PENALTY CALCULATION OF NONLINEAR LOADS IN ELECTRIC POWER DISTRIBUTION NETWORK

Mahnaz YOUHANNAEI
GEPDC* – Iran
myouhannayee@gilanpdc.ir

Hossein MOKHTARI
Sharif univercity of technology – IRAN
mokhtari@sharif.edu

M.E. HONARMAND
GEPDC* – Iran
honarmand@gilanpdc.ir

Adham SHARIFI
GEPDC* – Iran
power72sharif@yahoo.com

Jamshid TALEBI
GEPDC* – Iran
talebi@gilanpdc.ir

*Gilan Electric Power Distribution Co.

ABSTRACT

Considering increasing nonlinear loads in distribution grid, power quality has been affected by customer's equipment. These loads not only cause disturbance in power quality and customers satisfactory but also damage grid equipment. Therefore it is necessary to control the customers and applying the mechanisms of reward and punishment. One of these ways is to define harmonic penalty for the customers who inject harmonics. Considering different of customers and grids, specifying unique formula is too difficult. This paper studied the effect of harmonics on load loss and lifetime of seven medium voltage transformers and five feeder of first transformer at Gilan distribution company, Iran. Then according to economics rules, Damages are calculated and harmonic penalty formula has been expressed.

Index terms: Medium voltage transformer, cables and wires, harmonic penalty.

INTRODUCTION

Harmonics is caused due to the nonlinear characteristics of loads and network equipment. The harmonics increase losses in various sectors of power system including generation, transmission and distribution and even the consumer. On the other hand, the increase in temperature of the equipment cause depreciation and damage and reduces the lifetime of them. Malfunctioning of equipment, especially protective equipment is another effect of harmonics on the network. so it is necessary to control the customers and applying the mechanisms of reward and punishment.[1] propose harmonic pricing model based on the harmonic costs and the effects of excessive harmonic current. [2] proposes a marginal price model of harmonic injection based on the harm of harmonics and discusses the program how to apportion resources to reach optimal mechanism.

This paper present a method to calculate the harmonic penalty. First the effect of harmonic over grid equipments have been studied theoretically such as cables and wires, transformers, protective relays, Inductors and capacitors, fuses, CT, PT and lightening arrester. The results have shown that the most damages appear due to harmonics over cables, wires and transformers. The harmonics have effect on temperature, life and transformers loss [2-5]. About 50 percent of reduced life is due to thermal stress which has been produced by nonlinear loads [3-4]. Harmonics mostly effect on life time, loss and capacity of wires and cables [6].

This paper is organized as follows: seven medium-voltage transformers which feed official, residential and business customers have chosen at Gilan distribution company, Iran. Then power quality items have been measured by HIOKI9624 and analyzed. The substation with the most quantity of pollution has been selected to measure the harmonics of feeders. Then the power qualities of five feeders have been measured and analyzed over above factors. The main factors to determine the customer's penalty are power losses in cables, wires, transformers and reducing their life. Finally a formula expresses to calculate harmonic penalty according to all above fact.

This formula has calculated harmonic penalty for the customers of sample substation and feeders.

HARMONIC EFFECTS ON TRANSFORMER

Power distribution transformers are affected by harmonics in two respects: losses and lifetime. Transformers loss increases in presence harmonic currents, followed by the increased temperature of the transformer, resulting in a significantly reduction in their lifetime.

The transformer loss calculation at harmonic condition

Transformer losses are divided into two categories: copper losses and magnetic losses. Some factors such as resistance of coil, Eddy currents, hysteresis losses, deformation due to the magnetic flux, stray losses, and cooling system affect the loss level. Much of load losses are due to the resistance of the coil. While Eddy current and hysteresis losses account for 90% no-load losses.

The transformer loss calculations incorporating the voltage harmonic

The effects of voltage harmonics on transformer losses are mostly caused by the core (hysteresis and eddy current losses). It should be noted that the voltage harmonics can cause current harmonics, which in turn affect losses.

