HARMONIC REDUCTION DUE TO MIXING SINGLE-PHASE AND THREE-PHASE LOAD CURRENT UNDER NON-IDEAL SUPPLY CONDITION

M. Ashari * S. Islam** S.S. Matair**

* Dept. of Electrical Engineering, Faculty of Industrial Technology,
Sepuluh Nopember Institute of Technology (ITS) Surabaya, Indonesia, email: ashari@ieee.org

** Centre for Renewable Energy and Sustainable Technologies Australia (CRESTA),
School of Electrical Engineering, Curtin University of Technology, Australia

Abstract;
This paper presents harmonic reduction due to mixing single-phase and three-phase rectifiers in low voltage distribution systems. The rectifiers use the full bridge involving inductor, capacitor and resistor. Three types of three-phase power sources: an ideal source, a non-ideal with balanced magnitude and a non-ideal with unbalanced magnitude voltages are used in the simulations. The non-ideal source refers to a three-phase source that the voltages are not exactly shifted by 120^o. The harmonic currents in the line when supplying individual and mixing loads are investigated. Harmonic reduction occurs in the line current due to the counter-phase of individual harmonics. Results from simulation using PSCAD computer software are included in the paper.

1. INTRODUCTION

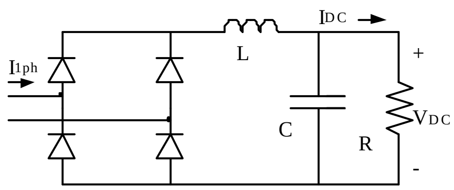
Loads in low voltage distribution systems are mostly single-phase rectifiers, which are included in electronic equipment such as radio, television, etc. Three-phase loads that use three-phase rectifiers in distribution systems include adjustable motors, uninterruptible power supply systems, battery charger, etc. The rectifier units have been known to draw a non-linear current (harmonics) when connected to the supply mains.

Without any harmonic cancellations, non-linear loads may cause an excessive distortion in the phase current. The neutral current of this system may reach more than 100% of phase current magnitude resulting in thermal overloading of the neutral wire [1]. This is due to the vector sum of the triple-n harmonic currents from each phase. Excessive harmonic current in the line and in the neutral may cause serious malfunction of the protection equipment, interference to computers and reduce transformer efficiency[2]. However, harmonic cancellation may occur due to the counter-phase of single and three-phase harmonics [3].

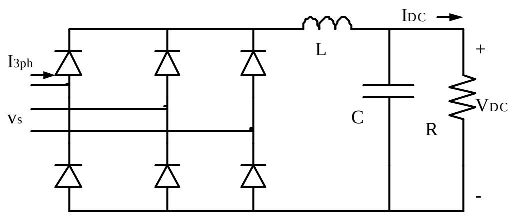
This paper presents harmonic reduction due to mixing single-phase and three-phase load current in low voltage distribution systems. Full bridge rectifiers involving inductor-capacitor filter and resistor are used in the simulations. The harmonics current in each phase when supplying the individual and mixing loads is investigated. Three conditions of the three-phase power sources are used in simulations: ideal source, non-ideal with balanced magnitude and non-ideal with unbalanced magnitude voltage. The non-ideal three-phase source is assumed having voltages that are not exactly shifted by 120^o. This voltage supply is typically provided by voltage controlled inverters [4], [5], [6]. Results from simulation using PSCAD computer software are included in the paper [7].

2. HARMONICS CAUSED BY SINGLE-PHASE AND THREE-PHASE RECTIFIERS

Harmonic performances in a normal distribution system, which supplies single-phase and three-phase rectifiers, are presented. The circuits of the full bridge rectifier for the single-phase and three-phase systems are shown in Fig. 1.



(a)



(b)

Fig. 1: (a) Single-phase and (b) three-phase rectifier

In applications, the rectifiers may include inductor L and capacitor C. This LC filter is for smoothing the current and attenuating the ripple voltage in the DC side. The resistor R represents the DC load. For an idealized case without filter LC, the average DC output voltage is [8]:

$V_{dc} = 2\sqrt{2}\ V_S / \pi$ for the single-phase (1)

$V_{dc} = 3\sqrt{2}\ V_{LL} / \pi$ for the three-phase (2)

The magnitude of h^{th} (odd) harmonic current in the line is computed using equations (3) and (4).

