DEVELOPMENTAL STUDIES OF A SUBMERGED ARC FURNACE TRANSFORMER

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Abstract: *For steel making, electric arc furnace (EAF) is preferred rather than oxygen furnace method because of its lower capital cost, less energy requirement, flexibility, can be rapidly started and stopped and allowing varying production according to the demand. EAF can effectively remove the sulphur, phosphorous and other impurities and is suitable for high quality steel smelting. The modern submerged electric arc furnaces are highly efficient recycler of steel scrap. This paper discusses about the design and analysis of a submerged arc furnace transformer of rating 1MVA, 11kV/200-133-80V.*

Key words: *Electric arc furnace transformer, steel making, oxygen lancing, constant kVA, constant current*

1. INTRODUCTION

The increasing demand for Ferro-alloy and oxidation agents in steel making in the beginning of the 20th century led to the development of the first furnaces. DEMAG started the construction of the first submerged arc furnace in 1905 [1]. With the development of electrode systems, advanced transformer technology, submerged electric arc furnace has emerged as one of the most efficient and economically feasible method of steel making and has found applications in Iron & steel industry, Non-ferrous metal industry, Refractory & grinding industry and chemical industry [2].

Conventional transformers do not produce a very high current which is required for melting of metals. Normal transformer has constant flux variation and voltage principle whereas "Falling Flux Density" is the specialty of submerged arc furnace transformer producing desired high current for melting. Industrial electric arc furnace temperatures can be up to 1,800 °C, while laboratory units can exceed 3,000 °C.

The melting process in an arc furnace can be divided into two periods, which largely differ from each other in the energy to be consumed i.e. the period of melting of solid charge and that of refining of the metal.

During the former the charge materials must be heated to their melting point and this temperature is maintained till full meltdown. During this period the power supplied to the furnace is more. Later the energy is needed mainly to compensate the heat losses, since the furnace and metal have already been heated to the specified temperature. The heat required to melt down the additives and for refining is substantially lower than that needed to melt the main charge [3].

1.1 Principle of Operation of EAF

The schematic of submerged arc furnace transformer is shown in fig 1.The furnace is charged with recycled steel scrap and the roof is closed. The three phase supply from an EAF transformer is given to the graphite electrodes. Graphite electrodes are preferred because they withstand high temperatures and are good conductors [3]. These electrodes are lowered towards the scrap and electric arc strikes between electrodes and metal mass and scrap starts melting. Initially the currents are very high and proper control mechanism is required to move the electrodes to bring the current to normal limits [4]. Power is controlled by varying the arc distance between electrodes or by varying the applied voltage to the electrodes [5-6].

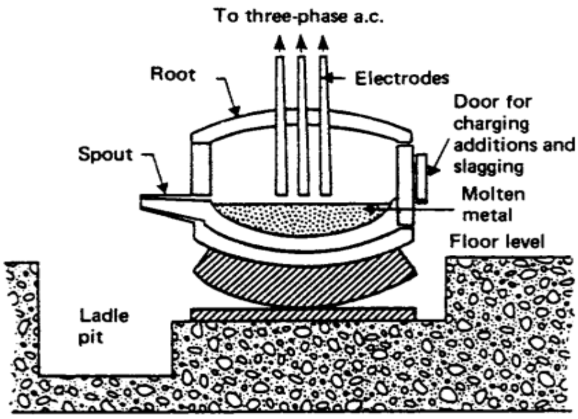

Fig 1. Schematic of submerged arc furnace transformer

1.2 Significance of Submerged arc furnace transformer

The advantage of electric arc furnace transformer is that it can be precisely designed for each application, which requires different voltages, currents and power. The most significant factor of this transformer is its constant kVA, when secondary side voltage is approximately above 133V and constant current when secondary side voltage is approximately below 133V. The voltage levels are decided based on the process requirements.

Initially more power is required to melt the raw material or scrap. After some time the material does not require that much of power. Hence when metal gets melted completely the capacity is reduced, but the current is kept constant. The current is maintained constant to maintain the temperature of the molten metal and to obtain a uniform homogenous mixture. Additives can also be added at this step.

