Effects Of Harmonics On Major Equipments In Power Distribution Network

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Abstract: Power Quality in the electric distribution system is a developing concern. Also customer loads are generating increased amount of harmonic currents that can be magnified on the distribution system due to resonance condition and pose new issues of Power Quality in the power System. As substation equipments are the interface between the supply and non-linear loads, the results of harmonics on those equipments is of incredible significance. These harmonics can cause immoderate loss and extraordinary temperature rise, as a consequence reducing their operational life span. A case study of distribution network supplying linear and nonlinear load is presented, which encompasses the effects of harmonics on transformer losses and efficiency to find out the solutions to be implemented. The aim of study is to identify the level of harmonics in the supply system feeding power to various categories of consumers.

Index Terms: Harmonic distortion, Nonlinear load, Harmonic standard, Life Expectancy, Total Harmonic Distortion (THD)

1. INTRODUCTION

The gradual rise in awareness of effect of power quality disturbances on substation equipments has lead to many utilities, taking much pro-active approach towards the measurement of power quality levels on their networks. Utility may define a power quality as reliability whereas manufacturer of load equipments, define it as the characteristics of power supply that enable the equipments to work properly [1]. The power quality is ultimately a consumer driven issue and the end users point of reference takes precedence. Thus power quality is any problem manifested in voltage, current or frequency deviations those results in failure and mal-operation of substation equipments [2]. In this paper theoretical aspect of effects of harmonic distortion on the behavior and performance of several important electrical equipments such as transformer, lightening arrestors have been described. The measurement and analysis has been done by using advanced power quality analyzer. A survey was carried out on different feeders to understand the existing level of harmonics. The ill-effects of harmonics on life expectancy of sub-station equipments are also discussed.

The main objectives of this paper are-

- To study the effects of voltage and current harmonics on efficiency of the transformer.
- To study the effects of harmonics on winding losses and core losses.
- To analyse the effect of harmonics on life expectancy of lightening arrestor.
- To summarize the overall adverse effect on substation equipments.

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2 EFFECT OF HARMONICS ON MAJOR EQUIPMENTS

2.1 Effect of Harmonics on Transformation Ratio (K)

The e.m.f. equation of the transformer on primary side (E1) is given by the

$$E1 = 4.44\ fB_m AN1 \quad (1)$$

Where, f - frequency in Hz; B_m - the maximum flux density in Tesla; A - Area of cross section of the transformer core in sq. m.

; N1 - Number of turns on primary side of the transformer.

B_m, A and N1 are constants.

Thus

$$E1 \alpha f \quad (2)$$

$$E1 = K1 * f \quad (3)$$

Where, K1 is the constant of proportionality.

Similarly the e.m.f. equation of the transformer on secondary side (E2) will be

$$E2 \alpha f \quad (4)$$

$$E2 = K2 * f \quad (5)$$

The non-linear loads are connected at the secondary side of the transformer. This injects harmonic currents of frequencies other than fundamental. It results in effective frequency of (f+Δf). For a transformer connected to a harmonic dominant load, e.m.f. Equations can be written as

$$E2 = K2 * (f + \Delta f) \quad (6)$$

Dividing eq. (6) by eq. (3), we get

$$E2 / E1 = K2 * (f + \Delta f) / K1 * f \quad (7)$$

$$E2 / E1 = K * (1 + \Delta f / f) \quad (8)$$

Where,

$$K = K2 / K1 \quad (9)$$

In harmonic prone areas, effective transformation ratio is changed to [E2/E1] / (1 + Δf/f) .The effective transformation ratio increases, thereby secondary e.m.f. increases and secondary voltage gets distorted.

2.2 Effect of Harmonics on Losses

With the exception that harmonics carried out to transformers might also result in an increased audible noise, the outcomes on these components typically are those arising from parasitic heating. The effect of harmonics on transformers is twofold; current harmonics cause an increase in copper losses and stray flux losses, and voltage harmonics purposes growth in iron losses. It has to be referred to that the transformer losses as a result of each harmonic voltages and harmonic currents are frequency structured. The losses increase with increasing frequency and consequently, higher frequency harmonic components can be extra critical than lower frequency components in causing transformer heating. Transformer losses can be segregated into load losses and no load losses. Load loss may be further divided with the aid of I^2R (winding losses) and stray losses. Stray losses are of unique significance while evaluating the delivered heating because of the effect of a non-sinusoidal waveform. Stray losses are eddy-current losses because of stray electromagnetic flux inside the windings, core, core clamps, magnetic shields, tank wall, and other structural parts of the transformer. The winding stray loss includes winding conductor strand eddy-current loss and the loss due to circulating currents between strands or parallel winding circuits. This loss will rise in proportion to the square of the load current and the square of frequency. The temperature may also rise inside the structural components because of eddy currents, again approximately as the square of the load current and the square of the frequency. Losses in transformers comprises the load (copper) loss which scales with the square of the load current, and the no-load (core or iron) loss that is independent of the load, i.e.

