Design and Analysis of 1.5KVA Leblanc Connection Transformer

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Abstract : Various types of specially connected transformers have been adopted in order to reduce the system imbalance causedduetonon-linearloadsandfortheconversionfromthree phase to two phase or two single phase and vice versa. Leblanc is one such special connection transformer. The modeling of Leblanc transformer is analyzed in this paper, with detailed documentation of the transformer design, its connection, protection,advantagesandapplications.Basedonitsconnection diagram, the design parameters are calculated theoretically, according to international standards. In order to validate its application for the reduction of voltage and current unbalance, the simulation is done using MATLAB**.**

Index Terms **- connection, system unbalance, MATLAB.**

I. INTRODUCTION

In many situations, three-phase AC power supply is not always the best option for utility applications. In fact, there is a need of three- phase to single-phase, three-phase to dual-phase and three-phase to multiphase transformers, for various applications around the world.

The main reasons for the above mentioned transformations are: to supply an existing two phase system from a three phase supply, to supply two phase furnace transformers from a three phase source and in applications where there is high current requirement for a single phase load. The phase-to-neutral voltages in two phase systems are 90° out of phase with each other.

One of the main problems that occur in AC power systems is the voltage and current unbalance due to the asymmetric operation during three phases to two phase conversion. This asymmetric operation produces negative and zero sequence current. If these currents exceed the allowable limits, the system will suffer more losses and heating effects and will turn out to be less stable, also leading to failure in some cases. This is aggravated by the fact that a small unbalance in the phase voltages can cause a disproportionately large run balance in the phase currents. Distortion caused in voltage and current is very common in railway traction systems which predominantly work on non-linear single phase loads. Another major problem in the railway traction system is the voltage fluctuation caused due to sudden shifts in traction loads. A switch of traction load from one supply section to the adjacent section connected to a different substation gives rise to a step change in voltage which again gives rise to fluctuations in the public grid voltage and affects the operation and performance of connected voltage sensitive loads. The main application of Leblanc transformers is to reduce voltage and current imbalance caused due to uneven loading in railway systems. This imbalance in the three- phase power system, coming from unbalanced loads, un-transposed transmission lines, blown fuses on power factor correction capacitors, etc., has been in existence for a longtime.

II. REDUCINGVOLTAGEIMBALANCE

The railway is a large power consumer that can cause uneven loading of the phases in the high voltage grid. This uneven loading by the utility may lead to voltage and current imbalance in the system and thereby affect other consumers connected to the same network.

A three-phase power system is said to be balanced or symmetrical, if the voltages and currents have the same amplitude and each phase has a phase difference of 120°. Otherwise, it is termed an asymmetrical or unbalanced power system. A perfectly symmetrical power system does not occur due to some internal effects such as mutual coupling.

Voltage unbalance occurs mainly due to unbalanced currents at the points of common coupling drawn by unevenly distributed loads. Due to a significant amount of negative sequence current being injected into the system, the power system components will suffer from consequent negative effects such as overheating, additional losses of lines and transformers, interference with communication systems etc.

In order to reduce the effects of unbalance, several techniques can be applied depending upon the technological justification. A basic solution would be to distribute the loads evenly between the different phases. However, this method alone will not be sufficient due to the different traffic intensity occurring at each substation. The possible solutions can be categorized into two different types. First one is based on transformer connections, i.e. passive solutions. There are various types of specially connected transformers being employed in the railway substation, such as Scott transformer, V-V transformer, Leblanc transformers etc., and each connection has its own influence on treating the imbalance. These transformers are widely used in electrified railway systems as a load balancer.

Electrification of a railway line implies that the line can be operated by electric trains apart from diesel. Electrification involves large investments compared to diesel but operating costs are lower, as propulsion and maintenance are cheaper.

The second one is based on controllable high voltage power electronic equipment, i.e. active solutions such as Conventional Static Var Compensators (SVC) or Voltage Source Converters (this part is not within the scope of this paper.

III. LEBLANC CONNECTION

A Leblanc connection is used for transforming a three-phase to a two-phase supply (or two single-phase supplies) or vice versa and can reduce the degree of voltage imbalance especially in systems with small short-circuit capacity. The LeBlanc transformer provides one of the best unbalance mitigation strategies. It is usually composed of two, three- winding transformers and one, two-winding transformer.

