Modelling of Nonlinear Loads and Estimation of Harmonics in Industrial Distribution System

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Abstract— **This paper discusses the modeling of nonlinear electrical loads used in domestic and small scale industrial distribution systems. Harmonic analysis of the distribution system is essential to study the behavior of equipments connected in the non-sinusoidal system environment for designing and optimal location of filters. Simulation models are developed for various nonlinear loads based on practical waveforms of voltage and current obtained in the laboratory. Analysis of voltage and current harmonics is performed for these loads individually. These models are used for harmonic analysis of typical domestic and industrial loads. THD is used as the harmonic index to study the effect of these nonlinear loads at the utility. Validation of the load models is done by performing case study for an industrial supply system and comparing the THDs obtained from simulation using PSCAD/EMTDC package with the THD values obtained by measurement.**

Index Terms-- **Current harmonics, industrial system, nonlinear load, THD.**

I. Introduction

IT is the objective of the electric utility to supply its customers with a sinusoidal voltage of fairly constant magnitude and frequency. The generators that produce the electric power generate a very close approximation to a sinusoidal signal. However, there are loads and devices on the system which have nonlinear characteristics and result in harmonic distortion of both the voltage and current signals. As more nonlinear loads are introduced within a facility, these waveforms get more distorted.

The planning, design, and operation of industrial and commercial power systems require several studies to assist in the evaluation of the initial and future system performance, system reliability, safety, and the ability to grow with production and/or operating requirements. The studies most likely to be needed are load flow studies, cable ampacity studies, short-circuit studies, coordination studies, stability studies, and routine motor-starting studies. Additional studies relating to switching transients, reliability, grounding, harmonics, and special motor-starting considerations may also be required. The engineer in charge of system design must decide which studies are needed to ensure that the system will operate safely, economically, and efficiently over the expected life of the system.

A harmonic-producing load can affect the neighboring sensitive loads if significant voltage distortion is caused. The voltage distortion caused by the harmonic-producing load is a function of both the system impedance and the amount of harmonic current injected [1]. The mere fact that a given load current is distorted does not always mean there will be undue adverse effects on other power consumers [2],[3]. If the system impedance is low, the voltage distortion is usually negligible in the absence of harmonic resonance. However, if harmonic resonance prevails, intolerable harmonic voltage and currents are likely to result.

Harmonic currents cause additional line losses and stray losses in transformers. Watthour meter error is often a concern. At harmonic frequencies, the meter may register high or low depending on the harmonics present and the response of the meter to these harmonics. The problems caused by harmonic currents are overloading of neutrals, overheating of transformers, nuisance tripping of circuit breakers, over stressing of power factor correction capacitors and skin effects[4]-[6].

Analysis is commonly done to predict distortion levels for addition of a new harmonic producing load or capacitor bank. The general procedure is to first develop a model that can accurately simulate the harmonic response of the present system and then to add a model of the new addition [6]-[8].

The objective of this paper is to consider the effect of nonlinear loads ranging from adjustable speed drives, to house hold appliances, such as TV sets on the utility voltage and current harmonics. Some of the commonly used loads in the domestic and industrial systems are modeled in PSCAD/ EMTDC, by considering the voltage and current waveforms obtained during laboratory experiments. Harmonic analysis of an industrial distribution system is performed. A case study is also presented to validate the nonlinear load models by performing harmonic analysis of a distribution system of CARTOSAT-2A at ISRO, Bangalore, India.