$$P_T = P_L + P_{NL}$$

(10)

No Load Loss This loss is independent of the load and caused by the induced voltage in the core. It comprises 2 components: hysteresis and eddy current losses [2]. The core losses such as iron loss and eddy current loss, being the functions of frequency, are higher at higher harmonics.

$$P_{NL} = H + E = k_h \times f \times B_m^n + k_e f^2 \times B_m^2 \quad (11)$$

Where, k_e and k_h are constants of the core material, B_m is the maximum flux density, and n = [1.5, 2.5] is material dependent. The effect of harmonic loads on no-load loss is often insignificant since the voltage harmonics are dominated by the fundamental component and hence V_{THD} usually does not exceed 5%. Load loss:Total load losses encompass ohmic (DC) losses and total stray losses.

$$P_L = P_{DC} + P_{TSL}$$

(12)

P_{TSL} includes winding eddy current losses and losses in other Structural components excluding the winding, caused by AC magnetic field of the transformer.

Ohmic Loss:

This loss represents with square of the rms value of the load current increased by the current harmonic components.

$$P_{DC} = R_{DC} \times I_{rms}^2 = R_{DC} \times \sum_{h=1}^{h\max} I_{hrms}^2$$

(13)

R_{DC} is the DC resistance of the transformer winding.

Eddy Current Loss:

$$P_{EC} = P_{EC-R} (I_h / I_R)^2 \times h^2$$

(14)

Where P_{EC-R} is the rated eddy current loss at 50 Hz, and I_R is the total rms current. Thus eddy current loss is directly proportional to the square of frequency. It means that at high harmonic frequencies, the eddy current loss will be very high. The sum of hysteresis and eddy current losses is called core loss as both the losses occur within the core (magnetic material). Can be expressed as;

Core loss = Hysteresis loss + Eddy current loss. Thus total losses can be considered with respect fundamental frequencies and also at high harmonic frequencies.Similarly efficiency can be calculated with respect to both conditions.

Efficiency (η) at Linear Load (LL) condition

$$\eta_{LL} = 1 - \frac{\text{Total Losses at LL}}{\text{output at LL}}$$

(15)

Efficiency (η) at nonlinear load (NLL) condition

$$\eta_{NLL} = 1 - \frac{\text{Total Losses at NLL}}{\text{output at NLL}}$$

(16)

Numbers of experiments were conducted to verify the above expression. The harmonic measurements were carried out at various substations. The following conclusions have been drawn from the studies; more harmonics are present on secondary side as compared to primary side of the transformer.In the vicinity of non-linear loads, current on secondary side, where nonlinear load is connected, is higher than the rated current. This may also cause tripping of transformer due to over current, although actual load is not increased.So far as system voltage is concerned, the Total Harmonic Distortion (THD) on primary side is lower. It is high on secondary side. Thus, the THD recorded at 400 kV, 220 kV, 132kV, 100 kV sides were found to be less as compared to the THD recorded at 33 kV, 22 kV and 11 kV sides. Drastic reduction in efficiency of transformer if the non-linear load is connected at LV side of the transformer. Observations during Harmonic Measurements on TransformerNon-linear load is connected on secondary side of the transformer, harmonics get introduced. It is as good as saying that the fundamental frequency gets increased to (f+Δf). This statement is done to take into account the superimposition of various harmonic frequencies on the fundamental. This leads to increased losses (iron and copper loss) thereby decrease efficiency of transformer. Also increased heat generated by cu loss will affect adversely on insulation coordination and hence indirectly degrade the life of transformer. Three different case studies are analyzed and observations are shown in table 1.