During the operation of furnace transformers, low losses and less noise are achieved by keeping initially high flux density as 1.77T at first tap for economical design and it is for only a very short duration of time, and at every successive taps the flux density reduces. Hence this transformer is called Falling Flux transformer.

2.0 LITERATURE SURVEY

The work (design, development, parameters estimation and power quality problems) carried out by the earlier researchers in the area of electric arc furnace transformers are briefly presented below:

The power in an arc furnace transformer is regulated by adjusting the arc length and changing the transformation ratio. Tappings are done by changing the number of turns preferably on low voltage winding to achieve high output current. Korn et al [7] presented the simulation and experimental results of power electronic transformer tap changer used for high rating arc furnace transformer.

Electric arc furnaces cause power quality problems like harmonics, voltage sag, unbalance etc. Jagiela et al [8] presented the digital measurement of arc current using Rogowski coil, arc voltage. Also, arc furnace model was developed in Matlab software and simulation was carried out. The arc voltage, arc current, total harmonic distortion and active power of harmonics on the secondary side of the arc furnace transformer were estimated.

Electric arc furnace absorbs more reactive power, causing voltage fluctuations and harmonics distortion. Che Xuezhe et al [9] described a high impedance electric arc furnace with a fixed reactor. Experimental results reveal that, this high impedance arc furnace resulted in low energy consumption, reduction in the capacity of compensating devices, reduction in the level of voltage flickering and improved arc stability.

In arc furnace transformer, variable current is produced due to variable arc resistance of individual phases and is dependent on arc length. This leads to voltage unbalance. SVC or STATCOM compensating devices are used to reduce flickering to a great extent. Martin Cernan et al [10] developed a mathematical model for high arc currents as well as low arc currents. This model finds importance to use SVC for reactive power compensation, passive resonant filter for eliminating high harmonics and active filters (UPQC) to reduce the flickering.

3.0 DESIGN OF SUBMERGED ARC FURNACE TRANSFORMER

The flow chart for designing of submerged arc furnace transformer is shown in fig 2

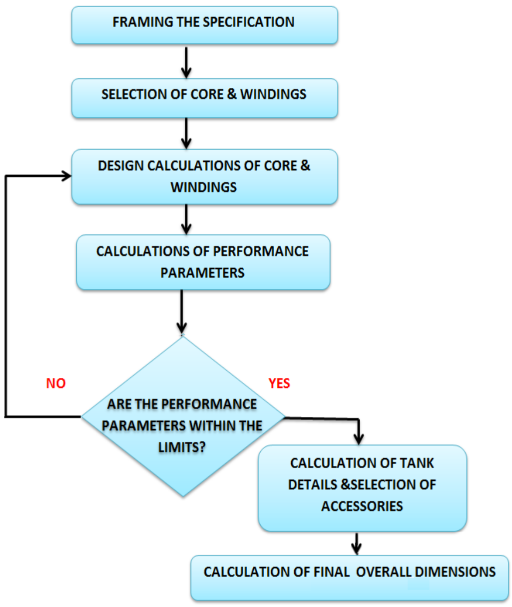

Fig 2. Flowchart for design of EAF

3.1 Design of winding

The HV main winding consists of 381 turns and a maximum LV voltage of 200V is obtained. The tapings are done by dividing the HV turns of each tap into groups called FINES. Fine1 (F1) has 190 turns, Fine2 (F2) has 191 turns and Fine3 (F3) has 190 turns. The disposition of windings depends on impedance. Impedance depends on ampere turns, gap between HV and LV, voltage per turn and height of the windings. The impedance of a furnace transformer must be between 4 to 6%. By placing HV winding near the core, then F1, F2, F3 and LV winding are placed successively which gives an impedance of 5.9%.

3.2 Design of voltage table

The rating of EAF is 1000kVA, 3ph, 50 Hz, 11000/200-133-80V, ONAN cooled, vector group Y-Δ iii. Fix the values of primary side voltage equal to 11000V and secondary turns to 12. Here in this case, the principle followed is for secondary voltage greater than 133V, constant kVA is maintained and for secondary side voltage is less than 133V, constant current is maintained. Table 1 gives the voltages and capacity for different tapings.

