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Selection of an optimum flux density to offer reduced core loss and its effect on temperature rise of transformers

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Commonly used grades for transformer core stampings are Cold Rolled Grain Oriented Steel of grades M3, M4, M5 and M6. As the flux density increases, the magnitude of no load loss and no load current increases. But studies also indicated that, a given magnitude of core loss can be attained with both high and low magnitudes of no load current. This result can be used to ascertain the presence of inferior grade core material. It is essential to operate the transformer in the linear region of BH curve. Operation in saturated state will result in increased no load current which in turn will have a detrimental effect on the temperature rise of transformer as additional I^2R losses are generated. With the limits of temperature rise being more stringent in IS standard than in IEC, the choice of flux density is crucial. In this paper an attempt is made to realize the best operational flux density, which gives a benchmark for deciding the magnitude of no load current and the corresponding no load power factor.

Keywords: *No load losses, copper losses, temperature rise, CRGO*

1.0 INTRODUCTION

With the view of transmitting bulk power over longer spans, utilities and power industries all over the globe are resorting to High Voltage AC (HVAC) and High Voltage DC (HVDC) transmission systems. The transmission of power from remote locations of generating station, to villages, urban and sub urban areas of load centers; with minimal losses poses a challenging job. To address this issue, HVAC transmission was started [1].In India 400 kV transmission lines are more predominant as compared to 765 kV transmission lines [2]. Due to limitation in transmitting power over longer distances in AC systems, HVDC transmission came to existence. At present, only a few number of ±500 kV HVDC transmission lines are in operation in India. An Experimental line of capacity 1200 kV AC, over two kilometer, to validate the design of the equipment's like transformer, circuit breaker, lightning arrestor, current transformer, capacitive voltage transformer etc. is available at Bina, Madhya Pradesh [3]. A HVDC line of rating ±800 kV is under progress for further development.

Various losses in a power system comprises of transmission losses, corona losses and losses incurred in transformer circuits. In this paper, a study is made on transformer losses, namely no load losses or core loss and load losses or copper loss, its effect on temperature rise on different transformers. Also, an attempt is made to realize the best operational flux density in laboratory to set a benchmark for deciding the magnitude of no load current and the corresponding no load power factor.

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2.0 TRANSFORMER LOSS

2.1 No load loss and copper loss

The no load losses of a transformer depends upon the quality of core used, the flux density selected and Watts/kg of the core used. Majority of the transformer manufacturers use high quality, primary grade Cold Rolled Grain Oriented steel (CRGO) for core material. But the core loss also depends upon the grain orientation of CRGO steel. During the multiple processing treatments of annealing and punching, these grain orientations are susceptible to change. During cutting of core, the grain orientation is to be made parallel. This will ensure that the magnetic properties of CRGO are retained to the maximum extent [4]. If a higher degree of freedom is given for grain orientation in CRGO steel, substantial differences in mechanical properties in the direction of rolling will be attained. Even a marginal small change in the orientation of grains will cause a significant increase in the no load current [5].

Apart from core losses, copper losses also play a significant role in temperature rise of transformers. Copper loss mainly depends on the purity of the material used in primary and secondary windings, and also on the current density of winding material. During the measurement of load losses, to pass the rated full load current at the secondary, a small voltage is applied to the primary. The active power needed to pass the full load current will be very small. Since the power is mostly reactive in nature, the power factor measured will be in the range of 0.02 to 0.04.

2.2 Effect of stacking factor

Yet another factor which influences the core loss is the lamination or stacking factor. By definition, lamination factor is the ratio of calculated volume to the measured volume at a given lamination stack pressure and is expressed in percentage. The typical values for lamination factors at 50 psi for grain oriented electrical steel, in variety of thickness and finish varies from 95% to 98%. Certain categories of grain oriented electrical steel requires stress-relief annealing to reduce the mechanical stresses and to yield optimum magnetic properties[6]. This process will also prevent the contamination of steel with oxygen and carbon and thereby improving the insulation property. Annealing is generally carried out in the range of 760°C to 845°C in the presence of an inert protective atmosphere to protect the steel from oxidation[6].

3.0 TEMPERATURE RISE TEST ON TRANSFORMER

During temperature rise test on transformer, the total losses i.e., both the no load loss and load loss will occurat a low power factor. Any change in no load power factor will affect the magnitude of no load current which in turn will influence the temperature rise of transformer winding. If the total current carrying capacity of a transformer is considered, then it is always viable to have a smaller current with higher power factor than a higher magnitude of current with lower power factor for same no load losses. This will ensure the use of reduced conductor size in transformer windings. When the above conditions of no load loss is paraphrased in terms of active and apparent power, it can be said that, active power (W) will have lower power factor with more apparent power (VA), and active power (W) will have better power factor with low apparent power.