It falls under the Dii vector group i.e. the primary of the Le Blanc-connected transformer is connected in three-phase delta, to transform three phase to two phase, which is the normal interphase connection in case of a step-down unit supplied from a HV source. This type of connection on the primary side has an apparent advantage of suppressing the third-harmonic voltages. For two phase to three phase conversion, it's more convenient to connect the secondary in three phase star connection. The secondary is open connected and is made of five windings, which are separated into two phases, as shown in figure below.

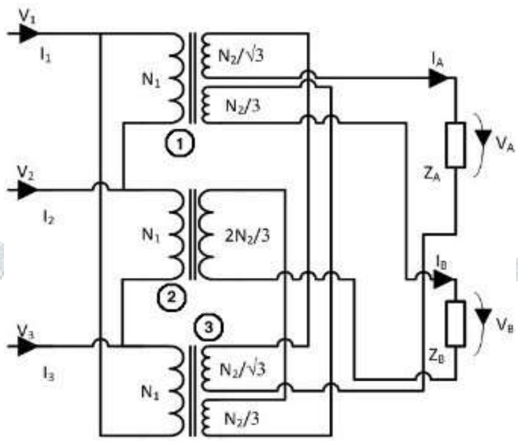

Fig. 1. Leblanc transformer connection diagram

A three-phase, three-limb core design is used for the development of a Le Blanc transformer, and hence one tank is sufficient. This makes the transformer more economical in floor space, having better balancing features, easy manufacturing and less maintenance compared to Scott transformers.

The phasor diagram of Leblanc is as shown in figure2, which shows the normal delta connection and two parts of the two phase secondary output, separated by an angle of120°.

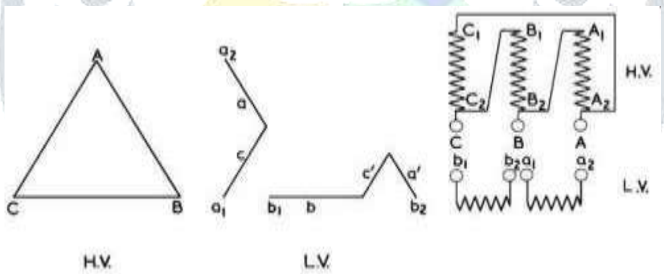

Fig. 2. Phasor diagram of Leblanc connection

The Leblanc connection can be used to setup either two-phase three- wire or four-wire output windings. When supplying a balanced three-phase load from a star-connected secondary the regulation of the Le Blanc transformer will be comparable with that of a three- phase star/star-connected transformer. If it is required to load the transformer windings between line and neutral, which would cause appreciable unbalanced loading, tertiary delta-connected winding should be provided

IV. DESIGN PARAMETERS OF LEBLANC TRANSFORMER

Using standard formulas, the various parameters of the transformer core, HV winding and LV winding has been calculated. The tolerance for some of the design parameters according to international standards and the specifications calculated for each of the transformer parts are listed below:

Table 1. Name plate details of the transformer

Parameters	Leblanc connection
Capacity	1500VA
Frequency	50Hz, +/- 5%
Rated voltage	415V/110V
Primary	Delta
Secondary	Single phase, open connection
Insulation type	Class F
Cooling	Air natural
Vector group	Dii
Total mass	19.3kg

Table 2.Tolerance levels to be maintained

Load loss and no load loss	+15% each
Impedance	+10%
Stray loss	+10%
Limit for class F transformer	90℃

4.1 Design of transformer core

- Diameter (D) = 40mm, Window height(L) =120mm, Centre distance(A) = 80mm.
- Gross Core cross section: Width x Depth=40mmx55mm=2200 Sq. mm.
- Consider, 3% reduction for insulation, another 7% reduction for stacking
- Thickness for sheet taken is 0.3mm
- Stacking factor: Depth/Thickness of sheet= 55/0.3 = 184 Sheets.
- Net Core Area is 90 % Gross Core Area (10% taken for insulation) that is 90% of 2200 = 1980 sq mm.
- Area of core= 1980 mm^2
- Length of core =2D + 3L + 4A = 2(40) + 3(120) + 4(80) = 760mm

Weight of core = volume x density = length x Area x density
= 760 x 1980 x 7.65 g/cc X 10^{-6}
= 11.6 Kg