$I_{1ph(h)} = 2\sqrt{2}\ V_S / (R\pi h)$ for the single-phase (3)

$I_{3ph(h)} = \sqrt{6}\ V_{LL} / (R\pi h)$ for the three-phase (4)

where V_s is the dc source voltage, V_{LL} is the line-to-line voltage. Each harmonic has a phase angle φ_h, because a harmonic is a vector. The Total Harmonic Distortion (THD) of the current is presented in equation (5).

$$I_{THD} = \frac{100\%}{I_{h=1}} \sqrt{\sum_{h=2}^{\infty} I_h^2} \quad (5)$$

Fig. 2 shows the block diagram of a typical 240/ 415 volts distribution system for simulation purposes. The system is initially simulated supplying a single-phase rectifier in each phase, the harmonic distortion is examined. A three-phase rectifier is then installed in the system.

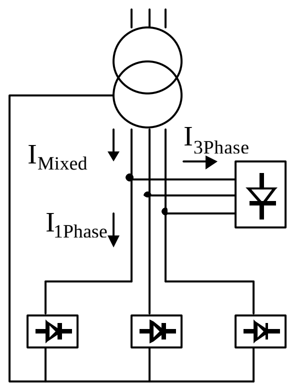


Fig. 2: Single-phase and three-phase rectifiers in a typical distribution system

The rectifiers are simulated using L= 10 mH and C=1000 µF. The resistors as the DC loads of the single-phase and three-phase rectifiers are R= 5Ω and 5/3 Ω respectively. Fig. 3 shows the waveform of the DC voltage.

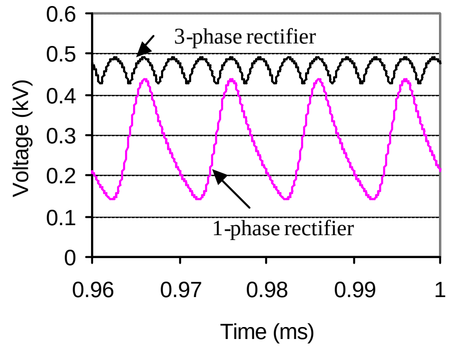


Fig. 3: DC voltage waveform

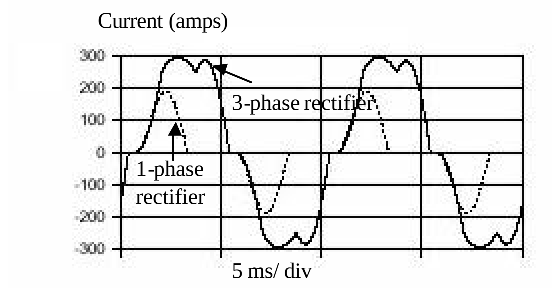


Fig. 4: Current waveforms of single-phase and three-phase rectifiers

Fig. 4 shows the current waveform of the single-phase and three-phase rectifiers. The mixed current between those rectifier currents is shown in Fig. 5.

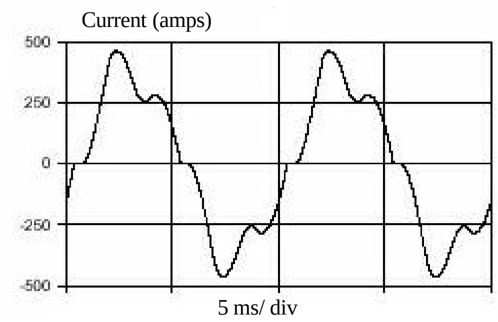


Fig. 5: The mixed current

The current magnitudes of the single-phase and three-phase rectifiers are shown in Fig. 6. The fundamental current of the three-phase is nearly three times of the single-phase rectifier. Odd harmonics appear in both the single-phase and three-phase systems, but the triple-n harmonics do not appear in the three-phase system.

