. In [5] the harmonic currents phase angle dependency of the dc-link inductance for both single- and three-phase diode rectifier is shown. The influence of the ac-side impedance is not included. This is done in this paper.

This paper will analyse the phase angle of the harmonic currents in single- and three-phase diode rectifiers both with and without dc-link inductance. The effect of mixing both single- and three-phase diode rectifiers will be analysed too. Furthermore, the influence of the harmonic currents phase angle on the background voltage distortion will be investigated. A number of experimental results will validate the theory.

II. HARMONIC VOLTAGE BACKGROUND DISTORTION

The voltage on the low voltage (LV) distribution line is in most cases distorted even at no load. This is due to the background distortion on the medium voltage (MV) and high voltage (HV) line. Refs. [1] and [6] have pointed out that the harmonic current distortion in the LV distribution system is caused by a large number of switch mode power supplies used in PC's, TV's, VCR's and stereos. These current

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distortions add up in the MV and HV networks. This means the harmonic background voltage distortion is mainly caused by a large number of small single-phase diode rectifiers. The resulting voltage with this kind of load is shown in Fig. 1 and can be seen/measured almost everywhere across Europe. The dominant harmonic voltage is the 5th harmonic. In the MV and HV network the 3rd harmonic is hardly present since it is not transmitted over the delta-wye transformer which is widely used for LV distribution lines. Ref. [1] has also observed that the higher harmonics tend to cancel each other, since the phase angle of the higher harmonics differs widely.

The resulting harmonic voltage distortion to be measured at the transformer secondary side equals the vectorial sum of the background voltage distortion and the load distortion. A circuit diagram is shown in Fig. 2.

This means the resulting voltage distortion is dependent on the background voltage distortion, the amplitude and phase angle of the harmonic current and the harmonic impedance. This is also shown in (1).

$$\overline{U_{h,PCC}} = \overline{U_{h,0}} + \overline{U_h} = \overline{U_{h,0}} + \overline{I_h}(R + jhX) \qquad (1)$$

where:

$U_{h,PCC}$ is the resulting voltage distortion at the point of common coupling (PCC).

$U_{h,0}$ is the background distortion.

U_h is the voltage drop of the harmonic currents.

I_h is the h'th harmonic current

R is the real part of the impedance Z_h

jhX the imaginary part of the impedance Z_h as function of the harmonic number h

It is important to notice that the background voltage distortion is fixed and will not change as a function of the load on the secondary side of the transformer. This is because the background distortion comes from the MV side and thereby has a high short circuit power. To give an example of the background voltage distortion a measurement on a MV-line is done. These measurements are shown in Fig. 3 and Fig. 4.

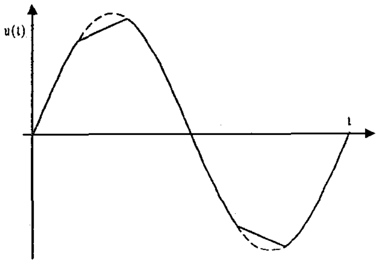


Fig. 1. Typical background voltage waveform with distortion from single-phase loads.

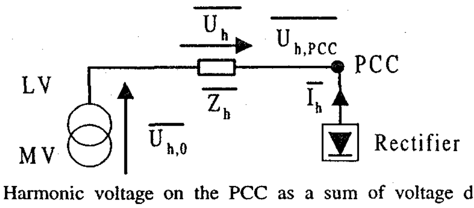


Fig. 2. Harmonic voltage on the PCC as a sum of voltage drop at the transformer and background distortion.

The voltages are measured at the secondary side of a 50/10 kV transformer. The 10 kV distribution line is supplying 16 MV/LV substations where three substations are supplying industry, eight substations are supplying domestic area and five substations are supplying miscellaneous. As expected the dominant harmonic voltage is the 5th harmonic. However, the 5th harmonic current is below 1% when the voltages were measured. This means that the 5th harmonic voltage origins from the 50 kV line.

III. HARMONIC ANALYSIS OF RECTIFIER

A common used model of the diode rectifier is to assume that the rectifier works as a harmonic current generator. But simulations in [4] and [5] have shown the harmonic currents of the rectifiers are dependent on both ac and dc impedance.

Therefore simulations using SABER are made with respect to both varying ac side impedance and with/without a dc-link inductance.