Flux density is recalculated,B = (V/T)/ (4.44* f* A_i* 10^{-6})
= 0.557/ (4.44 * 50 *1980 * 10^{-6}) =1.268 T

From the Core Maker's Table, for 7.65 density and 0.35 thickness core (Grade 35 Rn 360)

The Specific loss per Kg @ 1.17 is 1.45 W and for 1.57 it is 3.6 W, Interpolating for 1.277:
= (3.6 -1.45)/50 x 27 + 1.45 = 2.611 W/Kg @1.277

Core loss equals = Core weight x specific loss x Buildfactor
= 11.6 x 2.611 x 1.3 = 40 W

Specific loss = 2.611 W/kg under 1.27 T

This particular loss can be achieved easily with available material in India

4.2 Design of HV Winding

Current = $\frac{capacity}{3 \text{ x} \frac{voltage}{phase}}$= $\frac{1000}{3 \text{ x } 415}$≈1.205 amperes

Considering hot rolled grain oriented silicon steel for core, the flux density can be approximated 1.4T.

E=4.44 x BAFN x10^{-6} Where B is in Tesla and A in mm^2

$\frac{E}{N}$ = 4.44 x 1.4 x 1980 x 10^{-6} x 50

N = $\frac{\text{voltage}}{\text{volts}/\text{turns}}$ = $\frac{415}{0.615}$ =675

675 is the minimum number of turns but anything above 675 will reduce the operating flux density.

Let the current density be 3 A/mm^2so as to reduce load losses considerably.

(Max. Permissible current density as per Indian standards is 3.64 A/mm^2)

Cross section of conductor = $\frac{current}{currentdensity}$= 0.401$mm^2$

Therefore Diameter, $\frac{\pi d^2}{4}$= $\frac{1.205}{3}$d= 0.711mm.

Closest conductor from the Standard Wire Gauge (SWG) is, 22 SWG = ø0.711 mm

For ø0.711mm,

Cross section of conductor = 0.40 mm^2

Current density ≈ 3.035 A/mm^2

These values are for bare diameter.

22 SWG HV conductor –ø0.711mm, Area of cross section = 0.40 mm^2

Current density = 3.035A/mm^2

Now insulated conductor size:

Assuming Super enamel insulation of 0.07mm

Thickness of insulated conductor = 0.711 + 0.07 ≈ 0.8 mm

Window height = 120mm

Let the end clearance be = 10+10 = 20mm

Therefore,

Winding length = 120 – 20 = 100mm

Conductor size with insulation is approximately 0.8mm, Therefore the number of turns that can fit in 100mm is,

$\frac{100}{0.8}$-1 =124

Therefore Turns/Layer = 124

No. of layers ≈ $\frac{Minimum\ turns\ per\ limb}{Turns/Layer}$

No. of layers = $\frac{675}{124}$ = 5.44≈ 6

Choosing 6 full layers to reduce operating flux density

No. of Turns on primary = 6 x 124 = 744 Turns

Radial height= (Thickness of insulated conductor x no. of layers) + (inter-layer insulation)

= (0.8x6) + (0.05x5)

≈6mm

We know that core size = 40 x 55 mm

Easily available insulation thickness = 2mil

Core to primary side clearance = 2 x 3 mm

Therefore,

Inner dimensions of HV main coil = 46 x 61 mm

Outer dimensions of HV main coil = 58 x 73 mm

Length of mean turn= 2 x [$\frac{(46+61)}{2}$+$\frac{(58+73)}{2}$]

= 238 mm

Total wire length = Length of mean turn x No. of Limbs x Turns/Limb +Tolerance (1 or 2%)

= 238 x 744 x 3 x 1.02 x 10^{-3}

= 540 m

Resistance, $R_{75} = \rho \frac{l}{a}$
Resistivity of copper (corrected to 75℃) = 0.02128

$R_{75} = 0.02128 \text{ x } \frac{0.238 \text{ x } 744}{0.397}$
$\approx 9.5\ \Omega$

$R_{28} = \frac{235+28}{235+75} \text{ x } R_{75} = \frac{263}{310} \text{ x } 9.5 = 8\ \Omega$

Bare weight of HV main winding = volume x density x 10^{-3}
= l x a x density x 10^{-3}
= 0.23 x 744 x 3 x 0.397 x 8.89 x10^{-3}
≈ 1.88 kg