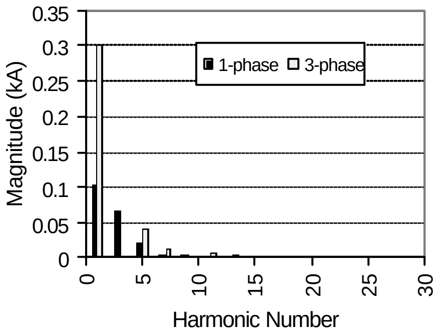


Fig. 6: Magnitude of the harmonic currents

The harmonic phases are shown in Fig. 7. The fundamental component of the single-phase current is nearly in-phase with the three-phase one. The 7th harmonics have a counter-phase. Some harmonics have several degree differences, but some of them have more than 90° differences.

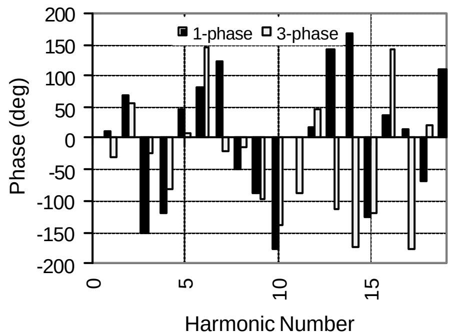


Fig. 7: Phases of the harmonic currents

3. HARMONICS IN A NON-IDEAL WITH BALANCED MAGNITUDE VOLTAGE

Using the same loads, harmonic performance under a non-ideal source is investigated. The phase voltages of the three-phase source are simulated as shown in Fig. 8. The magnitudes are set equal, thus the voltages are $V_A=240\angle 0^o$, $V_B=240\angle 110^o$, $V_C=240\angle 230^o$ volts. A non-symmetrical winding distribution of generators and voltage source inverters may produce the non-ideal source voltage [4], [5].

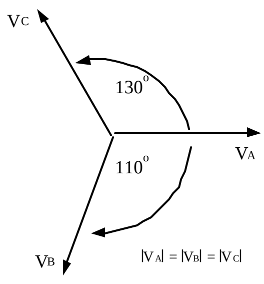


Fig. 8: A typical non-ideal source with balanced magnitude voltage

Since the magnitude is balanced, the harmonic current of the single-phase rectifiers should remain the same as those under the normal source. The harmonic current of the three-phase rectifier is given in Fig. 9. The phases are depicted in Table 1. The current contains the triple-n harmonics.

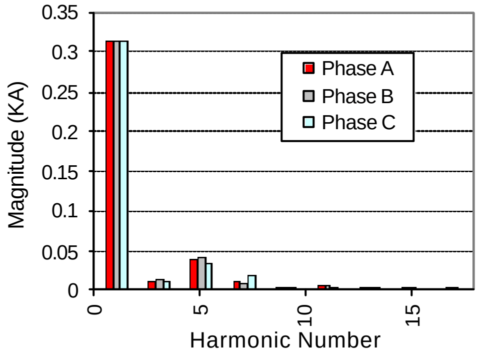


Fig. 9: Harmonic currents of the three-phase load under a non-ideal balanced voltage system

Table 1: The triple-n phase harmonics in the three-phase system

h	$\varphi_{A(h)}$ (deg)	$\varphi_{B(h)}$ (deg)	$\varphi_{C(h)}$ (deg)
1	-18.6	-132.0	109.9
3	-141.8	-130.3	-121.0
6	110.4	-117.8	10.1
9	-84.8	44.4	23.7
12	37.4	91.9	-83.0
15	-137.1	48.5	10.8
18	176.1	-127.7	51.7

4. HARMONICS IN A NON-IDEAL WITH UNBALANCED MAGNITUDE VOLTAGE

Using the same loads, the non-ideal three-phase voltage source is simulated having an unbalanced magnitude as follows: $V_A = 240\angle 0^o$, $V_B = 220\angle 110^o$, $V_C = 200\angle 230^o$ volts.

