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Analysis of Accumulative Effect of Harmonics on Low Voltage Distribution Network

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Abstract : *In typical Low voltage (LV) customer are supplied through single phase and three phase supply from distribution transformer. As the residential and commercial loads are linear and nonlinear in nature. These nonlinear loads produces harmonics into the system. These harmonics are varying in nature and the collective effect of harmonics on the LV system is considerable. It is necessary to analysis of collective harmonic impact of distributed harmonic source on LV system. This paper presents a experimental study of harmonic distortions caused by nonlinear loads in residential and commercial customers through power quality(PQ) monitoring. After the harmonic measurement, and monitoring it become necessary to discuss a model to analysis of accumulative harmonic impact on LV distribution system. The identification of the pattern of energy and the prediction of load profile is essential in order to analysis of harmonics sources in LV network. The usage pattern varies depending on many parameters such as type of habit, weather, working time and type of day either weekend or weekday is necessary to conduct harmonic analysis for each low voltage network load. There are two major probabilistic model for random harmonic assessment i.e. top-down model and bottom up model. This model is ideally suited for studied the consumer behavior and pattern.*

Keywords -*Distributed harmonic source, harmonic distortion, low voltage network, power quality, power quality monitoring.*

I. Introduction

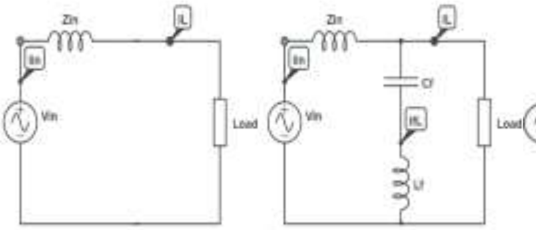
Recently, residential customers input voltages are becoming more distorted due to the widespread use of new energy efficient nonlinear load. As adoption from linear load to nonlinear loads for technological advancement. Several issues of concern to utilities, such as neutral to earth voltage rise, the overloading of distribution transformer [1-2]. This changing scenario of these load could result in an increase of total harmonic distortion (THD) by about 10% to 20% per year. It has been estimated that by 2020, 70% of the loads on LV network in India will be nonlinear loads. The penetration of harmonics in residential and commercial power system networks can cause severe problems such as decrease in power factor, increase in voltage distortion, increase system losses, unbalancing in phases and decrease the overall system efficiency[3,4,5] The response of the power system at each harmonic frequency determine the true impact of nonlinear load. All energy efficient equipment results a reduction in active power consumption, a reduction in peak current and reduction in losses in distribution. All have a positive impact on energy consumption but this new nonlinear load results in increase in reactive power consumption. The positive impact of energy savings equipment is too small. So reduction in harmonics and reactive power is required [6,7]. The non-linear loads used in single phase LV network are Compact Fluorescent Lamps (CFLs) , Light Emitting Diode (LED) lamps, Television, audio, PCs, laptop etc. are also utilizing nonlinear power supplies are becoming more widespread and introduce nonlinearities into supply [8]. As the demand for low prices pressure manufacturers to make the circuit as simple as possible and exclude costly components, even if the power quality is worse. This ultimately create a new challenging situation for planning of the LV distributed network. In future the LV distribution network faces the problem of harmonics, unbalancing of phases, overloading and difficulty in maintaining voltage level all these problem leads to power quality issues.

1.1. Types of Load

1.1.1. Current Source Load Type

Typical commercial and residential appliances, such as motor, refrigerators, freezers, washing machines, air-conditioner, cloth dryer and dish washer, which impose current distortion, are the electromagnetic devices. For this type of current type harmonic source, a shunt harmonic filter, should be preferred and capable of absorbing the load's harmonic currents, according to the relative admittances of the filter ($1/Z_{fL}$) and the feeder ($1/Z_{in}$). According to Fig. 1, the relationship between the ac supply current and the load current may be estimated by

$$\frac{I_{in}}{I_L} = \frac{Z_{fl}}{Z_{fl} + Z_{in}} \quad (1)$$



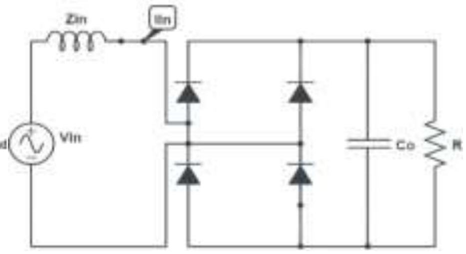


Fig.1. Current source load with and without filter **Fig.2. Voltage source type load**