Table1: Voltage variation table

Tap No	HV Turns	HV Current (A)	kVA	LV Current (A)	LV side (V)
1	381	52.5	1000	2886	200
2	428	52.5	1000	3243	178
3	475	52.5	1000	3608	160
4	523	52.5	1000	3982	145
5	571	52.5	1000	4340	133
6	634	47.2	900	4340	120
7	698	43.0	819	4340	109
8	762	39.5	752	4340	100
9	952	31.6	601	4340	80

3.3 Design of core [13-15]

3.3.1 Parameters of a stepped core

From the given rated values of the transformer
Secondary voltage = 200V,
Secondary turns=12,
Frequency=50Hz and
B=1.73T, the EMF equation of a transformer is given by equation (1)

$E=4.44fBAN *10^{-6}$ ------------- (1)

Substituting the above values in equation (1), Net area, A obtained is equal to 43310mm^2 and

$$\text{Gross area } A_i = \frac{\pi D^2}{4} = \frac{\text{Net area}}{\text{packing factor}} = \frac{43310}{0.93} = 46570\ mm^2$$

Therefore, D=243mm

Inner diameter (ID) of conductor = outer diameter of HV + (2* radial height) ---- (2)

Outer diameter (OD) =ID + (2* radial height) –(3)

The eleven step core parameters are shown in table 2 and the schematic of core is shown in fig 3

Where D is the diameter of the core =243mm,

A is the centre distance and is given by

OD of HV winding + phase to phase clearance ---- (4) and is equal to 465+10=475mm,

Table 2: stepped core parameters

Steps	Width mm	Stack Mm	Gross Area mm^2	Net area mm^2	Σ Area mm^2
1	240	38	9120	8846	8846
2	230	40	9200	8924	17770
3	215	34	7310	7090	24860
4	200	26	5200	5044	29904
5	180	24	4320	4190	34094
6	160	20	3200	3104	37198
7	135	20	2700	2619	39817
8	110	14	1540	1493	41310
9	85	10	850	824	42134
10	60	8	480	465	42599
11	35	6	210	203	42802

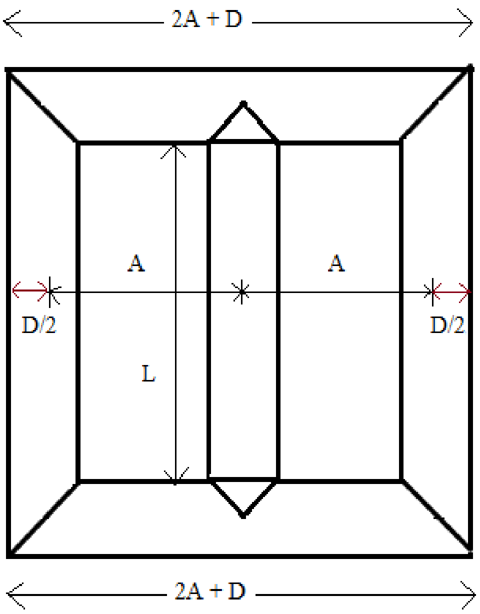

Fig. 3 Schematic of core

Winding length L=700mm and length of the core=4A+2D+3L --- (5) and is equal to 4486mm.
Weight of core= length * area*density of CRGO steel [11] ---- (6) and is equal to 1486kg.
Core loss=weight of core * specific loss * build factor ----- (7) and is equal to 1486*1.37*1.25=2545W

3.3.2 Design of core blades

3.3.2.1 Side limb

Length of side limb=L+D ---- (8) and is equal to 940mm,
Width=240mm,
Stacking factor =0.97,
Density of CRGO steel=7.65g/cc,
Core stack=38mm and from equation (6), weight of side limb= 940*240*0.97* 38* $7.65*10^{-6}$ =63.6kg

