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Power Quality Enhancement by DC Distribution

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Abstract. Most of the electric equipment used in residential buildings operate with electric energy in the form of direct current (dc) in their internal circuits. The advent of many modern equipment in residential buildings which operate on dc has necessitated an in-depth study of their impact on the distribution system. This paper presents an analysis of the performance of distribution system if these appliances are directly supplied by dc. As a part of this investigation a prototype conventional alternating current (ac) distribution system is analysed for different combinations of utility and load conditions by simulation. A hybrid ac-dc distribution network with minimum conversion stages is proposed.

Keywords

Harmonics, Total harmonic distortion, Rectifier, DC distribution.

1. Introduction

The urge to improve energy efficiency and reduce power consumption have led to the massive use of nonlinear loads in the power system. With the evolution of power electronics, the modern high-tech loads are electronic circuits which require dc rather than ac supply. The presence of nonlinear loads has brought about the injection of voltage and current harmonics into the distribution system. Many types of distribution systems have been suggested for the suppression of harmonics and improvement of efficiency of the distribution system. The feasibility of dc distribution in commercial buildings is investigated in ref. [1] in which a dc voltage of 326V is proposed. In the analysis of small scale residential dc distribution system [2] different voltage levels of 325V, 230V and 20V are suggested. The possibilities of different methods of integration of renewable energy sources with dc distribution are suggested in ref. [3], [4] and reviewed in [5] . Efficiency of ac and dc grids is compared in ref. [6] in which equal ratio of ac and dc loads is found to be economical. The total conversion efficiency is found to be better than or equal to that of an ac distribution system when a residence is supplied by fuel cell or any other dc source [7]. Ref. [8] suggests that incorporation of dc distribution into the existing ac system will require a new algorithm for fixing the ratio of ac and dc distribution.

However in all these investigations there are unnecessary usage of many rectifiers and inverters for giving supply to ac and dc loads. Hence in this paper the power quality of conventional distribution system and dc distribution system are analyzed and a hybrid distribution network which causes minimum disturbance to the existing distribution system is proposed.

The remaining portion of the paper is organized in 6 sections. Section 2 discusses the loads in residential buildings which involve ac-dc power conversion in their internal circuits. Section 3 analyses the harmonics of conventional ac distribution system for different load conditions. In section 4 the feasibility of dc distribution is investigated. A hybrid ac/dc distribution system is proposed in section 5. The results are discussed in section 6 and section 7 gives the conclusion.

2. Analysis of Residential Loads

A survey of loads has been taken in various residential buildings in the urban areas. It is observed that majority of loads have a single phase rectifier at the front end of their internal circuits to convert the ac supply into dc. Depending on the presence of single phase rectifiers the loads are classified into two groups as shown in Table I.

Table I: Domestic loads

Loads with rectifier	Loads without rectifier
Television	Conventional Refrigerator
Laptop Charger	Conventional Air Conditioner
Mobile Charger	Mixer
Inverter	Grinder
Water Purifier	Fluorescent Tube (Magnetic Ballast)
Induction Cook Top	Fan
Microwave Oven	Electric Kettle
Washing Machine	Electric Iron Box
Refrigerator (Inverter Technology)	Geyser
Air Conditioner(Inverter Technology)	
Compact Fluorescent Lamp	
Fluorescent Tube (Electronic Ballast)	
LED Lamp	
Uninterrupted Power Supply(UPS)	

From the table it is observed that almost 80 % of the loads have a single phase rectifier in their internal circuits. If these loads are directly provided with dc supply it is possible to skip one conversion stage and improve efficiency. Loads like mixer, electric kettle, electric iron box and geyser can work with dc supply also.

3. Impact of Loads on Distribution System

A. Power quality analysis by measurement

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate, which is termed as the fundamental frequency [9]. Harmonic distortions repeat every cycle and are represented by the Fourier series consisting of a dc component, a fundamental sinusoidal component and a series of higher order sinusoidal components. The Fourier series of a periodic function $x(t)$ repetitive in an interval T is given by equation (1).

$$x(t) = a_0 + \sum_{n=1}^{\infty}\left[a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right)\right] \quad (1)$$

a_0 – Average value of function $x(t)$
a_n, b_n – Coefficients of the series or rectangular components of n^{th} harmonic

The dc component is not present in power system and most of the electronic loads have the property of half wave symmetry. When both positive and negative half cycles of a waveform have identical shapes, the Fourier series contains only odd harmonics. Hence the coefficients a_n and b_n are given by equations (2) and (3) respectively.

