MODELING AND HARMONIC DISTORTION ANALYSIS IN INDUSTRIAL POWER DISTRIBUTION NETWORK IN MEKELLE CITY

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ABSTRACT:* POWER SYSTEM HARMONICS ARE MULTIPLES OF THE FUNDAMENTAL POWER SYSTEM FREQUENCY AND THESE HARMONIC FREQUENCIES CAN CREATE DISTORTED VOLTAGES AND CURRENTS. DISTORTION OF VOLTAGES AND CURRENTS CAN AFFECT THE POWER SYSTEM ADVERSELY CAUSING POWER QUALITY PROBLEMS. NON-LINEAR DEVICES SUCH AS POWER ELECTRONICS CONVERTERS CAN INJECT HARMONICS ALTERNATING CURRENTS (AC) IN THE ELECTRICAL POWER SYSTEM. TO MAINTAIN THE QUALITY LIMITS PROPOSED BY STANDARDS TO PROTECT THE NON-LINEAR LOADS, IT IS NECESSARY TO INCLUDE SOME FORM OF FILTERING DEVICE TO THE POWER SYSTEM. FILTERS HAVE BEEN DEVISED TO ACHIEVE AN OPTIMAL CONTROL STRATEGY FOR HARMONIC PROBLEMS. IN THIS PAPER, THE CASE STUDY IS CARRIED OUT AT MESIFIN INDUSTRIAL ENGINEERING DISTRIBUTION SYSTEM. THE MODELS ARE IMPLEMENTED FOR HARMONIC ANALYSIS OF TYPICAL INDUSTRIAL LOADS IN MESIFIN INDUSTRIAL ENGINEERING DISTRIBUTION NETWORK BY ETAP POWER STATION SOFTWARE BASED ON DISTORTION, THE FILTERS HAVE BEEN DESIGNED. PASSIVE FILTERS ARE INSTALLING AT POINT OF COMMON COUPLING (PCC) OF EACH BUS IN DISTRIBUTION TRANSFORMER TO REDUCE THE HARMONIC DISTORTION WITHIN IEEE 519-1992 STANDARDS.

KEYWORDS - ELECTRICAL DISTRIBUTION SYSTEM, NONLINEAR LOAD, TOTAL HARMONIC DISTORTION, HARMONIC FILTERS.

1. INTRODUCTION

ELECTRICAL DISTRIBUTION SYSTEMS ARE AN ESSENTIAL PART OF THE ELECTRICAL POWER SYSTEM. IN ORDER TO TRANSFER ELECTRICAL POWER FROM AN ALTERNATING CURRENT OR A DIRECT CURRENT SOURCE TO THE PLACES THOSE ARE INDUSTRIES, HOMES, AND COMMERCIAL BUILDINGS WHERE IT WILL BE USED. DISTRIBUTION SYSTEMS USUALLY EMPLOY SUCH EQUIPMENT AS TRANSFORMERS, CIRCUIT BREAKERS, AND PROTECTIVE DEVICES.

IN ETHIOPIA POWER QUALITY IS ONE OF THE BIG ISSUES TO BE CONSIDERED IN THE COUNTRY POWER SYSTEM TRANSMISSION AND DISTRIBUTION. ETHIOPIA IS CURRENTLY BUILDING NUMBER POWER STATIONS IN VARIOUS PARTS OF THE COUNTRY AND ALSO FACTORIES ARE INSTALLING LATEST TECHNOLOGICAL ELECTRONIC DEVICES FOR IMPROVING THEIR PRODUCTIVITY. MESIFIN INDUSTRIAL ENGINEERING IS A GOOD EXAMPLE IN THIS REGARD. IN EARLY TIMES, THERE HAD NOT BEEN THAT MUCH CONCERN FOR THE QUALITY OF POWER IN ETHIOPIA BECAUSE THE DEMAND AND GENERATION OF POWER IS LESS. THE DEMAND OF POWER IS FOR LIGHTING AND FOR SOME HOUSEHOLD APPLIANCES. THAT IS, THE LOAD IS LINEAR. HOWEVER, NOWADAYS THE CAPACITY OF POWER GENERATION IN THE COUNTRY IS GOING ON INCREASING AND THE DEMAND IS ALSO VERY HIGH AS A NUMBER OF INDUSTRIES AND BUILDINGS ARE UNDER CONSTRUCTION. THIS INDICATES THAT LOADS ARE CHANGING FROM BEING LINEAR TO NON-LINEAR. ADDITIONALLY, CUSTOMERS ARE EXPECTING QUALITY OF POWER SUPPLY FROM EEPCO. THESE ALREADY BUILT FACTORIES AND THOSE UNDER CONSTRUCTION ARE USING LATEST ELECTRONICS DEVICES LIKE PLCS, ASDS, PCS, HEATERS ETC TO BOOST THEIR PRODUCTION. AMONG THOSE, MESIFIN INDUSTRIAL ENGINEERING IS THE ONE TO BE MENTIONED. THESE DEVICES ARE VERY SENSITIVE TO POWER DISTURBANCES SO THAT NUMBER OF MACHINE PRODUCES HARMONICS DUE TO UNEVEN DISTRIBUTION OF FLUX IN AIR GAP OF ROTATING MACHINE THIS TENDS TO NO SINUSOIDAL VOLTAGE AND CURRENT GENERATION IN ROTATING MACHINE SUCH A SYNCHRONOUS MACHINE. POWER QUALITY PROBLEMS LIKE HARMONICS, VOLTAGE SAGS AND VOLTAGE TRANSIENTS COULD BE COMMON IN THE COUNTRIES POWER SYSTEM IN GENERAL AND FACTORIES IN PARTICULAR. THEREFORE, THE STUDY OF INVESTIGATING POWER QUALITY PROBLEMS IN CONNECTION WITH THE WAY OF MITIGATING THEM IS VERY VITAL TO THE COUNTRY AND FACTORIES, TO MINIMIZE HARMONIC DISTORTIONS, TO SATISFY CUSTOMERS DEMAND, TO MAXIMIZE PRODUCTION AND TO DECREASE THE COST INCURRED.