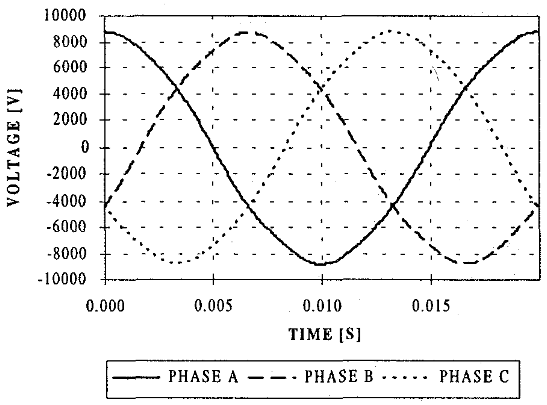


Fig. 3. Measured phase voltages on a 10 kV distribution line.

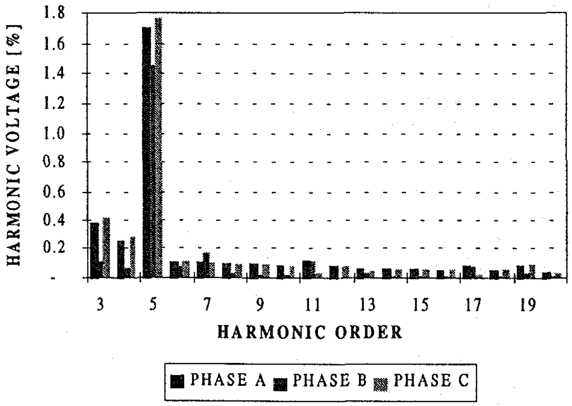


Fig. 4. Harmonic analysis of the measured 10 kV distribution line voltages.

The per-unit notation used in the following is obtained by dividing the 50 Hz impedance (Z_{50Hz}) by the base impedance (Z_B) of the transformer/rectifier. This is shown in (2).

$$Z_B = \frac{U_{LL}^2}{S_{nom}} \qquad Z_{pu} = \frac{Z_{50Hz}}{Z_B} \tag{2}$$

where:
U_{LL} is the line to line voltage.
S_{nom} is the nominal power of the transformer/rectifier

The circuit diagrams of the simulations are shown in Fig. 5. A transformer with e_x = 5% and e_r = 0.9% is connected to a three-phase diode rectifier with (Fig. 5 A) or without (Fig. 5 B) a dc-link inductance. The input power of the three-phase rectifier is S_L = 200 kVA. A similar simulation is also made with three single-phase rectifiers with (Fig. 5 C) and without (Fig. 5 D) a dc-link inductance. The input power of the single-phase rectifiers is S_L = 67 kVA each. This gives a three-phase load of 200 kVA. The dc-link capacitor used in A, B, C and D is C_d = 30 % related to the rectifier per-unit notation. The dc-link inductance used in B and D is L_{dc} = 3 % and it is also related to the rectifier per-unit notation.

The transformer size S_{trafo} is varied from 200 kVA to 6 MVA which gives a varying ac-side impedance on the secondary side of the transformer. The short circuit power on the secondary side of the transformer is thereby varied from 4 MVA - 120 MVA which gives a short circuit ratio $R_{sc} = S_{sc} / S_L$ = 20 - 600.

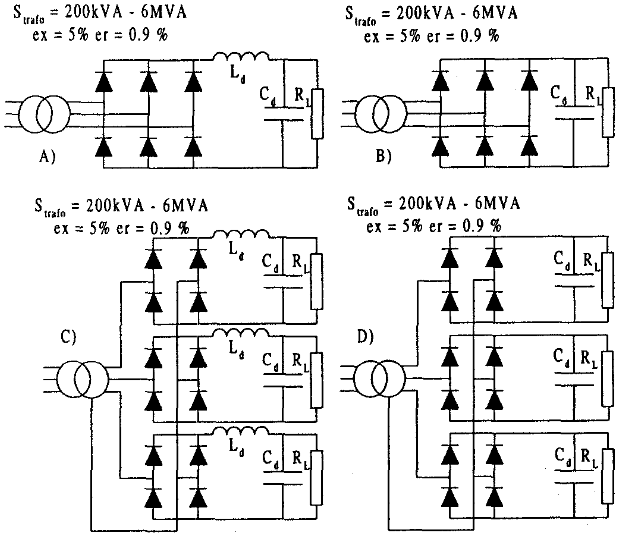


Fig. 5. Circuit diagrams of the simulations. A) Three-phase rectifier with dc-link inductance. B) Three-phase rectifier without dc-link inductance. C) Single-phase rectifier with dc-link inductance. D) Single-phase rectifier without dc-link inductance.