Hysteresis losses in the transformer core sheets depend on level and waveform of magnetic flux density. If the hysteresis losses of a transformer which is fed by a sinusoidal voltage wave as P_R , then the ratio of harmonic losses (P) to rated conditon losses will be given by

$$\frac{P}{P_R}=\left[\frac{V_1}{V_R}\sum_{1}^{n}\frac{1}{n}\frac{V_n}{V_1}\mathrm{Cos}\ \theta_n\right]^S \qquad (1)$$

Where θ_n denotes harmonic phase angle of nth order, and S denotes steinmetz coefficient that ranges from 1.6 to 1.8. If the transformer operates within the linear region of its curve hysteresis, Eddy core losses can be estimated using the simplified equation (2).

$$\frac{P}{P_R}=\left[\frac{V_1}{V_R}\right]^2\sum_{1}^{n}n^2\left[\frac{V_n}{V_1}\right]^2 k_n \qquad (2)$$

Where factor K_n is a number larger than 1, and is a function of penetration depth of electromagnetic fields and frequency into the core [3]. Hystersis losses has little dependence on temperature, decrease slightly at temperatures above 100 ° C, but Eddy losses reduce with increasing temperature [3].

The transformer loss calculations incorporating the current harmonic

Harmonic current mostly affect load losses. It mention on IEEE std C57.110-1998. The per unit current incorporating the harmonics is presented in (3) [5].

$$I^2(pu)=\sum_{h=1}^{h=h_{max}}\left(\frac{I_h}{I_1}\right)^2 h^2 \qquad (3)$$

The per unit copper loss, eddy current loss, and other stray losses of transformer incorporating the current harmonics are expressed in (4)-(6) [5-6].

$$P_{I^2R(pu)}=1\times I^2(pu) \qquad (4)$$

$$P_{EC(pu)}=I^2(pu)\times F_{HL}\times\ P_{EC-R(pu)} \qquad (5)$$

$$P_{OSL(pu)}=I^2(pu)\times F_{HL-STR}\ \times\ P_{OSL-R(pu)} \qquad (6)$$

Where F_{HL} is the harmonic loss factor for winding eddy currents. It represents the increase in eddy current loss caused by the current harmonics. F_{HL-STR} is the harmonic loss factor for other stray losses. They are defined in [6]. Transformer's no-load losses are not significant at non-sinusoidal conditions and can be neglected. The load loss of the transformer at harmonic condition is presented in(7)) [5-6].

$$P_{LL}(pu)=I(pu)^2(1+F_{HL}P_{EC-R}(pu)+F_{HL-STR}P_{OSL-R}(pu))(7)$$

Impact of harmonic on the transformer temperature and lifetime

The temperature rise of top-oil over ambient temperature can be examined using equation (8).

$$\theta_{TO}=\ \theta_{TO-R}\times(\frac{P_{LL}+P_{NL}}{P_{LL-R}+P_{NL}})^{0.8} \qquad (8)$$

Obviously, in dry transformer, θ_{TO} is not defined, and therefore, there would not be such temperature rise. The hot spot temperature rises of dry and oil transformers are proportional to P_{LL} and are as follows.

$$\theta_{TO}=(\theta_W-\theta_{TO-R})\times(\frac{P_{LL}(pu)}{P_{LL-R}(pu)})^{0.8} \qquad (9)$$

Transformers hot spot temperature is calculated using the equation, θ_A is the ambient temperature.

$$\theta_H=\theta_{TO}+\theta_g+\theta_A \qquad (10)$$

Finally, the impact of temperature rise on transformer lifetime is expressed in(11) and (12)[6-7].

$$F_{AA}=\exp\left[\frac{15000}{383}-\frac{15000}{\theta_H+273}\right] \qquad (11)$$

$$\text{Real Life}=\frac{\text{Normal Insulating Life}}{F_{AA}} \qquad (12)$$

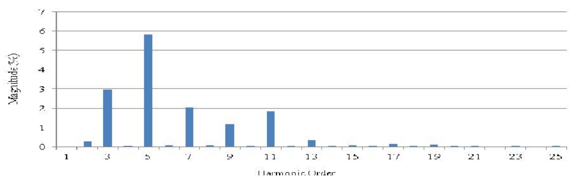
Aging acceleration factor is a coefficient which represents the effect of hottest-spot temperature on the transformer lifetime. the transformer is operating in the safe zone if its F_{AA} is smaller than one. Since load (and consequently temperature) vary on different days (and also in different months), accelerate the aging factor is defined as equation (13).

$$F_{EQA}=\frac{\sum_{n=1}^{N}F_{AAn}\Delta t_n}{\sum_{n=1}^{N}\Delta t_n} \qquad (13)$$

in this section, the effect of the current harmonics on distribution transformer is studied through experimental results. The component of load loss is calculated for all transformers over the test period and the results. Table 1 presents the component of load loss, average temperature, MPC and aging factor of one

