IJEAST

INTERNATIONAL JOURNAL
OF ENGINEERING APPLIED SCIENCE
AND TECHNOLOGY

VOLUME : 2 ISSUE : 2 Print / Issue Publication Date: 27-Jan-2017

ISSN : 2455-2143

Indexed In

Google Scholar | Open Access | doi | Crossref

WWW.IJEAST.COM

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International Journal of Engineering Applied Sciences and Technology, 2016
Vol. 2, Issue 2, ISSN No. 2455-2143, Pages 93-102
Published Online December-January 2016 in IJEAST (http://www.ijeast.com)

MODELLING AND ANALYSIS OF NONLINEAR RESIDENTIAL LOADS FOR THD STUDY AND ITS MITIGATION STRATEGY

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Abstract— **This paper deals with modelling of most of the nonlinear domestic loads like TV, Home UPS, CFL lamps, ASD washer and computer etc. Due to the advancement in power electronics industry, home appliances become more power electronics based. The widespread use of these nonlinear loads increases the harmonics in distribution systems and affects the voltage quality of power system. Harmonic analysis of the distribution system with nonlinear loads is essential for designing and optimal location of filters. In order to assess the harmonics produced by nonlinear loads precisely, accurate modelling of these loads is required. Simulation models are developed for various nonlinear loads using MATLAB-SIMULINK software. THD analysis is performed and the effect of filter and zigzag transformer on harmonic distortion is assessed.**

Keywords— **THD, UPS, CFL, Zigzag Transformer, ASD PC, Harmonics, SMPS**

I. INTRODUCTION

Harmonics are the by-products of modern electronic devices i.e. nonlinear loads, this harmonics by drawing current in abrupt short pulses, rather than in a smooth sinusoidal manner. Any distribution circuit feeding nonlinear loads will contain some degree of harmonic frequencies in multiples. Due to the rapidly increasing number of non-linear loads in distribution systems, the harmonic distortion of the current and voltage increases [1], [15]. Examples of non-linear loads are personal computer, fan with TRIAC [5] as regulator, television set (TV), fluorescent tube with electronic ballast, compact fluorescent lamp [4], battery charger, uninterrupted power supply (UPS) [6] and any other equipment powered by switched-mode power supply (SMPS) [2] unit. A term generally deployed to compute the harmonic pollution is Total Harmonic Distortion (THD) which can be defined as: “The ratio of the harmonic content to the fundamental quantity, expressed as a percentage” [9]. As the number of harmonics-producing loads in residences has increased over the years, it has become increasingly necessary to address their effects on the distribution system. Power Quality of distribution networks is severely affected due to the flow of these generated harmonics.

Harmonic currents generated by nonlinear loads can cause problems on the power system. These harmonics can cause excessive heat in many appliances, and hence reduce the life span of the distribution transformer supplying such loads, protecting equipments in power system. It can also increase power consumption and reduce system efficiency. It also lowers the system power factor. In this paper presents the results of a SIMULINK of harmonic distortion caused by different non linear home appliances and analysis of percentage total harmonic distortion. According to the IEEE standard, total harmonic distortion in voltage (THD_v) and individual harmonic distortion in voltage (THD_v) for the system voltage level up to 69 kV should not go beyond 5 % and 3 % respectively [9].

The higher level of harmonic distortion in a distribution system reduces the efficiency of the system because of the increased line and transformer losses. In order to reduce the harmonics caused by nonlinear loads in distribution system filtering action is usually employed which in some cases like shunt filter may raise the harmonic level instead of lowering [20]. In this paper the influence of Zigzag transformer on harmonics is presented as the Zigzag transformer has ability to cancel harmonics [8] because of its unique connection style. The zigzag connection is also called the interconnected star connection. This connection has some of the features of the Y and the Δ connections, combining the advantages of both. The zigzag transformer contains six coils on three cores. The first coil on each core is connected contrariwise to the second coil on the next core. The second coils are then all tied together to form the neutral and the phases are connected to the primary coils. Each phase, therefore, couples with each other phase and the voltages cancel out. As such, there would be negligible current through the neutral pole and it can be connected to ground. One coil is the outer coil and the other is the inner coil. Each coil has the same number of windings turns (Turns ratio=1:1) but they are wound in opposite directions.

The rest of the paper is organized as follows. Modelling of distribution network with nonlinear residential loads and

International Journal of Engineering Applied Sciences and Technology, 2016
Vol. 2, Issue 2, ISSN No. 2455-2143, Pages 93-102
Published Online December-January 2016 in IJEAST (http://www.ijeast.com)

zigzag transformer in SIMULINK is presented in section II. Experimental results are presented in section III. Concluding remarks are given in section IV.

II. PROPOSED NONLINEAR MODELS

A. Personal Computer –

A typical PC load model as shown in Fig. 1 uses SMPS [2] 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. The Fig 1 shows the personnel computer simulation model and Fig. 2-Fig. 5 shows Supply Voltage, Current waveforms, voltage and current THD's of Personal computer load. The 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. Generally computer loads produce sharp peaks due to capacitive charging currents drawn by the power supply.

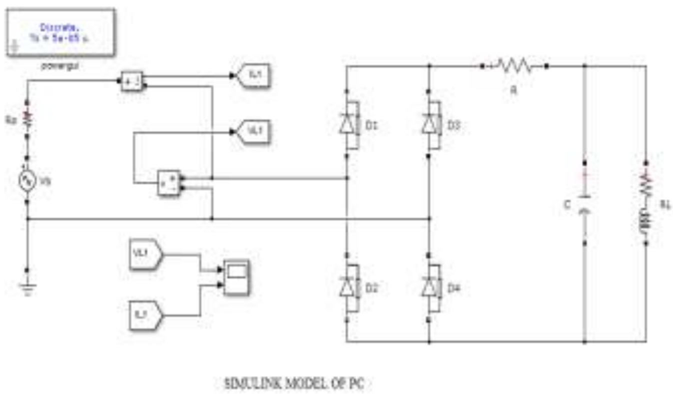

Fig. 1. Simulation model of PC

B. Compact Fluoroscent Lamp –

Compact fluorescent lamps (CFLs) are increasingly being used in residential and commercial buildings because of the desire to reduce electricity usage. CFLs are nonlinear which raises concerns over the widespread use of CFLs. Fluorescent lamps have a negative dynamic resistance behavior which necessitates the use of a ballast to limit the current. Due to the non-linear characteristics of the electronic ballast, the CFLs will inject harmonic currents into the distribution system [4]. The overall effect of these harmonic currents injection at the distribution level could result in unacceptable voltage distortion at some points in the network. As shown in Fig. 2 the electronic ballast employs half-bridge inverter and an LC filter used to acquire the nonlinear characteristics of the lamp. Fig. 2 shows the simulation model for the fluorescent lamp