Table 1: Results for Three Case Studies

	% Efficiency		Total Losses in (kW)	
	Linear Load condition	Non Linear Load condition	Linear Load Condition	Non Linear Load condition
16 kVA	97.82	87.03	0.188	1.495
200 kVA	86.80	46.13	12.290	97.985
400 kVA	76.73	29.99	49.106	392.389

3 Analysis of Effect of Harmonics on Lightning Arrester

The healthiness of Lightning Arrestor (LA) is determined on the basis of two parameters, internal resistance of the arrestor and its leakage current. The internal resistance of EHV LAs should be more than 20 Mega ohms. This can be ascertained by recording Megger values of LAs. For example, the internal resistance of a 220 kV LA should be more than 25 mega ohms. The leakage current of Lightning Arrestors is the significant parameter to determine the life expectancy. Leakage current of LA should be less than 150 micro amp. If is greater than this value then it is to be considered as LA is in danger zone.

Observations:

- It is observed in most of the cases under presence of nonlinear load, the magnitude of third order harmonic current is very high. This results into very high value of leakage current more than permissible limit.
- In normal condition leakage current of LA should be less than 300 micro amp.

Table 2: Observations at nonlinear load consumer (Shirval Substation, 11kV/440V) for LA

Date	Time	I_3	Leakage Current of LA = $4*I_3$
		A	A
22-Mar-18	3:04:00 PM	8.67	34.68
22-Mar-18	3:04:05 PM	8.42	33.68
22-Mar-18	3:04:10 PM	9.03	36.12
22-Mar-18	3:04:15 PM	7.32	29.28
22-Mar-18	3:04:20 PM	5.63	22.52
22-Mar-18	3:04:25 PM	8.77	35.08
22-Mar-18	3:04:30 PM	8.79	35.16
22-Mar-18	3:04:40 PM	8.84	35.36
22-Mar-18	3:04:45 PM	6.98	27.92
22-Mar-18	3:04:50 PM	8.12	32.48
22-Mar-18	3:04:55 PM	6.66	26.64
22-Mar-18	3:05:00 PM	5.63	22.52
22-Mar-18	3:05:05 PM	7.21	28.84
22-Mar-18	3:05:10 PM	5.1	20.4

It is observed that Leakage current of LA = $4*I_3$ under such circumstances failure of LA chances are more. Empirical formula used to calculate life expectancy of LA, therefore
Actual Life (Years) = ((Expected life – leakage current)/300).
Normal life of LA is usually 15 Yrs. Due to dominance of third order harmonics significantly reduces life of LA.

4 ANALYSIS of Effect of Harmonics on Capacitors

The existence of harmonics in power grid due to increase in voltage and current through the capacitor. Though it is permissible that its power consumption with harmonics in power grid is 1.38 times of it power consumption without harmonics in power grid for membrane composite medium capacitor and its power consumption with harmonics in power grid are 1.43 times of the one without harmonics in power grid for whole membrane capacitor, the capacitor will have over-current and over-load, its power consumption will exceed the above values, then it will heat abnormally. The aging of insulation media will be speed up under action of electric field and temperature if more harmonics exist in power grid and go beyond the limitation of capacitor. Especially when the capacitor is installed in the power grid where voltage has been distorted, the harmonics in the power grid can be strengthened. The harmonics expanding phenomenon can turn up. In addition, the existence of harmonics tends to enable voltage to produce tip waveform. The tip voltage waveform easily induces partial discharge in the media. Because voltage changes now and then, partial discharge is intensive, the aging of insulation media is speed up and the lifetime of capacitor is lessened. It is noticed that if voltage is increased by 10%, the life-time of capacitor will be lessened by 50% around. Furthermore, the capacitor will be swelled up, broken and blasted under condition of serious harmonics. To prove the above facts case study has been carried out at Indrayani Steel, Forecast Pvt. Ltd, Pune on Transformer of 1500kVA, 11kV/440V and (Automatic Power Factor Control) APFC panel of rating 750 kVAR for power factor correction. Observations of 1500 kVA and APFC Panel are shown in Table 2.

Table 2: Observations of 1500 kVA and APFC Panel

As per IEEE 519 -1992 observation are taken at PCC			
1	Transformer KVA	1500	KVA
2	Transformer Impedance (Z %)	5.20%	%
3	Network Operating Voltage (V)	440	V
4	Short Circuit Current Capability for Transformer I_{sc}	37851	A
5	Load Current (I_L)	1093	A
6	Ratio of I_{sc} / I_L	34.63	
Hence as per IEEE 519-1992, for Ratio = 34 the compliance will be as under			
7	Limits for Voltage Harmonics (V_{THD})	5	%
8	Limits for Current Harmonics (I_{THD})	12	%

Observations:

As per survey, following problems are observed.Parallel resonance is observed in APFC Panel which is the cause of significant harmonics which results into frequent failures of capacitors & contactors Provision for harmonic correction is necessary.At high harmonic frequencies, the capacitive reactance is very less resulting in excessive current i. e. capacitor bank consequently acts as a sink for higher harmonic currents.