$$a_n = \frac{4}{T}\int_0^{\frac{T}{2}} x(t)\cos\left(\frac{2\pi nt}{T}\right)dt \quad \text{, for 'n' odd} \quad (2)$$

$$b_n = \frac{4}{T}\int_0^{\frac{T}{2}} x(t)\sin\left(\frac{2\pi nt}{T}\right)dt \quad \text{, for 'n' odd} \quad (3)$$

Harmonic distortion levels are described by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. Harmonic distortion is measured by the quantity Total Harmonic Distortion (THD). It is a measure of the effective value of harmonic components of a distorted waveform. The THD for voltage and current are given by equations (4) and (5) respectively [10].

$$\text{THD}_V = \sqrt{\frac{\sum_{h=2}^{\infty} V_h^2}{V_1^2}} \times 100\% \quad (4)$$

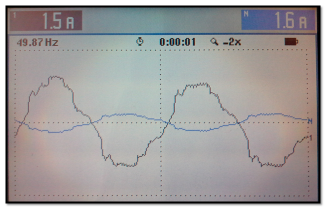
$$\text{THD}_I = \sqrt{\frac{\sum_{h=2}^{\infty} I_h^2}{I_1^2}} \times 100\% \quad (5)$$

V_h – Rms value of harmonic component 'h' of the voltage
I_h – Rms value of harmonic component 'h' of the current
V_1 – Fundamental component of voltage
I_1 – Fundamental component of current

In this paper the harmonic impact of residential loads on the power supply is analyzed by measuring the harmonic distortion using a power quality analyzer. The measurements are performed during the peak time of demand at night. The THD, odd harmonic components, harmonic spectrum, voltage and current waveform are recorded using the power quality analyzer.

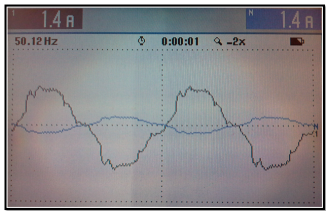
The typical current waveform of power supply of four residential buildings are shown in Fig. 1. The corresponding harmonic spectra are shown in Fig. 2.

(a) Load current = 0.3A



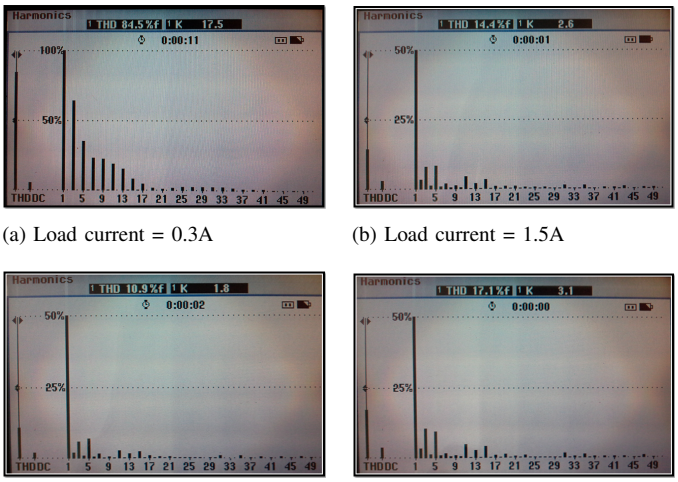
(b) Load current = 1.5A

(c) Load current = 2.2A



(d) Load current = 1.4A

Fig. 1: Waveform of current



(a) Load current = 0.3A (b) Load current = 1.5A

(c) Load current = 2.2A (d) Load current = 1.4A

Fig. 2: Harmonic spectra

From Fig. 1 it is observed that the current waveforms are highly distorted from their usual sinusoidal shape. The harmonic spectra given in Fig. 2 show that THD and triplen harmonics of supply current in all buildings are above the limits specified by IEEE standards [11].

B. Power quality analysis by simulation

Based on the survey of loads and measurements taken using the power quality analyzer, the harmonic impact of large number of rectifier loads on the distribution system is investigated by analyzing a prototype conventional distribution system. A three phase 5kVA, 400/400V, delta-star transformer with different combinations of loads as shown in Fig. 3 is simulated using Matlab/Simulink.