The harmonic currents are simulated with a step of R_{sc} = 20. The results of the simulations are shown in the polar plots in Fig. 6 and Fig. 7. The 5th harmonic current of the three-phase rectifier is within the range of 110° and 215°, while the 5th harmonic current of the single-phase rectifier is within the range of 295° and 45°. The phase angles of the 5th harmonic current for the single- and three-phase rectifier differs up to 110° and they are often in counter phase. This means the vectorial sum of the 5th harmonic current of the three- and single-phase rectifier will always be significant less than the arithmetical sum and often a total reduction can be obtained. Furthermore, if the only load is a large single- or three-phase rectifier load there will be no cancellation of the 5th harmonic current because they will be in phase. Due to the large amount of single-phase non-linear loads on the LV-line the 5th harmonic voltage is the most dominating harmonic distortion on the MV-line.

The 7th harmonic current of the three-phase rectifier is in the range of 30° and 230° while it is in the range of 255° and 60° for a single-phase diode rectifier. The worst case is a dc-link inductance in the three-phase rectifier while the single-phase rectifier is connected to a strong distribution line where an arithmetical addition is possible. In a typical case a large number of single-phase rectifiers are without any dc-link inductance and they are connected to a weak line (long cables) and a few three-phase rectifiers with dc-link inductance are connected to a strong line (near the transformer) then the 7th harmonic currents will be in counter phase.

The phase angle of the 7th harmonic current for the single-phase rectifier differs almost 180°. This means that there will be some cancellation of the 7th harmonic current of single-phase rectifiers. This is also the reason why the 7th harmonic distortion on the MV-line is less than the 5th harmonic distortion.

The 11th and 13th harmonic currents for both the single- and three-phase rectifier are in the range of a complete cycle and they are therefore very dependent of the transformer impedance (and cable). The phase angle of the 11th and 13th harmonic current differs so much, that there is a high possibility that they will be cancelled in the distribution line.

Another interesting conclusion is that using a dc-link inductance makes the amplitude and phase angle of the harmonic current less dependent of the ac-line impedance. The dc-link inductance of the single-phase rectifier behaves like an ac-line impedance.

Fig. 6 and Fig. 7. gives a powerful tool to evaluate the phase angle and amplitude of possible rectifier configurations as a function of R_{sc} in many industrial applications.