2. HARMONICS SOURCE AND ITS EFFECTS ON POWER SYSTEM

HARMONICS ARE SINUSOIDAL VOLTAGES OR CURRENTS WITH FREQUENCIES THAT ARE INTEGER MULTIPLES OF THE FUNDAMENTAL POWER FREQUENCY, WHICH MIGHT BE 50 OR 60HZ. THESE WAVES RESULT WHEN THE CURRENT WAVEFORM CHANGES SLIGHTLY DUE TO NONLINEARITY OF THE LOAD [13].

F_H= (H) X (FUNDAMENTAL FREQUENCY) **(EQ2.1)**

WHERE H IS HARMONIC ORDER. IN THE POWER SYSTEM, THESE HARMONICS INTERACT WITH FUNDAMENTAL FREQUENCY WAVE AND EACH OTHER TO PRODUCE A DISTORTED WAVEFORM. HARMONICS DISTORTION IS THE CHANGE IN SUPPLY WAVEFORMS FROM THE IDEAL SINUSOIDAL WAVEFORM. BECAUSE OF THE PERIODICITY,

$$\mathbf{H_n = \frac{1}{T}\int_0^T \{F(t)\} * \cos(n * w_o * t + \emptyset_n)\}dt} \qquad (\mathbf{eq2.2})$$

WHERE, HN IS THE NTH HARMONIC, T IS PERIOD OF THE VOLTAGE/CURRENT WAVEFORM, F (T) IS VOLTAGE/CURRENT WAVEFORM AS A FUNCTION OF TIME T, N IS THE HARMONIC NUMBER, ΩO IS THE FUNDAMENTAL ANGULAR FREQUENCY AND N IS THE PHASE ANGLE OF THE NTH HARMONIC.

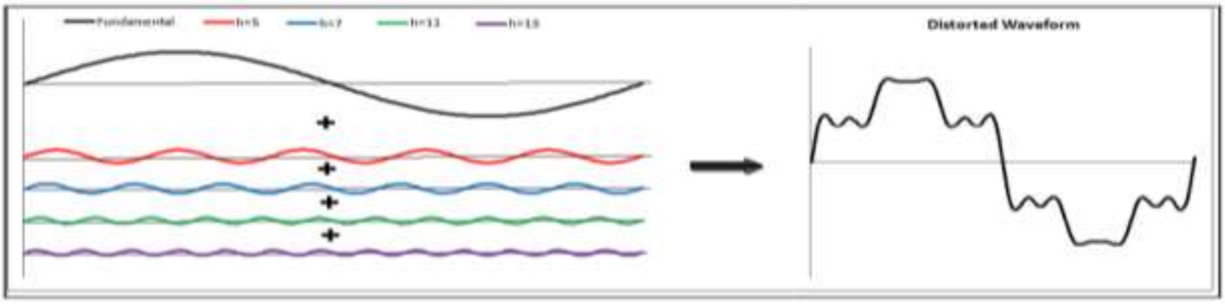

Figure1. Fourier series representation of a distorted wave form.

The Fourier series is also used to deconstruct a waveform into the fundamental and harmonic components. This is the principle behind performing a harmonic analysis on a power system.

Some of the more common power electronic loads include

- Switch mode power supplies - present in computers, televisions, microprocessors,
- Rectifiers – present in DC motor drives, regulated power supplies, battery chargers,
- Inverters – present in variable speed AC drives,
- Static VAr compensators,
- Cyclo-converters, and
- High voltage DC transmission converters.

Harmonics lists the following areas of harmonic effects are

- Failure of capacitor banks due to dielectric breakdown or reactive power overload;
- Interference with ripple control and power line carrier systems, causing mis operation of systems
- Excessive losses resulting in heating of induction and synchronous machines;
- Over voltages and excessive currents on the system
- Dielectric breakdown of insulated cables resulting from harmonic over voltages in the system;
- Inductive interface with telecommunication systems; Errors in meter readings;
- Signal interference and relay malfunction, particularly in solid state and microprocessorcontrol1ed systems;
- Interference with large motor controllers and power plant excitation systems;

3. SIMULATION AND MODELING OF HARMONIC DISTORTION

Equipments Utilized for simulation of harmonic is **ETAP (E**lectromagnetic **T**ransient **A** analysis **P**rogram) power station software. The software is designed for modeling and analyzing power systems, so that models of power system parameters are available in its library. And also for the non-linear loads ETAP has specific library with alternatives current source and voltage sources.

In order to achieve the objectives, the following method had been set:

Gathering of the system information on transformers, loads ratings, types and quantities, cable size, distance and rating for calculation and simulation.

Decide method of calculation, simulation and method of equipment modelling for harmonic analysis.

Model the selected facility distribution network for simulation.

Construct the model by different methods of calculations for each component.

Simulate the network for different **cases** and analyze data obtained from simulation, and compare with standards.

Propose Solution for distortion levels exceeding limits from both calculation and simulation.

