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Full Length Article

Pollution impact of residential loads on distribution system and prospects of DC distribution

Elizabeth Cherian [a,*], G.R. Bindu [a], P.S. Chandramohanan Nair [b]

[a] Dept. of Electrical Engineering, College of Engineering Trivandrum, Thiruvananthapuram 695016, Kerala, India
[b] Valiakoonambaikulathamma College of Engineering & Technology, Chavarcode, Parippally, Trivandrum, Kerala, India

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ABSTRACT

Unlike in the previous decades, the recent past saw the advent of many modern appliances in residential buildings. The unique feature in most of these appliances is that they use direct current (dc) in their internal circuits. With an already established alternating current (ac) distribution system in the present scenario, this situation calls for an in-depth analysis for a suitable dc distribution scheme to improve power quality and efficiency. In this paper an extensive survey of loads is conducted in various residential buildings supplied by different distribution transformers and their harmonic pollution impact on the system is investigated. To improve the efficiency and power quality of the traditional domestic distribution system, a dc distribution scheme is proposed which reduces harmonics and neutral loading of distribution transformers. The scheme can be made effective by shifting the harmonic inducing loads to the dc network side. This system also eliminates redundant power conversion stages involved in the integration of renewable energy sources in the conventional distribution system. The effectiveness of the system is validated by simulating a prototype distribution system and the results are verified experimentally.

1. Introduction

The massive use of electronic equipment in the power system has increased the awareness of power quality in recent years. The technical advantages imparted by power electronic equipment have made them pervade all sectors of the power supply system. However, an adverse effect of power electronic equipment is that it achieves its intended function at the expense of generating harmonics which causes voltage and current distortions. The harmful effects of harmonic voltages and currents on power system equipment often go unnoticed until an actual failure occurs. Harmonic currents can cause overheating of conductors,dielectric failure or rupturing of capacitors,false operation of circuit breakers and also lead to excessive overheating of transformers. The modern high-tech loads are electronic circuits which require dc rather than ac supply. Previous researches have been done on certain aspects of harmonic pollution and dc distribution. A preliminary survey [1] reveals that non linear loads like fluorescent lighting,variable frequency drives, switch mode power supplies and uninterrupted power supplies are the main source of harmonics in an electrical distribution system. Harmonic pollution control at various points in distribution system using route control method [2] and mitigation of harmonics by various techniques like single tuned, double tuned, reactance one port filters [3] have been investigated. The analysis of the type of harmonics present in the electrical distribution system of an institutional campus [4] using a power quality analyzer shows that the contribution of harmonics by nonlinear loads is very high. Harmonics on distribution transformer leading to increased load current and energy loss is found to decrease its life [5]. The types of distributed generation units, its interfaces with the utility system and the location of distributed generation units are found to affect the amount of harmonics injected into the system [6]. DC distribution of electrical power has been suggested as an efficient method of power delivery [7–9] as both energy source and loads are getting towards dc. The output power obtained from most of the renewable energy sources is dc and the problems involved in inverter -interfaced distributed generation systems are grid synchronization,harmonic injection and reduction of efficiency due to increase in number of conversion stages [10]. The advantages of a dc micro-grid for harnessing wind and solar energy are given in [11–13]. The feasibility of dc supply to offices and commercial buildings has been analyzed in [14] and a dc voltage of 326 V is found to be most suitable. Ref. [15] shows that residential dc distribution is efficient when a combination of high and low voltage dc supply is used.

* Corresponding author.
E-mail addresses: ecpc200@gmail.com (E. Cherian), bgr100@gmail.com (G.R. Bindu), pscnair@gmail.com (P.S. Chandramohanan Nair).