Insulated weight $=\{[\frac{(thickness of insulated conductor)^2-(diameter of conductor)^2}{(diameter of conductor)^2}$ x (density ratio)] + 1} x bare weight
$= \{[\frac{(0.8)^2-(0.711)^2}{(0.711)^2} \text{ x } (\frac{1.85}{8.89})] + 1\} \text{ x } 1.88$
= 1.99 kg

Ordering quantity = Add 2% extra per conductor
= 1.26 x 1.02
≈ 2.03 kg

Stray loss $= [\sqrt{(\frac{b*\frac{turns}{layer}}{(bi*\frac{turns}{layer})-insulation}} \text{x stray factor x} \frac{h}{10})^4 \text{x} \frac{(radial conductor)^2-0.2}{9} \text{x } 100 = [\sqrt{(\frac{0.711*124}{(0.8*124)-0.07}} \text{x}0.8\text{x}\frac{0.711}{10})^4 \text{x} \frac{(6)^2-0.2}{9} \text{x } 100$

= 0.0033%

Load loss = load loss factor x bare weight x (current density)^2 + stray loss
= 2.4 x 1.88 x 3.05^2 + 1.000003 (…load loss factor for copper = 2.4)
≈ 42 W

Temperature gradient$=\frac{load\ loss}{heat\ dissipation\ factor*no.of\ effective\ surface\ areas\ available\ for\ cooling*lmt*h*no.of\ limbs} = \frac{42}{3*0.75*2*6*0.238*0.1}$

= 65.35℃< 90℃ Limit for class F Transformer

4.3 Design of LV Winding

The LV winding consists of five windings which can be split into three limbs of voltage and turns ratio as shown below.At the output two loads can be connected giving rise to two phase output.

Capacity of each LV = 750 VA

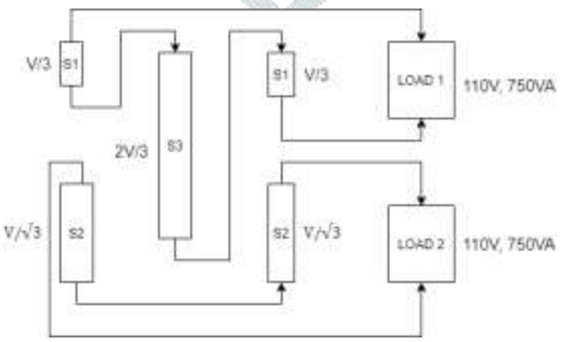

Fig. 3. Secondary winding connection

Current $= \frac{capacity}{\frac{voltage}{phase}} = \frac{750}{110} \approx 6.82$ amperes
Choose a current density of 3.3 A/mm^2 so as to reduce load losses considerably.
Therefore,

LV cross section $= \frac{current}{current density} = \frac{6.82}{3.3} = 2.067$ mm^2

Therefore, Bare Diameter = 1.622 mm
Hence, From British SWG Table (Table 10.1), we consider 16 SWG.
The corresponding diameter = 1.625 mm
Total LV cross section = $A = \frac{\pi d^2}{4}$= 2.0739 mm^2

Insulated Conductor size (using 0.07 mm Super Enamel insulation)=1.695 mm
Hence, the actual LV current density = $\frac{current}{cross\ section}$= $\frac{6.82}{2.0739}$= 3.288 A/mm^2

Volts/Turn=E/N=4.44 x 1.4 x 1980 x 10-6 x 50 =0.615

Number of turns = $\frac{LVvoltage}{volts/turn}$= $\frac{110}{0.615}$≈ 180 turns
S1=114 turn, S2 =66 turns
The Number of turns that can be accommodated has to be 180/3 = 60 turns , to avoid space constraints.
Thus, Number of Layers=3

The LV winding length = (60+1)*1.7=104mm
End Clearance=Window Height-104 mm =16 mm i.e. 8 mm on each side

Radial thickness = (Thickness of insulated conductor x no. of layers) + (inter-layer insulation)
= (1.7 x 3) + (5 x 0.05)=5.35 mm≈ 6 mm

Easily available insulation thickness = 2mil

Let the clearance core to winding = 2mm (on all sides)
Therefore,
Inner dimensions of LV winding = (outer dimensions of HV) + clearance= (58+ (2x3)) x (73+(2x3))= 64 x 79 mm
Outer dimensions of LV winding = (64+ (6x2)) x (79+ (6x2))= 76 x 91 mm