4. HARMONIC MITIGATING TECHNIQUES APPLIED TO DISTRIBUTION NETWORK

Non-linear loads can inject the harmonic current into the supply system, depending on their loads. The substation and utility supply companies must ensure a certain voltage quality at the PCC (point of common coupling) in the distribution system that recommends the IEEE standard 519- 1992. There are several basic methods for reducing harmonic voltage and current distortion from nonlinear distribution loads such as adjustable frequency drives (AFDs).

- Line reactors
- Isolation transformers
- 12 and 18 pulse rectifiers
- Harmonic filters
- Larger transformer (derated
- K-rated transformer

Among these methods, passive type filters are applied to Mesifin Industrial Engineering in this paper.

PASSIVE FILTER

Passive elements like resistance, inductance and capacitance are used by the passive filters to control the harmonics. They are the most commonly used filters in industry. Three-phase harmonic filters are shunt elements that are used in power systems for decreasing voltage distortion and for power factor correction. Nonlinear elements such as power electronic converters generate harmonic currents or harmonic voltages, which are injected into power system. The resulting distorted currents flowing through system impedance produce harmonic voltage distortion. Harmonic filters reduce distortion by diverting harmonic currents in low impedance paths.

Figure below shows simple example of an industrial power distribution system.

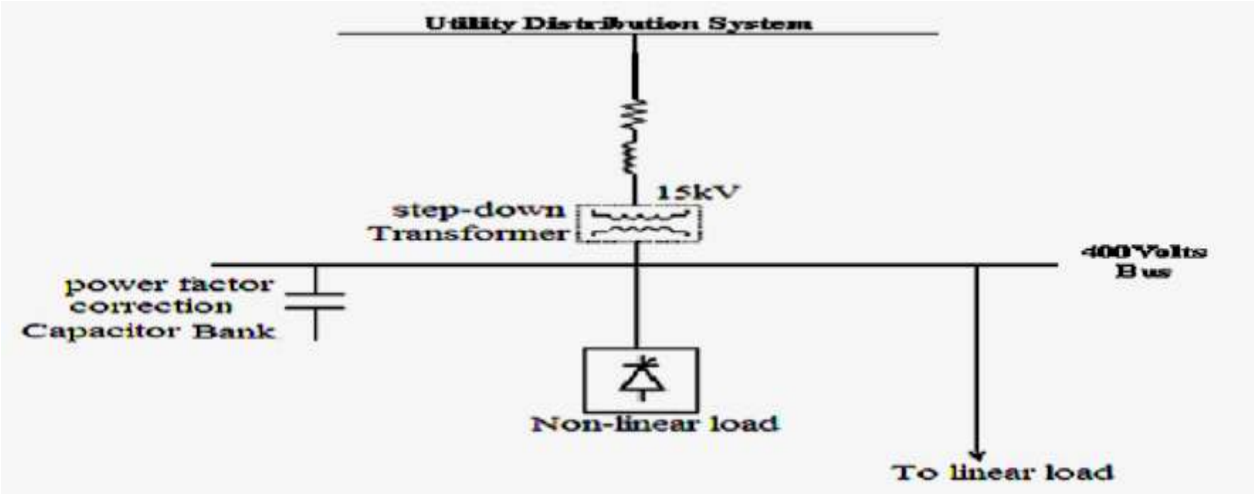

FIGURE2. SIMPLE EXAMPLE OF AN INDUSTRIAL POWER DISTRIBUTION SYSTEM [5]

AS IT CAN BE SEEN FROM THE POWER DISTRIBUTION SYSTEM ABOVE THE POWER-FACTOR-CORRECTION CAPACITOR BANK, WHICH IS CONNECTED ON THE 400 VOLTS BUS, CAN CREATE A PARALLEL RESONANCE BETWEEN THE CAPACITORS AND THE SYSTEM SOURCE INDUCTANCE. THE SINGLE PHASE EQUIVALENT CIRCUIT OF THE DISTRIBUTION SYSTEM IS SHOWN BELOW.

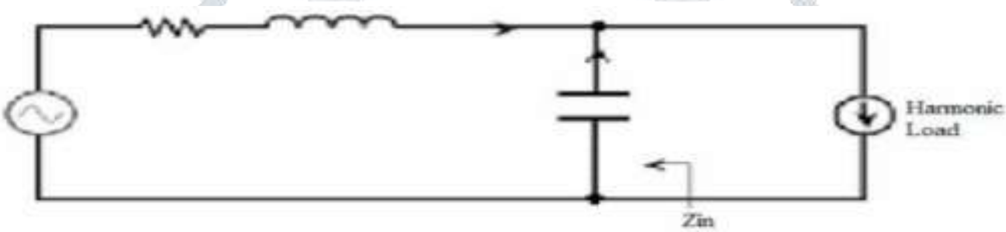

FIGURE3.THE SINGLE-PHASE EQUIVALENT CIRCUIT OF THE DISTRIBUTION SYSTEM

USING THE ABOVE CIRCUIT THE FOLLOWING EQUATIONS HOLD.[5]

$$R_{SYS} = \frac{KV_{L-L}^{\ 2}}{MVA_{SC}}.\cos\left[\tan^{-1}\left(\frac{X}{R}\right)\right],\quad R'_{SYS} = \frac{R_{SYS}}{A^2} \qquad (4.1.$$

$$X_{SYS} = \frac{KV_{L-L}^{\ 2}}{MVA_{SC}}.\sin\left[\tan^{-1}\left(\frac{X}{R}\right)\right],\ X'_{SYS} = \frac{X_{SYS}}{A^2} \qquad (4.2).$$