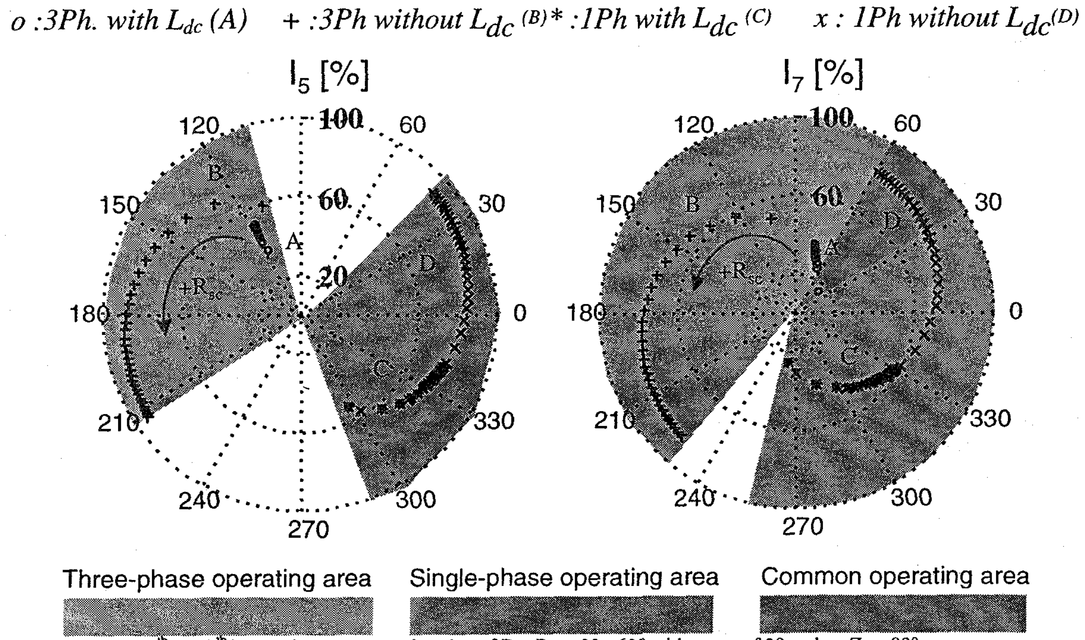


Fig. 6. Polar plots of the 5th and 7th harmonic current as a function of R_{sc}. R_{sc} = 20 - 600 with a step of 20 and $\arg Z_{SC}$=80°.

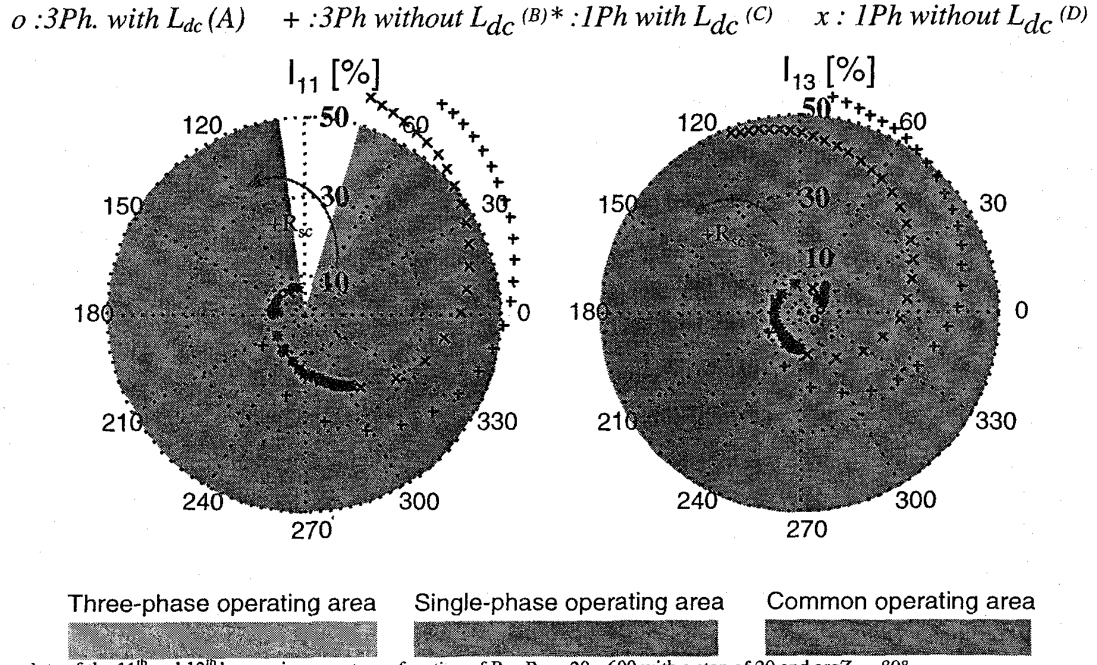


Fig. 7. Polar plots of the 11th and 13th harmonic current as a function of R_{sc}. R_{sc} = 20 - 600 with a step of 20 and $\arg Z_{SC}$=80°.

IV. HARMONIC CURRENT AND VOLTAGE DISTORTION REDUCTION

In a typical industrial distribution network or a large office building there will be a few large three-phase non-linear loads, e.g. ASD for heating and ventilation, while there will be many small single-phase non-linear loads especially PC's. The short circuit capacity S_{sc} in a LV network is mainly limited by the LV transformer and the LV cable impedance. The MV impedance can be neglected.