Table 1 average load loss, temperature and life tim of the 1st transformer

transformer-sample 1					
$I_{(pu)}$	1.002	$P_{EC(pu)}$	0.891	θ_g	15.23
F_{HL-STR}	1.009	$P_{LL(pu)}$	3.634	θ_H	107.7
F_{HL}	1.05	$P_{cu(pu)}$	1.003	$I_{max(pu)}$	0.992
$P_{OSL(pu)}$	1.739	θ_{TO}	52.51	F_{AA}	0.977



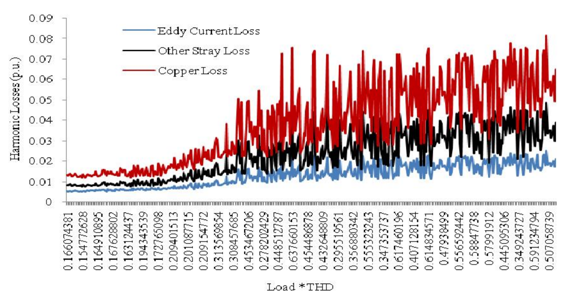
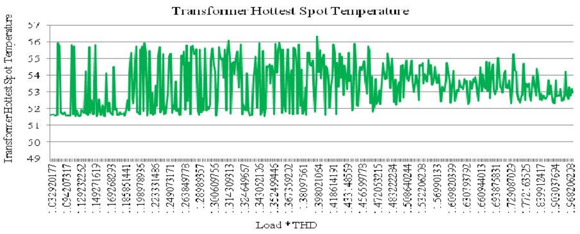


Fig 2 The variation of the load loss with respect to the current load*THD over the test period.- 1st transformer



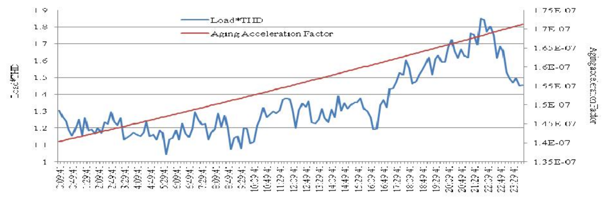


Fig 4 Calculated and measured aging factor and load*THD of the first transformer

The current harmonic spectrum of the first transformer are shown in Fig1. The variation of the load loss, the hottest-spot temperature, Calculated and measured aging factor with respect to the current THD multiple load are illustrated in Fig.2, Fig.3 and Fig4. The load loss increases with the rise of THD.

THE IMPACT OF HARMONICS ON THE WIRES AND CABLES

According to Budaneau's model, the quantity of S depends on three quantities P, Q, D and it is given by equation(14) [8].

$$S = \sqrt{P^2 + Q^2 + D^2} \tag{14}$$

The quantity D is harmonic power, and is simply called distortion volt-ampere. this power occupy the network.
According to Standard IEC-60287, the value of the cable DC resistance (R_{dc}) at the maximum rated temperature is given by equation (15).

$$R_{dc} = R_{20}\big(1 + \alpha_{20}(\theta - 20)\big) \tag{15}$$

In this equation, R_{20} is DC resistance of cable per unit length at temperature of $20°C$, α_{20} is constant temperature coefficient for conductor material, and θ is maximum rated temperature [9]. As seen, the AC resistance is frequency-dependent completely, which fact is used to evaluate the impact of harmonics in electrical grids on temperature and lifetime.

The cable loss calculations incorporating the harmonic

In totally sinusoidal and full load conditions, a total of three cable's conductors loss were calculated using equation 16.

$$\mathrm{W_s} = \left[\mathrm{I_{1R}^2 R_{ac(1)}}\right]_\mathrm{R} + \left[\mathrm{I_{1R}^2 R_{ac(1)}}\right]_\mathrm{Y} + \left[\mathrm{I_{1R}^2 R_{ac(1)}}\right]_\mathrm{B} \tag{16}$$

In this equation, $R_{ac(1)}$denotes the AC cable resistance at the base frequency under sinusoidal conditions. Under non-sinusoidal conditions, harmonic loss power add to each phases and name $\mathrm{W_{NS}}$. Thus, per unit power under harmonic condition is given by equation 17. [8]

$$\mathrm{W_{NS-pu}} = \left(\frac{\mathrm{W_{NS}}}{\mathrm{W_s}}\right) \tag{17}$$

Temperature rise of cable under harmonic condition

Cable Operating temperature under full load in harmonic environment can be calculated by equation 18.