A=THE TURNS RATIO OF THE TRANSFORMER AT PCC.

$$R_{TR} = R_{PU}\frac{1000 \times KV^2{}_{LL}}{KVA_{TR}} \qquad (4.3.).$$

$$X_{TR} = X_{PU}.\frac{1000 \times KV^2{}_{LL}}{KVA_{TR}} \qquad (4.4)$$

$$R_{TOT} = R'_{SYS} + R_{TR} \qquad (4.5).$$

$$X_{TOT} = X'_{SYS} + X_{TR} \qquad (4.6).$$

$$L_{TOT} = \frac{X_{TOT}}{\Omega} = \frac{X_{TOT}}{2\Pi F} \qquad (4.7).$$

$$X_C = \frac{1000 \times KV_{CAP}^{\ 2}}{KVAR_{CAP}} \qquad (4.8).$$

$$C = \frac{1}{\Omega X_C} \qquad (4.9).$$

$$F_O = \frac{1}{2\Pi\sqrt{L_{TOT} \times C}} \qquad (4.10).$$

$$H = \frac{F_O}{F} \qquad (4.11).$$

THE IMPEDANCE Z_{in} LOOKING INTO THE SYSTEM FROM THE LOAD CONSISTS OF THE PARALLEL COMBINATION OF SOURCE IMPEDANCE $R_{tot} + jX_{tot}$ AND THE CAPACITOR IMPEDANCE.

$$Z_{in} = \frac{(R_{tot} + j\omega L_{tot})\cdot(-j/\omega C)}{R_{tot} + j\omega L_{tot} - j\frac{1}{\omega C}} \qquad (4.12)$$

$$\omega_o L_{tot} = \frac{1}{\omega_o C}, \quad f_o = \frac{1}{2\pi\omega_o} \qquad (4.13)$$

THE EQUATION FOR Z_{in} CAN BE USED TO DETERMINE THE EQUIVALENT SYSTEM IMPEDANCE FOR DIFFERENT FREQUENCIES. THE HARMONIC PRODUCING LOADS CAN RESONATE (PARALLEL RESONANCE), THE ABOVE EQUIVALENT CIRCUIT. DESIGNATING THE PARALLEL RESONANT frequency by w_O (rad/sec) or F_O (Hz) and equating the inductive and capacitive reactance. Harmonic current components that are close to the parallel resonant frequency are amplified and also Higher order harmonic currents at the PCC are reduced because the capacitors are low impedance at these frequencies.

5. Case Study

The detailed study is carried out at Mesfin Industrial Engineering power distribution network. The industry is located at Tigray region Mekelle city.

