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Distribution Transformer Due to Non-linear Loads

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ABSTRACT
The transformers are designed and used for different types loads, at rated frequency and balanced supply voltage. Now a day's energy efficiency of electrical load device increases with solid-state electronics. But, due to the use of non-linear loads such as computers, variable speed drives in heating ventilation and air conditioning systems and electronic ballasts of fluorescent lamps, harmonic distortion is increasing in the commercial load and services. Because of this reason harmonics is injected into the power systems. The use of non-linear loads on electrical power systems causes different losses and aging problem of transformer. To prevent this problems rated capacity of transformer supplying non-linear loads must be reduced. Transformer derating is used for minimizing harmonic distortion in distribution transformer. In this paper the simulation are performed using Math works MATLAB 7.0.13 on 50KVA single phase transformer for derating purpose.
Keywords : Derating, Harmonic losses, non-linear loads

I.   INTRODUCTION

Power systems operate at frequencies of 50Hz. However, certain types of loads produce currents and voltages with frequencies that are integer multiples of the fundamental frequency(50Hz). These higher frequencies are a form of electrical pollution known as power system harmonics. Transformers are the major components in power systems and increased harmonic distortion can cause excessive winding losses and hence abnormal temperature rise. Temperature rise of transformers due to non-sinusoidal load currents was discussed in IEEE Transformer Committee in March 1980 [1].Rating system has developed called K-factor, a design which is capable of withstanding the effects of harmonic load currents. An application of this rating system to specify a transformer for a particular environment requires knowledge of the fundamental & harmonic load currents. Electrical insulation used in distribution transformers gets degraded when it is subjected to the thermal, electrical, power quality problem like harmonics and variation in frequency are responsible for accelerated aging of its insulating material. A transformer designed without considering all these issues will result into premature failure.
Basically transformer consist of ordinary parameters such as leakage inductances and dc resistances, magnetizing inductances and core resistance that obtain from no-load test , short circuit test and dc test. In this stray losses that consist of eddy current losses in windings and other stray losses are not considered. When transformer supplying harmonic loads these losses are proportional to frequency is more considerable.

II.   HARMONIC DEFINITION

A harmonic voltage or current frequency is integer multiple of the fundamental frequency. These harmonic sources have non-linear characteristics and these harmonic sources result in multiples of fundamental frequency or system frequency. The fundamental component is first harmonic or rated frequency. This voltage and current harmonics are generated in power systems by harmonic producing loads. Switching equipments used in industrial production process or electrical industry causes harmonic [2].

III.   TRANSFORMER LOSSES

Transformer losses consist of no-load or iron loss or core losses and load losses. As given in equation below.

$$P_T = P_{NL} + P_{LL} \qquad (1)$$

Where, P_{NL} is no-load losses, P_{LL} is load losses, P_T is total loss.

No load loss is due to induced voltage in the core. Load losses consist of ohmic loss, eddy current loss, and other stray loss.

$$P_{LL} = P_{DC} + P_{EC} + P_{OSL} \qquad (2)$$

Where, P_{DC} is loss due to rated current and dc resistance of the winding, P_{EC} is the winding eddy current loss; P_{OSL} is other stray losses in clamps tanks, etc.

Winding eddy losses consist of eddy current losses and circulating current losses, which are considered to be winding eddy current losses. Other stray losses are in structure other than windings, such as clamps, tank or enclosure walls .

$$R_{OSL} = 1.29 \left(\frac{f_h}{f_1}\right)^{0.8} \quad m\Omega$$

And for high frequencies (420-1200Hz) the resistance is

$$R_{OSL} = 9.29 - 0.59 \left(\frac{f_h}{f_1}\right)^{0.9} \quad m\Omega$$

In modern power systems, the total harmonic voltage distortion is normally below 5% and the magnitudes of the voltage harmonic components are small compared to fundamental components. Therefore voltage harmonics effects are neglected. The current harmonics are more significant. These harmonic load current components cause additional losses in the winding and other structural parts [1].