1.1.2. Voltage Source Type Load

The circuit of a diode rectifier with a capacitive output filter is an example of nonlinear load with harmonic voltage source behavior. This type of circuit is present in almost all residential and commercial nonlinear loads, such as computers, Laptop, printer, scanner, photocopier, video monitors, TV sets, electronic lamp ballasts, CFL and LED etc. as shown in Fig. 2. Such load usually absorbs constant power, and the current varies in order to compensate the input voltage changes. The compensation in this case is possible only with series filters or active solutions.

1.1.3. LV Distribution System

The 500 KVA, 33KV/433V distribution transformer having percentage impedance (%Z) of 4.95% with connection in DY11 supplied to a single and three phase load of residential and commercial load. In this paper main focus has been given on residential load because earlier these loads were ignored because of less nonlinear loads were used as a residential load. Now a day's situation is different and change continuously from linear load to nonlinear load. Due to continuous increment in the nonlinear loads, an assessment of harmonics is very important for planning and operation of LV network design. If the amount of nonlinear load is exceeding the 25%, the harmonic analysis is required to check the compliance with the harmonic limits. The effect of collective harmonics in the secondary of the transformer are voltage and current distortions in the LV side, neutral conductor current and voltage rise, losses due to impact of harmonics and overloading of distribution transformer.

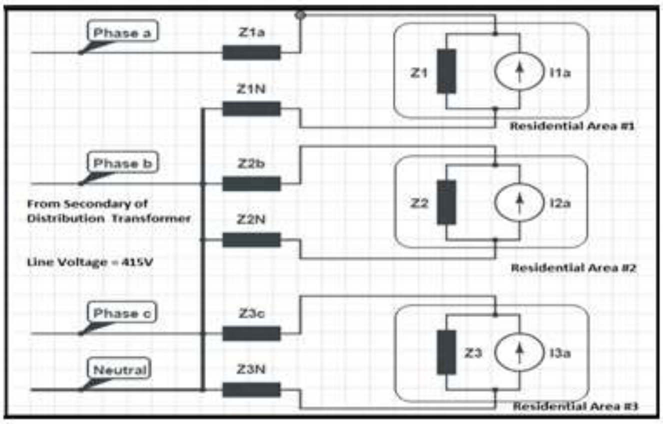


Fig.3. Low voltage distribution of load

II. Power Quality Parameter Measurement And Monitoring For Residential Load.

2.1. Power quality parameter measurement

This paper studies the different appliances individually in order to model the network response of nonlinear loads, different appliances were measured for real and reactive power, THD, PF and DPF. Here Fig. 4 to Fig. 7 shows the harmonic distortion and current taken by the laptop, THD and current monitoring for dishwasher and washing machine. The similar results are also taken for different appliances and the result for other appliance has been obtained from 3-phase power quality Analyzer as shown in table 1.

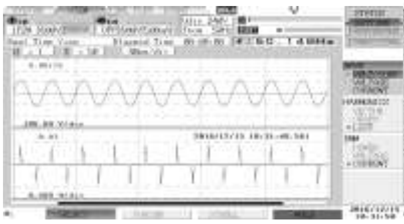
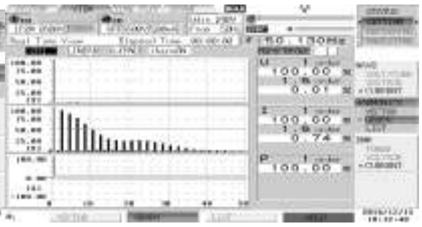