$$\theta_{\mathrm{NS}} = \mathrm{k.W_{NS}} \times \mathrm{R_{Th}} \tag{18}$$

The temperature of the cable under harmonic conditions is given by equation (19) [8,10].

$$\theta_{\mathrm{NS}} = 90\left(\frac{\mathrm{W_{NS}}}{\mathrm{W_S}}\right) = 90\left(\mathrm{W_{NS-pu}}\right) \tag{19}$$

Useful life of cable under harmonic condition

According to equation (19), if cable temperature rises above 90°C under harmonic conditions, useful life of cable will fall, compared with the level expected under sinusoidal conditions [8-9]. Lifetime of cable at heightened temperature caused due to presence of harmonics in the grid is given by Arrhenius Equation (equation 20[8-9].

$$\left(\frac{t_a}{t_s}\right) = e^{\left[\frac{E_a}{B}\left(\frac{1}{T_a} - \frac{1}{T_s}\right)\right]} \tag{20}$$

where t_s denotes lifetime of capable at service temperature (year), and, t_a denotes the lifetime of cable at accelerated aging temperature (year). Cable losses and consequently its operating temperature are both dependent on its current and AC resistance of cable's conductor in harmonic components of the current. So the useful life of the cables is reduced by the harmonics, resulting in economic losses through the cost of replacement of cables and the cost of resulting power cut-off. In this section, the effect of the current harmonics on feeders is studied through experimental results. the result of calculation and measurement for five feeders shows life time of most of them is about 90%.

ECONOMIC MODELLING OF ELECTRICAL NETWORK TO STUDY HARMONIC IMPACT

To solve the harmonic penalty problem, it is necessary to determine the cost of a specified distortion level in the electric power grid. For the purpose, system variables must specify such as assessment method, economic authority to compensate the losses, the assessed year and sensitive variable of power system. Then methods, models and tools must be specified in detail. The modeling is categorized in function of the users (model for utilities or end user), available data (direct method, indirect method), the distortion type (events, variations), and the scenario (deterministic, probabilistic) [2, 11]. So, the best method to solve this paper problem is the direct and deterministic method.

General economic model for increased losses

Single $\mathrm{K^{th}}$ electrical component in the grid is considered.

The cost of loss in the time interval ΔT_i must be obtained. It is assumed that harmonics flown in the grid range from h_1 to h_{max}. The effects of voltage and current harmonics are represented by the factors ranging from G^{h_1} to $G^{h_{max}}$ 33. Thus, the cost of loss is expressed by equation (21) [6].

$$(Dw_k)_{\Delta T_i} = K_w P_k \left(G^{h_1}, \dots, G^{h_{max}} \right) \Delta T_i \qquad (21)$$

where K_w is the unit cost of electrical energy and P_k denotes losses appeared on k^{th} element based on harmonics. $(Dw_k)_{\Delta T_i}$ expresses loss cost for the entire period ΔT_i.

It is clear that the total loss for a year is calculated by the sun of the loss costs of all time intervals present in the considered year which is obtained [11].

$$(D\,w_k)_n = \sum_{i=1}^{q} (D\,w_k)_{\Delta T_i} \qquad (22)$$

$(D\,w_k)_n$ gives the cost of losses of K^{th} element and nth year. The cost of loss in the year n for the whole system in which m component is loss costs of all time intervals present in the considered year. This can be mathematically expressed as follows:

$$(D\,w)_n = \sum_{k=1}^{m} (D\,w_k)_n \qquad (23)$$

$(D\,w)_n$ expresses cost of losses for all elements in the N^{th} year. If the study period is a year, the formula (23) will be sufficient, and provide the marginal cost; however, if the study period exceeds more than one year, which is usually assessed for a 10-year or longer period, ten, one year must be set as base year, and the cost of losses for the coming years be transferred to such base year.equation (24) and (25) express the unit cost variation of electric energy in coming years and the cost present worth value in every year.

$$(Dw_k)_n = (Dw_k)_1 (1+\beta)^{n-1} \qquad (24)$$

$$(Dw)_{n,pw} = \sum_{n=1}^{N} \frac{(Dw)_n}{(1+\alpha)^{n-1}} \qquad (25)$$

In these equations, $(Dw_k)_1$ and $(Dw_k)_n$ denotes the price of the element in the first year and the price of the element in the n^{th} year, and β represents interest rate.