A. Eddy current losses in windings

There are two effects that cause increase in winding eddy current losses, namely the skin effect and proximity effect. The winding eddy current loss in power frequency spectrum tends to proportional to the square of the load current and square of the frequency due to both skin effect and proximity effect [2].

Other stray losses increase with power of 0.8 at low frequencies and decreases at high frequencies with power of 0.9.

Hence other stray losses can be calculated as

$$P_{OSL} = P_{TSL} - P_{EC} \qquad (6)$$

The other stray loss resistance for the primary and secondary side in terms of other stray loss at rated current

$$R_{OSL-R,1} = \frac{P_{OSL-1}}{I^2_{1-R}} \qquad (7)$$

$$R_{OSL-R,2} = \frac{P_{OSL-2}}{I^2_{2-R}} \qquad (8)$$

IV. HARMONIC EFFECT ON LOAD LOSSES [5]

$$EC \quad I^2 x \quad f^2 \qquad (3)$$

A. Effect of harmonics on dc losses

Type of Loads	K-factor
Incandescent lighting Electric resistance heating, Motors, Control transformers without solid state controllers.	K-1
Electric discharge lighting UPS, Induction heating equipment, Welders, PLC's.	K-4
Telecommunication Equipments, UPS without filtering, General health care and classrooms of schools, Various testing equipments.	K-13
Mainframe computer loads, Motors with VFD's, Health care equipments in critical care areas and operating rooms of hospitals.	K-20
Multi-wire receptacle circuits in industrial ,medical, educational laboratories etc.	K-30
Loads producing high order harmonics	K-40

Skin effect

Skin effect is the trend of current to flow on the circumference of the wire so that the current density is greater at the surface than at the core. High frequency noise in the range of 1kHz-1.5MHz increases the inductive reactance of the wire. This forces the electrical charge towards the outer surface of the wire. This means that the total available space of the wire is not used to carry the electrical power.

Proximity effect [3]

These losses will increase with square of load current. A dc component of the load current will increase the transformer core loss slightly

$$P_{dc} = R_{dc} \times I^2 = R_{dc} \times \sum_{h=1}^{hmax} I^2_{h,rms}$$ (9)

B. Effect of harmonics on eddy current losses:

Winding eddy current loss (P_{EC}) in power frequency spectrum tends to proportional to square of the load current and square of frequency

Along with skin effect, proximity effect is a common problem found in every electrical system. Proximity effect is defined as the jumping magnetic field from one conductor to another conductor nearby. The major causes of proximity effect are closeness of the wires, bends in the wire, skin effect and high frequency noise.

B. Other stray losses in transformer

Fluxes in transformer and inductor induce eddy current in metallic parts over the surrounding e.g., enclosures and clamps. The eddy current losses outside the winding are other stray losses as losses in core, clamps and structural parts will increase with square of the load current but not proportional to the rate of frequency. The ac resistance of the other stray losses at low frequencies (0-360Hz) is equal to [3]:

$$P_{EC} = P_{EC-R} \sum_{h=1}^{h=max} \left(\frac{I^2_h}{I^2_R}\right) h^2$$ (10)

The harmonic loss factor for winding eddy current

$$F_{HL} = \frac{\sum_{h=1}^{h=hmax} h^2 \left(\frac{I_h}{I_R}\right)^2}{\sum_{h=1}^{h=hmax} \left(\frac{I_h}{I_R}\right)^2}$$ (11)

Effect of

harmonic on other stray losses

The heating due to other stray loss is not considered for dry type transformer but having effect on oil filled transformer. Therefore losses

due to bus bars connection, structural parts, tank are proportional to the square of the load current and the harmonic frequency to the power of

0.8.

$$P_{OSL} = P_{OSL-R} \sum_{h=1}^{h=hmax} h^{0.8} \left(\frac{I_h}{I_R}\right)^2$$ (12)

Harmonic loss factor for other stray losses

$$F_{HL-STR} = \frac{P_{OSL}}{P_{OSL-R}} = \frac{\sum_{h=1}^{h=hmax} h^{0.8} \left(\frac{I_h}{I_R}\right)^2}{\sum_{h=1}^{h=hmax} \left(\frac{I_h}{I_R}\right)^2}$$ (13)