II. Power and Harmonics in Nonsinusoidal System

With a sinusoidal voltage, current harmonics do not lead to average power. However, current harmonics do increase the rms current, and hence they decrease the power factor. The average power is

$$P_{av} = \frac{V_1 I_1}{2}\cos(\varphi_1 - \theta_1) \qquad (1)$$

where V_1 and I_1 are the peak values and, φ_1 and θ_1 are the phase angles of fundamental voltage and current respectively. The rms current considering the harmonics is given by (2) as

$$\text{Rms current} = \sqrt{I_o^2 + \sum_{n=1}^{\infty}\frac{I_n^2}{2}} \qquad (2)$$

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where I_n is the peak current at any harmonic number n. Power factor of the system is given by (3).

$$\text{Power factor} = \sqrt{\frac{\frac{I_1}{\sqrt{2}}}{I_o^2 + \sum_{n=1}^{\infty} \frac{I_n^2}{2}}} \cos(\varphi_1 - \theta_1) \quad (3)$$

= (distortion factor) (displacement factor)

where the distortion factor is defined as the ratio of fundamental rms current to the total rms current. The total harmonic distortion (THD) which is the harmonic index is given by (4)

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \quad (4)$$

Distortion factor expressed in terms of THD is given by

$$\text{Distortion factor} = \frac{1}{\sqrt{1 + (THD)^2}} \quad (5)$$

Single-phase non-linear loads, like personal computers, electronic ballasts and other electronic equipment, generate odd harmonics (i.e. 3rd, 5th, 7th, 9th, etc.). Triplen harmonics (3rd order and its odd multiples) are troublesome for single-phase loads because the A-phase triplen harmonics, B-phase triplen harmonics and C-phase triplen harmonics are all in the phase with each other. They will add rather than cancel on the neutral conductor of a 3-phase, 4-wire system. This can overload the neutral if it is not sized to handle this type of load. Additionally, triplen harmonics cause circulating currents on the delta winding of a delta-wye transformer configuration. The result is transformer heating similar to that produced by unbalanced 3-phase current.

On the other hand, 3-phase non-linear loads like 3-phase ASDs, 3-phase DC drives, 3-phase rectifiers, etc., do not generate current triplen harmonics. These types of loads generate primarily 5th and 7th current harmonics and a lesser amount of 11th, 13th, and higher order based on the configuration of the converter used.

A digital oscilloscope is needed to measure the wave shape, THD and amplitude of each harmonic. Harmonics are to be continuously monitored and preventive action is to be taken to improve the power factor in the facility and also save energy by reducing losses on power system components[8],[9].

III. MODELLING OF DOMESTIC/INDUSTRIAL LOADS

Nonlinear loads used in industries introduce current harmonics at the utility. This causes malfunctioning of the sensitive loads connected at the PCC. Hence harmonic analysis of the nonlinear loads is essential. Computer simulation is the most convenient way of harmonic analysis provided that the system components are modelled accurately and verified either through measurements or mathematically. This section presents the simulation models for some of the commonly used industrial loads. This can be used for estimating the harmonic currents injected at PCC by an industry.

The current and voltages of the industrial loads are non-sinusoidal due to their nonlinear characteristics. Laboratory experimentations were performed on the nonlinear loads listed in Table I. All the loads are supplied from 230 V, 50 Hz ac system. The supply voltage and current waveforms, and the instantaneous values are recorded using Tektronix TDS 3032B, 300 MHz digital storage oscilloscope. Harmonic spectrum for each load is also recorded and THDs are calculated for analyzing the effect of harmonics introduced by these loads. Based on these parameters simulation models are designed for every load and their combined effect is studied. This section presents the practically recorded waveforms for some of the loads and their simulation models in PSCAD/EMTDC.

TABLE I
RATINGS OF DOMESTIC AND INDUSTRIAL LOADS MODELLED IN PSCAD

S.No.	Domestic load	Ratings
1	Television set	50W
2	CPU & Monitor	100W
3	Battery Charger	12V; 3A
4	Fan with electronic regulator	80W
5	CFL lamp	2 x 55W
6	Air conditioner	cooling/heating 5/5 A; IP = 1100/1100 W
7	Refrigerator	190 liters;1 door; 4.4A
8	Washing machine	500W; 2.8A
9	Water lifting pump	1hP; 4A
10	Hot water system	1000W; 5A
11	Adjustable speed drive	3-phase, 400 V, 10 hP

A. Personal Computer (PC)

Personal computers are one of the most widely used electronic loads in modern life. It produces harmonic current especially when there is a large concentration of them in a distribution system. It utilizes the switch mode power electronics technology which draws highly non-linear currents that contain large amounts of third and higher order harmonics. A switch mode power supply (SMPS) has a large capacitor which maintains approximately constant voltage for the DC bus in the power supply.