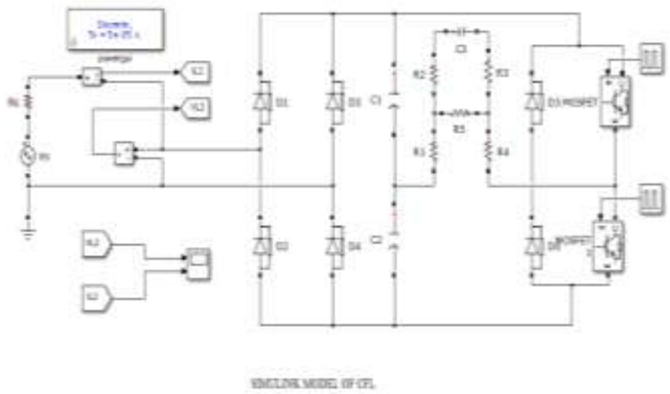

Fig. 2. Simulation model of CFL

C. Fan Regulator (TRIAC) –

Ceiling fan is the most commonly used domestic load. During initial days speed control of fan is achieved with resistive voltage regulator which has many drawbacks like bulk in size, huge power loss etc. Now a day's resistive voltage regulator is being replaced with electronic voltage regulator (TRIAC) [5] as shown in Fig. 3 which is small in size does not incur power loss. Triac has non linear characteristics due to this it will introduce harmonics. Voltage can be regulated by changing the firing angle of the TRIAC and THD varies with firing angle. Fig. 3 shows simulation model of fan with regulator.

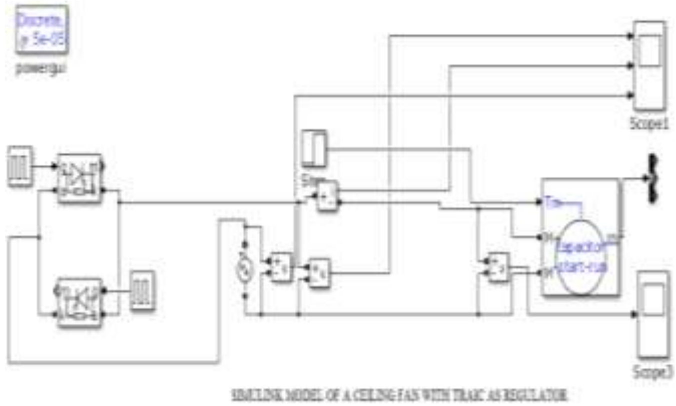

Fig. 3. Simulation model of fan

D. Uninterruptable Power Supply –

Generally UPS differs from an auxiliary or emergency power system or standby generator in that it will provide instantaneous or near-instantaneous protection from input power interruptions by means of one or more attached batteries and associated electronic circuitry for low power users by means of diesel generators and flywheels for high power users. Fig. 4 shows the simulation model for uninterruptible power supply. The on-battery runtime of most

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uninterruptible power sources is relatively short and being typical for smaller units but sufficient to allow time to bring an auxiliary power source on line or to properly shut down the protected equipment. Input stage of UPS (Rectifier) converts input AC into DC and stores energy in a battery. During power interruption output stage of UPS (Inverter) converts DC back into AC [6].

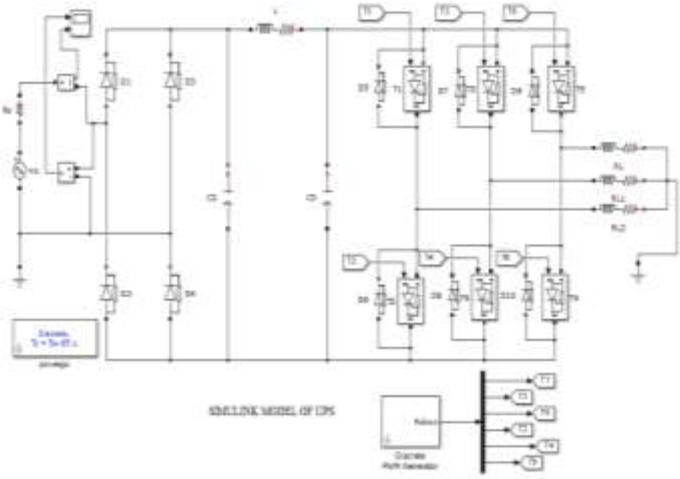

Fig. 4. Simulation model of UPS

E. Adjustable Speed Drive –

Normally ASD consists of an induction motor supplied by variable AC voltage derived from converters [3]. From Fig. 6 we can see that 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) shown in Fig. 6 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. 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. Fig 6 shows the simulation model of Adjustable Speed Drive.