DERATING OF TRANSFOREMR

Derating is used to reduce the transformer KVA loading such that total transformer losses are limited to rated losses. The main methods for estimating transformer derating are: K-Factor, Harmonic Loss Factor, online harmonic loss measurement and computed harmonic losses [4]. The IEEE standard. C57.110-1998[5] introduced a term called the K-factor for rating a transformer as per their capability to handle load currents with significant harmonic contents .It is an alternate technique for transformer de-rating which considers load characteristics. It is a rating applied to a transformer indicating its suitability for use with loads that draw non-sinusoidal currents. It is an index that determines the changes in conventional transformers must undergo so that they can dissipate heat due to additional iron and copper losses because of harmonic currents at rated power. Hence the K-factor can be given as

$$\frac{\sum}{\sum} \overline{\qquad\qquad}$$

And the relation between K-factor and F_{HL} is given as

$$\sum \overline{\qquad\qquad}$$

TABLE1

TRANSFORMER K-RATINGS [6]

V. TRANSFORMER MODEL

The total flux linking the primary coil in linear loads is the sum of magnetizing flux limited to the iron core and the primary leakage flux which links only primary coil. In non-

linear   loads

$$\Phi_1 = \Phi_{ll} + \Phi_m + \Phi_{ec,1} + \Phi_{osl,1}$$ (17)

Secondary current has a negative polarity in respect of primary current. Therefore total flux in

Voltage V_1 can be further reduced to:

secondary windings is:

V_1 (V)	V_2(V)	I_1 (A)	I_2(V)	P_0 (W)	P_{LL}(W)	P_{dc} (W)
2400	240	20.83	208.3	173.62	700	555.44

$$\Phi_2 = -\Phi_{l2} - \Phi_m - \Phi_{ec,2} - \Phi_{osl,2} \qquad (18)$$

Where,

Φ_{l2}=Secondary leakage flux, which links only secondary coil

Φ_m= Magnetizing flux confined to iron core

$\Phi_{ec,2}$= secondary winding flux which cuts through secondary winding

$\Phi_{osl,2}$= Secondary other structural parts flux which cuts through the structural parts or tanks of the transformer

The supply voltage includes resultant mutual flux, in the core that brings about magnetizing current. This can be express as [7]:

The total flux in primary and secondary coil is:The primary voltage V_1 and the secondary voltage V_2, at the terminals of the transformer are given in terms of Ohm's and Faraday's laws:Primary and secondary voltages can be express in currents by substitution of (20) into (22) and (21) into (30)

TABLE 2

TRANSFORMER DATA

TABLE 3
HARMONIC LOAD SPECIFICATION[6]

Where, is equal to the induced emf in the primary coil.
The voltage V_2 in the secondary coil is
is equal to the induced emf in the secondary coil.

h	I_h/I	$(I_h/I)^2$	h^2	$(I_h/I)^2 h^2$	$h^{0.8}$	$h^{0.8}(I_h/I)^2$
1	0.969	0.938	1	0.939	1	0.936
3	0.367	0.134	9	1.212	2.4	0.3126
5	0.192	0.125	25	3.13	3.62	0.452
7	0.132	0.0104	49	0.509	4.74	0.049
9	0.0279	0.00078	81	0.063	5.799	4.52e^-3
11	0.073	0.0121	121	1.464	6.809	0.082
13	0.0057	0.0050	169	0.849	7.78	0.038
15	0.0259	0.00067	225	0.1509	8.727	5.84e^-3
$\sum$		1.0587		8.314		1.888

With the help of above equations the equivalent transformer model is shown in fig (1) below. Fig shows controlled voltage source of V_{ec} and V_{osl} in series with dc resistance and leakage inductance.
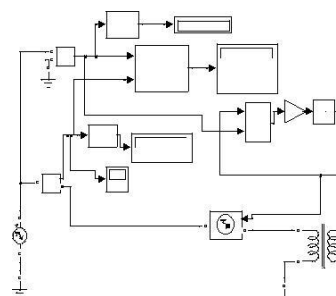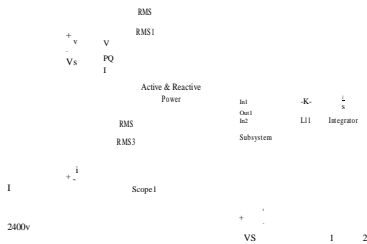
Fig. 1 Equivalent transformer model for harmonic studies