A case study is done and simulations are carried out to evaluate the results of Fig. 6 and Fig. 7. A small supply system from a DY5 coupled 1 MVA distribution transformer is simulated. The MV side is assumed sinusoidal and balanced. The transformer is loaded with single-phase rectifiers (the total load is 170 kW) and a 170 kW three-phase rectifier. The three-phase rectifier is located near by the transformer with a 50 m, 90 mm^2 copper cable. The single-phase rectifier loads are evenly distributed on the three-phases with a 200 m, 50 mm^2 copper cable. It is assumed that the single-phase rectifiers are plugged in the wall sockets and therefore a long cable is used for the single-phase rectifiers. Fig. 8 shows the simulated system.

The synchronous reactance of the cable is 0.07 Ω/km and the capacitive effects are ignored. The impedances of the cables are shown by their per-unit values related to the transformer. The fundamental voltage drop across the long cable is about 7% at 170 kW single-phase rectifier load. Related to the rectifier per-unit notation the cable impedance equals 7.3% + j1.5%. The impedance of the cable is the dominant short circuit impedance as seen from the single-phase rectifiers and some differences from the simulations in Fig. 6 are expected as the short circuit impedances there were predominantly inductive. Fig. *9*a shows a simulation result of the currents drawn by the two rectifier groups. The currents add up in the secondary winding of the transformer which is shown in Fig. *9*b.

Intuitively, it is seen that the two waveforms are supporting each other well. The single-phase current has a "valley filling" effect to the three-phase current, and the resulting waveform looks more sinusoidal than each of the two individual currents.

The total harmonic distortion (THD) of the three-phase current is 51% and 88% for the single-phase. When the currents are added in the transformer the resulting distortion is only 38%. This reduction in the distortion is mainly due to 5'th harmonic cancellation as it can be seen more clear from Fig. *10*. Fig. *10* shows the harmonic spectrum of the three currents of Fig. *9*

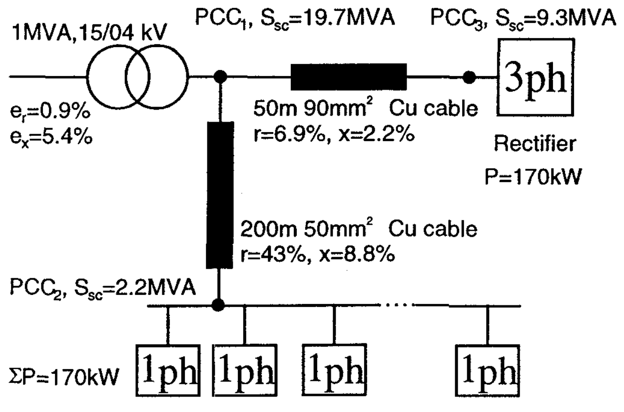
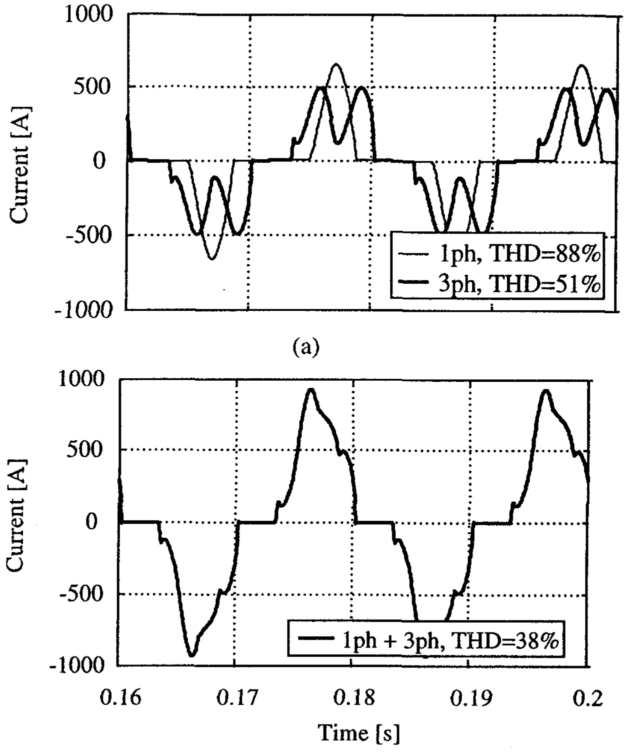


Fig. 8. Simulated system with transformer, cable and load.



(b)

Fig. 9. Simulated currents drawn in the system a) Rectifier currents b)Total current in the secondary windings of the transformer .