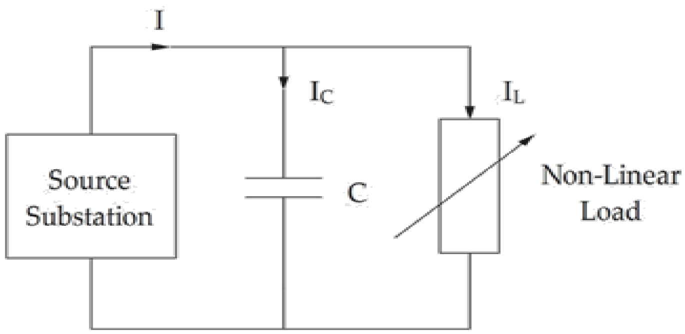

***Fig.1** General Diagram of source feeding to capacitor and non-linear consumer*

From the calculated values of capacitive reactance $X_{C.}$ It is found that Xc>>>X'c. Hence, Ic'>>>Ic; Ic'^2R>>>Ic^2R.It means that due to nonlinear loading condition total current supplied by source substation doesn't flow through the load but it will flow through the capacitor which leads to more heat generation across the capacitor. In such cases chances of capacitor failure is more.

Table 2: Observations at nonlinear load consumer (Shirval Substation, 11kV/440V) for Capacitor Bank

Sr. No.	Time	I(A)	V	p.f	$I_{3(A)}$	% I_{THD}	% V_{THD}
1	10.00AM	0.9	245	0.9	10	3.05	1.1
2	10.30AM	0.91	245	0.9	10	3.11	1.1
3	11.00AM	0.92	244	0.9	10	3.5	1.2
4	11.30AM	1.1	241	0.9	10.7	5.63	1.6
5	12.00PM	1.1	241	0.9	10.4	6.24	1.7
6	12.30PM	1.31	242	0.9	10.1	6.37	1.7
7	1.00PM	1.36	244	0.9	10.3	7.52	1.81
8	1.30PM	1.41	245	0.9	10.02	7.92	1.84
9	2.00PM	1.43	245	0.9	10.41	7.99	1.88
10	2.30PM	1.49	241	0.9	10.5	8.21	1.89
11	3.00PM	1.5	240	0.9	10.51	8.69	1.95
12	3.30PM	1.54	244	0.9	10.63	9.19	1.98
13	4.00PM	1.57	243	0.9	10.66	9.81	2.1
14	4.30PM	1.61	243	0.9	10.68	10.05	2.14
15	5.00PM	1.68	243	0.9	10.74	10.18	2.19

Table 2: Calculated Values for (Shirval Substation, 11kV/440V) for Capacitor Bank on the basis of above observations

Sr No.	I_H	V_H	Xc	X'c
1	0.02745	2.695	272.2222	98.17851
2	0.028301	2.695	269.2308	95.22632
3	0.0322	2.928	265.2174	90.93168
4	0.06193	3.856	219.0909	62.26385
5	0.06864	4.097	219.0909	59.68823
6	0.083447	4.114	184.7328	49.30075
7	0.102272	4.4164	179.4118	43.18288
8	0.111672	4.508	173.7589	40.36822
9	0.114257	4.606	171.3287	40.31263
10	0.122329	4.5549	161.745	37.23483
11	0.13035	4.68	160	35.90334
12	0.141526	4.8312	158.4416	34.13648
13	0.154017	5.103	154.7771	33.13271
14	0.161805	5.2002	150.9317	32.13869
15	0.171024	5.3217	144.6429	31.11669

5 CONCLUSION AND DISCUSSION

From the result of the harmonic survey done at various voltage levels in power system networks, it is observed that current harmonic levels are substantial. The higher level of current harmonic distortion causing overloading, overheating of transformer and other substation equipments and it adversely affects the life expectancy of these equipments. Although this study does not give accurate results but it gives an idea about the effect of harmonics on distribution transformer.

In short, the experimental study leads to following conclusions.
1. Compared to primary side more harmonics are present on secondary side of the transformer.
2. In the vicinity of non-linear loads, current on secondary side, where nonlinear load is connected, is higher than the rated current. This may lead to tripping of transformer due to over current, although actual load is not increased.

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