VI. SIMULATION MODEL [8]

Simulation model for 50KVA 2400/240V single phase transformer simulated in MATLAB/Simulink shown in fig(2). Model shows the harmonic load connected at the secondary of transformer. The load consists of current sources in parallel with different frequencies and magnitude. The harmonic load specification is given in Table 3 shows harmonic order and per unit values. The current waveform for the harmonic load is shown in fig (3)
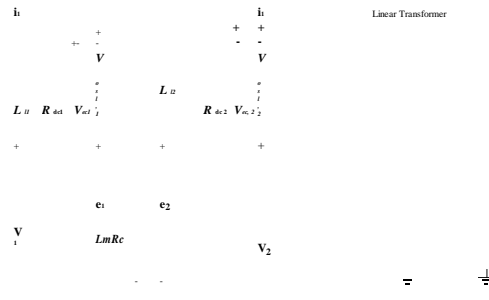
$P_{TSL} = P_{EC} + P_{OSL} = P_{LL} - P_{dc} = 700 - 555.44 = 144.56w$

The winding eddy current and other stray losses can be calculated as :

$P_{EC} = 0.33 \times 144.56 = 47.70w$

(0.33 for oil-filled transformer)

$P_{OSL} = 144.56 - 47.7 = 96.85w$

Hence, rated load losses when applied to linear load is
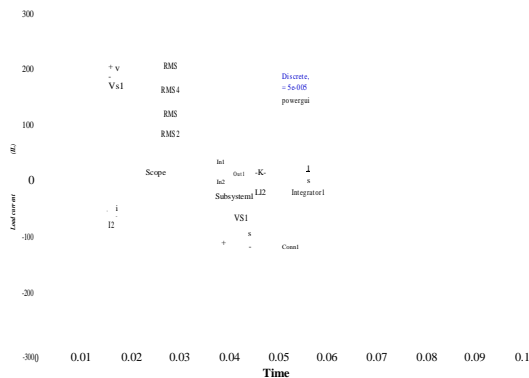
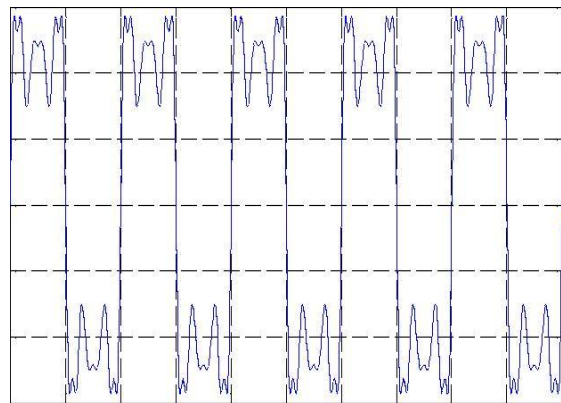Fig. 2 Simulation model of transformer

Fig. 3 Current waveform for non-linear load

Total stray losses P_{TSL} can be calculated as follows;

$$P_{LL-R}(pu) = 1 + P_{EC-R}(pu) + P_{OSL-R}(pu) \qquad (16)$$

$P_{LL-R}(pu) = 1.2601pu$

$I_{max(pu)} = 0.826pu$

Equivalent KVA can be obtain as follows:

Equivalent KVA = $50 \times 0.826 = 41.316$KVA

VII. CONCLUSION

The study of harmonic impact on distribution transformers is important because transformer is important equipment in power system. The harmonic losses factor for eddy current winding and other stray losses has been computed to evaluate the equivalent KVA of the transformer and permissible current for supplying non-linear loads calculated analytically. Derating is

studied in order to mitigate harmonic distortion problem.

VIII. ACKNOWLEDGMENT

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