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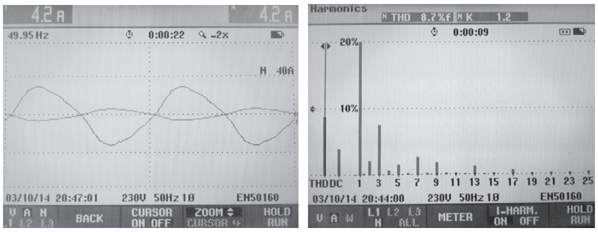
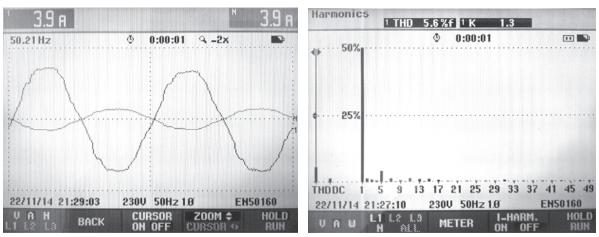


(a) Current waveform for a load of 4.2 A (b) Harmonic spectrum for a load of 4.2 A

Fig. 1. Observations of house No. 1.



(a) Current waveform for a load of 3.9 A (b) Harmonic spectrum for a load of 3.9 A

Fig. 2. Observations of house No. 2.

However in all these researches, there are unnecessary usage of many inverters and rectifiers. Also an in-depth study of harmonics due to domestic loads has not been conducted. Hence in this paper the pollution impact due to harmonics of residential loads is analyzed and the feasibility of a dc distribution scheme is investigated through simulation and by a prototype experimental set up. In the dc distribution system considered here, dc supply is given to dc loads through a three phase rectifier connected to the distribution transformer thus eliminating single phase rectifiers from the front end of the dc loads. AC loads if any, may be connected to the existing ac distribution network thus avoiding unnecessary inverters.

The remaining portion of the paper is organized in 7 sections. Section 2 discusses the impact of harmonic pollution of residential loads. Section 3 deals with the classification of common ac and dc loads in residential buildings based on the form of electric energy used in their internal circuits. In Section 4 the power quality analysis of the conventional distribution system for different fractions of ac and dc loads is performed by simulation of a prototype system. Section 5 investigates the feasibility of dc distribution by simulation. The experimental verification of the power quality analysis of the conventional distribution system and the dc distribution system are presented in Section 6. Section 7 gives the inference of the work and Section 8 gives the conclusion.

2. Pollution impact of residential loads

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 [16]. 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 or 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 Eqs. (1) and (2) respectively.

$$THD_V = \sqrt{\frac{\sum_{h=2}^{\infty} V_h^2}{V_1^2}} \times 100\% \tag{1}$$

$$THD_I = \sqrt{\frac{\sum_{h=2}^{\infty} I_h^2}{I_1^2}} \times 100\% \tag{2}$$

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, as a preliminary study, the quality of power supply is monitored using a power quality analyzer in various residential buildings supplied by different distribution transformers in Kerala,India. The distribution system is three phase four wire type with 11 kV/415 V delta-star transformer. The observations are made during the peak time of demand i.e. from 7 pm to 10 pm. The loads which are in use at the time of measurement are also observed. The voltage,current waveform and the harmonic spectra are captured using the power quality analyzer. The Total Harmonic Distortion of individual equipment used in residential buildings are also measured. The typical current waveform and the corresponding harmonic spectra of power supply of two residential buildings namely House No.1 and House No.2 supplied by two different distribution transformers are shown in Figs. 1 and 2 respectively. Fig. 1a and b correspond to a load current of 4.2 A. Fig. 2a and b correspond to a load current of 3.9 A.

It is observed that the current waveforms are very much distorted from their usual sinusoidal shape. Table 1 shows the harmonic contents (THD and odd harmonics (h3 to h15)) for load currents of 4.2 A and 3.9 A.

Loads which were in use during the power quality measurement are given in Table 2.

It is also observed that even though the magnitude of load currents are very close to each other (4.2 A and 3.9 A), as the number of loads which use an inbuilt single phase rectifier in their internal circuits increase, the THD also increases. In the first case when the current is 4.2 A, the number of single phase rectifier loads (dc loads) which are in use at the time of measurement is equal to 13, contributing to a THD of 8.7%. In the second case when the current is 3.9 A and the number of single phase rectifier loads is equal to 5, THD is reduced to 5.6%. THD of current waveform of individual equipment commonly used in residential buildings are given in Table 3. It is observed that all equipment except geyser,electric kettle and induction cook top show a high value of harmonics.