National and International standards followed for temperature rise test on transformers namely, IS 2026-2 and IEC 60076-2, makes no explicit mention to a defined set limits of no load current. In many cases, due to the lack of coherent information, it is mutually decided between the transformer manufacturers and the customers. However these losses are culpable for temperature rise in transformers. The permissible limits for temperature rise differ in both National and International standards. In case of IS standard, the limits towards temperature rise are more stringent than counterpart IEC standard. The limit of temperature rise for winding and oil, as mentioned in IS 2026-2 is 55K and 50K respectively, whereas for IEC 60076-2 it is 75K and 65K respectively [7, 8].

4.0 LABORATORY STUDY OF CORE MATERIAL

4.1 Procedure for preliminary tests

Preliminary material studies and experiments were conducted in laboratory using the Epstein Frame system. Epstein frame is a standardized method of evaluating the magnetic properties of electrical steels. The instrument comprises of primary and secondary windings, and behaves as a transformer. The test specimen is assembled from various strips, overlapped at edges and is weighed down by a force of 1N [9].

There are four grades of CRGO for transformer cores namely M3, M4, M5 and M6 of stamping thickness 0.23, 0.27, 0.30 and 0.35 respectively. Commonly used grades however are M3 and M4. Tests using the Epstein frame method were performed on 220µm thickness core stampings,with effective polarization as the running parameter with results tabulated in Table 1. Fig.1 and Fig.2 shows the variation in exciting current, no load loss and flux density as a function of inductionfor a typical M3 and M4 core material respectively [10].

4.2 Procedure for temperature rise test

Temperature rise test on transformers is performed to ascertain the temperature rise of windings and oil. The test is performed in two steps namely, the total loss injection and rated current injection. The transformer is subjected to a test voltage such that the input power equals to the total losses namely no load loss and copper loss; the input current will be above the rated current so as to simulate the additional no load losses.

Temperature of oil and the cooling medium is observed for a steady state oil temperature. When the rate of rise of oil temperature has fallen below 1K/hour and is maintained for 3 hours, the input voltage is reduced till full load current is reached and is run 1 hour, following whichthe test is terminated. Average temperatures of the two windings are determined from measurement of resistances [7].

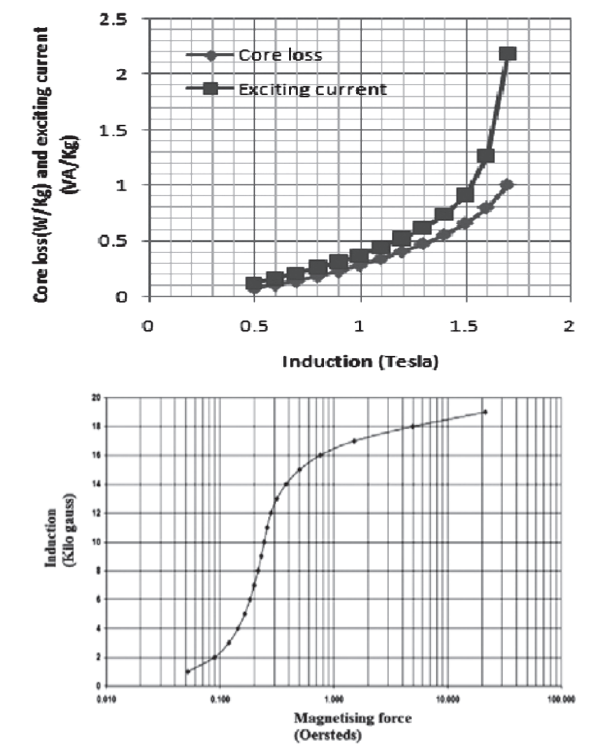

FIG.1 VARIATION OF CORE LOSS, EXCITING CURRENT AND INDUCTION WITH MAGNETISING FORCE FOR M3 GRADE CORE STAMPINGS

In this study a total of 32 different transformers were subjected to temperature rise test; load loss, total loss and temperature rise of oil and windings are noted down. Table 3 shows the measurements taken on representative transformers, with details limited to maximum temperature rise in each rating of transformer studied. During temperature rise test on these transformers no load losses were performed with voltage applications at 90%, 100% and 110%.Corresponding no load current, no load losses and power factor were also tabulated as in Table 2.

The purpose of this excise done could be explained in two fold manner. The tests performed at material level throws light on the variation of core loss, exciting current and induction with magnetizing force. These parameters enable to identify and understand the basic properties and type of transformer core stampings. Secondly, during laboratory testing of the transformers, these data especially core loss and no load current at100% voltage application, can be used as a reference to ascertain the grade of the material. With the above information, an attempt is made to deduce the optimum operating flux density that ensures low core loss.