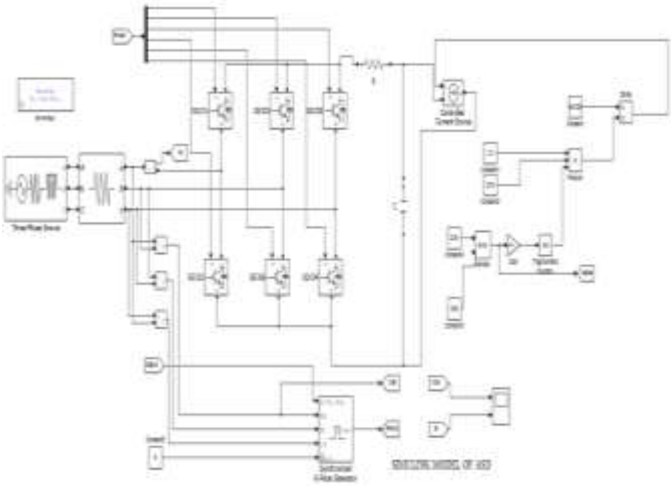

Fig. 5. Simulation model of ASD

F. Distribution Network Feeding Six Homes –

We considered a 3 phase distribution network consisting of a substation, distribution transformer and feeder lines connecting six individual homes consisting of non linear loads like PC, TV, CFL, FAN, UPS and ASD as shown in Fig. 7. Each home consists of above five loads and additionally three ASD's are also connected to the network. Distribution transformer is a shell type three winding transformer. Loads are uniformly connected to each phase of the distribution network. Fig. 7 shows simulink model of distribution system feeding six homes.

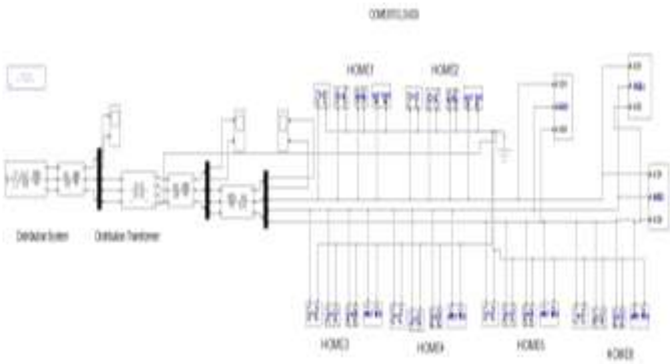

Fig. 6. Simulation model of distribution network feeding six homes

G. Distribution System With Zigzag Transformer

In this paper zigzag transformer as THD mitigation technique is proposed [8]. In Fig. 8 Zigzag transformer is connected in network and it is supplying 3 phase loads. Fig. 8 shows simulation model of distribution system with zigzag

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transformer. Zigzag transformer reduces third harmonic current components flowing in both the phase conductors and the neutral conductor up-line from the zigzag transformer installation [12] [13] [14]. This reduces neutral conductor loading and losses in all of the conductors and the supply transformer. It also reduces transformer heating for the supply transformer and can eliminate the need for k-factor transformers. They reduce the voltage distortion as well as the current distortion. Reduction of the harmonic currents flowing in the phase conductors and the supply transformer reduces the voltage distortion.

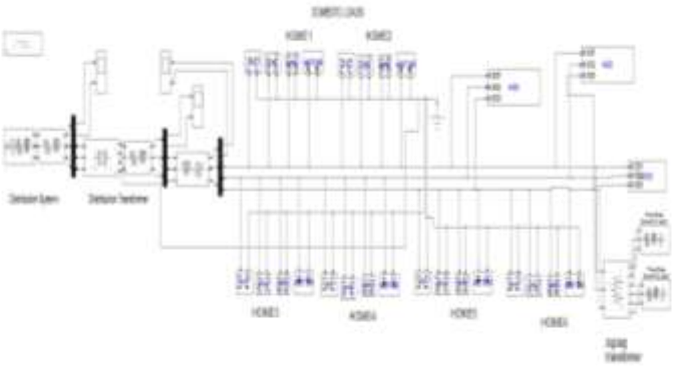

Fig. 7. Simulink model of distribution system with zigzag transformer

III. SIMULATION RESULTS

The nonlinear simulink models shown from Fig. 1 to Fig. 7 are simulated and respective THD analysis was performed. The simulation results are as follows

Case 1: PC model as shown in Fig. 1 is simulated for THD analysis as it is most widely used load in both domestic and commercial areas which poses nonlinearity with its SMPS circuit which is highly nonlinear due to rapid switching. The resulting waveforms of supply voltage and current obtained from simulation results are given in following figures.