A typical PC load model uses SMPS and comprises of a full wave rectifier, a DC storage capacitor, C, a diode bridge resistance, R and a series RFI choke which is represented by an inductance L. Fig. 1(a) shows the current waveform recorded in storage oscilloscope and Fig. 1(b) shows the harmonic spectrum of the current obtained by performing FFT analysis. Third and fifth harmonic components are more dominant in the PC current.

The PC's power supply converts the input ac voltage of 50 Hz to a desired direct current output voltage by means of a single-phase rectifier circuit. The PSCAD simulation model of PC is shown in Fig. 2. The R, L and C circuit parameters are varied for PC model and adjusted to match the practical data. The simulated waveforms of PC voltage and current are shown in Fig. 3(a).

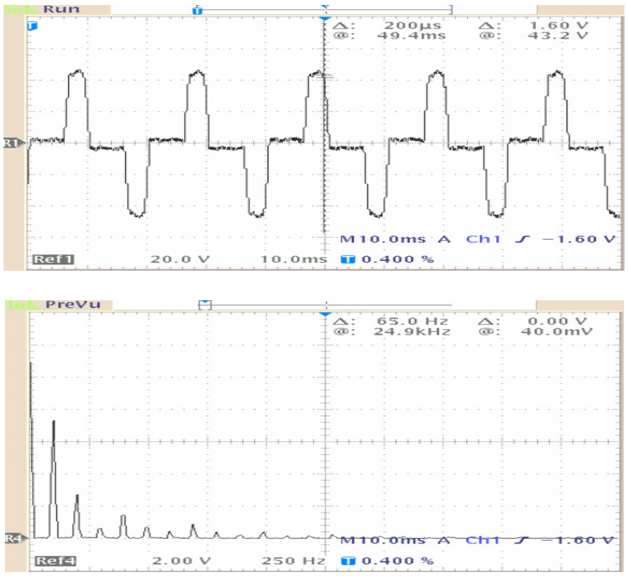


Fig. 1. (a). Recorded current waveform and (b). Harmonic spectrum for PC load current.

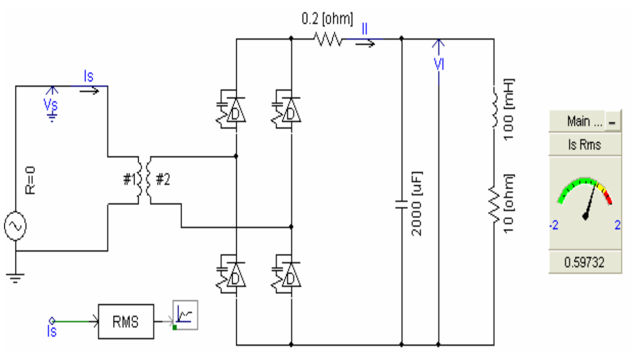


Fig. 2.Computer model and its equivalent circuit in PSCAD/EMTDC.

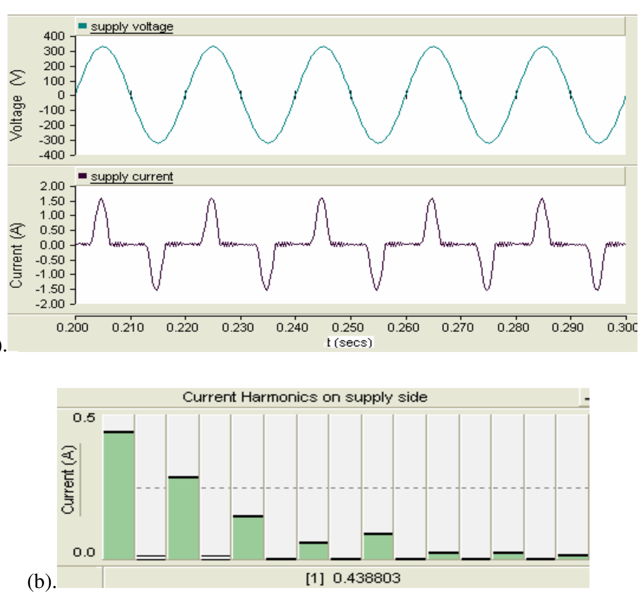


Fig. 3. (a). Voltage and current waveforms obtained from simulation model of PC and (b). Harmonic spectrum of current drawn by PC.