Fig.4. Supply voltage & current of Laptop **Fig. 5. THD of Laptop**

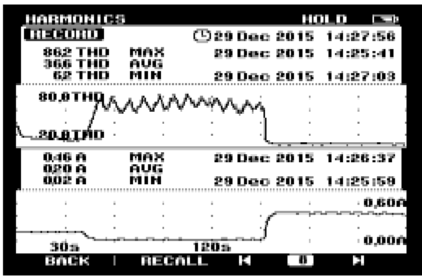
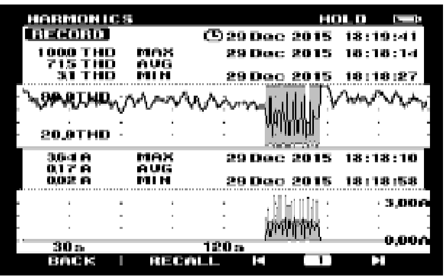



Fig.6.THD & current Monitoring of Dish washer **Fig.7.THD & current Monitoring of Washing Machine**

Table. 1. Power Quality Parameter

S.N	Device	Rating	VA	VAr	Watt	I_{rms}	P.F	DPF	Dominant harmonics	Thd
1	AC	0.6W	886	162	871	4.26	0.98	0.99	3rd and 5th	14.8
2	CFL	27W	41	33	25	0.19	0.60	0.90	3rd, 5th, 9th 11th, 13th ,15th,17th	74.9
3	Desktop	1,6A, 16Wh	50	45	21	0.21	0.43	0.55	3rd, 5th , 7th, 11th	36
4	Desktop with Printer		735	82	731	0.35	0.99	1.00	3rd, 5th , 7th, 11th , 13th	40.7
5	Dish washer	1200W	92	11	91	0.120	0.99	1.00	3rd	8.8
6	Cloth Dryer	1000W	154	27	152	0.68	0.98	0.99	3rd	17.5
7	Laptop	65W	96	83	48	0.40	0.49	0.96	3rd, 5th, 9th 11th, 13th ,15th,17th ,19th	84.9
8	LED	7W	22	12	19	0.10	0.85	0.99	till 50th are present	79.6
9	Microwave	1500W	1.53	0.43	1.47	7.12	0.96	1.00	3rd	24.9
10	Mobile charger	350mA	16	13	8	0.05	0.51	0.97	3rd, 5th, 7th ,9th 11th, 13th ,15th,17th ,19th	84.8
11	Printer	2.9A	577	230	530	0.05	0.94	1.00	3rd, 5th, 9th 11th, 13th ,15th,23rd	84.4
12	TV	136W	331	82	321	1.5	0.97	0.98	3rd	11.7
13	Washing Machine	575W	257	162	200	0.07	0.66	0.77	till 50th are present	95.8
14	Refrigerator	400W	200	160	120	0.8	0.64	0.7	3rd, 5th and 7th	60.3