Table 1
Table of harmonic content.

House no	Load current A	THD %	h3 %	h5 %	h7 %	h9 %	h11 %	h13 %	h15 %
1	4.2	8.7	7.4	1.7	2.4	1.7	0.2	1.2	0.4
2	3.9	5.6	1.0	4.3	1.2	0.6	1.5	1.2	1.1

Table 2
Loads during power quality measurement.

Voltage V	Current A	THD of Current %	Loads in use	Quantity (Number)	Number of dc loads
			Television	1	
			Fluorescent tube With Electronic Ballast	4	
239.3	4.2	8.7	Fan with electronic Regulator	3	13
			Incandescent lamp	2	
			Refrigerator	1	
			Compact fluorescent Lamp	4	
			Inverter	1	
			Fan (Electronic Regulator)	3	
229.5	3.9	5.6	Compact fluorescent lamp	2	
			Incandescent lamp	2	5
			Refrigerator	1	
			Electric Kettle	1	

Table 3
THD of current waveform of individual equipment.

Equipment	Voltage V	Current A	THD of current %
Refrigerator	240	1.7	9.8
Television	240	0.8	35.0
Inverter	240	0.2	59.0
Laptop Charger	240	0.3	118.0
Electric Kettle	240	7.6	2.8
Induction Cook Top	240	6.6	3.3
Microwave Oven	240	7.4	31.7
Washing Machine	240	2.8	41.0
Geyser	240	6.7	2.8
Air conditioner	240	7.8	18.5
Water Purifier	240	0.2	44.0
Mixer	240	1.3	11.3
Grinder	240	0.7	8.7
Compact Fluorescent Lamp	240	0.3	37.0
Fluorescent Tube(Electronic Ballast)	240	0.3	39.0
Fluorescent Tube (Magnetic Ballast)	240	0.6	25.0
Fan with Electronic Regulator	240	0.4	22.0
Mobile Phone Charger	240	0.2	55.0

Table 4
Classification of ac and dc loads.

DC Loads	AC Loads
Compact Fluorescent Lamp	Conventional Refrigerator
Fluorescent Tube (Electronic Ballast)	Conventional Air Conditioner
LED Lamp	Fluorescent Tube (Magnetic Ballast)
Television	Grinder
Refrigerator (Inverter Technology)	Fan
Air Conditioner (Inverter Technology)	Electric Iron
Laptop Charger	Electric Kettle
Mobile Phone Charger	Mixer
Uninterrupted Power Supply (UPS)	Geyser
Water Purifier	
Induction Cook Top	
Microwave Oven	
Washing Machine	
Inverter	

3. Segregation of loads

A survey of loads has been taken in various residential buildings supplied by different distribution transformers. It is observed that internally many appliances operate using a dc voltage. Many of the loads use a single phase rectifier at the front end to convert the ac supply into dc. The loads using single phase rectifiers in their power supply circuit are completely phased out from ac and considered as dc loads. The classification of loads is given in Table 4. Loads like electric kettle,electric iron,mixer and geyser can be operated with dc supply also. From the table it is found that almost 80% of the loads can be considered as dc loads. These loads can directly be supplied with dc so as to skip one conversion stage and thus reduce harmonics.

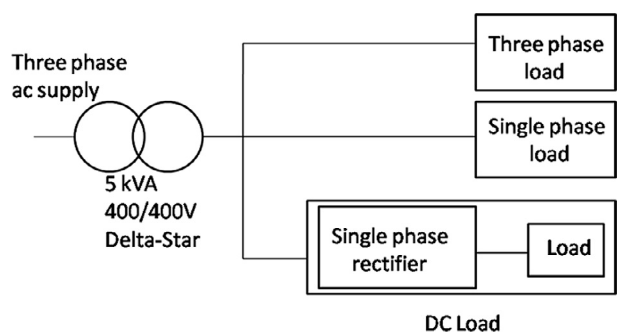


Fig. 3. Conventional distribution system.