Frequency spectrum shown in Fig. 3(b) is obtained from FFT analysis of the PC current. The current has 67% of 3rd harmonic, 25% of 5th harmonic and 7% of 7th harmonic obtained from simulation which is comparable with Fig. 1(b) where the experimental results are 65% of 3rd harmonic, 24.5% of 5th harmonic and 7.2% of 7th harmonic component in the PC current. All the harmonics are expressed with reference to the fundamental current.

B. Fluorescent Lamp

Fluorescent lamps have a negative dynamic resistance behavior, which necessitates the use of a ballast to limit the current [10]. The electronic ballast employs half-bridge inverter and an LC filter used to acquire the nonlinear characteristics of the lamp. Practical current waveform and its harmonic spectrum obtained for lamp load are shown in Fig. 4. Fig. 4(b) shows that the current has 3rd harmonic component of about 14% of fundamental, and the other harmonics are negligible.

Simulation model for the fluorescent lamp, shown in Fig. 5 is built with the electronic ballast as PWM based half-bridge inverter. Simulation results for lamp instantaneous current and harmonic are given in Fig. 6(a) and (b). The harmonic spectrum of lamp current in Fig. 6(b) has 19.5% of 3rd harmonic component.

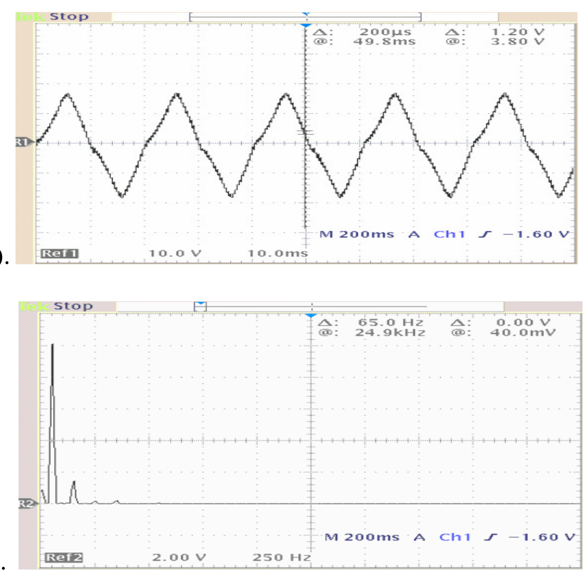


Fig. 4. (a). Current waveform recorded for fluorescent lamp and (b). FFT analysis of current waveform.

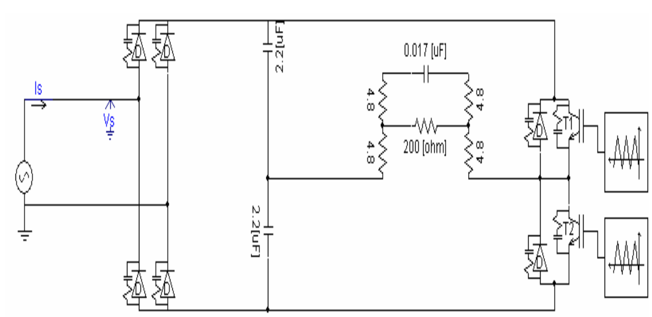
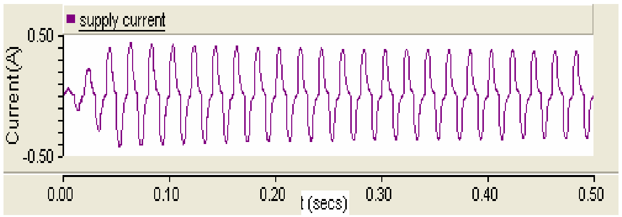


Fig. 5. Simulation model of fluorescent lamp.