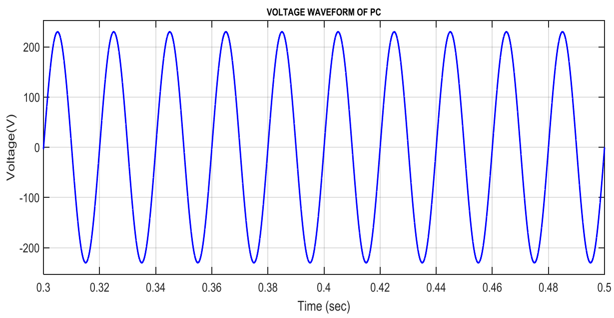

Fig. 8. (a) Supply voltage waveform of PC

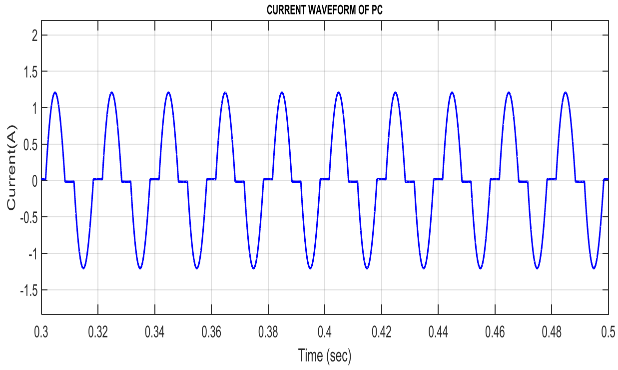

Fig. 8. (b) Supply current waveform of PC

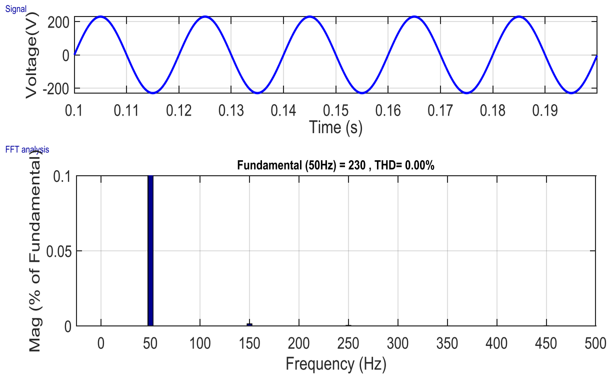

Fig. 8. (c) Voltage THD (THD_v) of PC

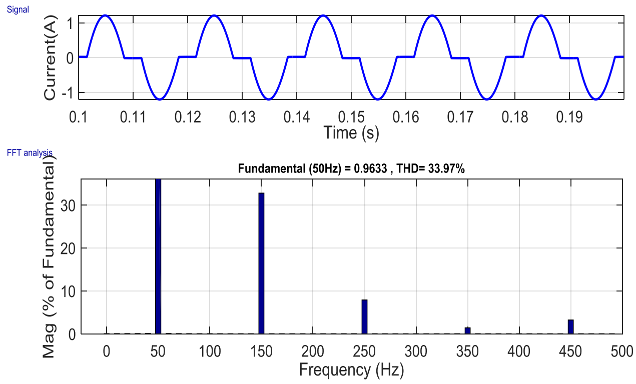

Fig. 8. (d) Current THD (THD_i) of PC

From Fig. 8 (a) we can observe that the voltage waveform is sinusoidal with no THD. The current waveform in Fig. 8 (b) is distorted due to harmonics. The THD of voltage waveform is almost zero as shown in Fig. 8 (c). The THD of current waveform is about 33% in Fig. 8 (d). 3rd, 5th and 9th order harmonics are more dominant in PC with 30%, 9% and 5% of fundamental.

Case 2: Compact fluorescent lamp as shown in Fig. 2 is simulated for harmonic analysis as it is used most widely in almost every domestic and commercial purpose and the simulation results obtained are given in the following figures.

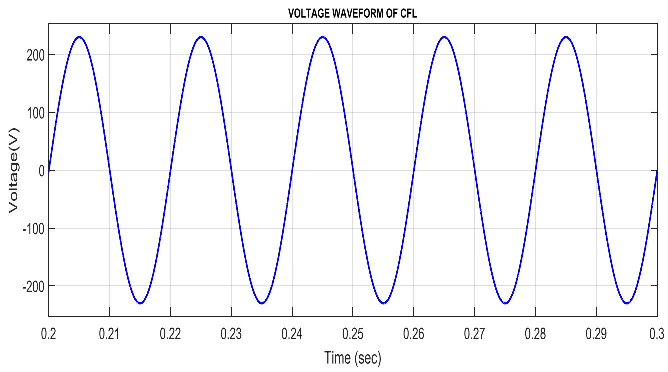

Fig. 9. (a) Supply voltage of CFL

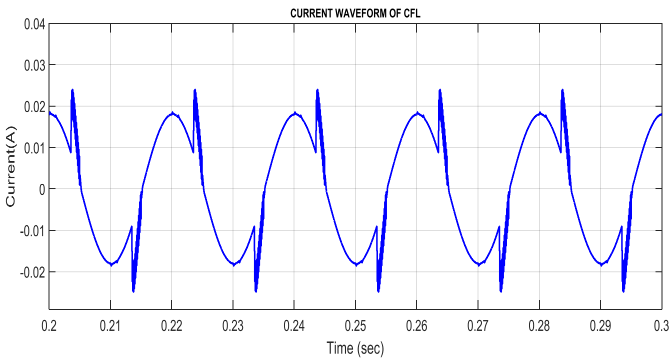

Fig. 9. (b) Supply current of CFL

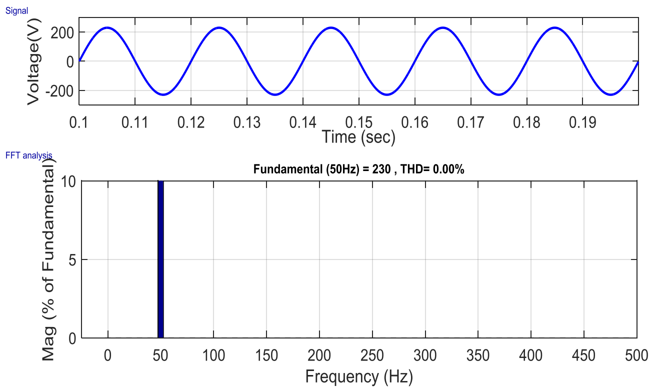

Fig. 9. (c) Voltage THD (THD_v) of CFL

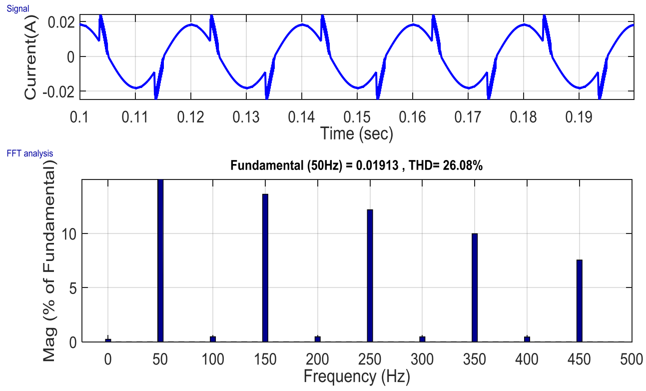

Fig. 9. (d) Current THD (THD_i) of CFL

From Fig. 9 (a) we can see that the voltage waveform is unaffected with zero or very small THD. The current waveform Fig. 9 (b) is affected by harmonics giving rise to distortion. The THD of voltage waveform is almost zero in Fig. 9(c). The THD of current waveform in Fig. 9 (d) is around 26%.In this case referring Fig. 9 (d) we can notice that 3^{rd}, 5^{th}, 7^{th}, and 9^{th} order harmonics are dominant with 17%,14%,10% and 7% of fundamental.