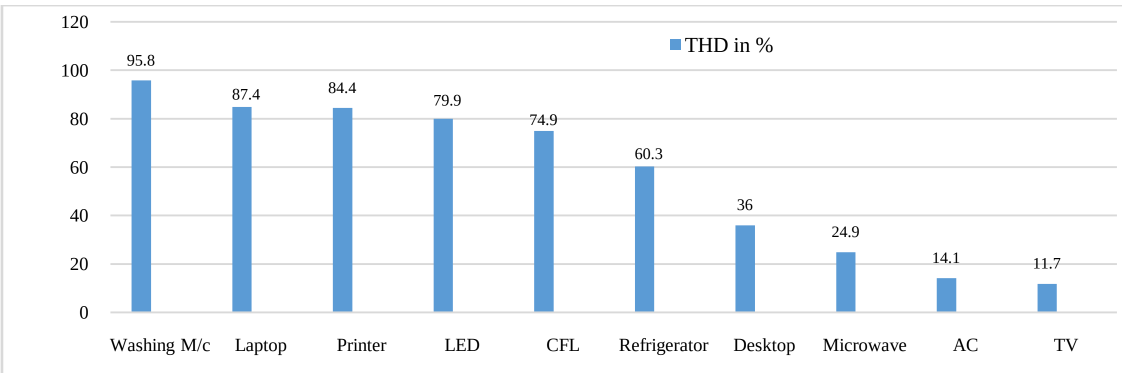


Fig. 8. THDs across each appliance

2.2. Power quality parameter monitoring for Power and THD

At the fundamental frequency linear and nonlinear loads in LV system are modeled as constant power loads but at harmonic frequency the linear load act as a impedance while nonlinear load act as a current source. These load impedances and harmonic current sources are varying throughout the 24 hour [8]. The loads are tentatively switched on and off to obtain the average profile of the residential load by monitoring. For obtaining a one day THD profile, monitoring of various power quality parameters in different schedule with tentative loading has been taken and shown in Fig.9 to Fig.13. The tentative load pattern has been shown in table 2.

Fig.9. Power consumption & THD monitoring in between 06:00am to 10:00am

Fig.10. Power consumption & THD monitoring in between 10:00am to 02:00pm

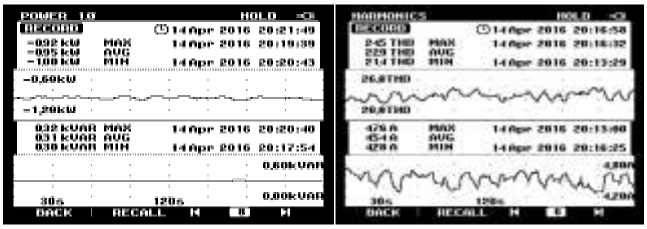


Fig.11. Power consumption & THD monitoring in between 02:00pm to 06:00pm

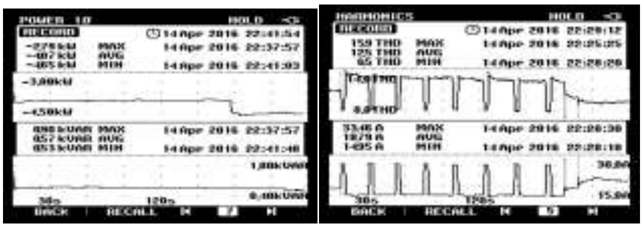


Fig.12. Power consumption & THD monitoring in between 06:00pm to 10:00pm

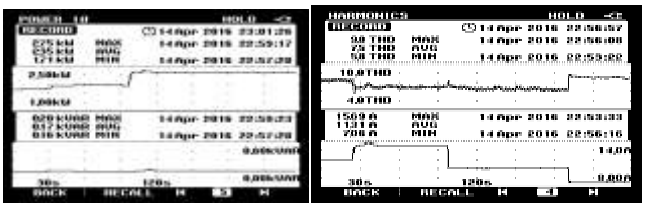


Fig.13. Power consumption & THD monitoring in between 10:00pm to 06:00am

Table 2. PQ Monitoring for tentative loading

S.N	06:00am-10:00am Tentative Load	No.	10:00am-02:00pm Tentative Load	No.	02:00pm-06:00pm Tentative Load	No.	06:00pm-10:00 am Tentative Load	No.	10:00 pm-6:00 am Tentative Load	No.
1	Refrigerator	01	LED	02	LED	02	Television	01	Refrigerator	01
2	CFL	02	CFL	01	CFL	02	Refrigerator	01	CFL	01
3	LED	02	Television	01	Television	01	Desktop	01	AC	03
4	Microwave Oven	01	Refrigerator	01	Refrigerator	01	LED	04		
5	Laptop	02	Washing Machine	01	AC	02	CFL	02		
6	Mobile Charging	04	Cloth dryer	01	Desktop	01	Mobile Charging	04		
7			AC	02			Laptop	02		