(a).


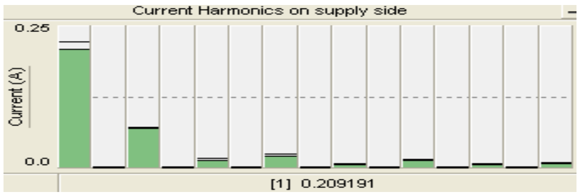
(b).


Fig. 6. (a). Current waveform obtained from simulation model of fluorescent lamp and (b). Harmonic spectrum of the current drawn by the lamp.

C. Adjustable Speed Drive (ASD)

ASDs consist of an induction motor supplied by variable AC voltage derived from converters. Hence, the ASD consists of three major components; the first is the front end, which is usually a 6 or 12 pulse rectifier. The second is the inverter stage that converts the generated DC voltage to controllable frequency and AC voltage to control the speed of the motor. The last stage is the DC link (shunt capacitor) that couples the two main stages and help in reducing the ripples of the DC voltage in case of VSI and PWM topologies.

The harmonics injected by the inverter is mainly dependent on the inverter topology and the motor characteristics. Therefore, the ASD can be modeled with a common three phase bridge converter circuit together with a DC link circuit and a harmonic current source to represent the inverter and the motor as shown in Fig. 7(a). The DC link capacitor in case of VSI and the DC inductor in case of CSI can block the propagation of the harmonics generated from the inverter side from entering the AC system [11]. This conclusion calls for a simple representation of the converter and the motor collectively by a DC current source instead of a harmonic current source.

Input data required to construct the above model are the firing angle of the converter thyristors (α), the direct current flowing into the inverter (I_{dc}) and the DC link R and C components. I_{dc} can be estimated from the motor load as (6).

$$I_{dc} = \frac{P}{2.3V_{ph}\cos\alpha} \tag{6}$$

where P is the motor load including losses and V_{ph} is the phase voltage of the supply system. Assuming the rated ASD frequency is ω_r and the operating frequency is ω, the firing angle can be determined as

$$\cos\alpha = \min.(\frac{\omega}{\omega_r},1) \tag{7}$$

Changing the converter firing angle α and the DC current source magnitude I_{dc} will reflect different operating conditions of the ASD. The PSCAD/EMTDC model of the 3-phase ASD is shown in Fig. 7(b) and the corresponding voltage and current waveforms are shown in Fig. 7(c). The current drawn by the ASD is nonsinusoidal as it is controlled by the PWM based converter. Table II lists the THDs of voltage and current due to the nonlinear loads obtained from simulation. The load current is also specified. These THDs are calculated based on the individual load ratings.