The fundamental components of the two rectifier loads are seen to add up arithmetically in the transformer. This means that the fundamental components are in phase. The third harmonic is not present in the three-phase spectrum (as long as it is balanced) and the single-phase rectifier third harmonic component is seen directly in the transformer. The interesting part is to observe what happens with the 5'th harmonic current. In this case a *110* A current from the three-phase rectifier is seen and 90 A from the single-phase rectifier.

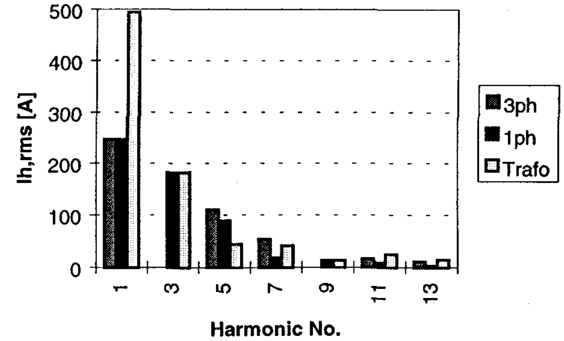


Fig. 10. Harmonic spectrum of rectifier and transformer currents.

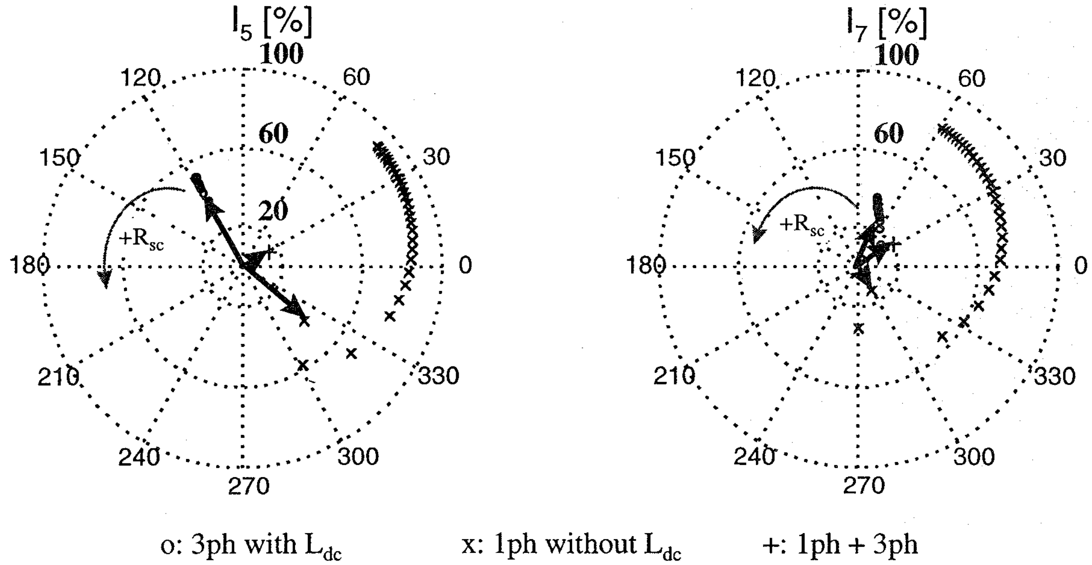


Fig.11. Polar plots of the 5th and 7th harmonic currents of the simulations together with the traces from Fig. 6.

On the transformer only about 45 A is seen. This is only about 20% of the arithmetical sum of the two rectifier contributions. The 7'th harmonic component in the transformer equals less than 60% of the arithmetical sum. Again, the polar plots show their applications. Plotting the 5'th and 7'th harmonic currents in polar co-ordinates (See Fig. 11) shows that the 5'th harmonics are almost exact in counterphase and thus almost cancelling each other completely. The 7'th harmonics are added with an obtuse angle which still shows a reduction.

The phasors of the 5'th and 7'th harmonic currents are plotted in Fig. 11 along with the traces from Fig. 6. The three-phase rectifier operates with a short circuit ratio $R_{sc} = 55$ while the single-phase rectifiers have a short circuit ratio (to the total power) of 10 which is a very weak grid. The resistive nature of the cable and the small short circuit ratio gives a deviation for the single-phase rectifier, but still the angles are added within the area as defined in Fig. 6.