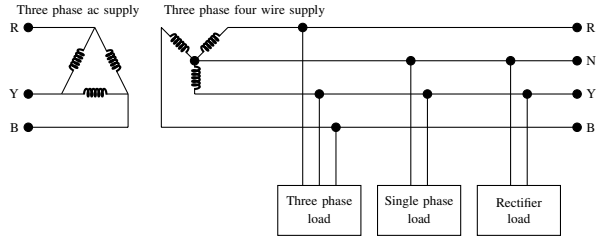
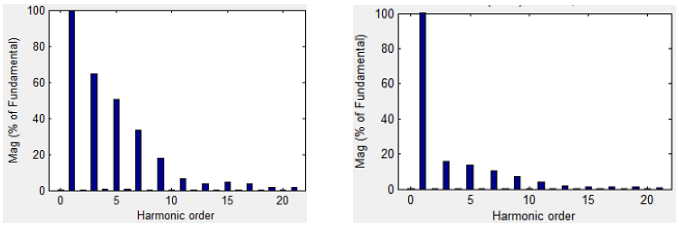


Fig. 3: Conventional distribution system

For comparison purpose it is assumed that all the three phases are loaded equally. The primary current is kept constant at 7A. The THD, odd harmonics (h3 to h15) and neutral current for two different rectifier load currents 5.6A (80% of full load current) and 1.4A (20% of full load current) are tabulated in Table II. The harmonic spectra are shown in Fig. 4.

The variations in THD, third harmonic component, neutral current and output power as the rectifier load current is varied from 1A to 6A are given in Fig. 5. It is observed that as the load current due to rectifier load increases the THD, third harmonic component (h3) and neutral current increases. The output power decreases with the increase of rectifier load current.



(a) Conventional distribution system with greater percentage of rectifier loads

(b) Conventional distribution system with lesser percentage of rectifier loads

Fig. 4: Harmonic spectra from simulation

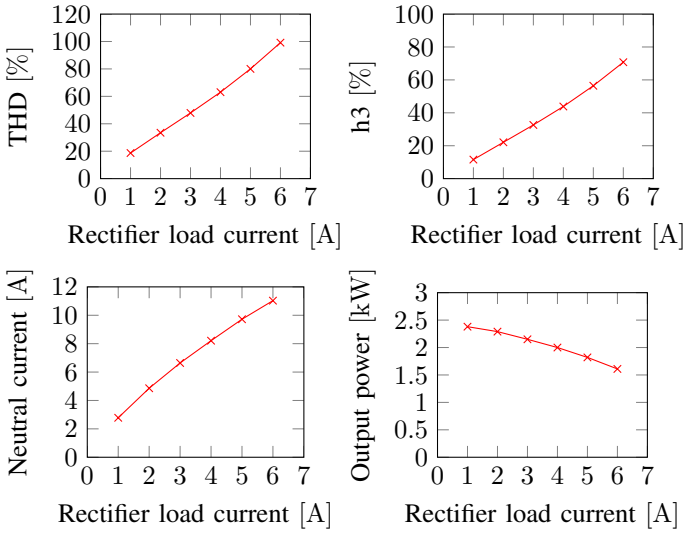


Fig. 5: Output current THD, third harmonic component(h3), neutral current and output power for varying rectifier load current

4. Feasibility of DC Distribution

Based on the analysis of harmonic impact of rectifier loads on conventional distribution system, the feasibility of dc distribution is investigated by removing all the single phase rectifiers from the loads and providing dc supply directly to these loads. A three phase rectifier produces lesser harmonics than a single phase rectifier and the output voltage ripple of a three phase rectifier is lesser than that of a single phase rectifier [12]. Also the efficiency of a three phase rectifier (99.83%) is higher than that of a single phase rectifier (81%) [13]. Hence in the investigation, dc supply is given to the loads through a three phase rectifier as in Fig. 6. A three phase 5kVA, 400/400V delta-star transformer is used for simulation. The primary current is maintained at 7A. The simulated results are given in Table III. The harmonic spectrum is shown in Fig. 7.

From Table III it is observed that THD of current in the secondary winding of transformer is much less than that of conventional ac distribution system with major share of single phase rectifier loads. The neutral current is zero and the triplen harmonics are also very much reduced in the case of dc distribution.