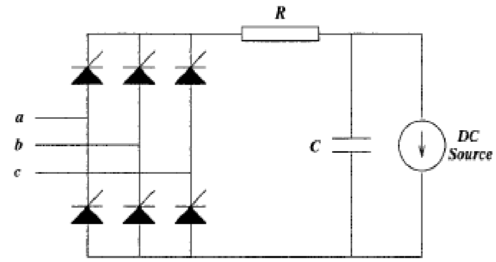


Fig. 7(a). ASD model

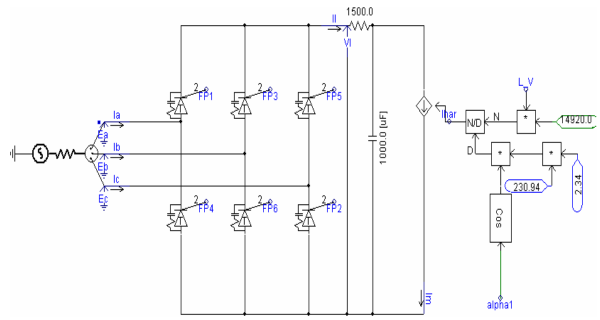


Fig. 7(b). Simulation model of ASD in PSCAD

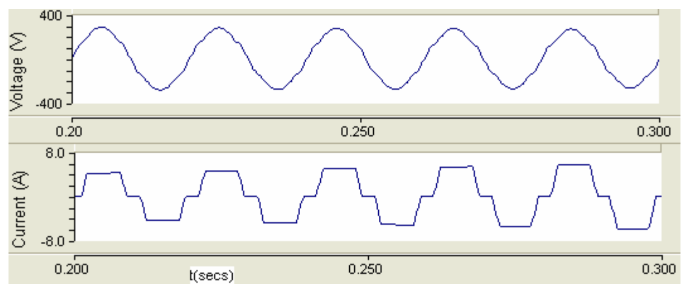


Fig. 7(c). Voltage and Current waveforms of ASD

TABLE II
SIMULATION RESULTS OF LOAD CURRENT AND THDS FOR DOMESTIC LOADS

Sl. no.	Equipment name	Simulated Irms (A)	THDV (%)	THDI (%)
1	Television set	0.374	3.331	91.244
2	CPU & Monitor	0.597	3.001	99.724
3	Battery Charger	3.068	3.286	45.581
4	Fan	0.401	0.343	13.178
5	CFL lamp	0.471	3.224	29.621
6	Air conditioner	5.028	3.285	44.719
7	Refrigerator	4.475	3.286	44.673
8	Washing machine	2.774	3.285	42.013
9	Water lifting pump	4.01	0.328	0.318
10	Hot water system	5.186	3.272	24.384

IV. CASE STUDY

A case study of harmonic evaluation was performed by employing the simulation models of nonlinear loads developed in PSCAD. The distribution system used for the launching of CARTOSAT-2A satellite at ISRO, Bangalore,

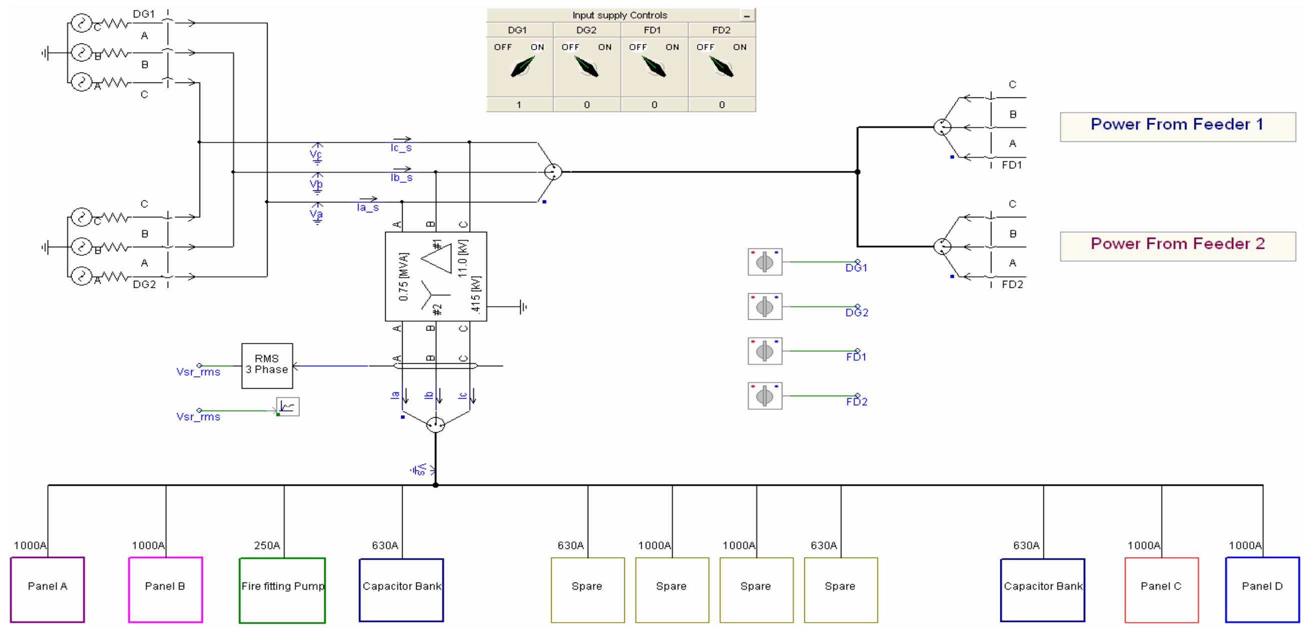


Fig. 8. Simulation model of the electrical load distribution used for Cartosat-2A.