Case 3: Fan regulator (TRIAC) as shown in Fig. 3 is simulated for THD study as most of the fans are being controlled by regulator called TRIAC which offers nonlinearity due to its switching. The TRIAC has on and off state characteristics similar to SCR but now the characteristic is applicable to both positive and negative voltages. This is expected because TRIAC consists of two SCRs connected in parallel but opposite in directions. The respective simulation results obtained are displayed in figures below.

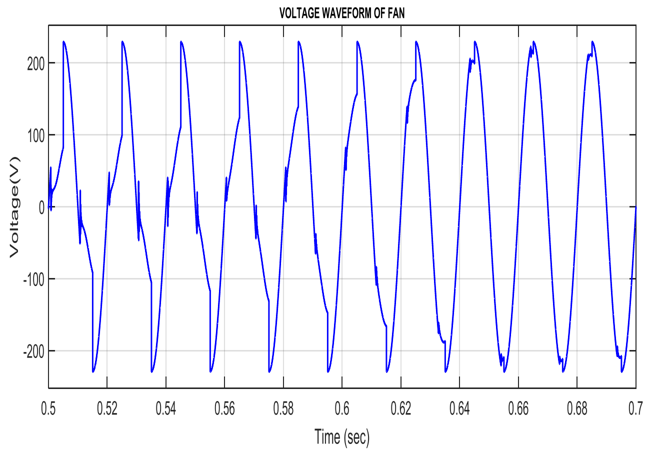

Fig. 10. (a) Supply voltage waveform

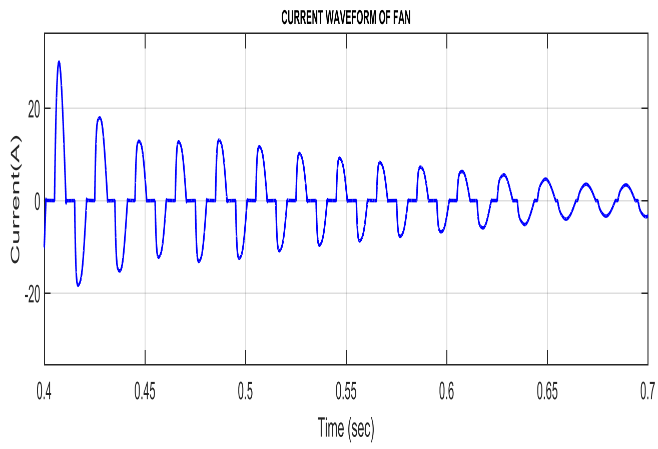

Fig. 10. (b) Supply current waveform

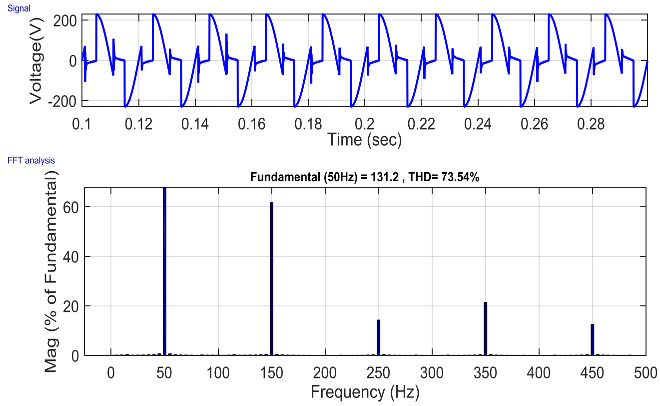

Fig. 10. (c) Voltage THD (THD_v) of fan

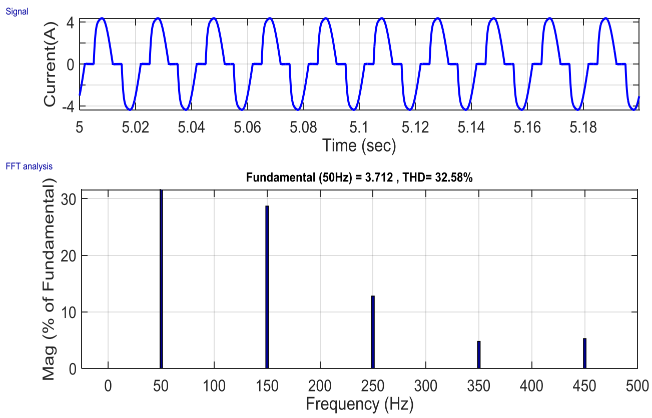

Fig. 10. (d) Current THD (THD_i) of fan

As triac acts upon supply voltage so as to have speed control it introduces voltage as well as current harmonics and hence both waveforms gets distorted as shown in Fig. 10 (a) and 10 (b). From Fig. 10(c) we can observe that voltage THD is about 73.6%. From the Fig. 10 (d) we can observe that the current THD is about 32% with 3rd, 5th and 9th order harmonics as dominant harmonics with 27%, 14% and 5% of fundamental.

Case 4: UPS model as shown in Fig. 4 is simulated for analyzing THD as it has nonlinearity in two stages, one in input rectifier and other in output inverter. The respective results are given in following figures.