8							Microwave Oven	01		
9							AC	04		

Table 3. Results of PQ monitoring

	Time	Range	THD	Irms	P(W)	Q(kvar)
1	06:00am-10:00 am	Max	20.8	11.9	0.9	0.23
		Avg	14.5	6.7	2.3	0.21
		Min	5.7	3.4	2.5	0.18
2	10:00am-02:00 pm	Max	17.0	13.2	3.9	0.29
		Avg	6.8	11.6	3.3	0.25
		Min	5.3	4.5	3.1	0.21
3	02:00pm-06:00pm	Max	24.5	4.76	0.9	0.32
		Avg	22.9	4.54	0.95	0.31
		Min	21.4	4.28	1.0	0.30
4	06:00pm-10:00am	Max	15.9	33.36	4.65	0.90
		Avg	12.5	18.7	2.79	0.57
		Min	6.5	14.7	4.07	0.53
5	10:00pm-6:00am	Max	9.8	15.69	2.75	0.2
		Avg	7.5	11.31	2.35	0.17
		Min	5.8	7.06	1.71	0.16

As shown in table 3, the monitoring results that, every time THD is changing according to the load ON/OFF. So it is very difficult to filter out harmonics from such varying load pattern.

2.3. Criteria for Residential Load Modeling

The LV systems are classified into three categories, residential, commercial and industrial. The criteria for the residential load profile modelling are type of family, number of working hour, number of person at home, type of day, type of weather and size of house. For the detail modelling of the LV network with respect to balancing and unbalancing phase require detailed switch ON and OFF pattern of load on each phase [9]. On the basis of published work consideration of some basic criteria are:

2.3.1. Socio Economic Influence

In India wealth, employment and population density considerably impact power consumption pattern.

2.3.2. House Size Factor (h.f)

The size of house and number of person living in the house is directly proportional to the load switch ON/OFF pattern as both are increases then switching frequency is also increases so it is necessary to include the house size factor k.

$$h.f = \frac{No.of\ person\ (n)}{Average\ \ no.of\ people\ /house\,hold}$$

(2)

2.3.3. Appliances Availability(k_a)

The appliance availability is directly proportional to the wealth of a family and size of house as it is difficult to get reliable information on the use of appliances.

2.3.4. Person Availability (PA(n))

The person availability pattern or number of persons in the house is depend upon the time of first person getting up in the morning and last person to go to sleep. This data is depending on type of habit, weather, working time and type of day either weekend and weekday. It is very difficult to accumulate the data for occupancy pattern by considering all of this data. The total energy load profile can be significantly varying from time to time depend on number of occupancy pattern. It is necessary to make assumption for the most common scenario of availability pattern. The availability factor is either one or zero depend on load condition.

2.3.5. Switching Frequency (S.F)

The switching frequency of load is depending upon all the factors which are mentioned above.

$$Swiching\ Frequency(s.f) = \frac{Load\ ON\ average\ hours\ per\ day \times 60}{Cycle\ in\ minute} \quad (3)$$

The table 4. shows the probability of occupancy factor of persons with the type of family and size of house. The table 5. shows the pattern of occupancy according to weather and time.

Table 4. Type of family with house occupancy Factor

Type of family with probability of their house living (BHK: Bedroom, Hall and Kitchen)	House type with scaling factor of loading		
	1-BHK	2-BHK	3-BHK
Single	√		
Couple	√	√	
Family		√	√

Table 5. Occupancy Pattern for Residential Consumer

Number of Working person: Single (FT: Full time and PT: Part time)				
Weather Type	Type of Day	Job Type	Waking up time	Sleeping time
Summer	Weekday	FT	6:00-7:30	22:00
		PT	7:00-8:30	23:00
	Weekend		7:00-9:00	23:00
Winter	Weekday	FT	6:30-8:00	22:00
		PT	7:00-9:00	22:00
	Weekend		7:00-9:00	23:00
Rainy	Weekday	FT	6:00-7:30	22:00
		PT	7:00-8:30	23:00
	Weekend		7:00-9:00	23:00
Number of Working person: two				
Weather Type	Type of Day	Job Type	Waking up time	Sleeping time
Summer	Weekday	FT	6:00-7:30	22:00
		PT	7:00-8:30	23:00
		FT & PT	7:00-9:00	23:00
	Weekend		7:00-9:00	23:00
Winter	Weekday	FT	6:30-8:00	22:00
		PT	7:00-9:00	22:00
		FT & PT	7:00-9:00	23:00
	weekend		7:00-9:00	23:00
Rainy	Weekday	FT	6:00-7:30	22:00
		PT	7:00-8:30	23:00
		FT & PT	7:00-9:00	23:00
	Weekend		7:00-9:00	23:00