TABLE III
RATINGS OF LOADS CONNECTED FOR CARTOSAT-2A CONTROL

Sl. no	Loads	Quantity	Ratings
1	Fire fiting Pump	3	75HP; 1440rpm, 0.8 pf; 415V; 50Hz, 100 A
2	Capacitor bank	1 in each phase	250 kVAr; with steps of 2.5% increment
3	UPS	4	Each 120kVA, 270 – 480 V
4	Antenna	4	4 servo motors, 600V; 3ph; 2kHz PWM inverter, 0.6A ~ 25A
5	Telemetry & Tracking Control	-	PCs and Lamp loads
6	Air Heating Unit	3	5HP; 1490rpm, 0.8p.f; 415V; 50Hz, 4A
7	Air Conditioner plant	3	10HP; 1490rpm, 0.8p.f; 415V; 50Hz
		3	100kW; 1490rpm, 0.8p.f; 415V; 50Hz
8	Machine Analysis Room	4PCs; 12 CFLs	PCs and Lamp(2x55W) loads with brightness control dimmer
9	Machine Control Room	7PCs; 12 CFLs	PCs and Lamp(2x55W) loads with brightness control dimmer
10	Logistic Room		PCs, Lamps and Fans

India is considered. The simulation model of the distribution is shown in Fig. 8.

Power supply is obtained from either of two 3-phase, 11 kV DG sets or from 11 kV feeders. 11 kV/415 V transformer is used to step down the voltage and connect to loads (phase voltage $= 415/\sqrt{3}$ volts). Three water pumps (fire fiting pumps) of rating 75hP used in emergency for fire extinguishing are connected. To improve the pf of the system 3-phase, 2.5 MVAr capacitors are connected in star.

Panel A and Panel B shown in Fig. 8 are the control panels connected to loads no. 3 to 10 listed in Table III. Four servomotors are present to control the tracking of antenna. The servo motor is modeled as RL load fed by a 3-phase, 600 volts inverter. Antenna position is controlled by the servomotor such that the antenna is maintained perpendicular to the satellite position. The current drawn by the motor varies from 0.6A to 20A depending on the position of the satellite. Air heating unit consists of three 5HP water pumps used to supply water to air conditioning system. Lighting and fan loads are used in machine analysis room, machine control room and logistic room. Table III shows the specification of all the loads connected in the system. In addition, spare panels are provided for future extension of distribution system.

For the above distribution system, simulation is performed using PSCAD/EMTDC and the voltage and current waveforms obtained from simulation are shown in Fig. 9. The three phase voltages given in Fig. 9(a) shows that the supply voltage is balanced. Figs. 9(b) to 9(d) are the currents in phase A, B and C respectively. These currents are unbalanced in magnitude due to non-uniform distribution of single phase loads.

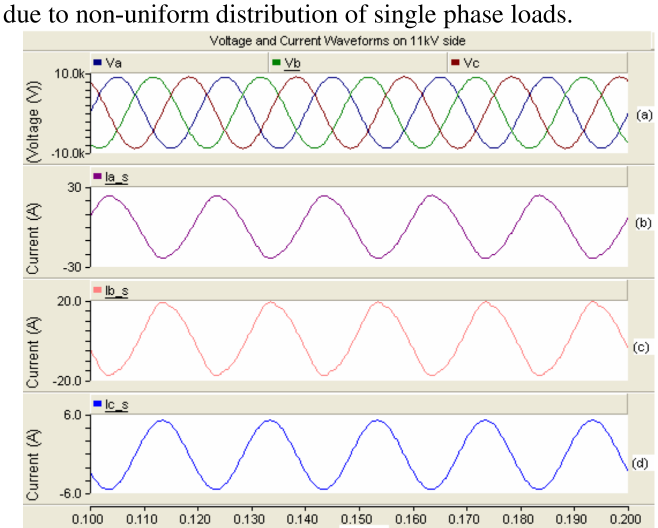


Fig. 9. Simulation waveforms for voltage and current on 11 kV side of the transformer. (a). 3-phase voltages, (b). Phase A current, (c). Phase B current and (d). Phase C current.