Circuit Model for Simulation on ETAP Software

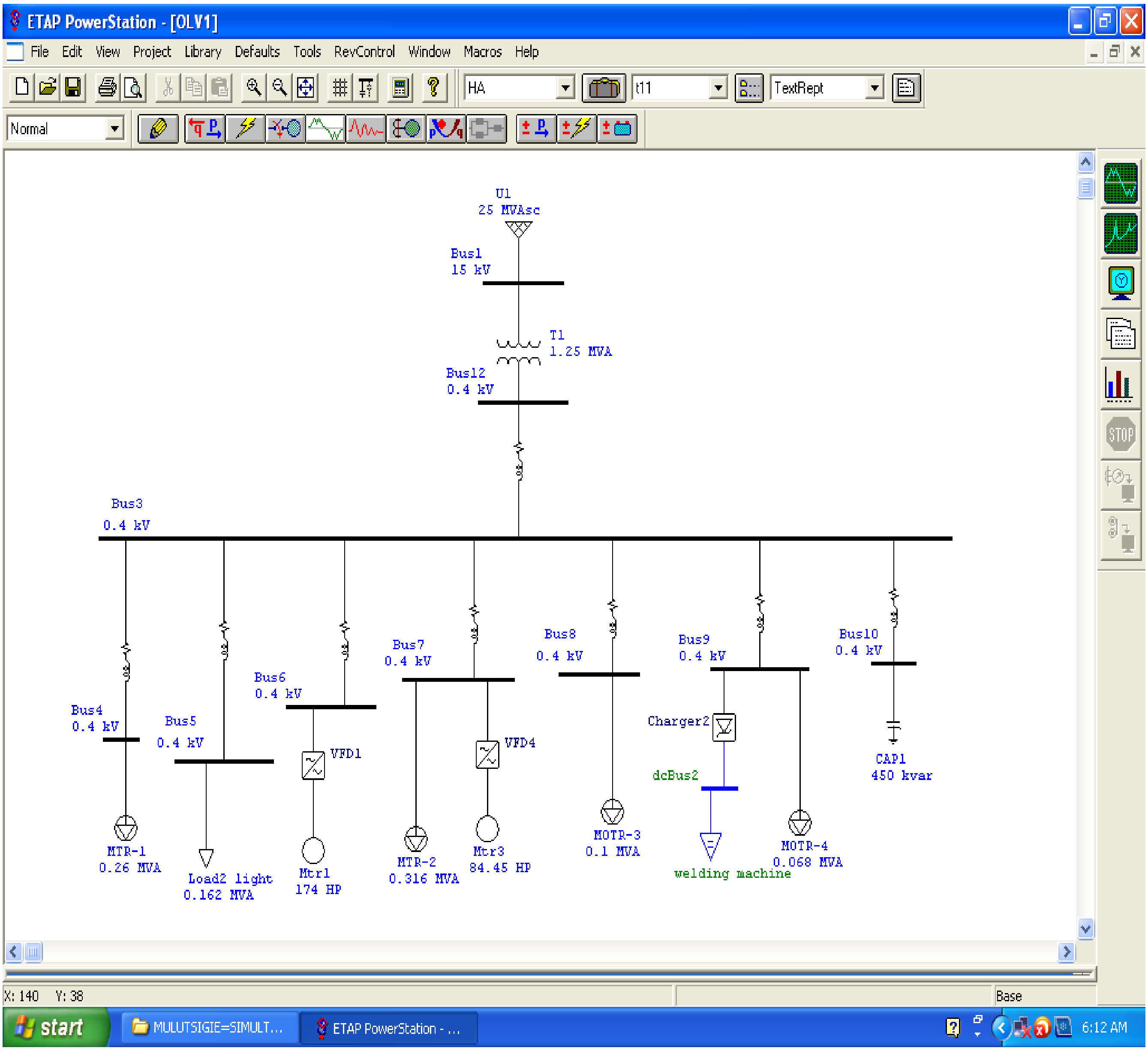

Figure4. Model of Transformer prepared by ETAP5.0 for simulation.

This transformer is constructed for supplying the electric power to Mesfin Industrial Engineering. Mesfin Industrial Engineering is the largest one in Tigray region. Since the dominant load of this transformer is industrial load. The incoming line of substation is taken from 15 kV bus of Mekelle Primary substation which is located at East of Mekelle city. Transformer No (1) comprise 1250 MVA, 15kV/ 11 kV. There are seven number of 0.4 kV main distribution feeder which are connected to 7 separate loads as shown in Figure. 4.

6. Cases Considered for Simulation

In the Simulation process to see the variation of loads in one day we consider 4 loading conditions for the transformer.

Case-1: This case represents the worst case in terms of loading. It assumes that all loads are working.

Case -2: Assumes most harmonic producing loads such as AC drives/ inverters machines ,welding machine in workshop, DC drives and some lightning are not working. But it assumes other such as, capacitor banks direct on line motors are working. This may represent 24:00 hours full day during Sunday.

Case -3: This case study repeats case 1 and it assumes there is no capacitor bank other loads are working. This condition approximately represents the duration of supply voltage increases (6:00 to 8:00 and 3:00 to 6:00 at day and night time.) and also during Sunday means load decreases.

Case -4: Reverse of case study 2

7. RESULTS AND DISCUSSION

THIS SUBTOPIC DISCUSSES AND ANALYSES THE SIMULATION RESULTS OBTAINED FROM THE DISTRIBUTION TRANSFORMERS IN THE FACTORY WITH AND WITHOUT FILTER. FOR THE ANALYSIS OF HARMONIC DISTORTION OF THE FACTORY POWER NETWORK SIMULATION WAS CARRIED OUT BY USING **ETAP SOFTWARE** ON THE TRANSFORMER

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TABLE1. RESULT OF HARMONIC CURRENTS AT EACH HARMONIC ORDER FOR ALL CASES OF THE TRANSFORMER.

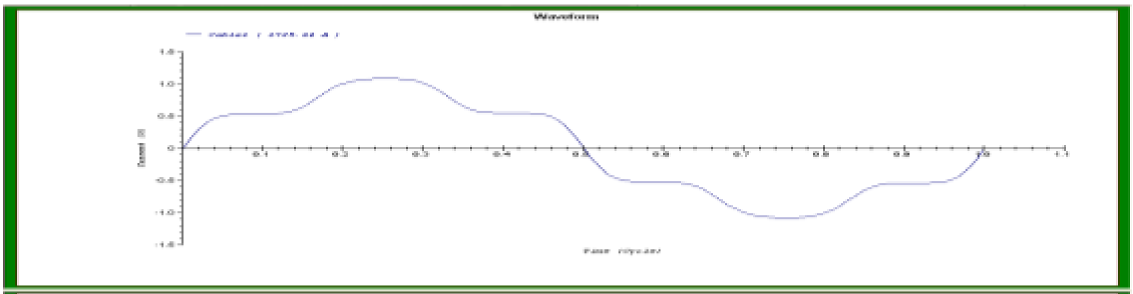
HARMONIC ORDER(H)	HARMONIC CURRENT AS % OF FUNDAMENTAL IN, A			
	CASE-1	**CASE-2**	**CASE-3**	**CASE-4**
5	17.54	2.76	61.63	22.84
7	7.59	0.43	19.03	10.10
9	-	-	-	-
11	1.34	0.05	3.14	1.6
13	0.67	0.02	1.55	0.85
15	0	-	-	-
17	0.07	-	0.17	0.11
19	-	-	0.09	0.04
21	-	-	-	-
23	-	-	0.01	0.04
25	-	-	0.01	0.04
THDI (%)	**12.17**	**2.8**	**20.21**	**19.1**

TABLE2. RESULT OF HARMONIC VOLTAGE AT EACH HARMONIC ORDER FOR ALL CASES OF THE TRANSFORMER.