4. Harmonic analysis of conventional distribution system

Power quality analysis of a prototype conventional distribution system given in Fig. 3 is performed by simulation using SIMULINK in MATLAB. A three phase, 5 kVA 400/400 V delta-star four wire distribution transformer is used for simulation.

The circuit is simulated for different ratios of ac and dc loads. For comparison purpose the output secondary currents are maintained constant at 6 A in all cases.The simulation results are tabulated in Table 5 and the harmonic spectra are given in Figs. 4 and 5.

From Table 5 it is observed that THD of secondary current of transformer of conventional ac distribution system with greater percentage of dc loads is much greater (83.9%) than that with greater percentage of ac loads(29.93%). The neutral loading and third harmonics are also higher in the former case. This obviously necessitates the need for a suitable dc distribution scheme so that the harmonics contributed by individual single phase rectifiers are avoided.

5. Feasibility of DC distribution

Based on the analysis of loads in residential buildings and their pollution impact on the distribution system, the feasibility of dc distribution is investigated by removing all the single phase

Table 5
Simulation results of conventional distribution system for different loading conditions.

Ratio of load	Secondary current A	AC load A	DC load A	THD of secondary current %	h3 %	h5 %	h7 %	h9 %	h11 %	h13 %	h15 %	Neutral current A
75% ac and 25% dc loads	6.0	4.50	1.50	29.93	19.14	16.14	12.30	8.67	5.08	2.43	1.30	3.79
25% ac and 75% dc loads	6.0	1.50	4.50	83.90	58.58	46.37	31.85	18.68	7.93	3.38	4.08	8.55

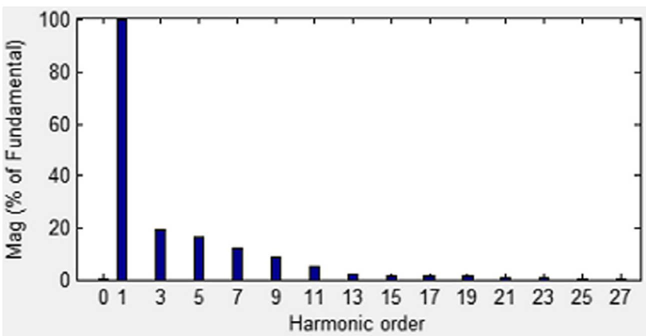


Fig. 4. Harmonic spectrum of transformer secondary current of conventional distribution system with greater percentage of ac loads.

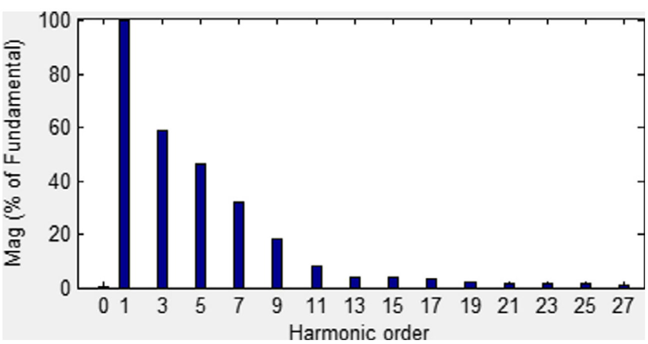


Fig. 5. Harmonic spectrum of transformer secondary current of conventional distribution system with greater percentage of dc loads.

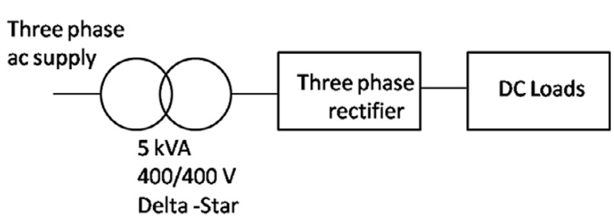


Fig. 6. DC distribution system.

rectifiers from the dc loads and providing dc supply directly to these loads.