3.3.2.2 Centre limb

The schematic of centre limb is shown in Fig 4

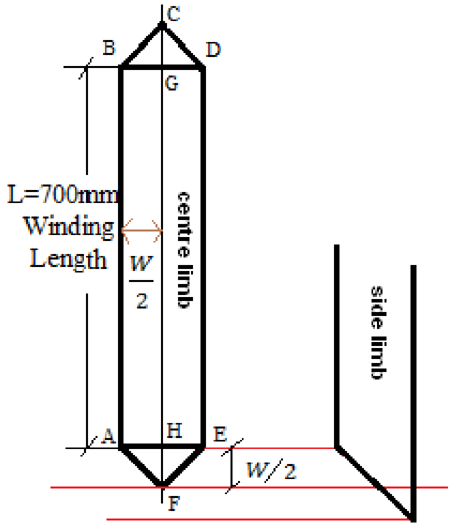

Fig 4. Schematic of Centre limb

From fig 4, total area of the centre limb= rectangle ABDE + area of four triangles (BCG, DCG, AFH & EFH) --- (9) and is equal to 196800 mm^2,
Stacking factor =0.97,
Density of CRGO steel [11] =7.65g/cc,
Core stack=38mm and
From equation (6), weight of centre limb= $196800*0.97*38*7.65*10^{-6}$=55.5kg

3.3.2.3 Top yoke

The schematic of top yoke is shown in Fig 5 Total area of top yoke is given by
Area of rectangle ABCD – area of triangles (EGH &FGH) i.e. 2AW – $(W^2/4)$ –-- (10) and is equal to 213600mm^2.
for stack= 38mm,
stacking factor =0.97 and
density=7.65g/cc,

the weight of top yoke is calculated using equation (6) and is equal to 60.23kg. and the weight of bottom yoke = weight of top yoke=60.23kg

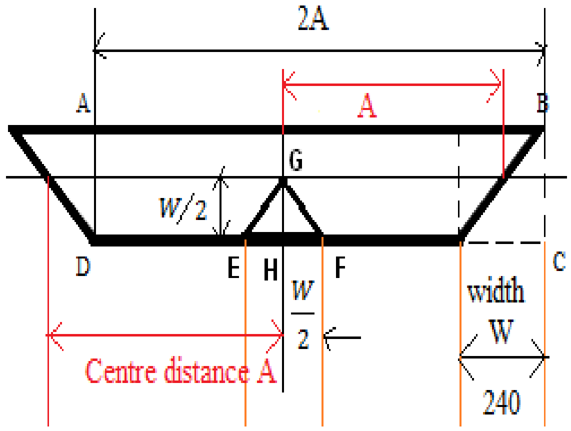

Fig 5. Schematic of Top yoke

3.4 Design of tank

The top view of the schematic of transformer tank with three phase windings is shown in fig.6

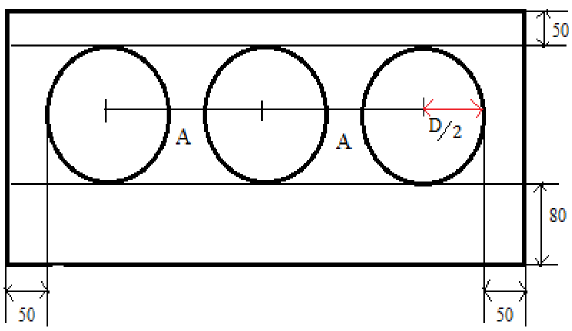

Fig 6.Schematic of top view of transformer tank

From fig 6, the centre distance is given by
A+ phase to phase clearance ---- (11) and is equal to 465+10=475mm,
Length of the tank = (2* tank to winding clearance) + OD of HV main + (2* centre distance) --- (12) and is equal to (2*50) + 465 + (2*475) =1515mm.
Width of the tank= winding to tank clearance at top and bottom (30mm extra + OD of HV main -- (13) and is equal to 50 +80+465 =595mm =0.595m.
Height of Tank = Winding length + Top and Bottom Yoke Diameters +clearance at bottom of tank + clearance at top of tank (for tap changer clearance) --- (14) and is equal to
700+ (2*240) +10+250=1440mm =1.44m

3.5 Design of winding

The line to line voltage is 11000V, voltage/phase= 6350V, Current/phase=52.5A, as it is a special case transformer choose current density (J) as 3A/mm^2, Therefore A=17.5mm^2. At the transposition points and when the conductors steps into next layer, the conductor is bent , during this process the conductor area at that bent portion is reduced , reduction in area due to corner radius [17] is considered, corner radius is considered. The corners are rounded instead of sharp edges to reduce the field intensity as radial forces are more at the corners and cause greater electrical stress in that region. Therefore, additional insulation is provided at these points. Gross Area =Net area + reduction in area due to corner radius=17.36 mm^2.