HARMONIC ORDER(H)	HARMONIC VOLTAGE AS % OF FUNDAMENTAL			
	CASE-1	**CASE-2**	**CASE-3**	**CASE-4**
5	10.38	1.06	14.12	10.31
7	6.17	0.23	6	6.27
9	-	-	-	-
11	1.71	0.04	1.55	1.55
13	1.01	-	0.91	0.98
15	-	--	-	-
17	0.15	-	0.13	0.17
19	-	-	0.07	0.07
21	--	-	-	-
23	-	-	0.01	0.01
25	-	-	0.01	0.01
THDV (%)	**10.14**	**1.02**	**13.14**	**11.25**

ACCORDING TO THE RESULTS, THE THD% OF VOLTAGE AND CURRENT EXCEEDS THE ACCEPTABLE LIMITS WITHIN IEEE 519-1992 STANDARDS FOR VOLTAGE AND CURRENT IN MESFIN INDUSTRIAL ENGINEERING POWER DISTRIBUTION NETWORK. THE DOMINANT ORDERS ARE THE 5TH, 7TH, 11TH AND 13TH HARMONIC ORDERS. THEREFORE, IT IS NEED TO REDUCE THESE ORDERS THAT THE 5^{TH}, 7^{TH}, 11^{TH} AND 13^{TH} ORDERS HAVE TO BE MITIGATED. PASSIVE FILTERS ARE INSTALLING FOR MITIGATING THE HARMONIC DISTORTION.

THE SIMULATION WAVEFORM WITHOUT FILTER IS SHOWN IN FIGURES.



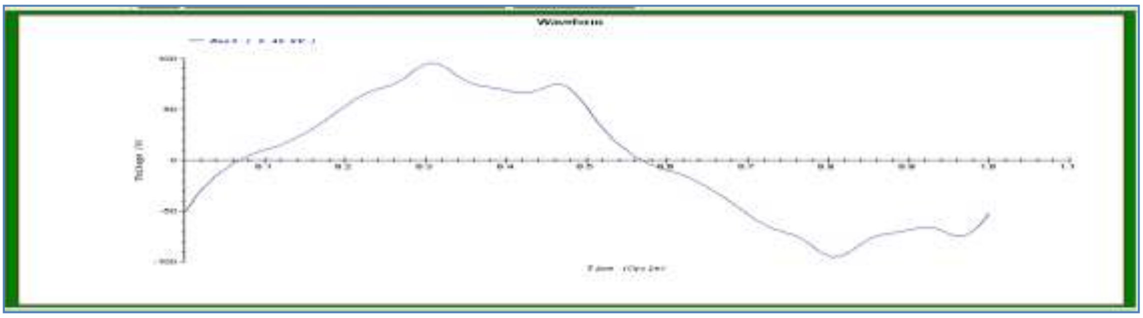


FIGURE5. WAVE FORM OF CURRENT AND VOLTAGE FOR CASE-1 RESPECTIVELY IN THE TRANSFORMER.

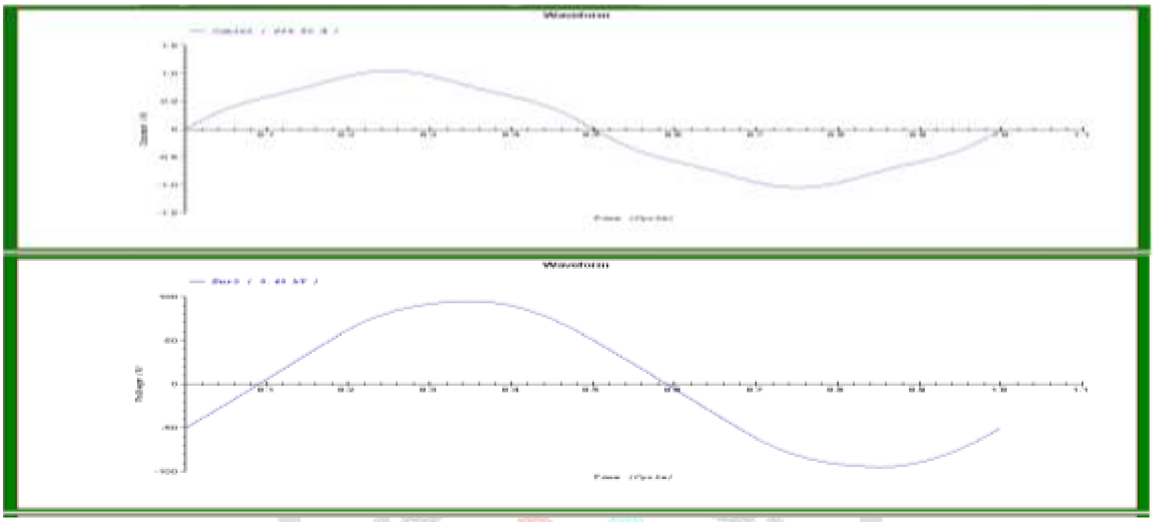


FIGURE6. WAVE FORM OF CURRENT AND VOLTAGE FOR CASE-2 RESPECTIVELY IN THE TRANSFORMER.