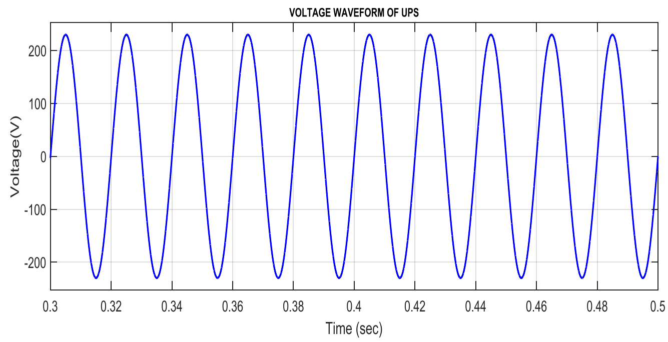

Fig. 11. (a) Supply voltage waveform of UPS

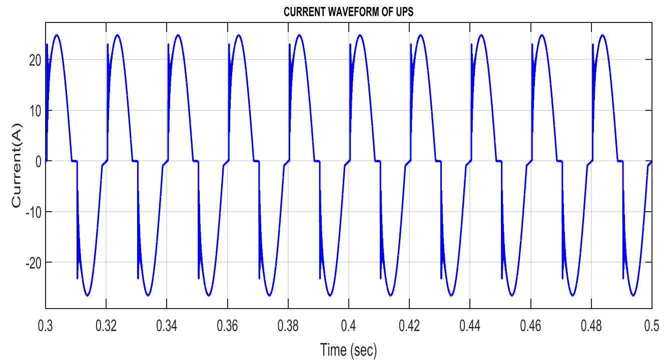

Fig. 11. (b) Supply current waveform of UPS

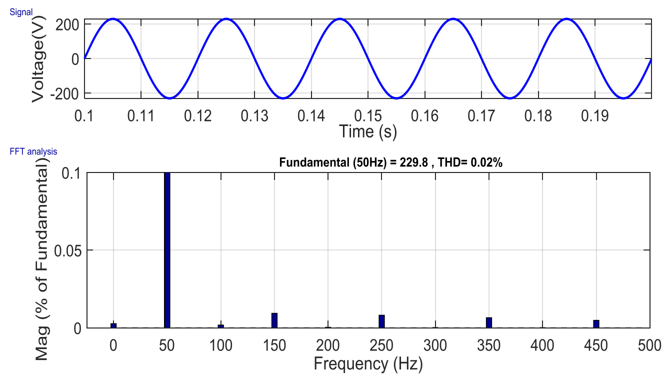

Fig. 11. (c) Voltage THD (THD_v) of UPS

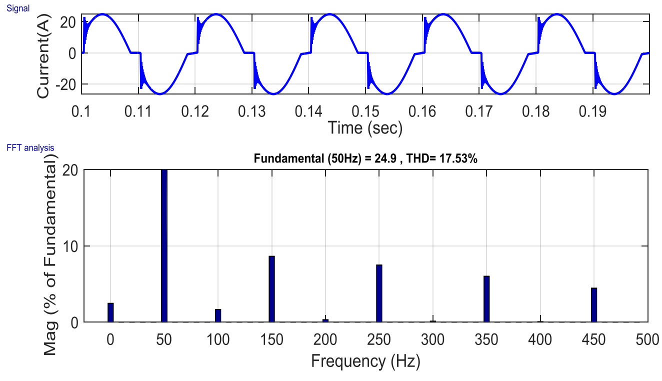

Fig. 11. (d) Current THD (THD_i) of UPS

Fig. 11(a) and 11(b) shows voltage and current distortions. From Fig. 11 (d) we can observe that the UPS under consideration produced a current THD of 17.53% with 3rd, 5th and 7th order as dominant harmonics. From Fig. 11 (d) we can notice that the current waveform contains small amount of DC offset and small amount of even order harmonics like 2nd and 4th.

Case 5: Simulation is performed on ASD model shown in Fig. 5 for THD analysis. As ASD consists of inverter circuit it inherently gives rise to harmonics in the system. There are three basic types of inverters commonly employed in adjustable AC drives: The variable voltage inverter (VVI), or square-wave six-step voltage source inverter (VSI), receives DC power from an adjustable voltage source and adjusts the frequency and voltage. The current source inverter (CSI) receives DC power from an adjustable current source and adjusts the frequency and current. The pulse width modulated (PWM) inverter is the most commonly chosen. The simulation results obtained are given in the following figures.