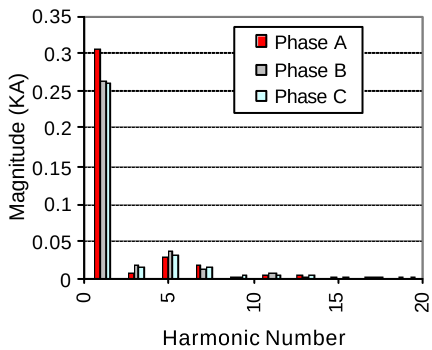


Fig. 10: Harmonic currents of the three-phase load under non-ideal unbalanced voltage system

Fig. 10 shows harmonic currents of the three-phase load. The triple-n harmonics appear in the line but each phase has different magnitude.

5. DISCUSSION

Mixing Single-phase and Three-phase Rectifiers

Installing a three-phase rectifier in a distribution system reduces harmonic distortions of the current, which are caused by single-phase rectifiers. If the h^{th} harmonic current of the single-phase rectifier is $I_{1ph(h)}$, the three-phase rectifier harmonic current is $I_{1ph(h)}$, the mixed current of both currents is the vector resultant as follows:

$$I^2_{Mixed(h)} = I^2_{1ph(h)} + I^2_{3ph(h)} - 2I_{1ph(h)}I_{3ph(h)}\cos(180^o - f_{1ph(h)} + f_{3ph(h)}) \quad (6)$$

The vector diagram of current is shown in Fig. 11.

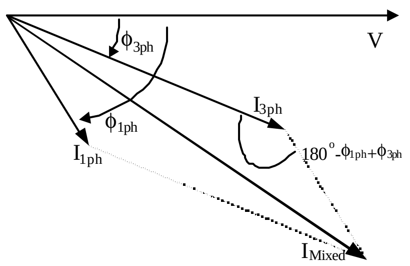


Fig. 11: Resultant of harmonic currents

Fig. 12 shows the magnitudes in one of the phase current under a normal voltage source. The total harmonic distortion (THD) of the current is resumed in Table 2.

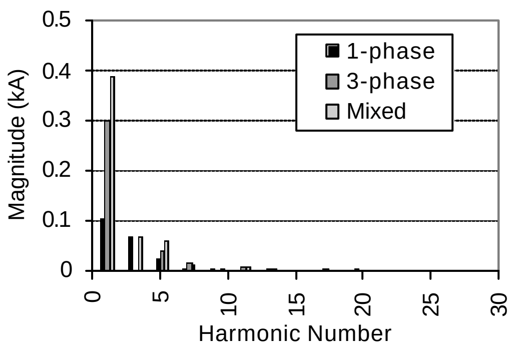


Fig. 12: Harmonic currents under a normal voltage system

Table 2: THD current under the normal voltage source

Current	THD (%)
Single-phase rectifier	67.8
Three-phase rectifier	14.5
Mixed current	23.5

When the source supplies the single-phase rectifiers without the three-phase one, the THD current in each phase is found as 67.8%. When the three-phase rectifier is involved in the system, the THD current reduces to 23.5 %. Factors that determine the reduction are as follows:

- Both the fundamental currents are nearly in-phase. Thus, the magnitude of the mixed current is increased nearly 300% compared to the single-phase one.
- The magnitude of the 3rd harmonic in the mixed current remains unchanged because there is no 3rd harmonic from the three-phase rectifier.
- The magnitude of the 7th harmonic in the mixed current is lower than the three-phase rectifier current because of the counter-phase.

Non-ideal with Balanced Magnitude Source

The DC current (I_{DC}) when the rectifier is supplied by the non-ideal source with balanced magnitude voltage is shown in Fig. 13. This is slightly different with the current under a normal source as given in Fig.3. In this condition, the conduction angle γ of the switching devices is not uniform.

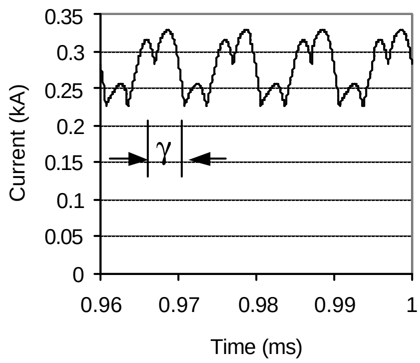


Fig. 13: The DC current when the rectifier is supplied by the non-ideal source

This condition causes the third harmonic current and its multiples appear in the distribution line. However, the THD current under this condition presents almost the same as the THD in the normal voltage source. The waveform of the mixed current when supplied by the ideal and non-ideal sources is presented in Fig. 14.