Maximum voltage on HV main is 11kV the voltage can vary a little due to overhang voltages, hence it is considered that HV main winding insulation is 22kV class. Therefore, clearance required is 12mm radially. From equation (2), Inner diameter of HV main winding = core diameter + (2*Radial height) = 243 + (2*12) =267mm

No of discs=54, turns/disc =7.05, if we choose mo of turns/disc as 7, the gap will be more and is not economical, if we choose 8, no of discs=48 and no of turns possible is 384, but we require 381 only. Hence, we use 3 dummy turns by replacing 3 turns in any 3 discs with pressboard of the same size of the conductor and using one turn per disc for correction.

3.5.1 Estimation of conductor size

From above, the values of various parameters obtained are given by,
Full discs=45,
Turns/disc=8;
No of turns=360,
Partial discs=45,
Turns/disc=7;
No of turns=21,
Oil duct thickness (t_o) =3mm,
Conductor insulation (t_c) =0.6mm,
winding length (l_w) = 600,
total no of discs (n) =48,
total compression of insulation (t_i) is 10% of (oil duct thickness + conductor insulation thickness)
Width of conductor without insulation (b) is given by $\left(\frac{l_w}{n}\right) - t_o - t_i - t_c \qquad --(15)$

and is equal to 9mm

Area= breadth * height --- (16), h= (A/b) ≈2mm

Therefore, choose HV conductor of 9 x 2p0.6

Similarly the conductor sizes for remaining windings are calculated.

Conductor size of Fine 1 is 2.5x7p0.6,

Conductor size of Fine 2 is 2.5x7p0.6,

Conductor size of Fine 3 is 2.5x4.5p0.6 and

Conductor size of LV winding is 10x3.6p0.6

In the above mentioned conductor size parameters 2.5mm represents the breadth of the conductor with insulation and 7mm indicates radial height and 0.6mm indicates the thickness of Kraft paper insulation.

3.5.2 Estimation of conductor parameters

Length of mean turn= $\pi * \left(\frac{OD+ID}{2}\right)$ --- (17)

Total length (l_T) of fine1=

(mean length * no of turns * no of parallel conductors* no of phases) + tolerance --- (18)

Resistance /ph of fine1 at 75°C

(Winding temp (55 °C) +ambient temp (20 °C))

$R_{ph} = \frac{\rho * l_{ph}}{A}$ ------- (19), Where Resistivity of copper [11] ρ = 0.02128 x 10^{-3} Ω-mm

Weight of bare conductor(w_c),kg is given by $\frac{(l_T * turns * area * no.of\ limbs * density\ of\ cu)}{10^6}$ --- (19)

Insulation weight w_i is given by

$\left(\frac{A_i - A}{A} * \frac{density\ of\ kraft\ paper}{density\ of\ copper} + 1\right) * w_c$ --- (20)

Ordering quantity, w_o is given by

Insulated weight + Extra copper required for leads ----- (21).

Copper of 100mm length is required for each lead.

Stray losses [12] are dueto the leakage flux comes in contact with mild steel, transformer tank wall and induce currents causing heat . These are of order 20-25% of total load losses[12].

% stray loss is given by

$$\left\{\sqrt{\frac{b*n}{(l_w - t_c)}} * strayloss\ factor * \frac{h}{10}\right\}^4 * \left(\frac{(turns/disc)^2 - 0.2}{9}\right) * 10^2 \quad ----(21)$$

$stray\ loss, w_s = 1 + \left(\frac{\%\ stray\ loss}{100}\right)$ ----- (22)

Load loss , W_L is given by

$load\ loss\ factor * w_c * J^2 * w_s$ ------ (23)

Estimation of various parameters for High voltage main winding, fine1, fine2, fine3 and LV winding were done based on the formulas mentioned in section 3.4.1 and summarized in table 3.