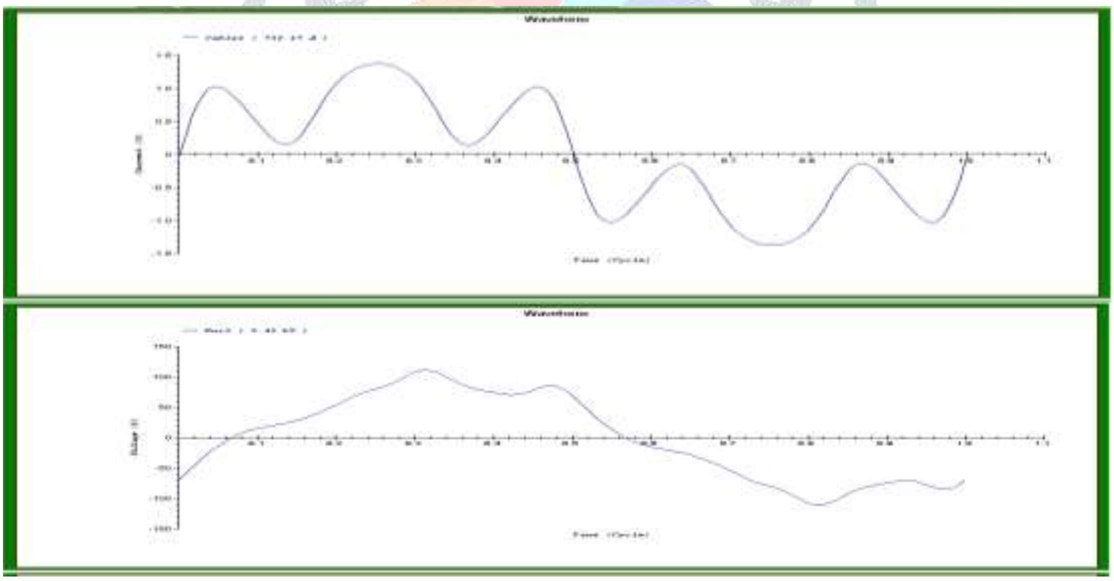
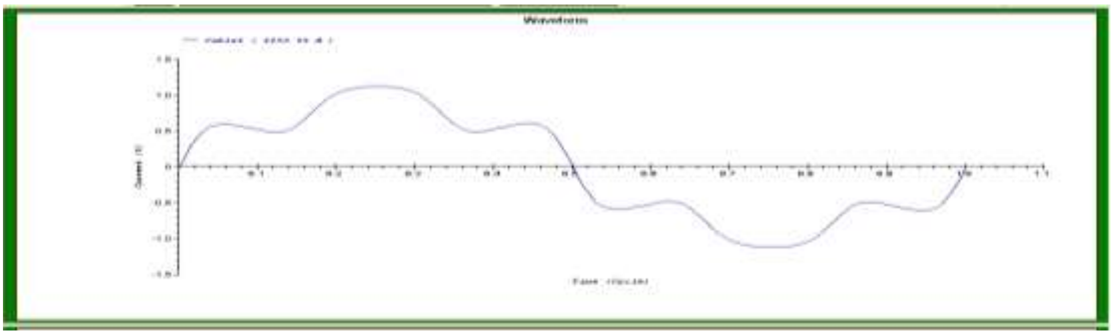


FIGURE7. WAVE FORM OF CURRENT AND VOLTAGE FOR CASE-3 RESPECTIVELY IN THE TRANSFORMER.



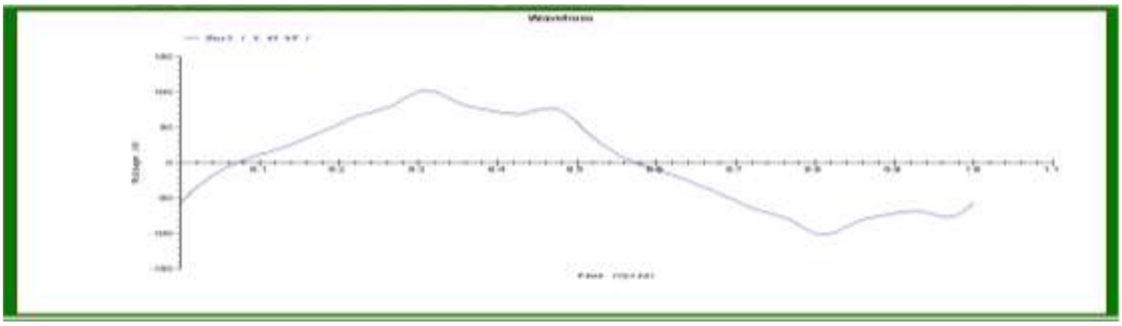


FIGURE8. WAVE FORM OF CURRENT AND VOLTAGE FOR CASE-4 RESPECTIVELY THE TRANSFORMER.

WITHOUT FILTERS, THE TOTAL HARMONIC DISTORTION OF THE VOLTAGE AND CURRENT IS ABOVE THE RANGE SPECIFIED BY THE POWER QUALITY STANDARDS. THE THD VALUE OF MESFIN INDUSTRIAL ENGINEERING POWER DISTRIBUTION NETWORK ARE SHOWN THAT THEY ARE EXCEED THE IEEE 519-1992 STANDARD. TO FOLLOW THE RECOMMENDED IEEE 519 POWER HARMONIC STANDARDS THE TOTAL HARMONIC DISTORTION MUST BE LESS THAN 5%.THIS CAN BE OBTAINED BY CONNECTING THE FILTERS TO THE SYSTEM. FOR REDUCING THE THD OF VOLTAGE AND CURRENT BELOW 5%, THE FILTERS HAVE BEEN DESIGNED.

8. THE DISTRIBUTION SYSTEM WITH PASSIVE FILTER

THE FOUR SINGLE TUNED PASSIVE FILTERS ARE DESIGNED TO CANCEL THE 5TH, 7TH, 11TH AND 13TH HARMONIC ORDERS. AS THE PASSIVE FILTER CAN BE CANCEL THE DESIRED ORDER AND CANNOT CONTROL OTHER THE HARMONIC ORDERS IN POWER SECTIONS. THE PASSIVE FILTERS ARE INSTALLING AT EACH FEEDERS IN MESFIN INDUSTRIAL ENGINEERING POWER DISTRIBUTION NETWORK**.** CALCULATION RESULTS OF THE PARAMETER OF FILTER DESIGN THE FOUR SINGLE TUNED PASSIVE FILTERS ARE DESIGNED TO CANCEL THE 5TH, 7TH, 11TH AND 13TH HARMONIC ORDERS. FILTER PARAMETERS ARE SHOWN THE FOLLOWING TABLES.