It can be concluded that adding a three-phase rectifier to an existing single-phase load or visa versa will not increase the current THD at the transformer but actually lower the THD and thereby lower the losses in the transformer.

In § II it was stated that the harmonic background distortion is caused by a large number of single-phase non-linear loads. The above simulations lead to the statement that the resulting voltage distortion can be reduced when connecting a three-phase diode rectifier to the utility grid due to (1).

An other simulation example is carried out to verify this statement. A small supply system from a DYn5 coupled 10/04 kV 800 kVA distribution transformer is simulated. The MV side is assumed to be distorted with the amplitude and phase angle of 5th harmonic voltage of the measured voltages in Fig. 3.

The transformer is loaded by a three-phase diode rectifier with a 3 % dc-inductance and varying nominal load from 0 to 650 kW. The three-phase rectifier is located near by the transformer. This is shown in Fig. 12.

The impact of the rectifier load on the transformer for the 5th harmonic voltage is shown in Fig. 13.

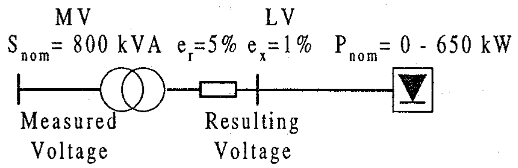


Fig. 12. Circuit diagram for simulation of rectifier influence on the resulting voltage distortion taking the voltage background distortion into account.

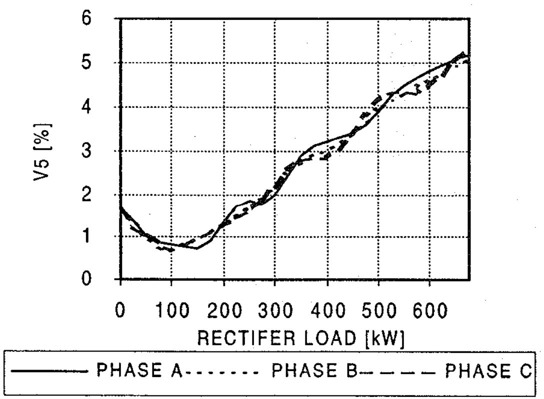


Fig. 13. The 5th harmonic voltage as a function of the rectifier load at the transformer.

Increasing the three-phase non-linear load of the transformer the resulting 5th harmonic voltage distortion will decrease. At approximately 12 % of the nominal transformer power the minimum distortion below 1% is reached. At approximately 25 % rectifier load of nominal transformer power the resulting 5th harmonic voltage distortion has reached the same level as the background distortion. Above 25 % the resulting 5th harmonic voltage distortion is higher than the background 5th harmonic voltage distortion. These interesting results have also been observed on-site in several applications.

V. TEST RESULTS

Some measurements have been done at an office building. They have been done on a three-phase 32 kVA ASD with a 4.3 % dc-link inductance and a 28 % smoothing capacitor. The ASD is connected to a 1.5 MVA transformer via a cable. The short circuit power for the cable is 5.4 MVA. A circuit diagram of the system is shown in Fig. 14. The resulting harmonic voltages are measured as a function of the drive input power.

Fig. 15a shows the harmonic voltages for both without ASD (background voltage distortion) and with the full loaded ASD. As expected the 5th harmonic voltage is lower with the ASD as without due to the phase angle of the 5th harmonic current of a three-phase diode rectifier. The 7th harmonic voltage is slightly increased. The 11th is remained constant and the 13th is increased.

Actually, in this measurement the voltage total harmonic distortion (THD) was decreased from 1.33% to 1.19% when the ASD was operating. Fig. 15b shows the 5th harmonic voltage as a function of the drive input power. There is a good agreement to the simulated result shown in Fig. 13 where the background voltage distortion approximately has the same level.

Another measurement has been made at a different place. Here the voltage background distortion is very high while the drive is smaller than in the previous measurement. The measurements have been made on a three-phase ASD with a nominal input power of 12 kW. The dc-link inductance is 3.7 % and the smoothing capacitor is 22 %. The circuit diagram of these measurements is similar as in the previous case. The results are shown in Fig. 16.

Again the 5th harmonic voltage is reduced significantly compared to the background voltage distortion and the there is a slightly reduction of the 7th harmonic voltage. The THD is reduced from 8.85 % to 8.08 %.