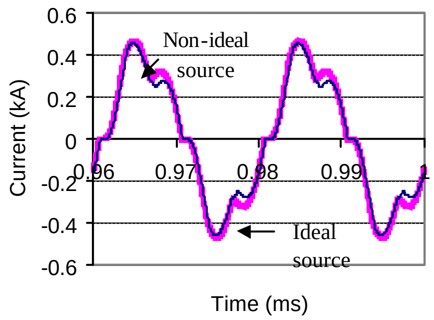


Fig. 14: The mixed current from ideal and non-ideal balanced voltage sources

The total harmonic distortion of the phase currents is presented in Table 3.

Table 3: THD current under the non-ideal balanced magnitude voltage

Current	I_{1ph}	I_{3ph}	I_{Mixed}
Phase A	67.8%	14.5%	23.5%
Phase B	67.8%	17.3%	23.6%
Phase C	67.9%	13.2%	24.1%

The current harmonics in one of the phases under this condition are shown in Fig. 15.

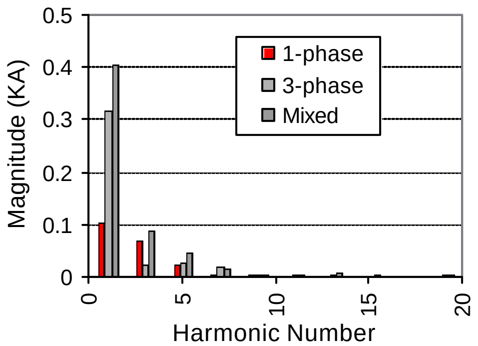


Fig. 15: The current harmonics under the non-ideal balanced magnitude voltage source

Non-ideal with Unbalanced Magnitude Source

The harmonic currents in one of the phases under non-ideal and unbalanced magnitude are shown in Fig. 16. This is very similar to the results from the previous system, non-ideal with balanced magnitude source. The THD is presented in Table 4, which is similar to Table 3.

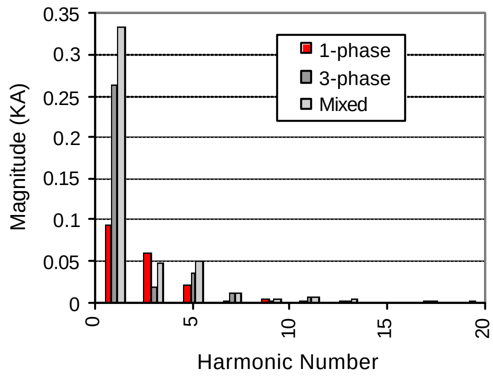


Fig. 16: The current harmonics under a non-ideal unbalanced voltage system

Table 4: THD current under the non-ideal unbalanced magnitude voltage

Current	I_{1ph}	I_{3ph}	I_{Mixed}
Phase A	68.3%	11.4%	22.7%
Phase B	68.0%	16.8%	21.0%
Phase C	67.8%	14.5%	24.5%

6. CONCLUSIONS

Installing a three-phase rectifier can reduce harmonic distortions caused by single-phase rectifiers in distribution systems. The harmonic reduction in the mixed current is due to the increase of the fundamental frequency magnitudes, absence of the 3^{rd} harmonic from the three-phase rectifier and cancellation on the 7^{th}.

When each magnitude voltage of the three-phase supply is balanced but not exactly phase shifted by 120^o, the triple-n harmonics present in the system. The THD is slightly higher than the THD in the ideal system. When the voltages are unbalanced, similar behavior is presented by the system.

7. REFERENCES

[1] Gruzus, T.M., "A Survey of Neutral Currents in Three-Phase Computer Power Systems", *IEEE Transac. on Industrial Appl.*, vol. 26, no. 4, July/ August 1990, pp. 719-725.

[2] Subjak, J.J., Jr. and J.S. Mcquilkin, "Harmonics-causes, effects, measurements, analysis: An update", *IEEE Transc. Ind. Applicat.*, vol. 26, pp. 1034-1042, Nov/Dec 1990.