For residential load modeling advance and accurate, probabilistic methods are necessary to be evaluated the load pattern. The probabilistic load profile model of household are used to assess the adequacy of distribution network and possible mitigation technique. The top-down model based on field measurement and second is bottom up model based on energy usage. For quicker result top-down model generate the best results while for detailed scenario the bottom up model is preferred.

2.4. Criteria for Load

2.4.1. Base load

These loads includes fridge, modem, freezer etc. and modeled independently as they are not dependent on person's availability. The energy use of these appliances is modeled as constant or variable switch usage.

2.4.2. Heating Cooling Load

These loads includes air conditioner, heater and oven etc. are partially dependent on the type of weather, temperature and person availability.

2.4.3. Active pattern load

The loads includes television, cooking appliances, hair dryer and lighting etc, which are directly depend on persons availability.

2.4.4. Active pattern load

The loads includes television, cooking appliances, hair dryer and lighting etc, which are directly depend on persons availability. The switching and working cycle pattern of appliances is shown in table 6.

Table 6. Switching and Working Cycle pattern of appliances

S.N	Load type (For family)	Rating (Watt)	Nos.	Avg. Hr/dy	Working Cycle (C_w)	S.F
	Entertainment					
1	Television	70	2	8	2hr	4
2	Play station	30	1	2	30min	4
	Communication					
1	Mobile charging	6	4	8	1hr	8
2	Cordless					
3	Wi-Fi	20	1	24		1
	Kitchen					
1	Refrigerator	500	1	24		1
2	Blender	1500	1	0.25	3m	5
3	Coffee Maker	800	1	0.5	5m	6
4	Microwave	1500	1	2	3m	4
5	Toaster	1200	1	0.25	3m	5
6	Electric Kettle	1200	1	0.25	3m	5
7	Mixer	1000	1	0.25	3m	5
8	Dish Washer	1200	1	2	40m	3
9	Water filter	80	1	1	30m	2
10	Exhaust Fan	30	1	3	30m	6
	Office					
1	PC	120	1	4	2hr	2
2	Laptop	65	3	4	2hr	2
3	Fax	20	1	0.25		-
4	Scanner	3.5	1	0.25		-
5	Printer	350	1	0.25		-
6	Tablet charging	10	2	1	30m	2
	Lighting					
1	CFL	30	4	10	2hr	5
2	LED	20	3	12	2hr	6
3	Tube light(LED)	40	3	10	2hr	5
	Other					
1	Washing M/c	500	1	1	30m	2
2	Vacuum Cleaner	500	1	1	10m	6
3	Cloth Dryer	1000	1	0.5	15m	2
4	Iron	1000	1	0.5	15m	2
5	Hair Dryer	1000	1	0.25	2m	8
6	Ceiling Fan	50	4	12	1hr	12
7	Air Conditioner	1500	3	10	2hr	5
8	Cooler	1000	2	12	2hr	6
9	Electric Heater	3000	2	2	30m	4

III. Algorithm

The commercial and residential load having random switching pattern and having different switching probability. Here an algorithm is developed to analysis of random harmonic loads switching pattern as shown in Fig. 17. The simulated house is 2 bedroom-hall-Kitchen in size with 4 persons and not available from 10:00 AM to 05:00 PM and the day type is weekday has been considered: Based on available data a switching pattern for a day, a bottom up approach using Monte Carlo is established for the profile [10,11,12].