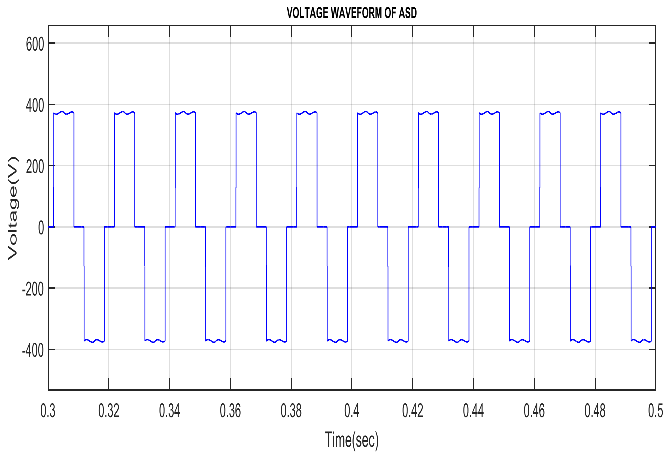

Fig. 12. (a) Supply voltage of ASD

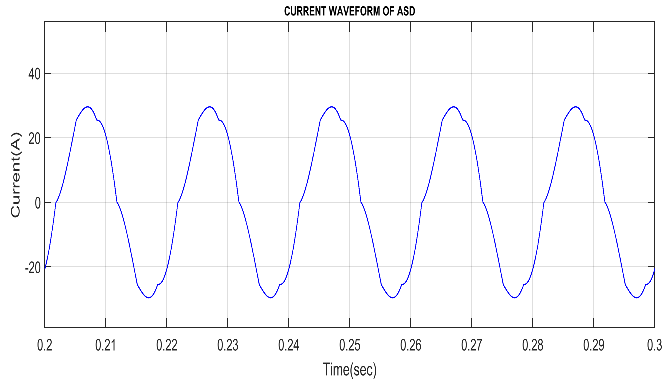

Fig. 12. (b) Supply current of ASD

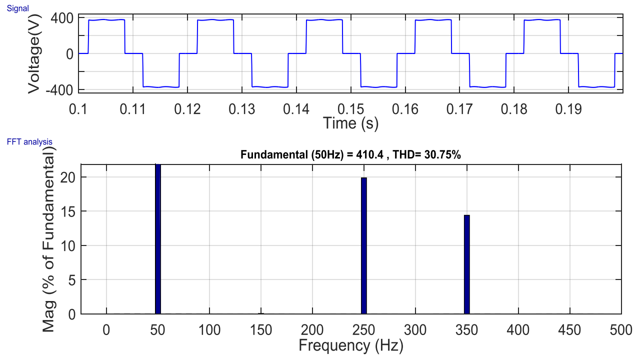

Fig. 12. (c) Voltage THD of ASD

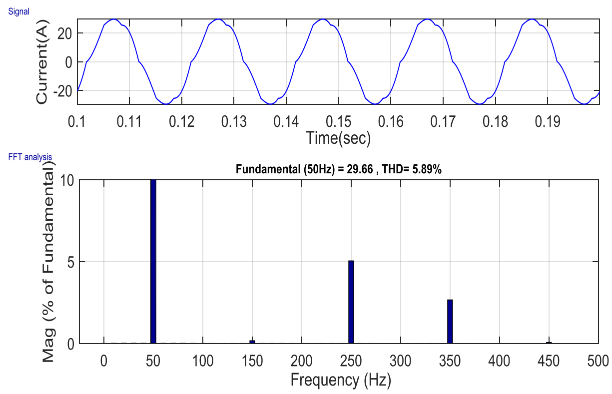

Fig. 12. (d) Current THD of ASD

Fig. 12(a) and 12(b) shows voltage and current distortions. From Fig. 12 (c) we can notice that ASD under simulation produces 30.75% of voltage THD with 3rd and 5th order as dominant harmonics with 20% and 15% of fundamental. From Fig. 12 (d) Current THD of 5.89% is observed with 5th and 7th order harmonics as dominant with 5% and 2.5% of fundamental.

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Case 6: Simulation is performed on distribution network model shown in Fig. 6 with six independent homes each with above mentioned loads for THD analysis and the results are mentioned in following figures.

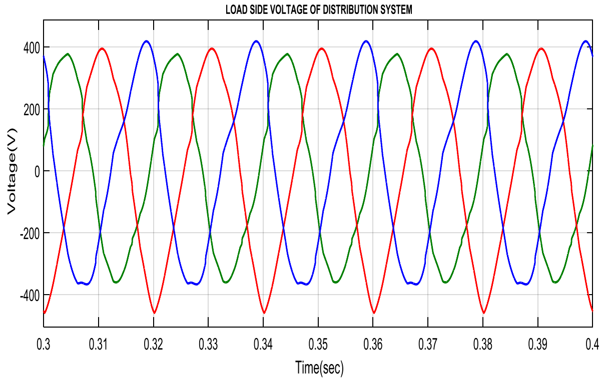


Fig. 13. (a) Voltage waveforms of 3 phase distribution network

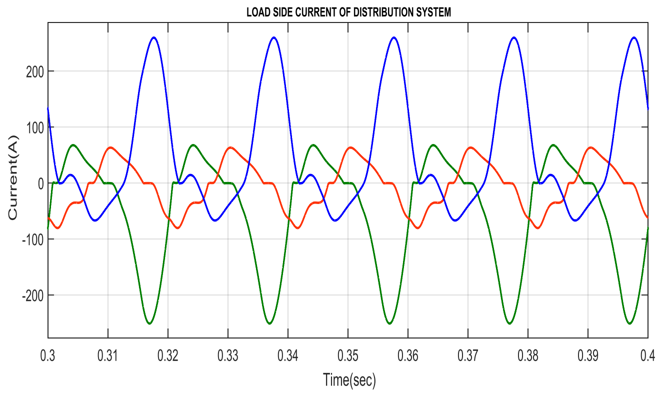


Fig. 13. (b) Current waveforms of 3 phase distribution network

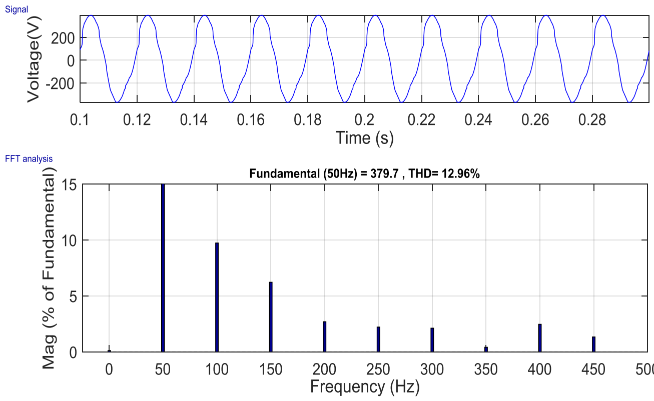


Fig. 13. (c) Voltage THD of distribution N/W

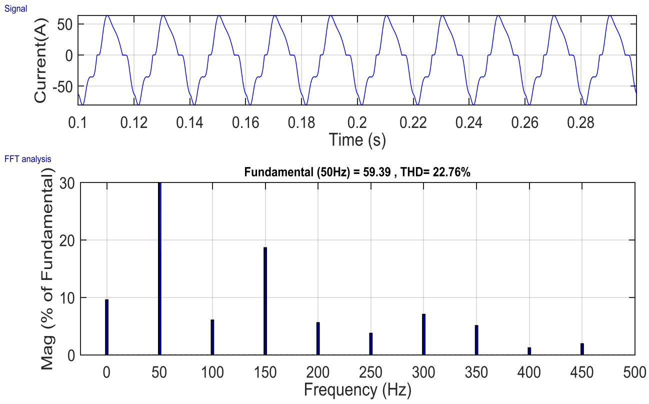


Fig. 13. (d) Current THD of distribution N/W

Fig. 13(a) and 13(b) shows voltage and current distortions. From Fig. 13 (c) we can see that the voltage THD is about 12.96% with 2nd and 3rd harmonics as dominant with 10% and 6% of fundamental. It is seen in Fig. 13 (d) that 22.76% current THD is recorded with 3rd order harmonics and 10% of DC offset. It is noted that recorded THD values are exceeding the IEEE recommendations [17]. It is suggested to take required action to limit the THD.

Case 7: Distribution model with Zigzag transformer shown in Fig. 7 is simulated for THD variation. The Zigzag transformer is connected in the distribution system and it is supplying two three phase loads. The simulation results obtained are shown in following figures.