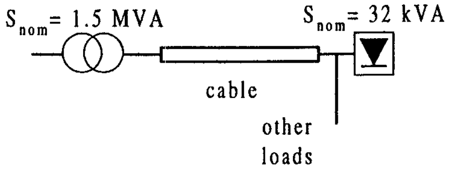
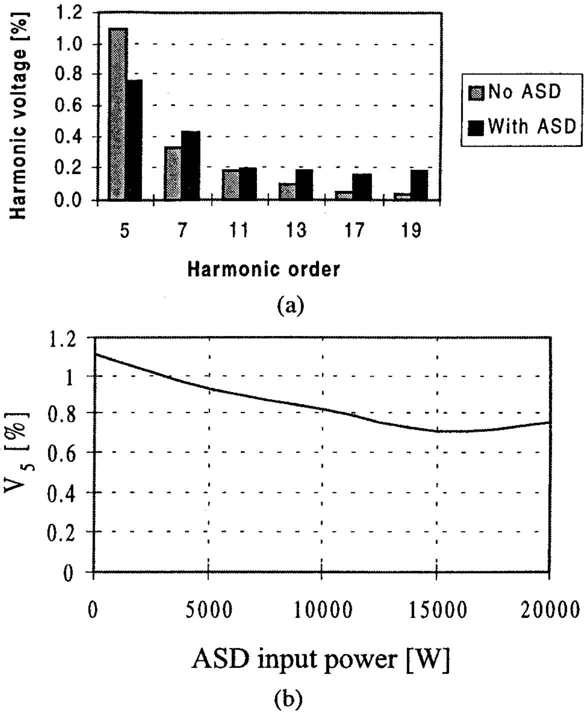


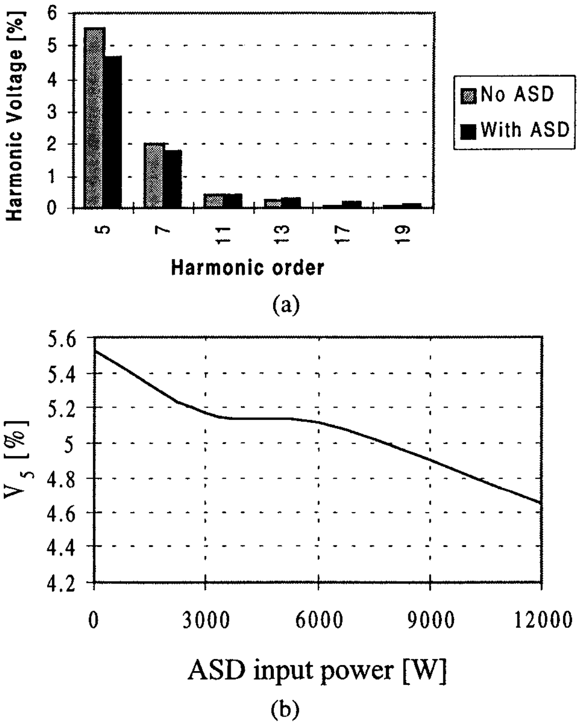
Fig. 14.Circuit diagram of the system where the measurements were done.



(a)

(b)

Fig. 15. a) Measurements of the resulting voltage distortion with and without a three-phase ASD. b) 5th harmonic voltage as a function of the drive input power.



(a)

(b)

Fig. 16. a) Measurements of the resulting voltage distortion with and without a three-phase ASD. b) 5th harmonic voltage as a function of the drive input power.

VI. CONCLUSION

This paper has shown that mixing single- and three-phase non-linear loads gives a reduced THD. The reason is that the 5th and 7th harmonic current of single- and three-phase non-linear load often are in counterphase.

Furthermore, it can be concluded that adding a three-phase rectifier to an existing single-phase load or visa versa will not increase the current THD at the transformer but actually lower the THD and thereby lower the losses in the transformer.

It is clearly shown that three-phase rectifiers actually can reduce the harmonic voltage distortion. This leads to an important point: Limiting the harmonic currents from three-phase non-linear equipment does not always assure a better power (voltage) quality. Care should therefore be taken when setting strict limits to harmonic current emission for three-phase diode rectifiers because of their positive effect.

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