3.1. Algorithm procedure

1. Select the data and probability profile and consider all necessary conditions.
2. The number of switch on event (S_{ON}) are modified according to switching frequency, house size factor, appliances availability and person availability.

$$S_{ON} = K_a \times P_a \times s.f \times h.f \quad (4)$$

3. The probability $P_t(\text{n})$ of switch on at present instant of time(t)

$$P_t(\text{n}) = P_r(\text{n}) \times K_c \times K_a \times P_a \times s.f \times h.f \quad (5)$$

$$P_t(\text{n}) = P_r(\text{n}) \times K_c \times S_{ON} \quad (6)$$

4. Compare the calculated probability $P_t(\text{n})$ with normally distributed random number (n).

5. If P_t(n)is greater than one then go to step 6 otherwise go to 7.
6. The load is switch on and the present time is updated to C_w and get back to 3.
7. The load remain off and the present simulation time is updated by (t+ΔT)

The calibration factor Kc shows the person availability PA(n). When PA(n) is 1,then persons is available at home and 0 then nobody is available. Some loads are independent on the person's availability like freezer, fridge etc. so K_c is equal to 1.

$$\sum_{n=1}^{N} P_t(\text{n}) = \sum_{n=1}^{N} P_r(\text{n}) \times K_c \times \text{s.f} = 1 \quad (7)$$

$$K_c = \frac{1}{\sum_{n=1}^{N} P_r(\text{n}) \times \text{s.f}} \quad (8)$$

The household probability profile is the result of interaction of person availability, appliance availability and switching frequency of the appliances shown in Fig 14 to Fig.16.