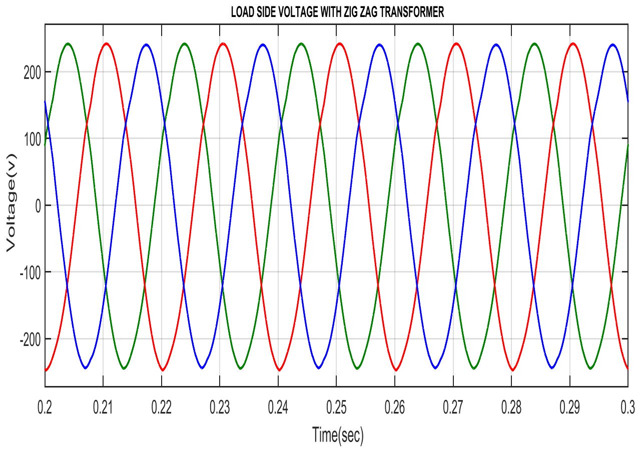
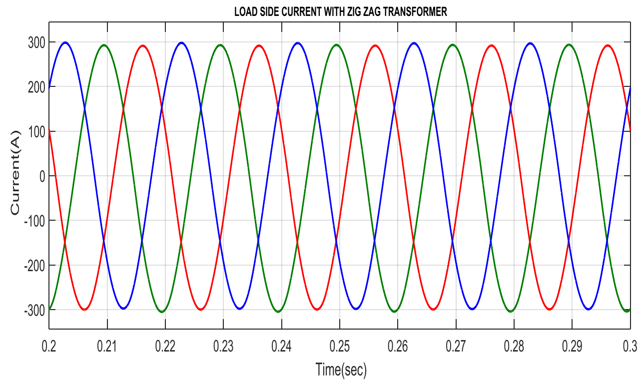


Fig. 14. (a) Voltage waveforms of distribution system with zigzag transformer



Ffig. 14. (b) Current waveforms of distribution system with zigzag transformer

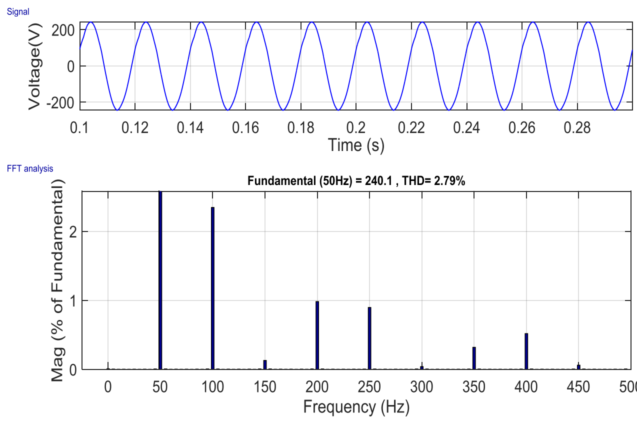


Fig. 14. (c) THD_v of distribution N/W with zigzag T/F

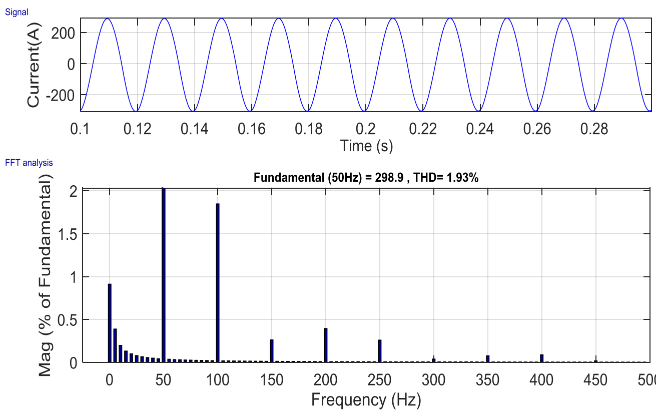


Fig. 14. (d) THD_i of distribution N/W with zigzag T/F

Fig. 14(a) and 14(b) shows voltage and current distortions. From Fig. 14 (c) voltage THD of 2.79% is observed with 5th and 7th order harmonics which are less than 1% of fundamental along with negligible even order harmonics. From Fig. 14 (d) we can notice that the current THD is about 1.93% with less than 1% of all other harmonics. It is observed that zigzag transformer has great influence on harmonic reduction.

IV.CONCLUSIONS

The THD of current waveform in case of PC is about 33%. The 3rd, 5th and 9th order harmonics are more dominant with 30%, 9% and 5% of fundamental. The THD of current waveform is around 26%. In CFL case we can notice that 3rd, 5th, 7th, and 9th order harmonics are dominant with 17%, 14%, 10% and 7% of fundamental. In case of fan with regulator we can observe that the current THD is about 32% with 3rd, 5th and 9th order harmonics as dominant harmonics with 27%, 14% and 5% of fundamental. We can observe that the UPS under consideration produced a current THD of 17.53% with 3rd, 5th and 7th order as dominant harmonics. It is observed that the current waveform contains small amount of DC offset and small amount of even order harmonics like 2nd and 4th. ASD under simulation produced 30.75% of voltage THD with 3rd and 5th order as dominant harmonics with 20% and 15% of fundamental. Current THD of 5.89% is observed with 5th and 7th order harmonics as dominant with 5% and 2.5% of fundamental.

In case of distribution system with six homes we can see that the voltage THD is about 12.96% with 2nd and 3rd harmonics as dominant with 10% and 6% of fundamental. It is seen in that 22.76% current THD is recorded with 3rd order harmonics and 10% of DC offset. It is noted that recorded THD values are exceeding the IEEE recommendations. It is suggested to take required action to limit the THD.

As harmonic mitigation strategy zigzag transformer is used, which has good influence on reducing harmonic content. Voltage THD of 2.79% is observed with 5th and 7th order harmonics which are less than 1% of fundamental along with negligible even order harmonics. We can notice that the current THD is about 1.93% with less than 1% of all other harmonics. It is observed that zigzag transformer has great influence on harmonic reduction. The results with zigzag transformer were proved to be satisfactory.

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