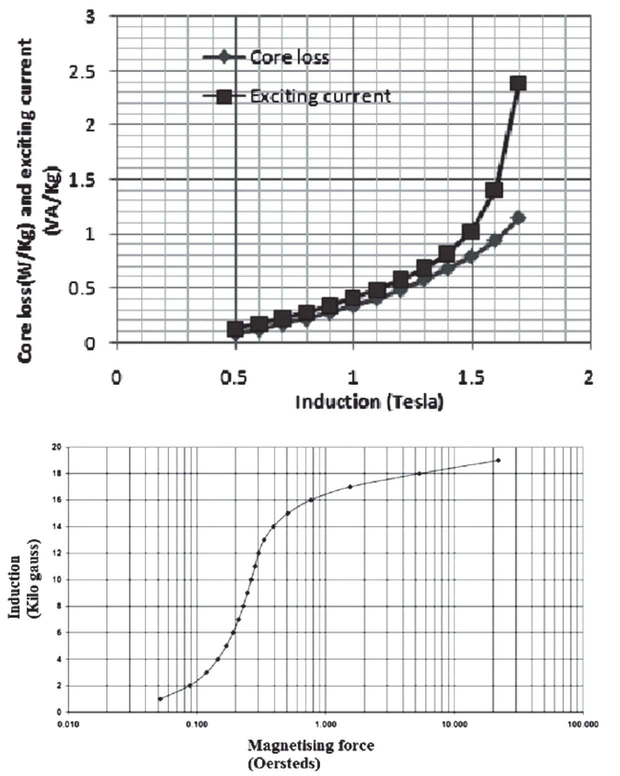

FIG.2 VARIATION OF CORE LOSS, EXCITING CURRENT AND INDUCTION WITH MAGNETISING FORCE FOR M4 GRADE CORE STAMPINGS

5.0 RESULTS AND DISCUSSION

Results of material testing on M3 core of 220 μm stamping thickness, using Epstein frame method are tabulated in Table 1. From this it is observed that with the increase in polarization, the magnitude of core loss, no load current and the corresponding power factor has increased. The power factor at 1.5T is around 0.62 and apparent power is 0.9 VA/kg while at 1.7 T, power factor is 0.43 and correspondingly the exciting current has increased by two fold times. From this observation it is clear that even a change as small as 0.2T, causes the power factor and exciting current during no load test to vary drastically.It is also evident that a core loss of 'x' W can be achieved with different apparent power and with different power factors. This raises a profound question regarding the grade of material used. Prime grade of CRGO stampings ensure low magnitude of no load current and higher power factor. But, a secondary grade or inferior grade CRGO stampings shows higher magnitudes of no load current and low power factor. In either case, the core loss is found to be marginally varying.

TABLE 1

VARIATION IN CORE LOSS, EXCITING CURRENT AND POWER FACTOR WITH POLARIZATION FOR STAMPINGS OF THICKNESS:220MM

Sl No	Effective Polar-ization (Tesla)	Core Loss (W/kg)	Excita-tion Cur-rent (VA/kg)	Imax (A)	Power Factor
1	0.99998	0.25251	0.3487	0.0223	0.7240
2	1.4998	0.56241	0.9051	0.0474	0.6210
3	1.6000	0.68351	1.2300	0.1206	0.5600
4	1.7000	0.80996	1.8890	0.1206	0.4280
5	1.8865	1.41360	13.470	1.0787	0.1050
6	1.8892	1.39230	13.620	1.0703	0.1022
7	1.8763	1.35910	13.630	1.0809	0.0997
8	1.8924	1.31010	13.500	1.0754	0.0970
9	1.8934	1.29410	13.440	1.0754	0.0960
10	1.8988	1.48050	16.910	1.3417	0.0896
11	1.9013	1.45810	16.940	1.3317	0.0860
12	1.8889	1.42090	16.840	1.3428	0.0840
13	1.8932	1.43590	17.300	1.3572	0.0830

TABLE 2

VARIATION OF NO LOAD LOSS, NO LOAD CURRENT AND NO LOAD POWER FACTOR AT 90%,100% AND 110% VOLTAGE APPLICATION FOR 12.5MVA,10MVA AND 8MVA POWER TRANSFORMER