[3] Hansen, S., Nielsen, P., Blaabjerg, F., "Harmonic cancellation by Mixing Nonlinear Single-Phase and Three-Phase Loads", *IEEE Transac. on*

Industrial Appl., vol. 36, no. 1, Jan/ Feb 2000, pp. 152-159.

[4] Nayar, C.V., M. Ashari and W.W.L Keerthiphala, "A Grid-interactive Photovoltaic Uninterruptible Power Supply System Using Battery Storage and a Back up Diesel Generator", *IEEE Transactions on Energy Conversion*, vol. 15, no. 3, September 2000, pp. 348-353.

[5] Ashari, M., W.W.L. Keerthipala and C.V. Nayar, "A Single Phase Parallely Connected Uninterruptible Power Supply/ Demand Side Management System", *IEEE Transactions on Energy Conversion*, vol. 15, No. 1, March 2000, pp.97-102.

[6] Ashari, M., C.V. Nayar and S. Islam, "Mitigation of Line and Neutral Current Harmonics in Three-Phase Distribution Systems", *35th IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy*, 8-12 October 2000, Rome, Italy.

[7] Manitoba HVDC Research Centre, *Getting started, basic and installation PSCAD/ EMTDC*, Revision 3.0 and 2.0, University of Manitoba, Canada.

[8] Mohan N., Undeland, T.M., and Robbins, W.P., "*Power Electronics Converters, Applications and Design*", John Willey and Sons, Second, edition, 1995.

8. BIOGRAPHIES

Mochamad Ashari received his Bachelor from the Institute of Technology Sepuluh Nopember (ITS) Surabaya, Indonesia, in 1989. He has been with ITS since 1990 as a lecturer in the Department of Electrical Engineering. Before receiving the Master of Engineering (Electrical) from the Curtin University of Technology, Perth Australia, in 1997, he has involved in the feasibility study, designing and installing the Solar-Home-Systems for rural areas in the East Java, Indonesia. He has actively involved in industrial research and applications including study of harmonic distortion, design of harmonic filter / power factor correction, relay setting and coordination. Currently, he is a full time research scholar working for his PhD degree at Curtin University of Technology. His research interests included power electronics and inverter applications, modelling and simulation of power systems, power quality and hybrid power systems involving renewable energy source.

Syed Islam received his B.Sc (1979), M.Sc (1983) and Ph.D (1988) in electrical power engineering. He is currently an Associate Professor of Electrical Engineering at Curtin University of Technology. He is also the Deputy Director of the Centre for Renewable Energy and Sustainable Technologies Australia. He is the Managing Editor of the International Journal of Renewable Energy Engineering. He has published over 60 research papers in the area of electric power engineering including many in the IEEE transactions. He is a member of the IEE, member of CIGRE AP12 on transformers, Senior Member of the IEEE and a chartered engineer in the United Kingdom. He received the Dean's medallion for research in 2000 from the Faculty of Engineering of Curtin University for his outstanding contribution to research. He is the recipient of the 1999 IEEE/PES prestigious T. Burke Haye's outstanding Faculty Recognition Award. He is General Chair for the 2001 Australasian Universities Power Engineering (AUPEC) conference. His current research interests are in power quality, energy efficiency, and hybrid renewable energy systems.

Dr. Samuel S. Matair received his undergraduate degree in Electrical Engineering from Surabaya Institute of Technology, Indonesia in 1977. After a period in the industry, he continued his study in Australia and received his Master degree from New South Wales University (1980) and PhD from Sydney University (1986). After completing his Post Graduate studies, he worked as lecturer at Surabaya Institute of Technology in the Department of Electrical Engineering. He was in charge of the High Voltage/Testing Laboratory and during that time he was heavily involved with various industry projects. He has designed and built large harmonics filters for the steel, cement and other industries. His expertise includes harmonics, power quality, electrical equipment testing, design of electrical system: main substation (HV), protection and PLC/SCADA. Prior to joining CRESTA he worked with the Power System Group at Canterbury University, New Zealand developing Harmonics State Estimation Models. He joined CRESTA - Curtin University of Technology in April 2000 as Senior Research Fellow.