Table 3: conductor parameters

	HV	Fine1	Fine2	Fine3	LV
A , mm^2	17.63	16.95	16.95	10.7	815.3
J,A/ mm^2	2.98	3.1	3.1	2.95	3.07
h, mm	22	8	8	6	25
ID, mm	267	323	351	379	415
OD, mm	311	339	367	391	465
l_c, mm	908	1039.8	1128	1210	1383
R_{ph}, Ω	0.417	0.248	0.270	0.457	0.004
w_c, kg	162.7	89.3	97.39	65.6	360.7
w_i, kg	170	95	101.2	68.59	368
W_o, kg	175	98	104	70	375
W_s, %	0.50	1.192	1.192	2.04	3.37
W_L, W	3490	2090	2280	1390	8460

3.5.3 Heat dissipated in Transformer Tank

No load loss=2210W, From table 3 , the total load loss due to HV main, Fine1, Fine2, Fine3 , LV winding and lead loss (2000W) is equal to 19710W.

Heat dissipated is given by

$\left(\frac{55}{50}\right)^{1/0.7} * (No\ load\ loss + 1.1 load\ loss)$ – (24)

and is equal to 27380W

Only 4 sides of the tank are considered. Since the bottom plate does not contribute to any heat dissipation and we ignore the top surface of the tank as the LV and HV bushings are present and do not allow any heat dissipation by tank wall surface. As per standards [13] 500W/m^2 is dissipated.

Surface Area is given by 2(l + b) * h ---- (25)

and is equal to 2(1.515+ 0.575) *1.440 =6.0192 m^2

Heat dissipated by Tank = 6.0192 * 500

= 3009.6 W ≈ 3010 W.

Heat dissipated in Radiators is given by

Heat to be dissipated – Heat dissipated by Tank

= 27380 – 3010 = 24370 W.

As per standards [13] the heat dissipated by radiator is 450W/m^2.Therefore surface area= 243710/450 and is equal to 54.15m^2

3.6 Design of Radiator

It is a standard practice [16] to mount the radiators top pipe at a distance of 90mm from the lid and 10mm clearance at bottom of tank, top pipe & bottom pipe is of 240mm diameter and width of radiator=520mm.

Height of radiator is given by

Height of tank – clearances – pipe diameter -- (26) and is equal to 1100mm. Surface area/fin=1.144, no of fins is given by surface area / surface area per fin and is approximately equal to 52 fins

4.0 CONCLUSIONS

This paper provides a detailed analysis of a design of a submerged arc furnace transformer. Also gives a better knowledge to an electrical engineer who aims to design core, windings, tank and radiator for a transformer of rating 1MVA, 11000/200-133-80V or similar ratings. With the estimated parameters reduced losses, high reliability, increased efficiency and long life of transformer can be achieved. A production of a homogenous mixture is the main purpose of these furnace transformers. Initially more power is required to melt the raw material or scrap. Therefore the submerged arc furnace transformer with LV side voltages above 133V is operated at full capacity i.e. 1MVA. Later the material does not require much power hence the EAF is operated at less capacity i.e. 601kVA for LV side voltages below 133V. The LV side current of 4340A was kept constant to maintain the temperature of the molten metal and to obtain a uniform homogeneous mixture. Tapping's on HV side were done by using Fine -1, Fine -2 and Fine -3 windings.

5.0 ACKNOWLEDGMENTS

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NOMENCLATURE

STATCOM=static synchronous compensator
SVC = Static VAR compensator
UPQC= Unified Power quality conditioner
D = diameter of the core, mm
A = centre distance, mm
ID =Inner diameter of conductor, mm
OD =Outer diameter of conductor, mm
A_i = Gross area of the core,mm^2
A = Net area,mm^2
f = Supply frequency, Hz
B = Flux density, tesla
HV = High voltage
LV = Low voltage
CRGO = Cold rolled grain oriented
L = Winding length
t_o = Oil duct thickness ,mm,
t_c = Conductor insulation, mm,
l_w = Winding length ,mm
l_{ph} =Winding length per phase ,mm
n = Total no of discs,
t_i = Total compression of insulation,mm
b = Width of conductor without insulation ,mm
b_i = Width of conductor with insulation ,mm
h = Radial height
W_s = Stray loss
W_L = Load loss
l_m = Length of mean turn
l_T = Total length of winding
R_{ph} = Resistance per phase
ρ = Resistivity
A = Area of the conductor,mm^2
J = Current density, A/ mm^2
w = Weight of bare conductor, kg
w_i = Weight of conductor with insulation, kg
w_o = Ordering quantity of conductor, kg

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