Mean turn length (LMT) = 2 x [$\frac{(64+76)}{2}$+ $\frac{(79+91)}{2}$]= 310 mm
Total wire length = Mean turn length x No of turns/limb x No of limbs x No of parallel conductors x 10^{-3}
= 310 x 180 x 10^{-3} x 2 x 1.02= 114 m

Resistance, R_{75} = ρ $\frac{l}{a}$
Resistivity of copper (corrected to 75℃) = 0.02128 (From table 10.2)
R_{75}= 0.02128 x 180 x $\frac{0.31}{2.073}$≈ 0.58 Ω

Bare weight of LV winding = volume x density x 10^{-3}= l x a x density x 10^{-3}= 310 x 180 x 2 x 2.073 x 8.89 x 10^{-3}≈ 2.06 kg

Insulated weight ={ [$\frac{(gross\ cross\ section)-(conductor\ cross\ section)}{(conductor\ cross\ section)}$x (density ratio)] + 1 } x bare weight
= {[$\frac{(1.7*1.7)-(1.626*1.626)}{(1.626*1.626)}$x ($\frac{1.85}{8.89}$)] + 1 } x 2.06= 2.1 kg
Ordering quantity = Add 1% extra per conductor
≈ 2.121 kg

Stray loss = [$\sqrt{(}\frac{b*\frac{turns}{layer}}{(bi*\frac{turns}{layer})-insulation}$x stray factor x $\frac{h}{10}]^4$x $\frac{(radialconductor)^2-0.2}{9}$x 100= [$\sqrt{(}\frac{1.626*1*60+0}{1.7-(60-0.7)}$) x 0.8 x $\frac{1.626}{10})^4$ x $\frac{8.8}{9}$x 100
= 0.026 %

Load loss = 2.4 x bare weight x (current density)^2 + stray loss
= 2.4 x 2.06 x 3.284^2 + [(0.025/100)+1]
≈ 54 W
Temperature gradient =$\frac{load\ loss}{heat\ dissipation\ factor*no.of\ effective\ surface\ areas\ available\ for\ cooling*lmt*h*no.of\ limbs}$

= $\frac{54}{2*1.75*3*0.310*0.104}$ = 60℃<90℃

Similarly, the design parameters for S3 are also calculated and the table listing the parameters calculated is shown below for all the limbs.

Table 3. Specification of the LV winding

Parameters	S1	S2	S3
Current	6.82A	6.82A	6.82A
Voltage/phase	110V	110V	110V

Net area of cross section (mm^2)	2.0739	2.0739	2.0739
Voltage (V)	110/3	110/√3	2*(110/3)
No. of turns	66	114	132
LV inner diameter	64*79mm	64*79 mm	64*79mm
LV outer winding	76*91mm	76*91 mm	76*91mm
Insulated weight	2.1kg	2.1kg	0.78kg
Radial thickness	6mm	6mm	6mm
Length of mean turns	0.31m	0.31m	.031m
Length of wire	114m	114m	42m
Resistance at room temperature	0.48ohm	0.48oh m	0.35ohm
Stray loss	0.026%	0.026 %	0.026%
Load loss	54W	54W	20W
Gradient	60°	60°	59°

V. Applications Of Leblanc Transformer

1) A configuration that is used as an interface from a single phase to the three-phase power grid and loads including five-level dc/ac converter uses Leblanc transformer/Scott transformer.
2) They are also used to supply single-phase loads such as Electrified railway systems, electric vehicle chargers or to supply residential groups using solar or wind energy connected from a three-phase network.
3) The multilevel power converter employs two single-phase voltage source converters as well as a four-wire voltage source inverter. The Leblanc transformer connects to the multilevel converter's output. The converter's structure can easily create a seven-level output wave form at the multilevel inverter's output. The Leblanc transformer is utilized to get a three phase balanced voltage systems at the power converter system's output.
4) Current and voltage asymmetry deteriorates the power system performance. The current and voltage asymmetry results in reduced efficiency, productivity and profits at the generation, transmission, distribution of electric energy and at the consumption/utilization level, respectively. This asymmetry can be deceased by making use of LeBlanc transformers.