Sl. No	MVA	%V	Vph	Iph	No Load Loss (W)	Power factor
1.	12.5 66/11 kV	90%	5715	0.47	6205.6	0.76
		100%	6351	0.62	7615.3	0.61
		110%	6985	0.85	9196.8	0.52
2.	12.5 66/11 kV	90%	5715	0.715	4460	0.36
		100%	6351	1.557	6380	0.22
		110%	6985	4.06	10288	0.12
3.	10 110/11 kV	90%	5715	0.468	6078	0.76
		100%	6351	0.518	7565	0.77
		110%	6985	0.602	9519	0.75
4.	8 66/11 kV	90%	5716	0.513	5685	0.65
		100%	6350	0.819	7222	0.46
		110%	6986	1.493	9117	0.29
5.	8 66/11 kV	90%	5716	0.418	5543	0.77
		100%	6350	0.597	6944	0.61
		110%	6986	0.987	8720	0.42

Table 2 is a consolidated table showing the no load current, no load losses and the power factor for power transformers of rating 12.5 MVA 66/11 kV, 8 MVA 66/11 kV and 10 MVA 110/11 kV from manufacturers A and B obtained from laboratory tests. From this table it is evident that for a particular voltage application, the no load power factor was seen to vary from 0.22 to 0.77 for 100% voltage application. This variation suggests the presence of a different grade core material in the transformers, even though they both are taken from the same manufacturer. Table 3 gives the copper losses and total losses measured during the temperature rise test performed on representative thirty two transformers. During type test of transformers, when the variation of flux density against no load current and no load power factor is observed,it is seen that as the flux density exceeds 1.7 T, the excitation current or apparent power consumed for same induction is very much on higher side with a lower value of power factor.

Fixing the flux density at 1.7 T will result in a higher magnitude of exciting current with low power factor causing a definite rise in temperature, along with an increased consumption of reactive power. Often magnitude of no load current become critical when the winding temperature and transformer oil temperature comes in close margin to the limit prescribed in the national and international standards.

Measurements taken at 1.9 T revealed a higher intake of both apparent power and reactive current leading to temperature rise. Choice of operation at 1.9 T, forces the transformer to go into saturation, where in any small increase in input voltage will further saturate the core and add to additional temperature rise. Measurements made at 1.5 T proved to be most satisfactory as the excitation current or apparent power observed was only 0.9051 VA/kg, where as for 1.7 T is was recorded at 1.889 VA/kg. Also at 1.5 T operation the power factor measured is 0.62 while that measured at 1.7 T it is 0.42 and at 1.9 T the power factor measured is 0.08. From the above observation it is clear that transformers are to be operated in the range of 1.5 T to 1.7 T, which falls in the linear region of BH curve.

TABLE 3

VARIATION OF LOAD LOSS, TOTAL LOSS AND TEMPERATURE IN 8 MVA, 10MVA AND 12.5MVA POWER TRANSFORMER FORM MANUFACTURERS 'A' AND 'B'

Sl No	R* MVA	Vph (V)	Iph (A)	Load Loss (W)	Total Loss (W)	Oil Max Temp (^{0}C)	HV$ Avg.T (^{0}C)	LV** AvgT (^{0}C)
1	8	526	420	36910	52500	32	43.2	40.1
		526	422					
		541	418					
2	8	483	422	38680	51400	35	50.1	44.4
		488	422					
		483	417					
3	10	585	526	35450	47100	31	46.7	44.7
		609	530					
		599	519					
4	10	600	529	34790	48100	29	48.8	45.1
		604	525					
		605	521					
5	12.5	595	659	39550	53900	34	46.4	41.9
		612	658					
		606	652					

*R stands for rating in MVA, $ and ** refers to average temperature rise of HV and LV winding respectively.

In the present study, the maximum no load current measured at customer works is4.06 A as seen in Table 2. Maximum temperature recorded for high voltage winding, low voltage winding and transformer oil is 50.1^{0}C, 45.1^{0}C and 35^{0}C respectively.

6.0 CONCLUSION

In this paper a quantitative analysis was performed on thirty two different power transformers with different kVA ratings from different manufacturers. The data collected during material tests in laboratory and at customer works, has been tabulated. Load losses and core losses for different flux densities have been recorded. It is found that testing and operation of transformers at 1.5 T yields the relatively lower magnitude of no load current and higher corresponding no load power factor as opposed to the case of testing at 1.7 T and 1.9 T. Even a small variation in the flux density level as small as 0.2 T is found to change the values of no load power factor drastically. As the magnitude of no load current increases, results of temperature rise test could be compromised, as it is actually the change in flux density that causes an increase in the magnitude of no load current, which in turn increases the I^2R losses. The temperature rise in transformer can be attributed to either core operating at nonlinear region or saturation or use of secondary core material in transformer at the time of assembly.

The work is further continued to evaluate the presence of inferior or secondary grade core stampings used in transformer. A measurement technique used to determine the same is being studied.

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