The efficiency of a three phase rectifier (99.83%) is higher than that of a single phase rectifier (81%) [17]. Also the output voltage ripple of a three phase rectifier is lesser than that of a single phase rectifier [18]. Hence in the investigation, supply is given to the dc loads through a three phase rectifier as in Fig. 6.

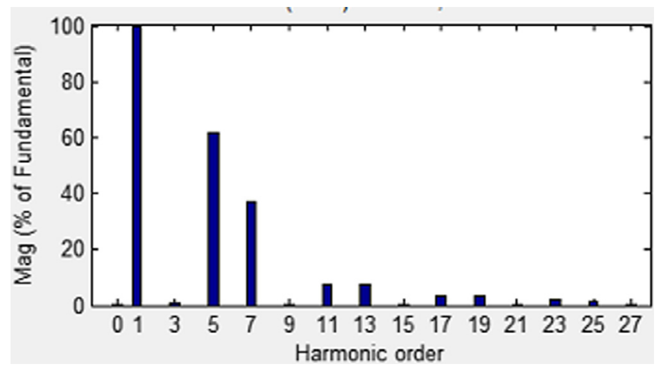


Fig. 7. Harmonic spectrum of transformer secondary current of dc distribution system.

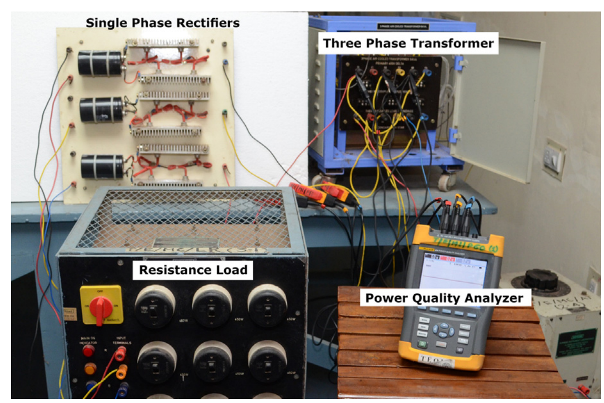


Fig. 8. Experimental set up of conventional distribution system.

The transformer used is three phase 5 kVA, 400/400 V with delta-star configuration. The secondary current is maintained at 6 A, as in the conventional scheme explained in previous section.

The simulation results are compared with the simulated results of conventional distribution system with dc loads as shown in Table 6. The harmonic spectrum of secondary current of transformer of dc distribution system is given in Fig. 7.

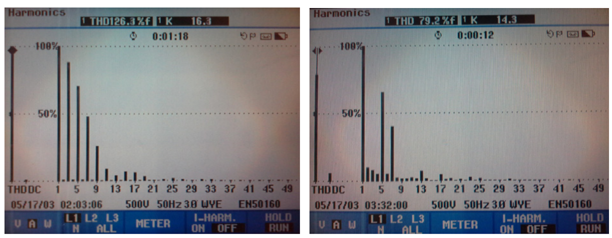
It is observed from Table 6 that THD of current in the secondary winding of transformer in the case of dc distribution system

Table 6
Simulation results of dc distribution and conventional distribution systems.

Configuration	Secondary current A	THD of secondary current %	h3 %	h5 %	h7 %	h9 %	h11 %	h13 %	h15 %	Neutral Current A
DC distribution system with dc loads	6.0	73.10	1.11	61.76	37.03	0.12	7.63	7.76	0.08	0
Conventional distribution system with dc loads	6.0	124.79	88.6	69.12	46.07	24.75	9.43	4.97	6.04	11.06

Table 7
Experimental results of dc distribution and conventional distribution systems.