General economic model for decreased life

To calculate the cost of decreased lifetime, first heat loss, and reduced lifetime of elements under sinusoidal conditions were evaluated. Then, the values obtained for different years are added up until their sum reaches 1 according to cumulative damage theory. The theory said the sum of relative life losses must equal unity which express in (26)[11].

$$\sum_{i=1}^{p} \Delta R_{L,i} = 1 \qquad (26)$$

The price of the element in year n is estimated, considering element must be replaced in year n, and so a new model to purchasing must be suggested. Engineering economics formulae are used to estimate the cost of the element in n^{th} year. Finally the cost present worth value in every year is expressed (27).

$$Cs = \sum_{n=1}^{N} \frac{(Cs)_n}{(1+\alpha)^{n-1}} \qquad (27)$$

In these equations, $(C_s)_1$ and $(C_s)_n$ denote the price of the element in the first year and in the n^{th} year . So, n denotes the number of year of life of the element (element's useful life). N represent the point in time the sum becomes equal to 1, and it is in year n that the element must be replaced[8,11].

All calculation is repeated on non-sinusoidal state to obtain C_{ns} [11]. The difference between these two values is called Da_k.

$$Da_k = C_{k,ns}\left(L_{k,ns}\right) - C_{k,s}\left(L_{k,s}\right) \qquad (28)$$

$C_{k,s}$ and $C_{k,ns}$ are the present worth value of the total investment costs for buying the kth component during the system life in sinusoidal and non sinusoidal operating conditions, respectively. L_s and L_{ns} represent useful lives. Using this value, the cost of reduced lifetime can be obtained.

METHOD OF CALCULATING HARMONIC PENALTY FOR CUSTOMER

In this paper the main factors to determine the customer's penalty power losses in cables, wires, transformers and reducing their life. Other important factors which have to be considered are occupying the lines capacity, office consideration included of analysis expert, measurement devices and the cost of measurement. Achieved formula for calculating harmonic penalty according to all above fact can be expressed as:

$$\text{Harmonic penalty} = \text{feeders harmonic losses} + \frac{\text{transformers harmonic losses}}{\text{customers numbers}} + \frac{\text{reduction of useful life}}{\text{customers numbers}} \qquad (27)$$

calculation of harmonic penalty-case study

In this section, the harmonic penalty to be imposed on end users connected to the 1st feeder of 1st transformer. The number of customers connected to the feeder and transformer should be considered. Since the calculations are very complicated and time consuming, a polynomial equation can be estimated for each of the harmonics using interpolation, which can provide an acceptable expression of the harmonic curves. In these formulae, the duration of harmonic injection can vary, in which case the equation must divided by 24*30 hours, and then to be multiplied by the amount of harmonics generated in a month, expressed in hours. Fig.5 shows the third harmonic penalty, in these graphs the vertical axis scale is in dollar multiple 3000 and the horizontal axis shows the ratio of generated harmonic to the main component of current. Since the reduction factor of transformer's lifetime is related to duration of generation of harmonic by subscribed connected to the transformer, and since transformers have heating coefficient, durations shorter than 1 hour may not be neglected.

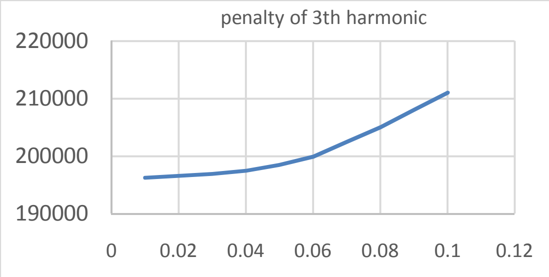


Fig 5 customer's penalty for injecting the 3th harmonic

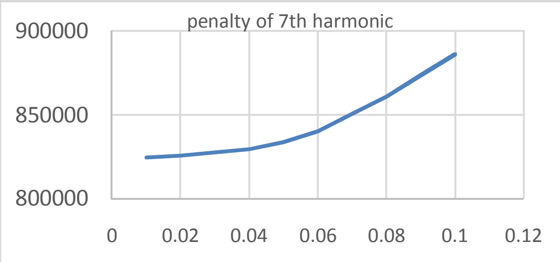


Fig 5 customer's penalty for injecting the 3th harmonic

In equations below, h denotes generated harmonic level, and k factors are penalties to be paid by each customer.