VI. Simulation

In this analysis, simulation of a Leblanc transformer in the presence of both linear and non-linear unbalanced load is witnessed. There are three AC voltage sources considered. First one is for zero degree phase shift, second one is 120 degrees and third one is 120 degrees. The connection of Leblanc transformer is built with a three-phase power supply which carries the peak value of 600V.The three phase voltage measurement block measures the three-phase voltage and current. The LeBlanc transformer is configured using the linear transformers available from the Simulink library. The primary voltage of 600V peak and 208V as the secondary peak is selected for all the three linear transformers. At the output two loads can be connected. The simulation results show the balancing of linear unbalanced loads connected to two single phase 90 º phase shifted supply. With a linear load, the relationship between the voltage and current waveforms are sinusoidal and the current at any time is proportional to the voltage (Ohm's law). A load is considered non- linear if its impedance changes with the applied voltage. The changing impedance means that the current drawn by the non-linear load will not be sinusoidal even when it is connected to a sinusoidal voltage. Secondary voltage shows that grid current is unbalanced but remains sinusoidal since the load side currents are sinusoidal. This unbalances may cause voltage drop depending on the cable and facility impedances and cause voltage distortion as well.

The circuit diagrams and the corresponding results are shown below.

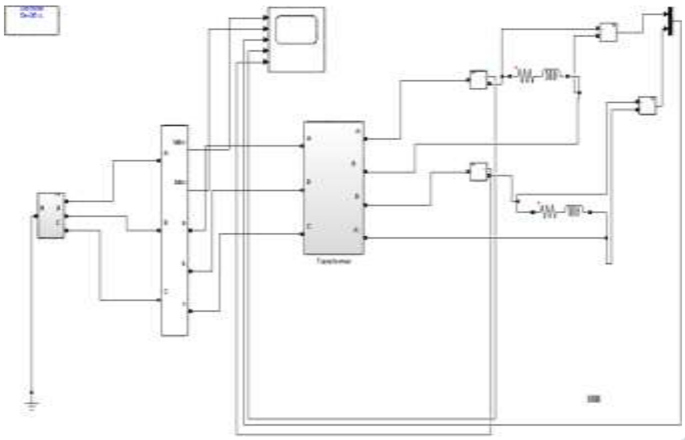

Fig 3.Simulink model for leblanc transformer with Linear unbalance load

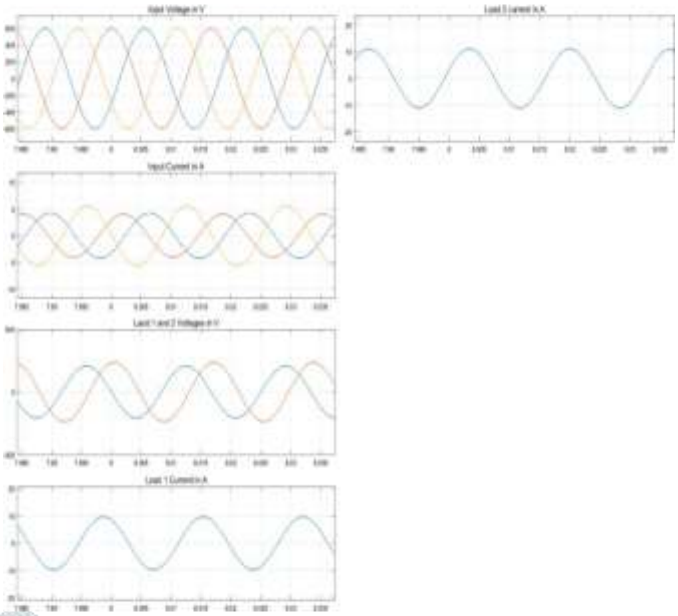

Fig. 4. Voltage and current waveforms for linear unbalanced load