PARAMETERS WITH FILTER

TABLE.3 RESULTS OF THE TRANSFORMER AFTER FILTERING.

INDIVIDUAL HARMONIC CURRENT OF CASE-1 FOR THE TRANSFORMER.						
AFTER FILTERING	2.27	2.56	0.98	0.25	0	0
HARMONIC ORDER, H	5	7	11	13	17	19
THD% FOR CASE1-4 OF THE TRANSFORMER.						
AFTER FILTERING	**2.17**	**0.97**		**2.75**	**2.78**	

INDIVIDUAL HARMONIC VOLTAGE OF CASE-1 FOR THE TRANSFORMER.						
AFTER FILTERING	**3.53**	**2.05**	**1.32**	**0.58**	**0.14**	**0.0**
HARMONIC ORDER, H	**5**	**7**	**11**	**13**	**17**	**19**
THD% FOR CASE1-4 OF THE TRANSFORMER.						
AFTER FILTERING	**2.69**	**0.47**		**2.71**	**1.66**	

THE SIMULATION WAVEFORM WITH FILTER FOR CASE-1 IS SHOWN IN FIGURES.

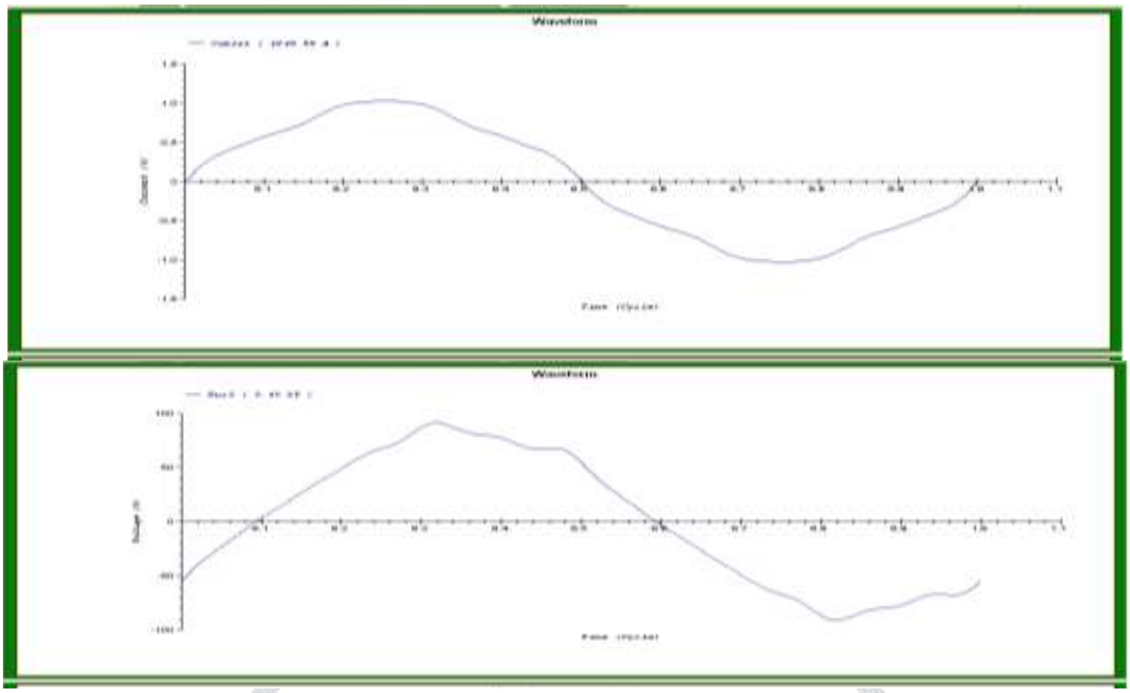


Figure9. Wave form of current and voltage for case-1 of the transformer after filtering respectively.

After installing the passive filters, the voltage and current of THD are significantly decline and waveforms are becoming sinusoidal in the power distribution network. All of the results of THD% are acceptable limit of IEEE 519-1992 standards.

9. CONCLUSIONS

In this paper, harmonics mitigation technique that is passive filter applied to Mesfin industrial engineering distribution network are analyzed. The models are implemented for harmonic analysis of typical industrial loads in Mesfin industrial engineering distribution network. In Mesfin industrial engineering Substation has the voltage and current distortion levels are over the acceptable limit under IEEE 519-1992 standards according to measure without filters. After installing passive filters, the voltage distortion and current distortion is under 3 %. The results of THD are significantly decline in Mesfin industrial engineering power network. Therefore, Passive filters can mitigate harmonic distortion.

10. RECOMMENDATION

The research results in this paper points to several issues where future research and the factory as a whole can be done; some of these issues are:

Since the factory is on the way of increasing the application of electronic loads, such as PLCs, three phase inverters, welding machines AC and DC VFD, So future work must incorporate a complete power quality study with the aid of Power quality analyzer (PQA), which is very important device nowadays for engineers in monitoring power quality problems. This device has the capability of measuring and displaying the wave shapes of the current, voltage, power, power factor, THDv and THDi. Due to lack of it in the factory, ETAP power station software and hand calculations were used in this thesis. But for future, since Real measurements are always preferred try to reflect accurately the true characteristics of the system we recommend the simulation results to be verified by measurement in the future.

The designed filters and the recommended solutions for the existing harmonic problems in the factory should be implemented.

Since Filters effectiveness will change when loads changes. Other options like active filters, phase-shifting transformers and series reactors must be considered in future research.

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