$$k_3 = 2*10^{11}h^6 - 7*10^{10}h^5 + 9*10^9h^4 - 5*10^8h^3 + 10^7h^2 - 134197h + 196737$$

$$k_5 = 5*10^{11}h^6 - 2*10^{11}h^5 + 2*10^{10}h^4 - 10^9h^3 + 3*10^7h^2 - 312680h + 458396$$

$$k_7 = 10^{12}h^6 - 3*10^{11}h^5 + 4*10^{10}h^4 - 2*10^9h^3 + 5*10^7h^2 - 563629h + 826294$$

$$k_9 = 2*10^{12}h^6 - 5*10^{11}h^5 + 6*10^{10}h^4 - 3*10^9h^3 + 9*10^7h^2 - 895096h + 10^6$$

$$k_{11} = 2*10^{12}h^6 - 7*10^{11}h^5 + 9*10^{10}h^4 - 5*10^9h^3 + 10^8h^2 - 10^6h + 2*10^6$$

$$k_{13} = 6*10^{12}h^6 - 2*10^{12}h^5 + 3*10^{11}h^4 - 2*10^{10}h^3 + 5*10^8h^2 - 8*10^6h + 3*10^6$$

in this paper functions K are calculated till K_{13} .Now, in proportion to the harmonic generated by each customer, penalty are calculated, and added up. To incorporate the duration of generation of harmonic by each customer into the calculations, a program was written in MATLAB, which received the amount of customer harmonic injection and duration of generation as input, and printed the penalty as output. It is assumed that customers generate harmonic in a constant trend; for example, the harmonic is generated for 2 hours at rate of 1% and for 4 hours at rate 2% in all days of a month. The program can be easily modified to calculate variable harmonic generation in different days.

CONCLUSION

This paper presents a method to calculate the harmonic penalty. First it studied the effect of grid harmonics on load loss and lifetime of transformer, cables and wires. Main factors to determine the customer's penalty are power losses in cables, wires, transformers and reducing their life. . Achieved formula for calculating harmonic penalty has been expressed according to all above fact.

- Other important factors which have to be considered are occupying the lines capacity, office consideration included of analysis expert, measurement devices and the cost of measurement should be studied.

-This paper studied the effect of the most important component of medium voltage grid to calculate harmonic penalty. The effect of other instrument as protective relays, Inductors and capacitors, fuses, CT, PT and lightening arrester should be investigated.

- Considering increasing nonlinear loads in distribution grid, power quantity has been affected by customer's equipment. It is necessary to prepare a standard to determine multifarious equipments damage in different level harmonic grid.

REFERENCES

[1]Yong Peng, Shun Tao, 2011," Harmonic Pricing Model Based on Harmonic Costs and Harmonic Current Excessive Penalty ", IEEE Conference (ALMSES), Deng Leng.

[2]Talacek P J, Watson NR,2002, Marginal Pricing of Harmonic Injections: An Analysis of the Resulting Paymen,IEEE trans on power systems,640-645.

[3]ANSI/IEEE Recommended Practice for Establishing Transformer Capability when Supplying Nonsinusoidal Load Currents, ANSI/IEEE Standard C57.110/D7, 1998.

[4]W. Frelin, L. Berthet, 2009,"Transformer winding losses evaluation when supplying non linear load," in Proc. of the Universities Power Engineering Conf..

[5]L. Pei, L. Guodong, X. Yonghai, 2010, "Methods Comparation and Simulation of Transformer Harmonic Losses," Power and Energy Engineering Conf..

[6]T. Shun; X. Xiangning, 2008 "Comparing transformer derating computed using the harmonic loss factor FHL and K-factor," Electric Utility Deregulation and Restructuring and Power Technologies Conf..

[7]Sumaryadi, H. Gumilang, A. Suslilo, 2009, "Effect of power system harmonic on degradation process of transformer insulation system," Properties and Applications of Dielectric Materials Conf..

[8]C. Demoulias, D. P. Labridis, P. S. Dokopoulos, and K. Gouramanis, 2007"Ampacity of low voltage power cables under non-sinusoidal currents," IEEE Trans. Power Delivery, vol.22, no.1, pp. 584-593.

[9]J. Desmet, G. Vanalme, R. Belmans, and D. Van Dommenlen, 2008, "Simulation of losses in LV cables due to the nonlinear loads," Proceedings IEEE Power Electronics Specialists Conference, 2008 (PESC 2007), 15-19, pp. 785-790.

[10]K. D. Patil, W. Z. Gandhare, 2011, "Effects of harmonics in distribution systems on temperature rise and life of XLPE power cables," IEEE Conference(ICPS),chennai.

[11] P. Verda,2010," Econimc of harmonic distortion ", University of Cassino