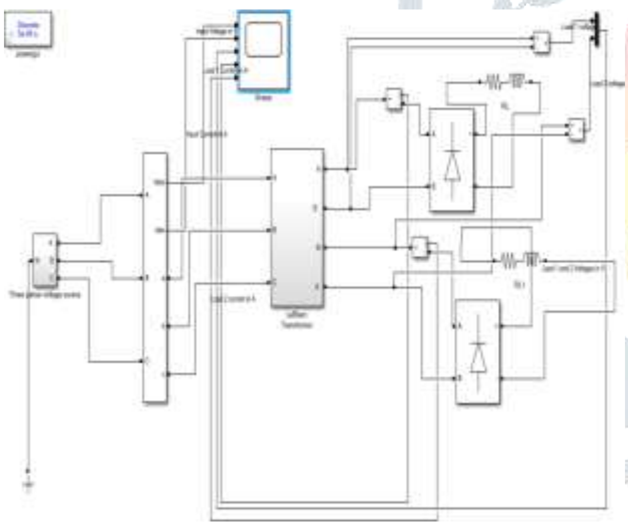

Fig. 6. Simulink model for Leblanc transformer with non-linear Unbalanced load

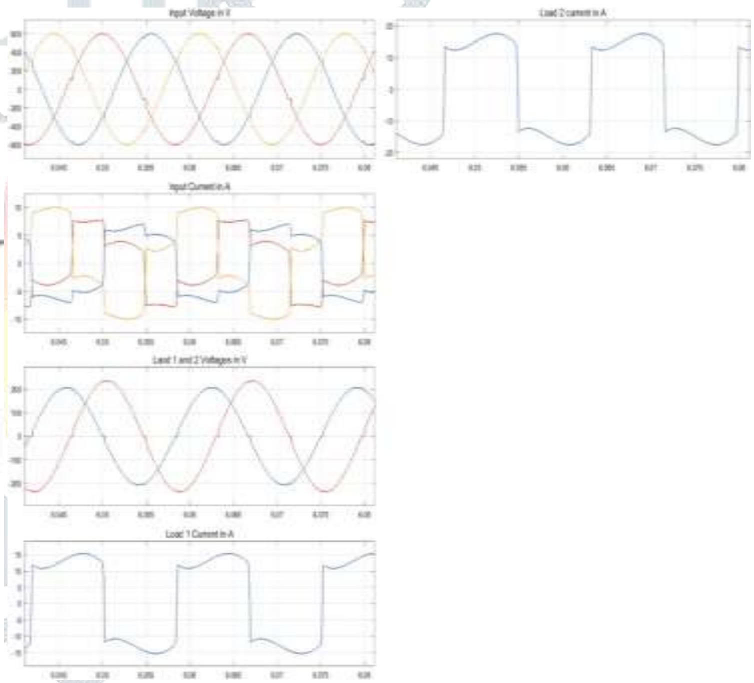

Fig 7. Voltage and current waveforms of non-linear unbalanced load

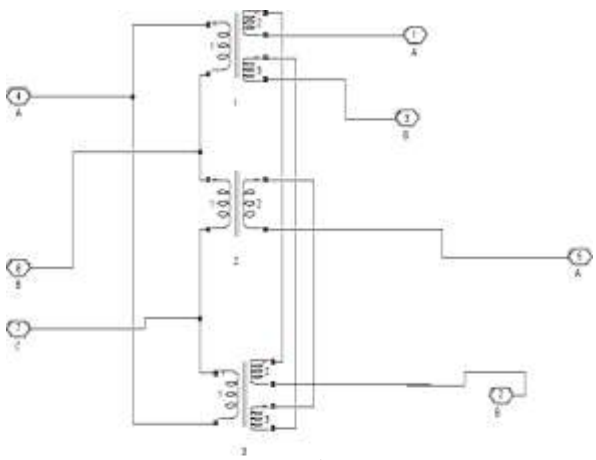

Fig. 5. Simulink model of Leblanc connection

VII. CONCLUSION

This paper provides a detailed study and design of the Class F, Leblanc connection transformer of primary – 415V, 3 phase delta connected, 1500VA capacity and secondary of two, 230V, single phase open connection, 750VA capacity, each. This transformer is predominantly used for conversion from three phases to two phase or two single phase and vice versa. It has not gained much popularity compared to Scott transformer (often used as its alternative) due to its complicated winding configuration. However, it has proven to be advantageous. It has a simpler standard core arrangement - A common core with three-limb, three-phase design is employed for the construction of a Leblanc connected transformer compared with two single - phase cores for the Scott connected transformer. Leblanc transformer is less costly to manufacture as less active materials are required for its construction. A single tank can be employed to house the Leblanc transformer hence the unit is much more economical in floor space than the Scott transformer, particularly if compared with the arrangement of two separate single-phase cores, each in its own tank. There is an additional voltage distortion in Scott connection as it does not possess a delta connection. Thus the third harmonic currents and voltage exist with this connection, while Leblanc provides an accurate conversion and elimination of the system unbalances.

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