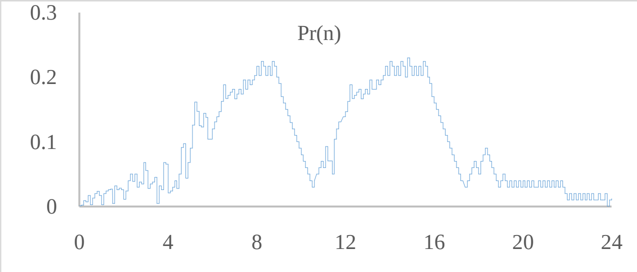


Fig. 14. Probability switch-on event of washing machine for one day

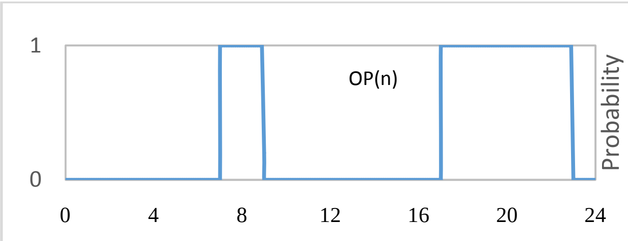


Fig.15.Probability switch-on event of washing machine

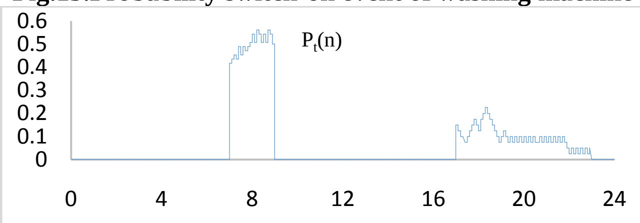


Fig.16. Probability switch-on event of washing machine

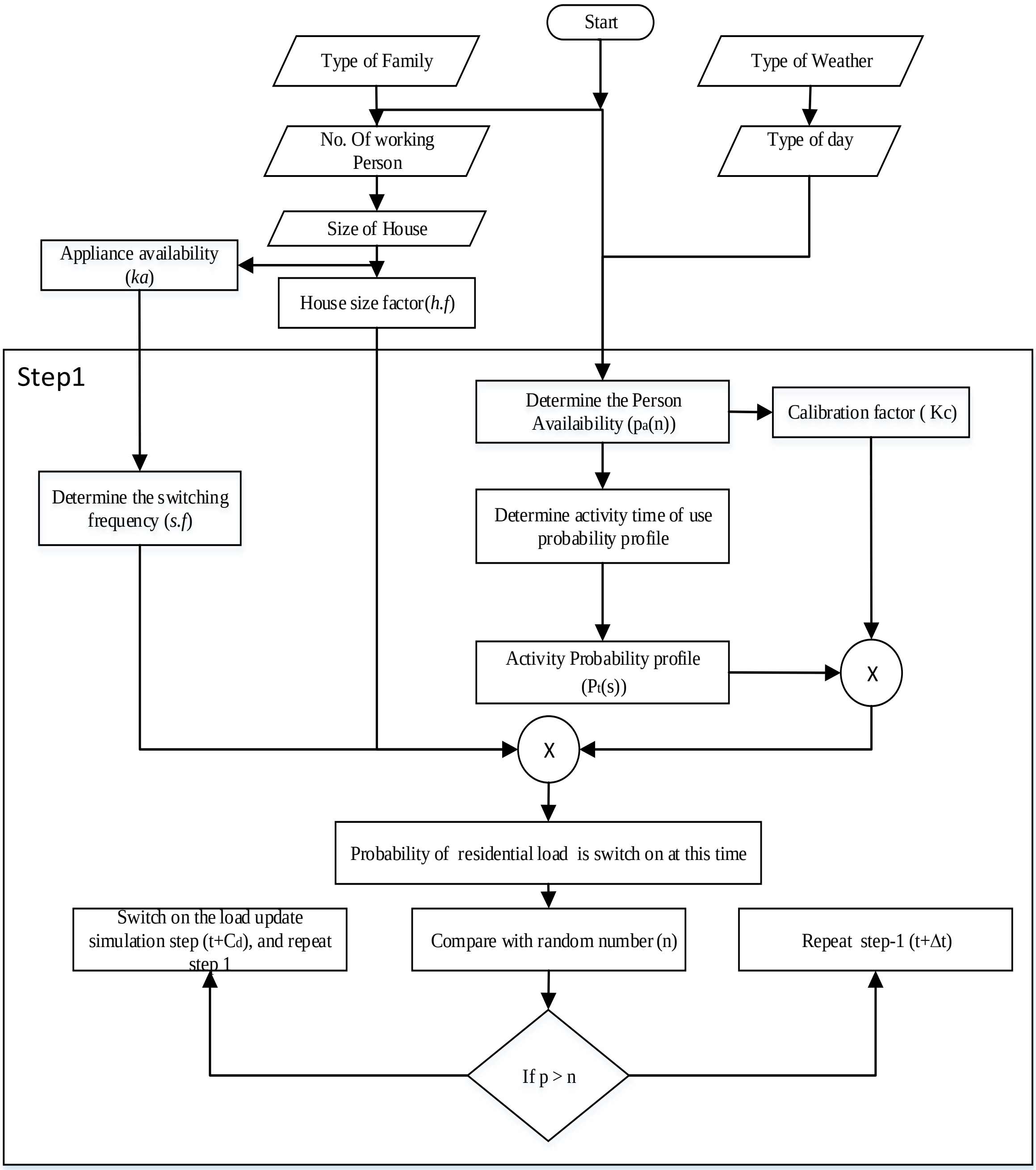


Fig.17. Flow chart

IV. Conclusion

In today's scenario, every residential house has nonlinear load. Earlier residential and commercial harmonics were ignored because all loads are not nonlinear. As the scenario is changing continuously, all new load and their characteristics is also changing. The effect of accumulative harmonics is a big problem for already connected distribution transformer. The entire nonlinear load has harmonic spectrum and only one or two harmonics will not significantly reduce the overall THD. The solution is to make a nonlinear load with harmonic filtering properties and make mandatory for manufacturers to limit harmonic effect on distribution system.Solution to harmonics problem is that one is to reinforce the distribution system to withstand the harmonics or to install devices to attenuate or remove the harmonics. So the LV network must be reconfigured according to the present and future scenario and enhance the quality of power supply to deal with new loads.

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