Table II: Simulation results of conventional distribution system

Rectifier load Current	**THD of secondary current**	**h3**	**h5**	**h7**	**h9**	**h11**	**h13**	**h15**	**Neutral Current**
A	%	%	%	%	%	%	%	%	A
5.6	95.31	65.27	51.83	35.86	20.76	9.42	4.31	4.33	10.57
1.4	24.95	16.03	13.52	10.32	7.06	4.10	1.98	1.13	3.73

Table III: Simulation results of dc distribution system

Load current	**THD of secondary current**	**h3**	**h5**	**h7**	**h9**	**h11**	**h13**	**h15**	**Neutral Current**
A	%	%	%	%	%	%	%	%	A
7.0	63.97	0.35	55.31	29.98	0.74	7.49	5.95	0.58	0.0

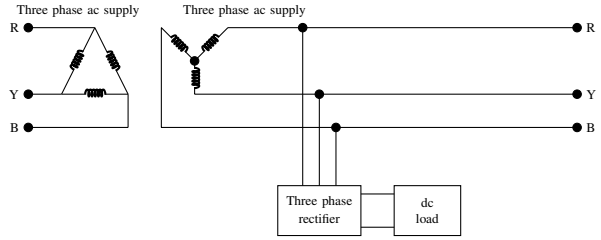


Fig. 6: DC distribution system

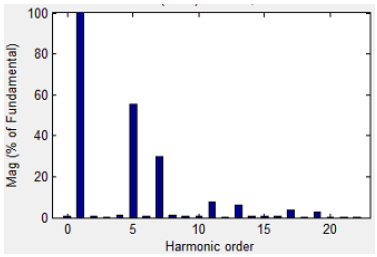


Fig. 7: Harmonic spectrum of dc distribution system

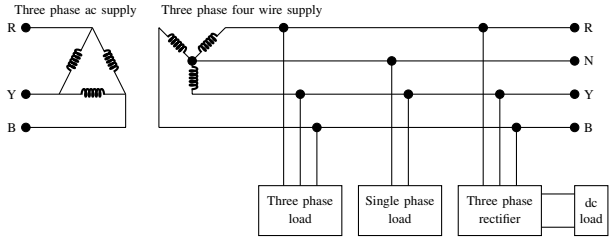


Fig. 8: Hybrid distribution system

5. Proposal of a Hybrid Distribution System

From the power quality analysis of dc distribution system it is suggested that if all the single phase rectifiers are removed from the front end of the loads and dc supply is given directly to these loads harmonics can be reduced. But ac distribution system is presently dominant and a sudden change to dc distribution system is not practical. Hence a hybrid ac/dc distribution network as shown in Fig. 8 is proposed. The ac supply is given directly to ac loads without any disturbance to the existing system and without using any converters. The dc loads are supplied with dc power through a three phase rectifier.

6. Discussion

When common loads in residential buildings are observed (Table I) it is found that many of the loads use a single phase rectifier in their internal circuits for converting the ac supply into dc. The power quality measurements in residential buildings (Fig. 1 and Fig. 2) and the analysis of a prototype conventional distribution system (Table II) shows that when current due to single phase rectifier loads increases THD, triplen harmonics and neutral current increases. The harmonic distortion causes the supply voltage and current waveform to deviate from the usual sinusoidal form which in turn affects other loads connected to the system. Since third harmonic current components are additive in the neutral of a three phase system, the increasing application of single phase rectifier loads causes overloading of neutral conductor which will lead to overheating in undersized neutral conductors.

The advantages of dc distribution as seen from Table III are that THD of secondary current and triplen harmonics are very much reduced when compared to conventional distribution system. Hence harmonic filter requirements will be decreased. It is also observed that neutral current is reduced to zero in the case of dc distribution. This is also a major advantage since it prevents overheating and leads to the reduction of neutral conductor size. DC distribution also facilitates easy integration of renewable energy sources. Since a sudden replacement of all existing ac loads is not possible, dc distribution alone is not feasible in the present scenario. Hence a hybrid system with ac and dc distribution is suggested. The hybrid ac-dc distribution system also facilitates easy integration of different types of sources, storage systems and loads.

7. Conclusion

The analysis of common domestic loads of the present day distribution system shows that majority of loads have a single phase rectifier in their internal circuits. The power quality measurements of the distribution system and the simulation results of a prototype conventional distribution system show that the harmonic pollution impact of the present day loads is very high. This reduces the quality of power supply which affects other loads connected to the system. It is further observed that when the single phase rectifier loads are directly supplied by dc as proposed in this paper, harmonics is very much reduced. Hence dc loads in residential buildings may be supplied directly with a suitable dc voltage to improve the power quality of the distribution system. Since ac distribution system is presently dominant and a sudden replacement of all existing ac loads is practically not feasible, a hybrid ac-dc network with minimum number of converters is proposed for improving the efficiency of the distribution system.

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