Configuration	Secondary current A	THD of secondary current %	h3 %	h5 %	h7 %	h9 %	h11 %	h13 %	h15 %	Neutral current A
DC distribution system with dc loads	6.1	79.20	7.30	65.60	42	2.40	3.60	7.30	1.30	0
Conventional distribution system with dc loads	6.0	126.30	88.30	70.80	48.20	26.10	9.60	4.10	6.90	11.40



(a) Harmonic spectrum of conventional distribution system (b) Harmonic spectrum of dc distribution system

Fig. 9. Harmonic spectra of transformer secondary current from experimental results.

(73.10%) is much less than that of conventional distribution system (124.79%) with dc loads. The neutral current is zero and third harmonics are also very much reduced in dc distribution system.

6. Experimental set up

The simulated results given in Table 6 are verified by a laboratory set up employing a three phase 5 kVA 400/400 V delta-star transformer, single phase rectifiers, three phase rectifier and resistance loads. The aim of the experiment is to compare the neutral loading and THD of current in the secondary winding of distribution transformer in the case of conventional distribution system and the dc distribution system presented in Section 5. In the conventional distribution system, single phase diode rectifiers along with variable resistance representing dc loads, are connected, one in each phase, as shown in Fig. 8. In dc distribution system, a three phase diode bridge rectifier is connected to the distribution transformer eliminating the single phase rectifiers. The dc supply obtained using the three phase bridge rectifier is given to resistance loads. The secondary current is maintained at 6 A in both cases.

The experimental results are tabulated in Table 7. The harmonic spectra of secondary current of transformer of conventional distribution system and dc distribution system obtained using the power quality analyzer are given in Fig. 9a and b respectively. It is observed that as in the case of simulation, the THD of current in the secondary winding of transformer with dc distribution is much less than that of the conventional distribution system.The third harmonics and neutral loading are also reduced in the case of dc distribution.

7. Inference

When residential energy consumption pattern is observed it is found that major part of the loads are becoming more and more dc in nature and THD of current harmonics in distribution system becomes higher with the increase in consumption of dc loads. Since the conventional power supply is ac, it implies that every time a dc load is connected to the power system, a conversion stage from ac to dc is indispensable. To avoid this conversion and reduce harmonics, dc supply may be given directly to the dc loads.

In the case of dc distribution system presented in this paper,in which dc supply is given to dc loads through a three phase rectifier, the THD of current harmonics in the secondary winding of distribution transformer is found to be very much reduced. This is a great advantage because this will reduce the harmonic filter requirements and transformer overheating due to reduced iron loss and copper loss. Again in dc system, the third harmonics are lowered leading to zero current in the neutral conductor. This is also a huge advantage because in the delta-star transformer of conventional distribution system, the triple harmonic currents in the star side are in phase and they add in the neutral. The problems involved with this are overloading of the neutral and telephone interference. Harmonic currents in undersized neutral conductors can cause overheating. The distortion of line to neutral voltage caused by harmonic voltage drop in the neutral conductor causes malfunctioning of devices. Also in practice the size of harmonic filter increases with the decrease in frequency of harmonics. Hence it is suggested that dc distribution using three phase rectifier is feasible. This facilitates the removal of single phase rectifiers from the front end of every dc load, thus improving power quality and efficiency.

8. Conclusion

The power quality measurement of the present day distribution system supplying domestic loads shows that the THD of current harmonics is much higher than that of the limits prescribed by harmonic standards. Based on the survey of loads it is observed that loads which use a single phase rectifier in their internal circuit are predominant in residential buildings. Simulation and experimental results of a prototype distribution system also show that the pollution impact of the present day loads is very high. Thus quality of power supply becomes very poor which affects other loads and power system equipment. It is further observed that when these loads are directly supplied by dc as proposed in this paper,harmonics is reduced and efficiency is improved. Hence single phase rectifiers in modern appliances may be eliminated and these loads may be shifted to the dc distribution side. The ac loads may be retained on the ac network side thus avoiding unnecessary converters. Since the output of most of the renewable energy sources is dc, these sources may also be connected to the dc network side thus minimizing power conversion stages.

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