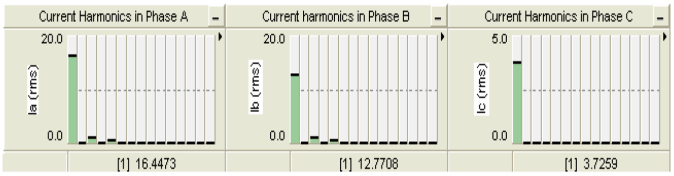


Fig. 10. Harmonic spectrums of the supply current in phase A, B and C.

Single phase loads such as lamps, PCs are connected in phase A and B. The peak values of currents are 23.24A, 19.05A and 5.03A in phase A, B and C respectively. The harmonic spectrum of supply current in Fig. 10 shows that the harmonics present are very small. The THD values of supply voltage and current obtained from simulation are given in Table IV. To improve the power factor (pf), 3-phase, star-connected capacitor bank is connected. The THD of current in all 3-phases are also reduced by adding the capacitor banks. The actual values of THD are 1.18% and 4.25% for voltage and current respectively; obtained during measurement in phase A. Table V gives the THDs of voltages and currents in all three phases. These values of THDs are comparable with the simulation results of THDs.

TABLE IV
SIMULATION RESULTS OF THDS OF INDIVIDUAL PHASEVOLTAGES AND CURRENTS

Voltage / Current	THD (%)		
	Phase A	Phase B	Phase C
Voltage	1.46%	1.45%	0.32%
Current without capacitor bank	5.35%	6.89%	0.59%
Current with capacitor bank connected	4.99%	6.40%	0.19%

TABLE V
MEASUREMENT VALUES OF THDS OF INDIVIDUAL PHASE VOLTAGES AND CURRENTS

Voltage / Current	THD (%)		
	Phase A	Phase B	Phase C
Voltage	1.18%	1.28%	0.35%
Current with capacitor bank connected	4.25%	5.80%	0.14%

TABLE VI
SIMULATION RESULT SHOWING THE IMPROVEMENT IN PF BY CAPACITOR BANK

Capacitor bank connection	Power factor		
	Phase A	Phase B	Phase C
Without capacitor bank (by simulation)	0.91	0.8	0.04
With capacitor bank connected (by simulation)	0.95	0.92	0.99
With capacitor bank connected (by measurement)	0.96	0.96	0.99

The pfs in phase A and B without capacitor bank connected in the system, are 0.91 and 0.8 respectively, which are acceptable. But in phase C without capacitor bank connected the pf is found to be 0.04 and is very low. Table VI shows the improvement in pf of phase B and C by the addition of 250 kVAr capacitor banks consisting of 1848.221 uF capacitor in each phase. These values of pfs obtained from simulation are comparable with the practical data given in Table VI and may be considered for the validation of simulation models of industrial loads.

V. CONCLUSION

Harmonic analysis of power system is performed to study the system behavior under harmonics and take preventive action to improve the pf or minimize losses. This paper presented the simulation modeling of various nonlinear loads used for both domestic and industrial applications. Case study of harmonic analysis is performed using these models for Cartosat-2A distribution system at ISRO, Bangalore. THD is used as the harmonic index and harmonic spectrum is presented for each load and for the industrial distribution system. Simulation result of power factor improvement by the addition of capacitor bank is also presented. The simulation results of THD and pf are acceptable with the practical measurement values. These models can hence be employed for harmonic analysis of a practical system and to design a suitable filter to mitigate harmonics in the distribution system.

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